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Thermal Performance of Radioactive Material (RAM) Packages in Transport Configuration

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ABSTRACT

Drum type packages are routinely used to transport radioactive material (RAM) in the U.S. Department of Energy (DOE) complex. These packages are designed to meet the federal regulations described in 10 CFR Part 71.[1] The packages are transported in specially designed vehicles like Safe Secure Transport (SST) for safety and security. In the transport vehicles, the packages are placed close to each other to maximize the number of units in the vehicle. Since the RAM contents in the packagings produce decay heat, it is important that they are spaced sufficiently apart to prevent overheating of the containment vessel (CV) seals and the impact limiter to ensure the structural integrity of the package. This paper presents a simple methodology to assess thermal performance of a typical 9975 packaging in a transport configuration.

INTRODUCTION

The 9975 package is designed to meet the requirements of 10 CFR Part 71. The package is normally designed considering the performance of a single unit. The performance of a package when a number of packages are placed close to each other, such as in a transport vehicle, depends upon the transport configuration. Therefore, the package must be evaluated for transport conditions to ensure the safety of the packaged material.

9975 Package

The 9975 package is a very versatile Type B package which is certified to transport and store a wide spectrum of radioactive materials. In fact it is the only Type B package that is certified to transport plutonium oxide. The 9975 has double containment, namely, primary containment vessel (PCV) and secondary containment vessel (SCV) and a lead shield for added protection against material and radiation leakage. The packaged is designed to ship heat sources up to 19 watts.[2] Figure 1 is a schematic of the 9975 package. The package is about 36-inch high and 18-inch in diameter. The package is certified to transport several content configurations including Food-Pack cans, and 3013 containers with LLNL, Rocky Flats, SRS cans, etc. Contents for the package are placed within the PCV, which is closed with a cone seal plug that has a set of double O-rings.

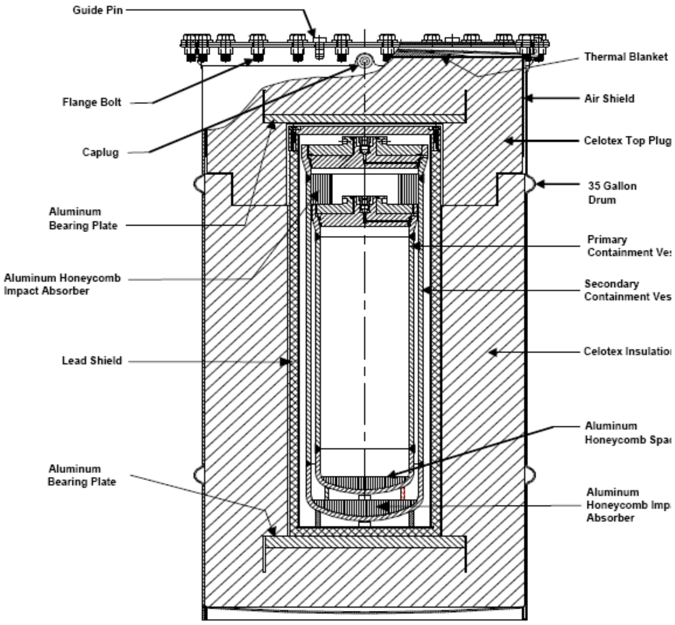

Figure 1 – 9975 Packaging

Package Functional Requirements

An important design limitation on 9975 is the maximum temperature of Celotex that acts as an impact absorbing and fire insulating medium. The maximum temperature limit is 250°F. The Celotex temperature mainly depends upon the content heat generation rate, insulation thickness, and the ambient conditions. The ambient conditions include the air temperature and the surrounding conditions that affect convection and radiation heat transfer.

Other critical components of the 9975 package are its containment vessels (PCV and SCV) and their seals. The containment vessel seals are O-rings that must be maintained below certain temperature for the seals to remain leaktight. Similarly the impact limiter mechanical properties must not degrade due to high temperatures from internal heating. Table 1 gives the temperature limits for these components for their structural and thermal integrity.

Table 1: Temperature Limits ºF

Component	Long Term
Impact Limiter	250
O-Rings	400
PCV Wall	300

Transport Configurations

Figure 2 shows a typical configuration of RAM packages in a transport vehicle. The arrangement in Figure 2 shows 4 packages on a Cargo Restraint Transporter (CRT) in a 1-high configuration. CRTs are then placed side by side and in multiple rows depending upon the size and the contents of the packages. A 2-high configuration will have 2 groups of 4 packages stored on top of each other with a middle separator. The CRTs are then firmly secured to the vehicle floor. Figure 3 shows a 5 package layout in a CRT. 9975 packages are transported in this configuration.

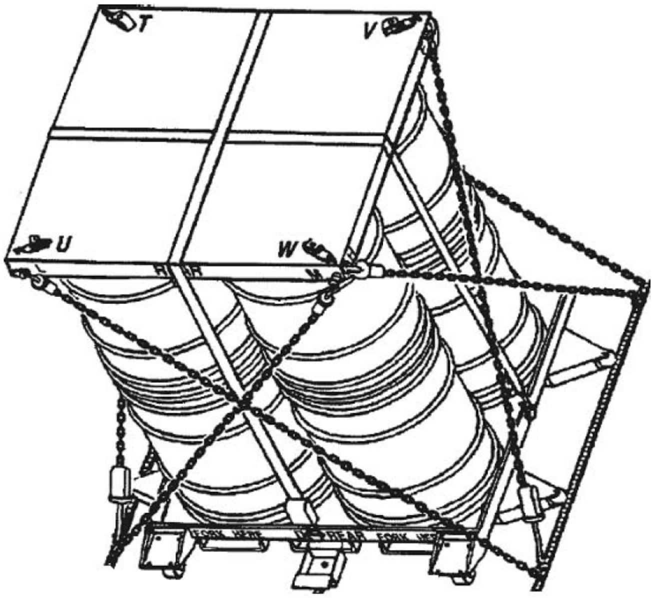

Figure 2 – Transport Configurations

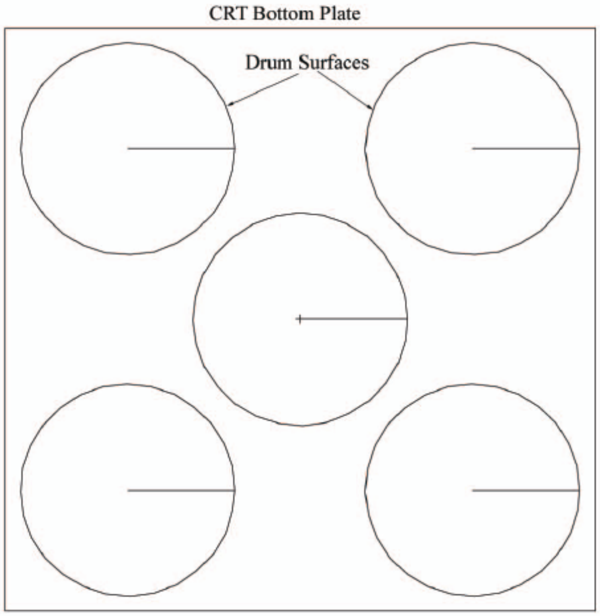

Figure 3 – 9975 Transport Configurations

SST Ambient Conditions

The transport vehicles are equipped with cooling systems to maintain ambient air temperatures that do not result in exceeding the component temperature limits of the package. In transit, air temperatures are maintained between 50-120°F. During winter season, 65°F is typical. During summer season, 100°F is typical. This paper analyzes two vehicle ambient air temperatures, i. e. 100°F and 120°F.

Five Packages Transport Configuration

The 9975 packages are transported fastened onto a CRT in a group of 5. Multiple CRTs are placed side by side in the transport vehicle until the required number is reached. The packages touch each other at the flanges and are held together with the CRT top and bottom sections fastened as shown in Figure 2. The CRTs loaded with 9975 are stacked only 1-high. Figure 4 gives a view of the 5 packages without the CRT top section and shows the relative spacing between the packages which is necessary for the convection and radiation cooling of the packages. It is clear that the spacing is the smallest where the flanges are touching.

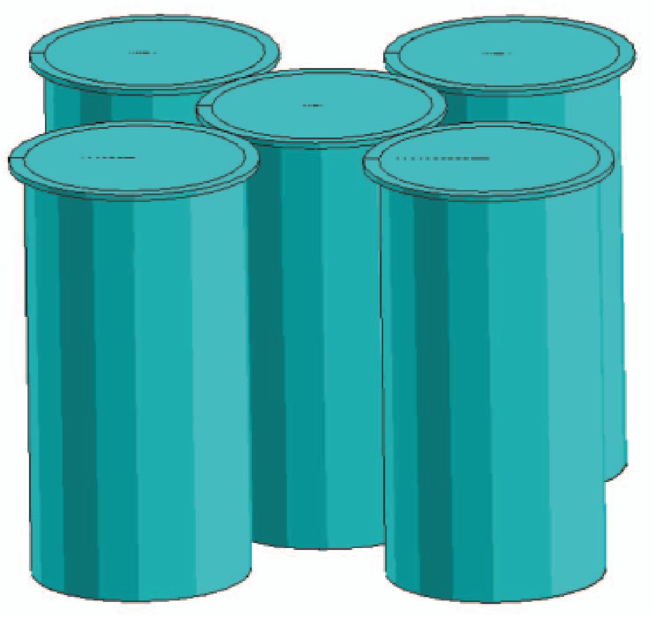

Figure 4 – 5 Package Configuration on a CRT

The above transport configuration alters the surroundings of the package in the middle by restricting the flow of cooling air around the packages. The surface of the middle drum is also not fully exposed to radiation cooling either. This paper analyzes the temperature distribution for the middle package when multiple CRTs are placed in rows. Following model configurations will be analyzed using detailed finite element methods to estimate the temperature of the critical components inside the package:

1. Scoping analysis of a single package in 3D geometry configuration without considering the impact of air flow restriction.
2. 2D model validation.
3. Five packages in 2D configuration with air trapped at minimum spacing locations.

MATHEMATICAL MODEL AND COMPUTATIONS

The computational thermal models solve the following steady state heat transfer equation in cylindrical coordinates.

$$k_1 \frac{\partial^2 T}{\partial r^2} + \frac{k_1}{r}\frac{\partial T}{\partial r} + k_2 \frac{\partial^2 T}{\partial z^2} + q''' = 0 \quad (1)$$

Where q''' is the volumetric heat generation by the fissile material per unit time, k_1 and k_2 are the thermal conductivities of the materials in the r and z directions, and T is the temperature. k_1 and k_2 are different for some orthotropic materials but they are same for the isotropic materials. In addition, for some materials, thermal conductivity is a function of temperature also.

Scoping Analyses

Scoping analyses were performed to simplify the true 3D axisymmetric models to 2D models. The 9975 package is a rather complex mechanical device with multiple materials, metal surfaces, gaps, vessels, and boundary conditions. To analyze the 5-package transport configuration using 3D models would be quite challenging and expensive. The scoping analyses help in identifying the upper bound internal heat generation per unit length of the package height for a simpler 2D model which is much easier to analyze for multiple packages in storage configuration.

Package Spacing

The packages are secured between the top and bottom CRT sections as shown in Figure 2. The bottom CRT section is then secured to the SST floor during transportation. As shown in Figure 2, no spacers are used to keep the drums apart but instead they touch each other at the flanges. If the spacing between the drum surfaces is large enough that the boundary layers (BL) between the drums do not interact, natural convection cooling will be effective to cool the packages. The spacing should be more than 2 times the maximum BL thickness on the side of the drum. If the flow is laminar for natural convection, the BL thickness on a vertical flat plate can be approximately calculated by using Equation 1.[3]

$$\frac{\delta}{y} = 3.93\,\mathrm{Pr}^{-1/2} \times (0.952 + \mathrm{Pr})^{1/4}\, Gr_y^{\,-1/4} \quad (2)$$

where:

δ is the BL thickness
y is the distance from the leading edge
Pr is the Prandtl number
Gr_y is the Grashof number at location y

3D MODEL ANALYSES

3D analyses are for the ideal transport conditions where air flow around the package is not obstructed by other packages. This means that the packages are placed sufficiently apart from each other such that the convection cooling is effective but the radiation cooling may not. The radiation cooling is affective only if the cooler surfaces in the surroundings are sufficiently away from the package such that all the thermal radiations from the package are absorbed by the surrounding surfaces. The main purpose for analyzing this configuration is to estimate the heat loss from the drum surface which will help in estimating source power per unit length for the 2D models and to estimate the convection BL thickness. This analysis will help in building 2D models for the transportation configuration with multiple drums on the CRT as shown in Figure 3. Figure 5 shows an axisymmetric finite element model of the single package configuration. The package geometry is cylindrical and can be accurately modeled using an axisymmetric model. Only half of the model is shown and the edge on the left hand side is the center line of the model.

The finite element analyses are performed using Patran/Thermal software.[4]

Boundary Conditions and Model Parameters:

1. The bottom of the package is adiabatic.
2. The heat generation is 19 watts.
3. The package in the middle is surrounded by similar packages such that the radiation loss from the side of the drum is ineffective.
4. Heat is lost through natural convection and radiation from the top of the package.
5. There is large enough head space above the package that radiation cooling from the top of the package is effective. This is a reasonable assumption because the SST has sufficient head space so as to transport packages in 2-high configuration.
6. The HVAC system in the SST is inoperative and the ambient temperature is between 100°F and 120°F.

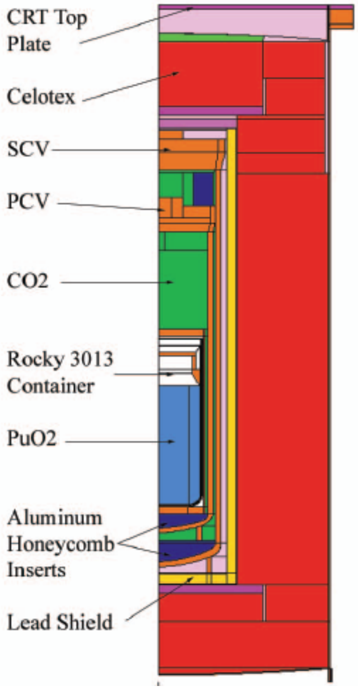

Figure 5 – Single Package on the Floor

The results for the two ambient temperatures are summarized in Table 2.

Table 2 – Maximum Component Temperatures (°F)

Ambient Temp (°F)	PCV O-rings	PCV Wall	Celotex
100	161	183	158
120	180	202	177

The boundary layer (BL) thickness is maximum at the top of the drum, y = 36 inches. If the Rayleigh Number, Ra, which is equal to Gr x Pr, is less than 10^9, the flow is laminar and Eq. 2 can be used to calculate the BL thickness. Table 3 gives the BL thicknesses for the two temperatures. If the separation between the drums is more than 2 times the BL thickness, convection cooling will be affective.

Table 3 Boundary Layer Thickness (Inches)

Ambient Temp (°F)	Gr	Pr	Ra (Gr x Pr)	δ
100	3.73×10^8	0.742	2.77×10^8	1.35
120	3.29×10^8	0.728	2.40×10^8	1.40

The BL thickness values in Table 3 show that the boundary layers on the two packages shown in Figure 3 will interact and the convection cooling will not be fully effective at some locations. This interaction will be addressed by using 2D models discussed in the later sections.

The 3D model analysis shows that the heat loss from the package side is about 16.2 watts. This represents about 85% of the source strength. The heat loss from the mid section of the package cylindrical surface is fairly uniform as shown in Figure 6. This observation is helpful in building a 2D model where the heat source strength is modeled as uniform in the package axial direction.

Figure 6 – Temperature Profiles of the 3D Package

2D MODEL ANALYSES

Model Validation

The 2D models help in estimating the impact of interaction between drums when placed close to each other in the transport. However, validation of the 2D model is necessary because it represents a significant simplification of the axisymmetric model. The 2D model assumes that the heat source is uniformly distributed along the entire length of the model while the axisymmetric model has heat source concentrated in the bottom half of the package. The concentration of the heat source in the 3D model has increased thermal effect in the bottom half of the package as compared to the 2D model. To validate the 2D model, the heat source strength is increased until the primary containment vessel (PCV) temperature matches with the maximum PCV wall temperature in the full 3D model. For validation, no consideration is given for the package BL interaction effect that is present in an actual storage condition. Also, the boundary conditions for the 3D axisymmetric model are altered to match the 2D model. The top and bottom of the 3D model are kept adiabatic to match the 2D model. In addition, no radiation losses from the package side are considered to match the transport storage environment.

The 2D model is essentially a 1-ft thick slice through the mid section of the package. All the cylindrical components with correct thicknesses are modeled for accuracy. Radiation heat transfer in the annular spaces is considered. However, no convection effects are modeled due to narrow spaces. This simplification has been found to be justifiable from the validation of the actual thermal tests. Figure 7 shows the material representation of the 2D model of the package.

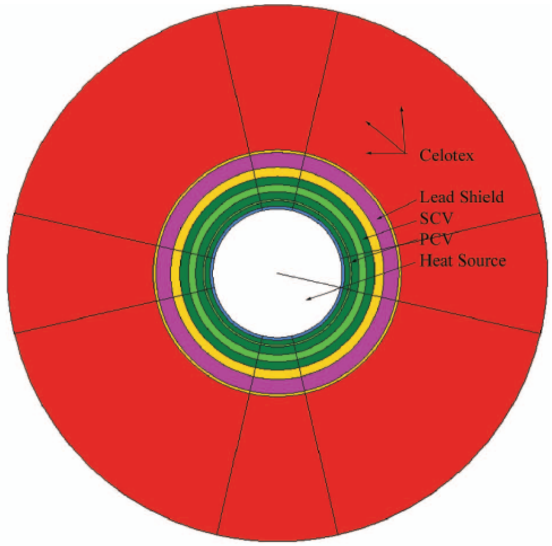

Figure 7 – 2D Model for Model Validation

The results of the validation with ambient temperature of 38°C (100°F) are shown in Table 4. The PCV and Celotex temperatures for the 3D model are the maximum values for the package.

Table 4 – 2D Model Validation Results

Model	Heat Source (Watts)	PCV Wall ºF	Celotex ºF
3D Model	19.0	185	160
2D Model	20.0	185	155

The validation results are very good considering the model simplification from 3D to 2D geometry. The revised heat source of 20 watts will be used in the 2D models discussed below. For the 2D model, the heat source strength is per unit length of the package. This is equal to 6.67 watts/ft based on the 914.4 mm (36") height of the package.

Model Analysis with BL Interaction Effects

In the 2D model, the five packages are touching each other at the flanges and are stacked 1-high. Since the spacing between the package surfaces is only 2.5 inches and each of the boundary layer is 1.34 inches thick, the boundary layers will interact and restrict the convection cooling. In addition, the spacing between the drums at the drum hoops is further reduced thus making the interaction between the boundary layers even more pronounced. Since it is difficult to model air flow in this restricted space precisely, it is assumed that the air is completely trapped in this space and therefore, there is no convection or radiation cooling in this affected zone. The restricted air space is extended until the longitudinal spacing between the surfaces is at least 3 inches. The 2D model geometry is shown in Figure 8. The restricted convection regions are clearly marked in Figure 8.

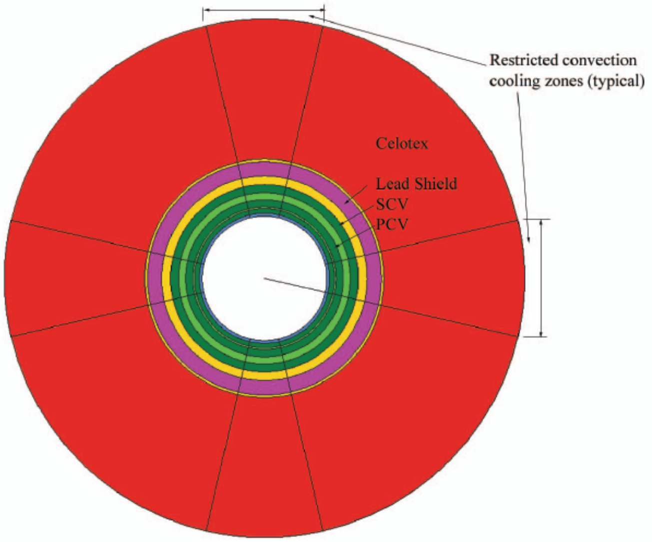

Figure 8 – 2D Model for Restricted Convection Cooling

Boundary Conditions

For the 2D models, only the curved surface of the drums exchanges heat with the transport vehicle environment. For the packages secured as shown in Figures 2 and 3, it is apparent that the package surfaces see each other and exchange thermal radiations. It is therefore reasonable to assume that the temperatures of the drum surfaces are equal for all the drums. The radiation cooling is therefore absent. However, the convection cooling is available around the drum surface except in the restricted air flow space where the air is assumed trapped.

The above 2D model represents a normal package model with a heat source uniformly distributed in the mid region and stored in upright position. In this region of the package, radial heat transfer is dominant (see Figure 6) and, therefore, a 2D model should be a reasonably good approximation of the 3D model. The convection correlations used are the same as in the full 3D axisymmetric models.

CRT SPACING ANALYSIS

The BL thickness calculations show that the minimum spacing between the drums must be at least 2.70” to ensure convective cooling. The CRT bottom section geometry in Figure 2 shows that the CRT footing geometry is such that it certainly maintains spacing more than 2.7 inches between the CRT’s. Therefore, convection cooling is not restricted.

RESULTS

2D Model Results

The results of the analysis when the packages are touching each other are given in Table 5.

Table 5 – 2D Model Analysis Results

Ambient ºF	PCV Wall ºF	O-rings ºF	Celotex ºF
100	191	191	158
120	210	210	178

In a full 3D model, O-ring temperatures are normally smaller than the maximum PCV wall temperatures because the O-rings are away from the heat source as compared to the PCV wall. However, since the 2D model cannot model the O-rings region of the package separately, O-ring temperatures are conservatively assumed to be the same as the PCV wall temperature. Celotex temperatures are well within the limit of 250˚F and are shown in Figures 7. The PCV wall temperatures, shown in Figure 8, are also well below the 300°F limit. A temperature increase of about 8°F for the PCV wall can be attributed to the lack of cooling on the drum surface in the restricted convection cooling regions.

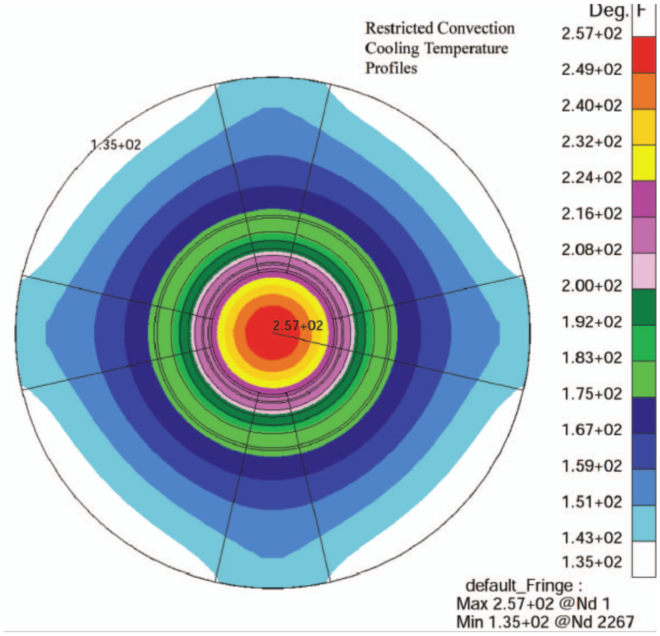

Figure 7 – Celotex Temperatures with Air at 120°F

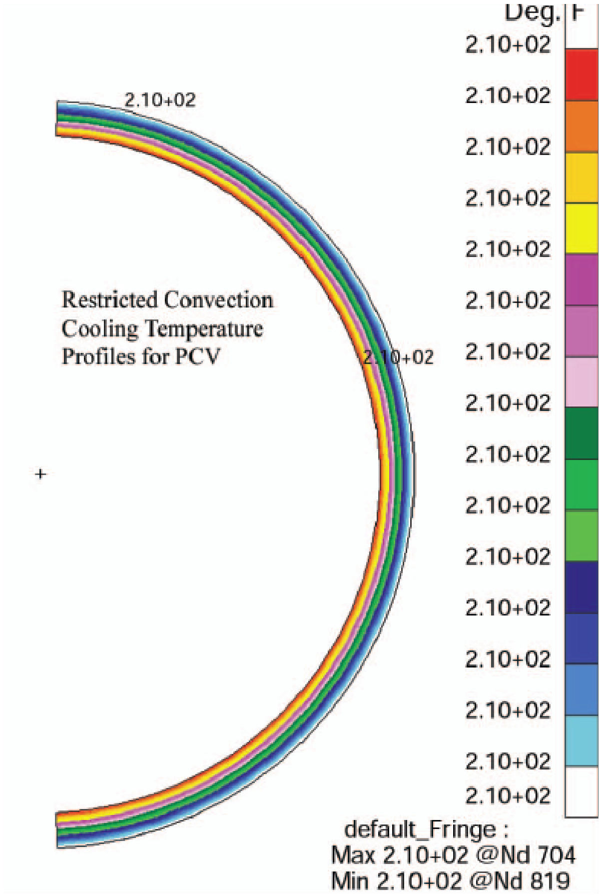

Figure 8 – PCV Temperatures with Air at 120°F

DISCUSSION

Type B radioactive material packages are transported in SST where multiple packages are stored in close proximity of each other. This stored configuration is different from the package design requirements where only one package is considered exposed to 100°F solar conditions. The analyses in this paper show that such packages can be safely transported in the CRT transport configuration and the component temperatures are well within the package performance requirements.

The analyses show that the air temperature has to rise well above 120°F to challenge the design limits of the critical components.

CONCLUSIONS

1. The analyses show that Type B radioactive material package 9975 meets all the package thermal performance requirements during transportation.
2. The small increase of 8°F in component temperatures due to close proximity of other packages will not impact the HAC performance of the package in an accidental fire scenario.
3. The CRT spacing is sufficient to maintain effective convection cooling of the packages.

DISCLAIMER

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