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Thermal Analysis of a 9975 Package in a Facility Fire Accident

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ABSTRACT

Surplus plutonium bearing materials in the U.S. Department of Energy (DOE) complex are stored in the 3013 containers that are designed to meet the requirements of the DOE standard DOE-STD-3013. The 3013 containers are in turn packaged inside 9975 packages that are designed to meet the NRC 10 CFR Part 71 regulatory requirements for transporting the Type B fissile materials across the DOE complex.[1] The design requirements for the hypothetical accident conditions (HAC) involving a fire are given in 10 CFR 71.73. The 9975 packages are stored at the DOE Savannah River Site in the K-Area Material Storage (KAMS) facility for long term of up to 50 years. The design requirements for safe storage in KAMS facility containing multiple sources of combustible materials are far more challenging than the HAC requirements in 10 CFR 71.73. While the 10 CFR 71.73 postulates an HAC fire of 1475°F and 30 minutes duration, the facility fire calls for a fire of 1500°F and 86 duration. This paper describes a methodology and the analysis results that meet the design limits of the 9975 component and demonstrate the robustness of the 9975 package.

INTRODUCTION

The 9975 package is designed to meet the requirements of 10 CFR Part 71. The package is designed for transporting RAM across the DOE complex and not for long term storage. The performance of a package when a package is stored for storage depends upon the storage conditions. To ensure package safety the storage conditions must include both normal and accident conditions. The accident conditions facility fire conditions considering the flammable material that might exist and the duration of the fire.

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.[2] 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.

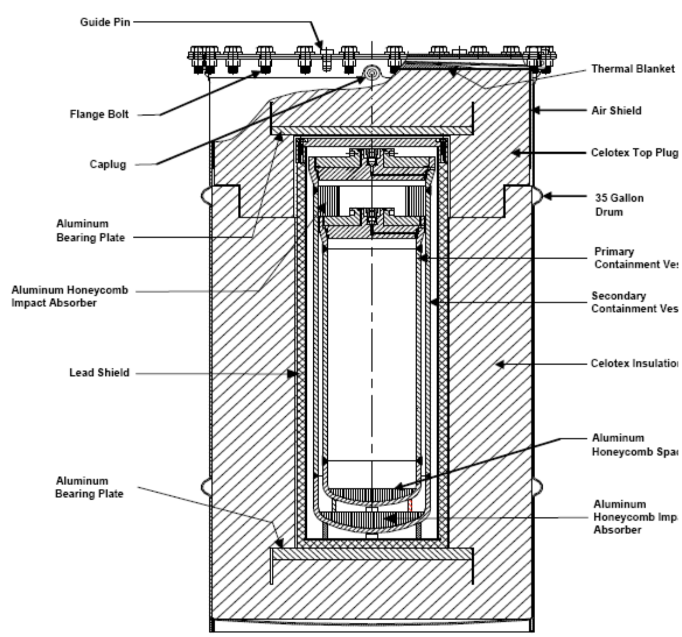

Figure 1 – 9975 Packaging

Package Functional Requirements

Critical components of the 9975 package during fire conditions are its containment vessels (PCV and SCV), the

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seals and the lead shield. The containment vessel seals are O-rings that must be maintained below certain temperature for the seals to remain leaktight. During fire, the impact limiter cane fiberboard (Celotex™) provides protection from excessive heating of these components. Under these conditions, good fiberboard and its char provide the required protection. Table 1 gives the temperature limits for these components for their structural and thermal integrity.

Table 1: Temperature Limits ºF

Component	Temperature Limits
O-Rings	400
PCV & SCV	300
Lead Shield	622

The package temperature design limits for the O-rings, PCV/SCV, and the lead shielding are 400ºF, 300ºF, and 622ºF respectively.[2] The O-ring design limit is based on 1000 hrs life at 400ºF and this is reduced to 300ºF for a continuous service for 10 years in KAMS following an assumed 2-year shipping period.

METHODOLOGY

The 9975 package is certified for the hypothetical accident conditions of a 30-minute 1475ºF (800ºC) fire. The fire in the KAMS facility is 86-minute long and 1500ºF hot. Since no testing has been performed for the KAMS fire, modifications are made in the SARP fire model to simulate the KAMS fire. The basic modification in the model was to break the 86 minutes duration into three intervals so as to be able to use the 9975 SARP fiberboard properties rather than extrapolate the properties of the 30-minute model. To account for the uncertainties, the thermal models were made conservative by using decomposition temperature commensurate with the maximum decomposition rate of the fiberboard and by not taking credit for the insulating properties of the degraded fiberboard called *char* that would be present in the real fire situation.

Since the amount of fiberboard that would be lost during the 86-minute fire is not known accurately, a conservative approach is adopted to assess the component temperatures and the fiberboard loss. There are three distinct temperatures that are observed during thermo-gravimetric analysis of the fiberboard samples. These are: the start of decomposition at 410ºF, the maximum decomposition at 759ºF, and the final decomposition of remaining organic materials at temperature 932ºF and above.[3, 4] Based on these observations, if 759ºF is used as the threshold temperature at which the fiberboard is lost, a conservative (higher) estimate of the component temperatures and the extent of fiberboard loss will be obtained.

The 9975 Safety Analysis Report for Packagings (SARP) 30-minute fire model was validated against an actual fire test.[5] The fire test was performed on a prototype in a radiant furnace under controlled condition. The fiberboard temperatures were monitored for the entire duration of the test. Following the test, a lumped model of the fiberboard was constructed where the fiberboard thermal properties were varied to match the observed temperature during the test. This reverse problem was solved by trial and error and avoided the complex chemical and thermal decomposition behavior of the fiberboard. The lumped thermal properties were derived for the undegraded fiberboard and the *char*.[5] These lumped properties of the undegraded fiberboard[1] and the *char* are used in the analysis in this paper. The lumped thermal properties approach preserves the important characteristics of the fire model in the 86-minute model discussed here. The resulting thermal models for the 86-minute fire are:

Model 1: Initial conditions
Model 2 of the fire: 0 to 30 minutes
Model 3 of the fire: 30 to 60 minutes
Model 4 of the fire: 60 to 86 minutes
Model 5 of the fire: postfire cooldown

The fire analysis was initiated from a steady state with ambient temperature of 137°F. For the fire analysis, the drum was upright and exposed to an ambient temperature of 1500ºF for the first 86 minutes and 137ºF thereafter. For all analyses, a 19 watt total decay power was uniformly distributed over the volume of the Pu oxide as an internal heat source. A short description of the 5 models is given below.

Model 1:

1. The bottom surface is adiabatic.
2. There is radiative heat transfer from drum sides and top to the ambient.
3. There is natural convection heat transfer from the drum sides and top to the ambient.
4. New fiberboard properties are applied to the whole fiberboard in the drum.

Model 2 (0 to 30 minutes):

1. There is forced convection from all surfaces of the drum. The convection coefficients, based on a 20 m/s air velocity, are: 5.9 Btu/hr-ft^2 ºF for the top and bottom of the drum and 3.0 Btu/hr-ft^2 ºF for the side of the drum.
2. There is thermal radiation heat transfer from all surfaces of the drum to the ambient.
3. The ambient temperature is 1500ºF.
4. Fire phase fiberboard properties are applied to the fiberboard in the drum

[1] The lumped properties for the undegraded fiberboard are different from the new fiberboard.[5]

Model 3 (30 to 60 minutes):

1. There is forced convection from all surfaces of the drum. The convection coefficients, based on a 20 m/s air velocity, are: 5.9 Btu/hr-ft^2 ºF for the top and bottom of the drum and 3.0 Btu/hr-ft^2 ºF for the side of the drum.
2. There is thermal radiation heat transfer from all surfaces of the drum to the ambient.
3. The ambient temperature is 1500ºF.
4. Fiberboard material with temperatures greater than or equal to 759°F in Model 2 is assumed 'char' and replaced with air.
5. Radiation allowed in new air space ('char' space).
6. Remaining fiberboard (< 759°F) retains fire phase fiberboard properties.

Model 4 (60 to 86 minutes):

1. There is forced convection from all surfaces of the drum. The convection coefficients, based on a 20 m/s air velocity, are: 5.9 Btu/hr-ft^2 ºF for the top and bottom of the drum and 3.0 Btu/hr-ft^2 ºF for the side of the drum.
2. There is thermal radiation heat transfer from all surfaces of the drum to the ambient.
3. The ambient temperature is 1500ºF.
4. Fiberboard material with temperatures greater than or equal to 759°F in Model 3 is assumed 'char' and replaced with air.
5. Remaining fiberboard (< 759°F) retains fire phase fiberboard properties.

Model 5 (Postfire cooling):

1. There is thermal radiation from the top, sides, and bottom of the drum to the ambient.
2. There is natural convection from the top and sides of the drum to the ambient.
3. The ambient temperature is 137ºF.
4. Fiberboard material with temperatures greater than or equal to 759°F at the end of Model 4 is assumed 'char' and is left in the model. In addition, the char removed in Model 4 is replaced with char in this postfire phase. The combined char space is assigned char properties. The purpose of this model change is to add additional thermal inertia for the postfire phase.
5. Remaining fiberboard (< 759°F) retains fire phase fiberboard properties.
6. Fire phase properties are applied to the whole fiberboard not marked as 'char' space.

MATHEMATICAL MODEL AND COMPUTATIONS

The computational thermal models solve the following transient state heat transfer equation in cylindrical coordinates for axisymmetric geometry.

$$\rho c \frac{\partial T}{\partial t} = k_1 \frac{\partial^2 T}{\partial r^2} + \frac{k_1}{r}\frac{\partial T}{\partial r} + k_2 \frac{\partial^2 T}{\partial z^2} + q''' \qquad (1)$$

Where q''' is the volumetric heat generation by the fissile material per unit time, k_1 and k_2 are the temperature dependant 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. This simplified model avoids the complex kinetics of the fiberboard as discussed above in the methodology section. The partial differential equations was numerically solved using Patran/Thermal software.[6]

THERMAL MODELS

Figure 2 shows an axisymmetric finite element model of the 9975 package. The package geometry is cylindrical and can be accurately modeled using an axisymmetric model. The axisymmetric 9975 models contain roughly 14,800 nodes. Only half of the model is shown and the edge on the left hand side is the center line of the model. This model was used for the Model 1 and Model 2 conditions. However, in Model 2 the fiberboard thermal properties are the derived properties from the validated fire model.

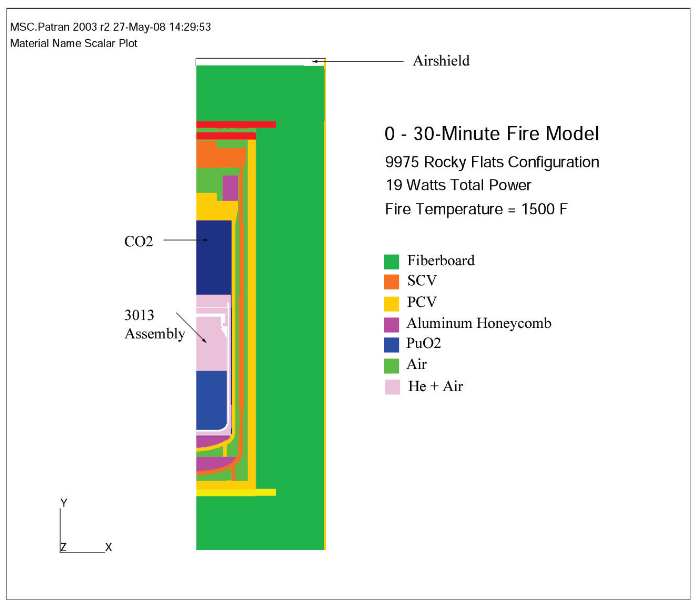

Figure 2 – Model Geometry for the 0 -30 minutes

As indicated in the introduction section above, the decomposition temperature of 759ºF was chosen as the threshold temperature for removing the fiberboard from the model. For the ease of modeling, fiberboard temperature greater than 750ºF is used to replace the burnt fiberboard (*char*) with air. The model for the 0 – 30 minutes step is identical to the thermal model in the 9975 SARP.[2] This model was benchmarked against actual tests and the fiberboard thermal properties were adjusted to match the test results. This model did not simulate any loss of fiberboard. However, in the models for the 30 – 60 minutes and 60 - 86 minutes steps, the fiberboard whose temperature was greater than 750ºF in the immediately preceding step was replaced with air. Also, since the amount of char lost during the entire fire transient is not known accurately, the char layer removed during the 60 – 86 minutes step is put back for the postfire cooldown phase. This replacement of air with char results in higher component temperatures.

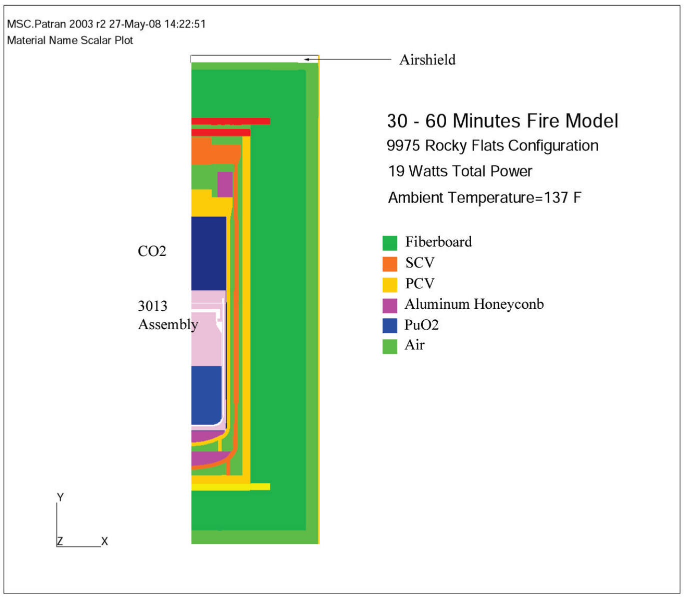

Figure 3 – Materials for the 30 to 60 minutes model

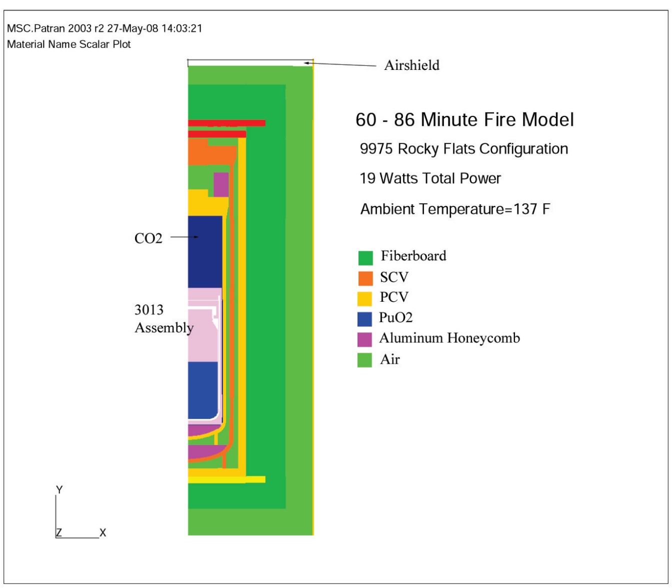

Figure 4 – Materials for the 60 to 86 minutes model

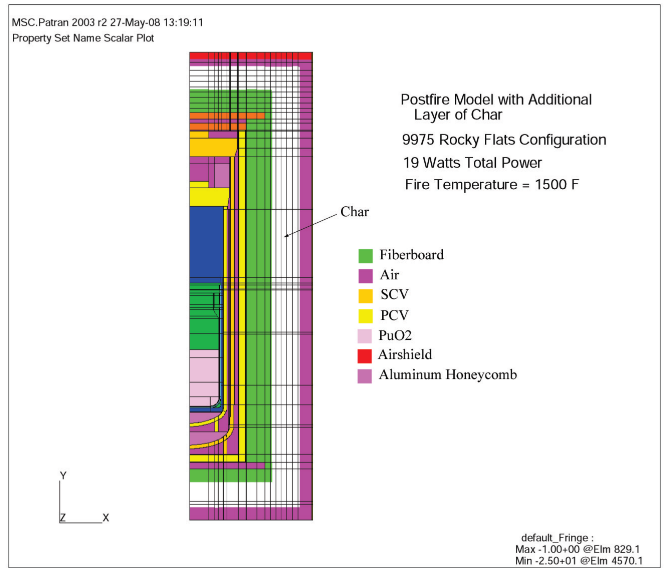

Figure 5: Materials for the postfire phase model

SENSITIVITY ANALYSIS

A sensitivity analysis was performed in which the pyrolysis temperature was assumed to be 410°F. The analysis steps are similar to the case when the pyrolysis temperature was 759°F. This was done as an extreme case to assess the impact on the CV and the O-ring temperatures. The sensitivity analysis showed that all the fiberboard was lost. However the CV O-ring temperatures were found to be within the design limits.

RESULTS

Table 4 gives the temperatures for the PCV/SCV and their O-rings at various times during the 86-minute fire. Table 5 gives the temperatures during the postfire cooling. The results show that the maximum component temperatures are below the design limits indicated in Section 2.0.

Table 4 - 86-Minutes Fire Results

After 86-Minutes Fire (ºF)		Maximum Postfire (ºF)	
O-Rings	PCV/SCV	O-Rings	PCV/SCV
202	232	258	295
194	226	258	292

Table 5: Postfire Results

Time (Hrs)	PCV (ºF)	PCV O-Rings (ºF)	SCV (ºF)	SCV O-Rings (ºF)	Lead Shielding (ºF)
0.00	220	193	202	186	192
0.50	220	193	202	186	194
1.00	221	193	207	188	211
1.4333	226	194	225	191	248
1.68	236	195	250	193	287
1.93	250	197	270	199	305
2.18	262	199	283	207	311
2.43	271	204	289	217	313
2.68	278	209	292	226	312
2.93	283	215	292	235	307
3.00	283	218	292	237	306
3.50	287	230	288	248	292
4.00	289	240	283	255	278
4.50	289	248	277	258	268
5.00	287	254	272	258	258
5.50	285	257	268	256	250
6.00	282	258	263	255	243
6.5	279	258	255	252	236

The char depths at the end of 86 minutes are summarized in Table 6.

Table 6 – Char Depth

Location	Time (minutes)				Un-charred Fiberboard (inches)
	0	30	60	86 + Cooldown	
Side	0	0.90	1.95	2.95	1.88
Top	0	1.05	1.85	2.00	1.70
Bottom	0	0.934	1.90	2.80	1.00

Temperature profiles predicted by the models during the three phases of the KAMS fire analysis are shown in Figures 7 – 9. Figure 10 shows the temperature variation for the PCV, SCV, and their O-rings during the fire and the postfire periods when the surveillance cane fiberboard properties are used. Figure 11 shows the fiberboard char thickness during the fire for the case when threshold temperature is taken as 759ºF.

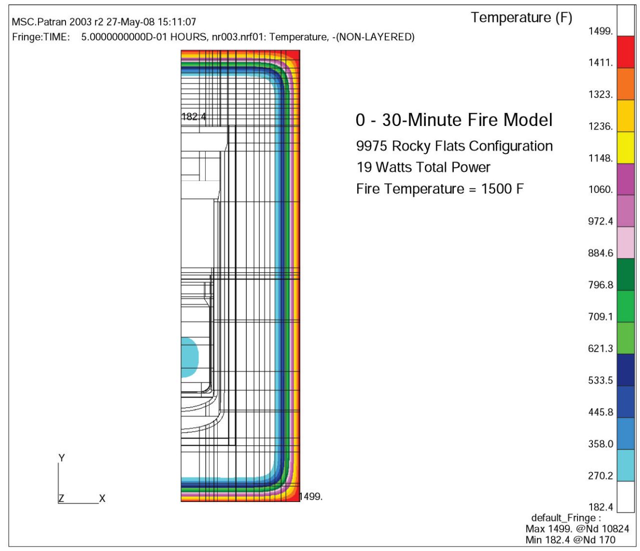

Figure 6 – Temperature profile after 30 minutes of KAMS fire

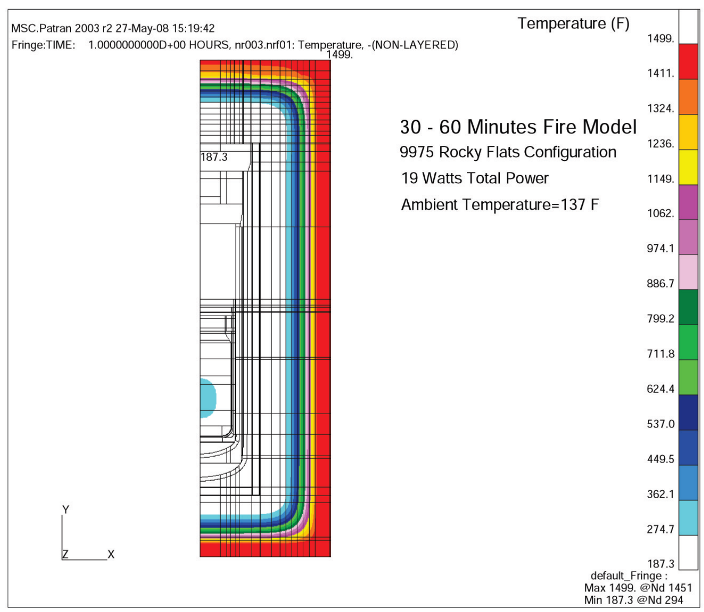

Figure 7 – Temperature profile after 60 minutes of KAMS fire

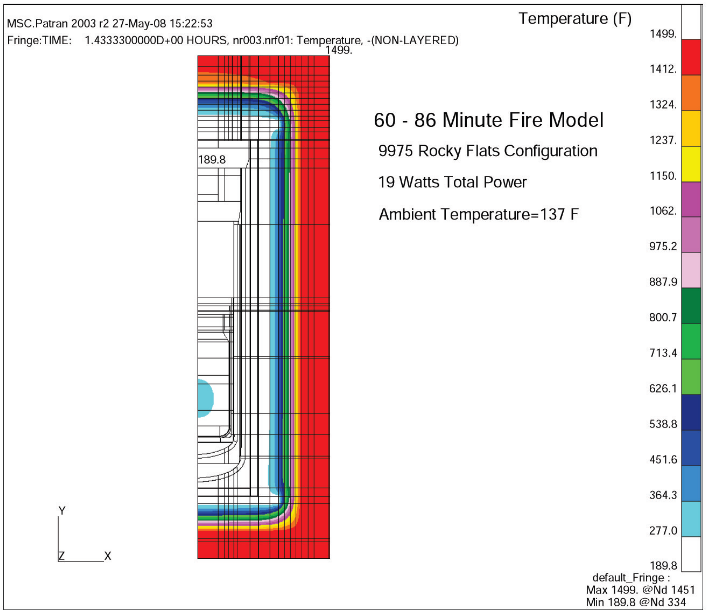

Figure 8: Temperature profile after 86 minutes of KAMS fire

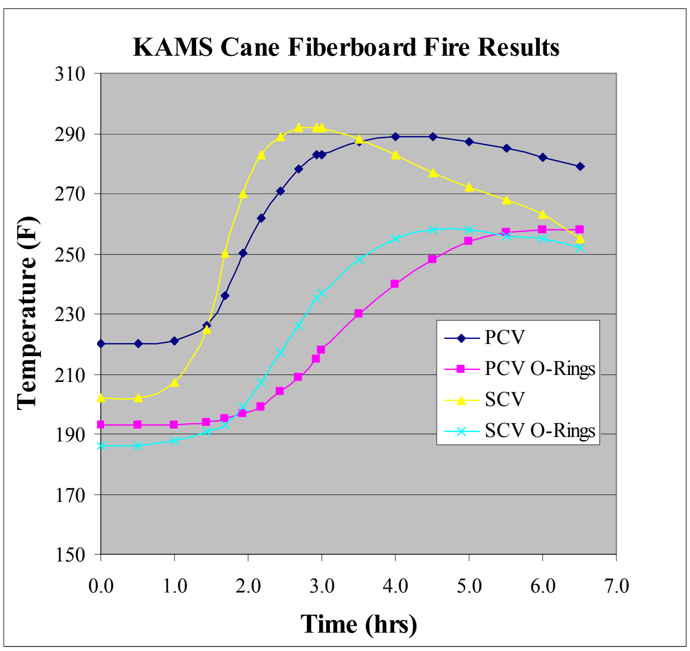

Figure 9: Temperature Curves for the Containment Vessels and O-Rings

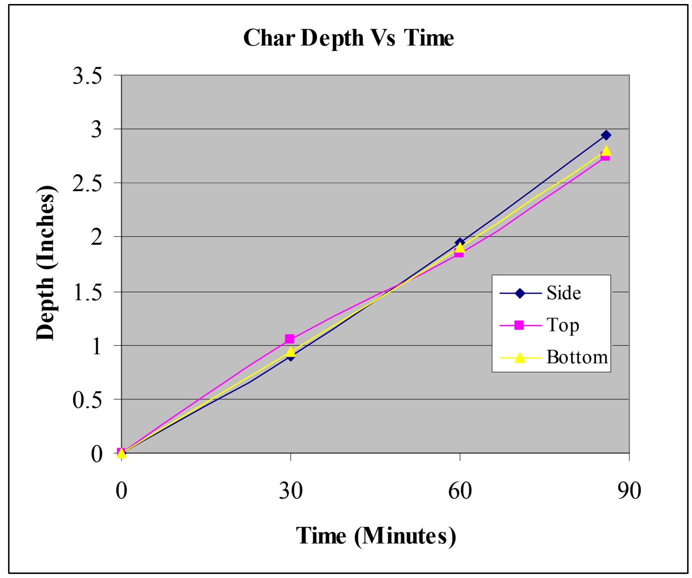

Figure 10: Char Depth Variation during Fire

DISCUSSION

Thermal analyses are performed to simulate a 1500°F, 86 minutes fire in the 9975 storage facility. The thermal models are based on the actual fire tests performed at 1475°F for 30 minutes. Justifications are provided to ensure that the models give conservative (higher) results for the containment vessels. The analyses demonstrate the robustness of the 9975 package.

CONCLUSIONS

1. The analyses show that the component temperatures are below their design limits. The analyses also show that the structural integrity of the containment vessels and the leak tightness of their O-rings are not impacted even if all the fiberboard is lost in the fire.
2. The analyses show that at least 26% of good fiberboard will be left at the end of 1500ºF 86-minute fire.

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