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PRACTICAL THERMAL EVALUATION METHODS FOR HAC FIRE ANALYSIS IN TYPE B RADIAOACTIVE MATERIAL (RAM) PACKAGES

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ABSTRACT

Title 10 of the United States Code of Federal Regulations Part 71 for the Nuclear Regulatory Commission (10 CFR Part 71.73[1]) requires that Type B radioactive material (RAM) packages satisfy certain Hypothetical Accident Conditions (HAC) thermal design requirements to ensure package safety during accidental fire conditions. Compliance with thermal design requirements can be met by prototype tests, analyses only or a combination of tests and analyses. Normally, it is impractical to meet all the HAC using tests only and the analytical methods are too complex due to the multi-physics non-linear nature of the fire event. Therefore, a combination of tests and thermal analyses methods using commercial heat transfer software are used to meet the necessary design requirements. The authors, along with his other colleagues at Savannah River National Laboratory in Aiken, SC, USA, have successfully used this 'tests and analyses' approach in the design and certification of several United States' DOE/NNSA certified packages, e.g. 9975, 9977, 9978, 9979, H1700, and Bulk Tritium Shipping Package (BTSP). This paper will describe these methods and it is hoped that the RAM Type B package designers and analysts can use them for their applications.

INTRODUCTION

The packages studied here are all drum type packages that are used to transport radioactive, including fissile, materials. The critical components of the packages are: the containment vessel (CV), the CV O-ring/C-ring seals, radiation shield, and the impact limiter that also acts as a thermal insulator. Thermal performance requirements specified in 10 CFR 71.73 are meant to protect the CV and the CV seals to prevent release of the RAM in a transport accident. The impact limiter first protects the CV and its seals from severe dynamic loads and also protects it from the subsequent fire. This paper discusses two separate fire analysis methods used for the 9975 and 9977 packages. The 9978 and 9979 packages were analyzed using same methods as for the 9977 and 9975 packages and therefore will not be discussed. The H1700 and BTSP are NNSA certified packages and were analyzed using a different method and will also not be discussed here.

THERMAL REQUIREMENTS DURING HAC FIRE

Fire test and thermal requirements are given in 10 CFR Part 71.73. These requirements are briefly described below.

Pre-fire Initial Requirements

1. The package loaded with its heat source is exposed to the 38°C (100°F) ambient to achieve steady state conditions. **Note: Solar thermal loading (insolation) is not required for this requirement**.
2. The package, with its CV pressurized to the Maximum Normal Operating Pressure (MNOP), is subjected to the impact tests sequence including the puncture test.
   Note: Normally, the CV is not pressured in HAC impact tests for safety and for conservatism since pressurization stiffens the vessel. The CV's in 9975 and 9977 tests were not pressurized.

Fire Test Requirements

1. The average fire temperature must be at least 800°C (1475°F) for 30 minutes.
2. The average fire emissivity must be 0.9.
3. The package surface absorptivity must be actual value or 0.8 whichever is higher.

Post-fire Requirements

1. The package must be allowed to cool naturally.
2. Package combustion must be allowed to extinguish naturally.
3. The package must be exposed to the full insolation as required in 10 CFR Part 71.

The CV after the test must pass the leakage test. Implicit in these requirements is the understanding that the package components must meet the acceptance criteria even if the pool fire temperatures are above the average 800°C, which they are.

FIRE TEST CHALLENGES

The requirements enumerated above present very difficult and impractical conditions to implement in an actual fire test. The impractical conditions are: (1) the implementation of an internal heat source during the impact and the fire test; (2) the package temperature field consistent with 100°F steady state conditions and; (3) insolation during the post-fire cool-down. These requirements are addressed through analyses.

9975 PACKAGE

The 9975 package is a very versatile Type B package which is certified to transport a wide spectrum of radioactive materials.[2] The 9975 has double containment, namely, both a primary containment vessel (PCV) and a secondary containment vessel (SCV), and a lead shield for added protection against material and radiation leakage. Double containment was required by regulations for plutonium packaging at the time of certification. The impact limiter, which also acts as a thermal insulator, is a cane or wood fiberboard with a trade name Celotex™. The packaged is designed to ship fissile materials with decay heat rates 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. 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.

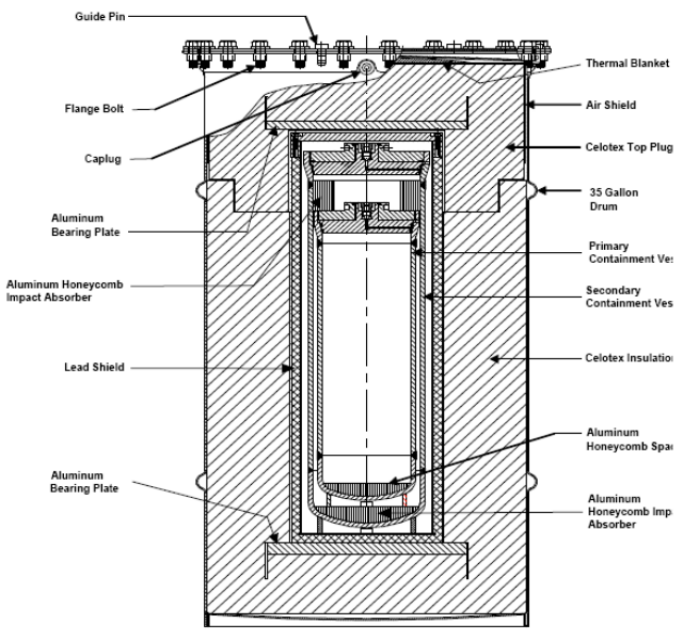

Figure 1 – 9975 Package

9977 PACKAGE

The 9977 package consists of a single 6-inch diameter Containment Vessel (identified as the 6CV), a drum overpack filled with rigid polyurethane foam, and a closure lid that has several layers of insulation.[3] The 6CV is identical to the well tested secondary containment vessel (SCV) used in the 9975 packagings. The 9977 package has been designed to conform to the latest regulations requiring only one containment vessel for the Type B quantities. The package can be used to ship heat sources up to 19 watts. Figure 2 shows the basic 9977 without any specific payload.

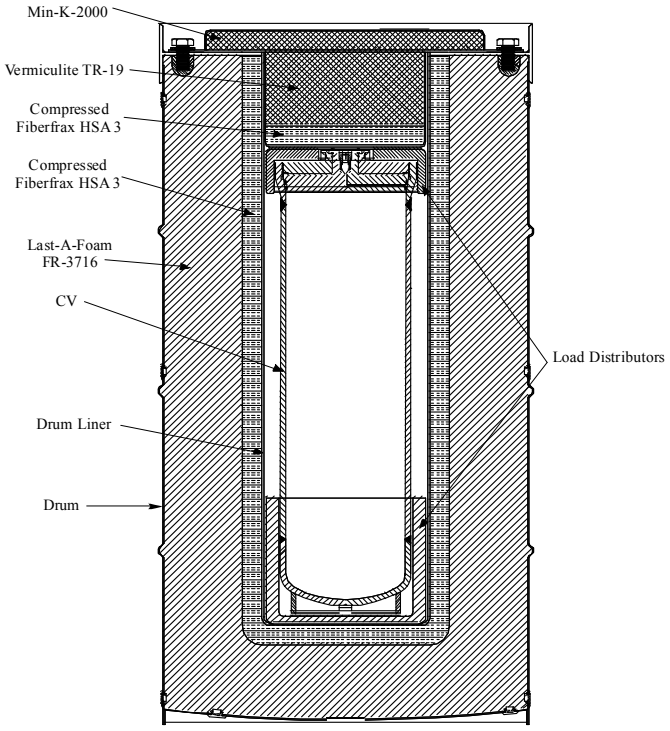

Figure 2 – 9977 Package

PACKAGE FUNCTIONAL REQUIREMENTS

Critical components of the two packages are the CVs and their seals, and the impact limiters. The containment vessel seals are O-rings that must be maintained below certain temperature for the seals to remain leaktight. The impact limiters (Celotex for 9975 and polyurethane foam for 9977) serve as insulators during fire through thermal decomposition and thermal ablative processes, respectively. These materials were significantly consumed in prototype tests and therefore no temperature limits are specified. Table 1 gives the temperature limits for these components to maintain their structural and thermal integrity.

Table 1: Temperature Limits

Component	Temperature Limits (ºF)
Viton O-Ring Seals	400
304L PCV/SCV (9975)	300
304L 6CV (9977)	400

9975 TESTS

An undamaged fully instrumented 9975 prototype with an approximate 21-watt electric heater source in the PCV was tested in a controlled environment at Sandia National Laboratories to create benchmarked thermal models. The package was first allowed to come to a steady state condition in a 75.5°F environment for 120 hours.[4] Next it was put in a furnace to simulate the HAC fire conditions. Since the PCV was fitted with an internal electric heater, the PCV was not pressurized. The PCV and SCV walls, O-ring seals and the impact limiter were instrumented to record the temperatures during these conditions. This test and other pertinent fire tests on other prototypes are described in the 9975 package Safety Analysis Report.

Note: The component temperatures were monitored until they reached their peak values during the fire test. The temperatures reach their peak during the post-fire period, a short time after the 30-minute fire. Inadvertently, the component temperatures were not recorded for the post-fire steady state conditions. The post-fire steady state temperatures are affected by the un-charred and charred Celotex thermal properties.

The prototype test did not quite meet the 100°F ambient initial test requirement but it was very helpful to creat the NCT thermal model. The test also did not meet the MNOP, the initial impact test damage and the post-fire full insolation requirements. MNOP requirement does not impact the thermal integrity of the package during fire except the possible leaktight integrity of the containment vessels. This requirement was easily fulfilled by helium leak testing following the fire test completion. The impact damage requirement was fulfilled by testing a damaged prototype to ensure the leaklight integrity of the package. The insolation requirement was fulfilled by analysis.

9975 ANALYSIS METHODOLOGY

The analysis methodology consisted of creating thermal models for the 100°F steady state and for the average fire temperature 800°C (1475°F) conditions. The thermal model for the steady state was described in an ASME paper and is not repeated here.[4] The fire model was described by Hensel in another ASME PVP paper and is also not repeated here.[5] A short description of the modeling methodology during fire is described below. Also the post-fire steady state model that was not covered in Reference [5] is described here.

Fire Model

The impact limiter Celotex protects the package during fire by its insulating ability, thermal decomposition and phase change, and by the eventual escape of the hot gases from the package during the fire test. Thermal decomposition, phase change and the escaping hot gases are endothermic in nature and play a very important role in protecting the internal components from excessive heating. However, these processes are multi-physics in nature and are very complex to model from first principles. Therefore, a simpler modeling approach like reverse engineering was adopted to simulate the temperatures observed during the fire test.

The fire thermal model was a lumped model where density, thermal conductivity, specific heat and latent heat of the un-charred Celotex were changed by trial and error to simulate the temperature distributions measured during the test. It should be noted that no chemical reactions, phase change, two phase flow or loss of mass were modeled in this lumped model. Thermal analysis software PATRAN was used to create the lumped model.[6] The density was reduced at higher temperatures from its nominal value to simulate loss of mass. Thermal conductivity was increased to simulate increased heat transfer due to two phase flow, and specific heat was increased to simulate solid to gaseous phase change as the temperatures increased. The overall effect was an increase in thermal diffusivity of the Celotex as the temperature increased from the normal to the fire conditions.

Post-Fire Steady State Model

The package post-fire steady state temperatures depend on thermal conductivity alone. Since there was significant loss of Celotex during fire and the ensuing post-fire period, effective thermal conductivity of the un-charred and charred Celotex and the air space is significantly lower than the virgin Celotex. As indicated before, post-fire steady state temperatures were not recorded and, therefore, a true thermal model could not be recreated. And since package component temperatures are higher with reduced Celotex thermal conductivity and increased drum surface absorptivity, a conservative approach was proposed to assess the post-fire component steady state temperatures. It was suggested that the annular Celotex space be assumed filled with air only. In addition, since the volume of air space is not known precisely, thermal radiation exchange was neglected between the drum inner surface and the lead shield surface. Full insolation in accordance with the 10 CFR 70.71 should be assumed. No results are presented here using this model.

9977 TESTS

For the 9977 package, a pool fire test was conducted on an undamaged prototype and several tests on damaged prototypes. Since it was impractical to install a heater in the package for the impact and the subsequent fire tests, the damaged prototypes were heated in a 200°F environment for 96 hours prior to the fire test to achieve 6CV and O-ring temperatures close to the temperatures if the package had a 19-Watt content in a 100°F environment. During the HAC tests, including the fire, the 6CV was not pressurized to MNOP. The 6CV and the O-ring seals were instrumented with temperature indicating labels (TIL) that could record the highest exposure temperature of the component during the entire fire transient, including the post-fire cool-down. TILs record only the maximum temperature reached, not the temperature history.

The pool fire met or exceeded all the regulatory requirements in 10 CFR 71.73. The average fire temperature was close to 1000°C, well above the 800°C regulatory requirement. After the fire test, the test package was disassembled and the temperature labels were read to record the highest exposure temperature of each label. The tested prototypes were also leak tested to ensure that the integrity of the O-ring seals was not impacted in the test. All prototypes passed the helium leak tests.

9977 ANALYSIS METHODOLOGY

Unlike the 9975 methodology, no attempt was made to simulate the pool fire test due the complexity of modeling the pool fire and the behavior of the polyurethane foam during fire. Instead, the pool fire test provided the maximum temperature of the 6CV, the O-ring seals and other components during fire. Now if we only knew the component temperatures before the fire, the increase in temperature due to the fire event alone could be determined. The temperature field before the fire was determined by the thermal model of the undamaged prototype that was heated for 96 hours in a 200°F environment and transported in 2 hours to the test site wrapped in a 4" thick insulating blanket prior to the fire. In this model that included the transportation time also, the initial 6CV temperature was quite uniform along its wall and was found to be 183°F.[3] This resulted in a maximum temperature increase of 87°F for any location on the 6CV wall and the O-ring seals due to the fire test.[3]

The fire test established the integrity of the containment vessel and its O-ring seals during the fire. However, since the fire test did not meet all the regulatory requirements, i.e., the heater and the insolation, additional analyses were performed to meet the acceptance criteria for the various components. The presence of heat generation and the insolation thermal loading has significant impact on the component maximum temperatures and this impact was assessed by analyzing thermal models, i.e., pre-fire and post-fire models

Pre-Fire Thermal Model

The pre-fire model included the exact geometry including the 19-watt contents and a 100°F environment. The model was analyzed for steady state conditions to satisfy the initial temperature requirement for the fire test.

30-Minute Fire Thermal Model

The fire test and the knowledge of ΔT during fire obviated the need for the detailed 30-minutes fire model. The CV temperature field at the end of 30-minute was established by superimposing the maximum ΔT on the CV temperatures from the pre-fire model. The resulting temperature was imposed uniformly on the entire CV. This is very conservative because in the actual test some 6CV locations experienced no temperature increase. The temperature labels readings in the fire test on other components and observations made on the un-charred and charred foam thickness measurements in the drum annulus helped in establishing the temperature field for the remaining components. This temperature field becomes the initial condition for the post-fire model.

Post-Fire Thermal Model

The post-fire model is the thermal model to predict the component temperatures for the post 30-minute period. For the post-fire model, the initial temperature field was established as described in the 30-minute fire model above. This model has the heat generation from the source and the full insolation as required by the regulations.

MATHEMATICAL MODEL AND COMPUTATIONS

The package components are cylindrical in geometry and the boundary conditions are uniform all around. Therefore, an axisymmetric model represents the package very well. The pre-fire model solves the steady state heat transfer Equation (1) in cylindrical coordinates for an axisymmetric geometry.

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

The post-fire model solves the unsteady state heat transfer Equation (2) with the initial temperatures estimated from the test and prefire model.

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

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. The partial differential equations was numerically solved using PATRAN/Thermal software.[6]

9975 MODELS AND RESULTS

Model results depend on the source configuration. The source configuration assumed here is the 3013 container with plutonium oxide as the heat source. Models and results presented here are for 19 watts source loading. Effective thermal properties developed by Hensel et. al. are listed in Table 2.[5]

Table 2: Fire Model Effective Thermal Properties

	Un-Charred Celotex (see Notes)			
Property	Temp.(°F)	Value	Temp.(°F)	Value
Conductivity, Btu/ft-hr-°F	80	0.035	200	0.55
	115	0.16	210	0.09
	150	0.37	220	0.09
	170	0.45	450	0.07
	185	0.55	500	0.07
Density, lb/ft^3	80	15.4	810	8.5
	475	15.4	1500	3.5
Specific Heat, Btu/lb-°F	70	0.25	500	0.50
	400	0.50	1500	0.50
	Charred Celotex			
Conductivity, Btu/ft-hr-°F	100	0.07	300	0.30
	140	0.07	500	0.07
	200	1.0	600	0.07
Density, lb/ft^3	8.1		For all temperatures	
Specific Heat, Btu/lb-°F	0.25			

Notes: (1) Phase Change: 50 Btu/lb @ 200°F. (2) In Table 2 above, un-charred Celotex effective properties are affected by decomposition of Celotex during fire and are different from the virgin Celotex.

9975 Pre-fire Thermal Model

Prior to the fire, Celotex is in virgin form and, therefore, the virgin Celotex thermal properties are used. Thermal properties for the virgin Celotex are taken from Reference [4] and are not repeated here. Pre-fire model parameters are given below.

1. The drum is in an upright position.
2. The ambient temperature is 100ºF.
3. The drum bottom surface is adiabatic.
4. There is radiative heat transfer from the side and the top of the drum to the ambient. Radiation heat transfer is considered in all internal cavities. Gray body assumption is used in all calculations.
5. There is natural convection heat transfer from the side and the top of the drum to the ambient. No convection is modeled in the internal cavities. This is conservative as it results in higher local temperatures.
6. The payload heat generation rate is limited to a maximum of 19 watts.
7. The pre-fire model is a steady-state model.

9975 Pre-fire Results

Table 3: Pre-fire Temperatures

Location	3013 Container Configuration
Drum Bottom/Side/Top	137ºF/109°F/103°F
Celotex	153ºF
SCV O-ring	156ºF
PCV O-ring	167ºF
SCV Bottom	171ºF
PCV Side	190ºF
Pu Oxide	437ºF

9975 30-Minute Fire Model

In the fire model, thermal properties are the lumped or effective properties as shown in Table 2. The model parameters are:

1. The drum is in an upright position.
2. There is forced convection from all surfaces of the drum:
   i. 5.9 Btu/hr-ft^2 ºF for the top and bottom of the drum.
   ii. 3.0 Btu/hr-ft^2 ºF for the side of the drum.
3. There is thermal radiation heat transfer from all surfaces of the drum to the ambient.
4. The ambient temperature is 1475ºF.
5. No insolation.
6. Fire phase Celotex properties are applied to all the Celotex in the drum.
7. Initial conditions are the pre-fire temperatures.
8. The payload heat generation rate is limited to a maximum of 19 watts.
9. The fire model is a 30-minute transient model.

9975 Fire Model Results

Table 4: 30-Minute Fire Temperatures

Time (Min)	Drum Top	SCV O-ring	PCV O-ring	SCV Bottom	PCV Side	Pu Oxide
0	103ºF	156ºF	167ºF	171ºF	190ºF	437ºF
5	1442ºF	156ºF	167ºF	171ºF	190ºF	437ºF
10	1444ºF	155ºF	167ºF	171ºF	190ºF	437ºF
15	1446ºF	155ºF	167ºF	171ºF	190ºF	437ºF
20	1447ºF	155ºF	167ºF	171ºF	190ºF	437ºF
25	1448ºF	155ºF	167ºF	173ºF	190ºF	437ºF
30	1449ºF	156ºF	167ºF	175ºF	190ºF	437ºF

An interesting observation from Tables 3 and 4 is that the PCV and its contents are unaffected by 30 minutes fire and the SCV temperature rises only 4ºF. This is partly due to high thermal inertia of the lead shield and partly due to the excellent insulating attributes of the Celotex impact limiter.

9975 Post-fire Model

Post-fire period starts after the 30-minute fire and is the cool-down phase of the fire. The model parameters are:

1. The drum is in an upright position.
2. There is thermal radiation from the top, sides and bottom of the drum to the ambient.
3. There is natural convection from the top and sides of the drum to the ambient.
4. The ambient temperature is 100ºF.
5. Insolation: 800 W/m^2 on drum top and 400 W/m^2 on drum side (solar absorptivity of the drum assumed unity).
6. "Char layer" properties are applied to the outer 1.4 inch layer of the top, bottom and sides of the Celotex contained in the drum.[5]
7. Fire phase un-charred Celotex properties are applied to the all Celotex not in the 1.4 inch outer layer.
8. The initial conditions are the temperatures at the end of 30-minute fire.
9. The payload heat generation rate is limited to a maximum of 19 watts.

9975 Post-fire Results

Table 5: Post-fire Temperatures

Time (hr)	Drum Top	SCV O-ring	PCV O-ring	SCV Bottom	PCV Side	Mid Pu
0.0	1449ºF	156ºF	167ºF	175ºF	190ºF	437ºF
0.5	249ºF	160ºF	167ºF	187ºF	192ºF	438ºF
1.0	249ºF	167ºF	169ºF	195ºF	196ºF	440ºF
1.5	249ºF	173ºF	172ºF	199ºF	201ºF	443ºF
2.0	249ºF	178ºF	176ºF	202ºF	206ºF	447ºF
2.5	249ºF	182ºF	180ºF	204ºF	209ºF	451ºF
3.0	249ºF	185ºF	183ºF	206ºF	213ºF	454ºF

9977 MODELS AND RESULTS

As explained in 9977 analysis methodology, the temperatures at the end of 30-minute fire were derived from the pool fire test measurements. But to meet all the regulatory requirements, the initial fire test conditions must be steady state conditions with 19 watts heat generation in a 100°F environment. Therefore, for the 9977 there are basically two computational models: pre-fire and post-fire models.

9977 Pre-fire Model

The pre-fire model parameters are similar to the 9975 model parameters and not repeated here.

9977 Pre-fire Results

The prime pre-fire results are given in Table 6. These results are used in assessing the temperatures of the 6CV and its contents at the end of 30-minute fire.

Table 6: Pre-fire Temperatures

Component	Temperature (°F)
Contents & Internal Air	259
6CV	220

9977 30-Minute Fire Model and Results

As explained in the 9977 Analysis Methodology, a detailed model was not created for the 30-minute fire. Rather, the results from the pre-fire analysis in Table 6 and the maximum temperature increase, $\Delta T = 87°F$, measured during the fire test are used to calculate the final temperature field at the end of 30-minute fire. The 6CV and contents temperatures at the end of 30-minute period are, therefore, obtained by adding 87°F to the temperatures in Table 6. Temperatures for the other components are conservatively assessed as explained below.

In the fire test, it was observed that the there were layers of un-charred (virgin) foam and thermally decomposed charred foam. The un-charred foam layer thickness varied from 1 inch to 2.3 inches. Therefore, this foam was given virgin foam properties. Charred foam is very light and was assigned air thermal properties opaque to thermal radiation.

Unlike Celotex in the 9975 package, the polyurethane foam is a closed cell structure and is impervious to the gases during the fire event. Therefore, the un-charred foam appearance and properties are similar to the virgin foam. Foam starts charring at about 400°F and since a significant layer of virgin foam was left after the fire, the maximum temperature of the un-charred foam could not have exceeded 400°F. Therefore, the un-charred foam was assigned a temperature of 400°F. The charred foam was assigned a maximum fire temperature of 1475°F. Based on these and other data, the temperatures at the end of 30-minute fire were assigned as listed in Table 7. These temperatures become the initial temperatures for the post-fire model.

Table 7: 30-Minute Fire Temperatures

Component	Temperature (°F)
CV Contents & Air	346°F
CV	307°F
Foam to CV	400°F
Min-K-2000®	1000°F
Vermiculite TR-19®	400°F
Char and External Metal	1475°F

Comparison of Fire Results between 9975 and 9977

It is interesting to note that the temperature rise for the 6CV for the 9977 package was 87°F while there was only 4°F (SCV) increase in the 9975 package analysis during the 30 minutes fire. The large difference could be explained considering: (1) The pool fire temperature in 9977 was nearly 1000°C as compared to 800°C for the 9975 package, (2) the 9977 temperature label observation included temperature rise during the post-fire period, (3) large thermal inertia of the lead shield, and (4) the initial temperature field for the 9977 was achieved using an external heater environment of 200°F.

The 200°F environment resulted in initial foam temperatures well above what would have been the true temperatures with a 19 watts heater in a 100°F environment. The true foam temperature for the 9977 could be assessed from the 9975 analysis. Since the thermal conductivity of foam (9977) and Celotex (9975), the source heat rate (19 watts) and the overall dimensions are similar, the foam temperature field for the 9977 will be quite similar to the Cellotex temperatures in the 9975 package. Therefore, the foam temperature could be estimated from Table 3. Table 3 gives a Celotex temperature of 153°F (and therefore foam) which is close to an average of PCV (190°F) and drum side (109°F) temperatures. Based on this observation, the actual foam temperature in the 200°F environment heated 9977 prototype prior to the fire was about 190°F [average of 6CV (183°F in the fire test) and 200°F] rather than 153°F. This will also result in the higher 6CV temperature as observed in the actual test. In conclusion, the 9977 30-minute test results are very conservative and well above the regulatory requirements.

9977 Post-fire Model

Post-fire period starts after the 30-minute fire and is the cool-down phase of the fire. The model parameters are:

1. The drum is in an upright position.
2. There is thermal radiation from the top, sides and bottom of the drum to the ambient.
3. There is natural convection from the top and sides of the drum to the ambient.
4. The ambient temperature is 100ºF.
5. Insolation: 800 W/m^2 on drum top and 400 W/m^2 on drum side (solar absorptivity of the drum assumed unity).
6. Virgin foam thermal properties are applied to un-charred foam. Charred foam is very light and, therefore, air properties were assumed for the charred foam. However, air was assumed opaque to thermal radiation due to uncertainty in the characteristics of the charred foam.
8. The payload heat generation rate is limited to a maximum of 19 watts.
9. The initial conditions are the temperatures at the end of 30-minute fire.
10. The post-fire cool-down analysis is run for 7 hours after the 30-minute fire.

Three separate analyses were run to address uncertainties in the charred and un-charred foam properties. One analysis included 1 inch un-charred layer and rest all charred; second model considered 2.3 inches un-charred foam and rest all charred foam; and the third model considered all charred foam. The all char condition produces the highest component temperatures.

9977 Post-fire Results

Table 8 gives the maximum post-fire temperatures, including the steady state conditions.

Table 8: Post-fire Temperatures

Time (Hrs)	O-Rings (°F)	CV (°F)
0.0	307	307
0.5	360	394*
1.0	375	383*
1.5	381	381
2.0	**381**	382
2.5	379	383
3.0	374	384
3.5	369	384
4.0	364	385
4.5	359	385
5.0	354	385
5.5	350	**385.4**
6.0	346	**385.4**
6.5	342	385
7.0	338	385
Steady State	263	325

*** This temperature anomaly is due to arbitrary assignment of initial temperatures in Table 7. The foam-to-CV temperature of 400°F in Table 7 affects the CV temperature momentarily until local equilibrium is established.**

DISCUSSION

Two simplified methods are presented to evaluate the thermal performance of Type B drum type packages during an HAC fire event. The methods avoid the complex multi-physics modeling of the impact limiters used in the packaging designs. However, it should be noted that the parameters developed are pertinent to the packages studied only and should not be considered generic. The thermal performance is based on both prototype tests and detailed finite element analyses to address all the design requirements and to make the analysis methodology robust. Though not evaluated here, it is estimated that the pool fire test methodology is more expensive to implement due to the test costs.

CONCLUSIONS

1. The methods developed are simple and can be adopted for other drum type packages.
2. The pool fire test methodology adopted for the 9977 package is simpler but the very conservative results could create difficulties in meeting the component acceptance criteria.

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