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THERMAL ANALYSIS OF A 9977 SHIPPING PACKAGE DURING A FIRE-DROP-SMOLDERING ACCIDENT

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ABSTRACT

The US Department of Energy (DOE) uses the 9977 shipping package to store and transport plutonium bearing materials. The shipping package utilizes a single 6-inch diameter containment vessel with the radioactive material within SAVY-4000 containers, 3013 food-pack containers, or other sealed storage containers separated by spacers. The 6-inch containment vessel is surrounded by load distribution fixtures and a foam insulation overpack to protect against fire and impact events. A facility fire-drop-smoldering accident, which is longer and hotter than the comparable regulatory transportation evaluation, is analyzed to ensure radioactive material containment is maintained. A sensitivity analysis of shipping package configuration and foam insulation reduction is considered with foam eliminated either along the inside wall of the drum body (Inner Foam) or eliminated from the outer walls of the inner chamber where the 6-inch containment vessel is located (Outer Foam). These two different foam reduction configurations were considered to conservatively simulate the potential aging effects on facility safety qualification during storage. In addition, the thermal properties of the foam insulation were varied to explore their potential aging effects. A minimum foam thickness needed to maintain containment during the hypothetical facility fire-drop-smoldering analysis is determined for both the Inner and Outer Foam configurations as well as for both the SAVY-4000 and 3013 food-pack container configurations.

Keywords: thermal analysis, nuclear material storage, insulation degradation.

NOMENCLATURE, ACRONYMS, & ABBREVIATIONS

ASME	American Society of Mechanical Engineers
CV	Containment Vessel
DOE	Department of Energy
Foam	Last-A-Foam® FR-3716 Insulation
HAC	Hypothetical Accident Conditions
KAC	K-Area Complex
LDF	Load Distributor Fixtures
NCS	Normal Conditions of Storage
PuO_2	Plutonium Oxide
SARP	Safety Analysis Report for Packaging
SRNL	Savannah River National Laboratory
SS	Stainless Steel

INTRODUCTION

In support of expanding its applicability to additional DOE missions, the Model 9977 Shipping Package has been reanalyzed for multiple content configurations beyond its original designs for the storage and transportation of fissile material. The 9977 Shipping Package consists of the following components:

- A 6-inch diameter containment vessel (CV),
- A drum overpack filled with foam,
- A lid containing several layers of insulation.[1]

Figure 1 provides schematics of the 9977 shipping package with a 6-inch CV and either two SAVY-4000 containers[2] or two 3013 food-pack containers[3]. The SAVY or 3013 containers are placed within the CV using spacers, which are closed using a cone seal plug having a double O-ring and a cone seal nut. The 6-inch CV is loaded into a cylindrical drum liner and held in place by upper and lower load distributor fixtures (LDF) and surrounded by a Heat Dissipation Sleeve. A Viton® tube damping device is installed between the upper LDF and the drum lid assembly. The 9977 package is closed by bolting the lid in place. The Safety Analysis Report for Packaging (SARP) provides the design and analysis details of the 9977 shipping package[1]. The K-area Complex (KAC) thermal analysis conditions that will be used to evaluate the two 9977 shipping package configurations are outlined in M-CLC-K-00788[4], which details a drop-fire-smolder evaluation of the 9975 shipping package.

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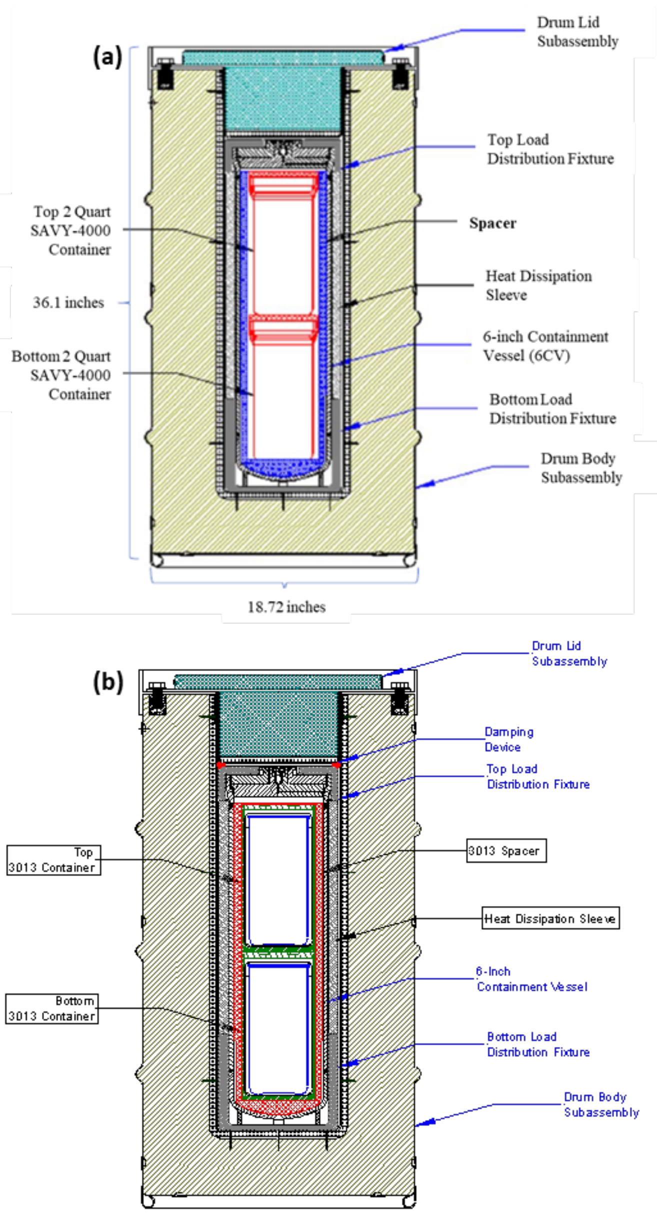

FIGURE 1: Schematic of (a) Typical Dual-SAVY Container Configuration and (b) Typical Dual-3013 Container Configuration in the 9977 Shipping Package.

1.0 MODEL INPUTS AND ASSUMPTIONS

The model inputs consist of package geometry, material thermal properties, thermal loading, and boundary conditions. These inputs are used in creating finite element thermal models that are used to analyze the Normal Conditions of Storage (NCS) and the Hypothetical Accident Conditions (HAC). All assumptions are documented and justified within the thermal model explanations as necessary. Additional thermal model explanations of the 9977 shipping packages can be found in References M-CLC-K-00789[5], M-CLC-A-00563[6] and M-CLC-A-00558[7]. The terms *heat source* and *contents* are used interchangeably to refer to PuO_2 or any other appropriate material as outlined in the SARP[1] or other applicable safety/design/analysis documents.

1.1 Model Geometry

The package drawings included in the SARP[1] provide geometric details and technical specifications of the 9977 shipping package components, including the applicable ASME Code requirements for the components and materials.

The outermost shell of the 9977 package is an 18-gauge 304L stainless steel drum with an 18.72-inch diameter and a height of 36.1 inches. Plastic Caplugs® (not included in the computational model) are used to plug the vent holes within the drum to prevent the entry of rainwater during NCS. These fusible Caplugs® are consumed during the HAC-fire events and allow the drum to vent gases generated from thermal decomposition of Foam insulation (short for Last-A-Foam® insulation[8]). A cylindrical drum liner constructed of 18-gauge 304L SS is concentrically located within the drum. Eight 5/8-inch bolts are used to secure the lid to the drum flange and close the drum liner. The drum lid is a combination of 14 and 18-gauge 304L SS sheet, 1/8" 304L SS plate, and three layers of insulating materials: Unifrax Corporation's uncompressed Fiberfrax® Lo-Con blanket, Thermal Ceramics Company's Min-K-2000 insulation, and Thermal Ceramics Company's Vermiculite TR-19 insulation.

A layer of Fiberfrax® Lo-Con blanket is wrapped around the side and bottom of the drum liner. The Fiberfrax® blanket, which is initially 1-inch thick, is compressed during the fabrication process by the Foam insulating material. The Foam, which is created by General Plastics Manufacturing, is a rigid polyurethane foam that expands to a density of approximately 16 lbm/ft^3 as it cures. It expands to fill the space between the inside of the outer drum and the Fiberfrax® blanket. The actual thickness of the Fiberfrax® blanket is unknown, but it is estimated to approximately ½-inch within the thermal analysis model. Because the thickness is halved, the density and thermal conductivity are assumed to be doubled, which is very conservative and will result in much higher thermal diffusivity.

The 6-inch CV is constructed from a 6-inch diameter, seamless Schedule 40, Type 304L stainless steel (SS) pipe. A Schedule 40, Type 304L SS pipe cap is used to close the lower end of the 6-inch CV, while the top is sealed using a ¾-inch 304L SS cone-seal plug. The cone-seal plug has two machined grooves for O-ring seals. The 6-inch CV assembly is supported and secured by upper and lower aluminum load distribution fixtures (LDF) insides the package liner cavity. A Heat Dissipation Sleeve fills the space between the lower LDF and the upper LDF to enhance heat transfer from the heat sources to the Foam in the overpack.

Viton® tubing is placed between the upper LDF and the drum lid assembly to dampen vibrations. The tubing is a fluorocarbon elastomer[8] and has a ½-inch outer diameter. Its thermal properties are assumed to be those of Viton GLT or GLT-S, as used for the O-Rings.

1.2 Material Properties

Axisymmetric 2-dimensional models were developed for the 9977 package geometries and analyzed using COMSOL Multiphysics®, version 5.4. Material representations of both the 9977-SAVY and 9977-3013 package thermal models are shown in **Figure 2**. Note that any variations from this geometry will be explained in the relevant section. Within the package, natural convection is neglected with heat transferred by only conduction and radiation across the internal gaps. All internal gases were assumed to be non-absorbing and treated as non-participating media in the radiation calculations. The gas within the SAVY container gaps and within the 6-inch CV gaps is assumed to be carbon dioxide. Carbon dioxide has a lower thermal conductivity than air and will yield slightly more conservative results in the NCS analysis. All remaining gaps within the 9977 package are assumed to be filled with air as the areas outside of the 6-inch CV are not credited for pressure containment.

General material properties for the NCS and HAC analyses are listed in **Tables 1** and **2**, respectively, with nominal surface emissivities listed in **Table 3**. Note that the density and thermal conductivity values for Fiberfrax® as shown in **Table 1** are adjusted (assumed double) for the compressed Fiberfrax®.

TABLE 1: Thermal Properties of Solid Packaging Materials.

Material Name	Thermal Conductivity (Btu/hr-ft-°F)	Density (lbm/ft^3)	Specific Heat (Btu/lbm-°F)
Fiberfrax* (compressed)	0.0455 @ 200°F 0.0600 @ 400°F 0.0798 @ 600°F	20.0	0.28
Vermiculite TR-19[9]	6.33E-02 @ 400°F 6.67E-02 @ 600°F 7.00E-02 @ 800°F 7.33E-02 @ 1000°F 7.75E-02 @ 1200°F 8.17E-02 @ 1400°F 1.08E-01 @ 1600°F	23.0	0.20
MIN-K 2000[10]	1.58E-02 @ 300°F 1.67E-02 @ 400°F 1.83E-02 @ 600°F 2.08E-02 @ 800°F 2.50E-02 @ 1000°F 3.33E-02 @ 1200°F 4.17E-02 @ 1500°F 4.50E-02 @ 1600°F	20.0	0.23 @ 400°F 0.25 @ 800°F 0.27 @ 1200°F 0.27 @ 1600°F
LAST-A-FOAM® FR-3716[11]	2.75E-02 @ 76.5°F 3.12E-02 @ 140.7°F 3.71E-02 @ 248.4°F 4.33E-02 @ 348.6°F 4.33E-02 @1000°F	16.0	0.353
304L Stainless Steel[12]	7.74108 @ 32°F 9.43444 @ 212°F 12.5793 @ 932°F 14.9983 @ 1292°F	494.429	0.120 @ 32°F 0.135 @ 752°F
Aluminium (Type 6061 T6)[13]	96.1 @ 70°F 96.9 @ 100°F 98.0 @ 150°F 99.0 @ 200°F 99.8 @ 250°F 100.6 @ 300°F 101.3 @ 350°F 101.9 @ 400°F	169.3	0.23
Viton® [14,15]	0.11	113	0.23

*Compressed to ½-thick, doubled density, and doubled thermal conductivity.

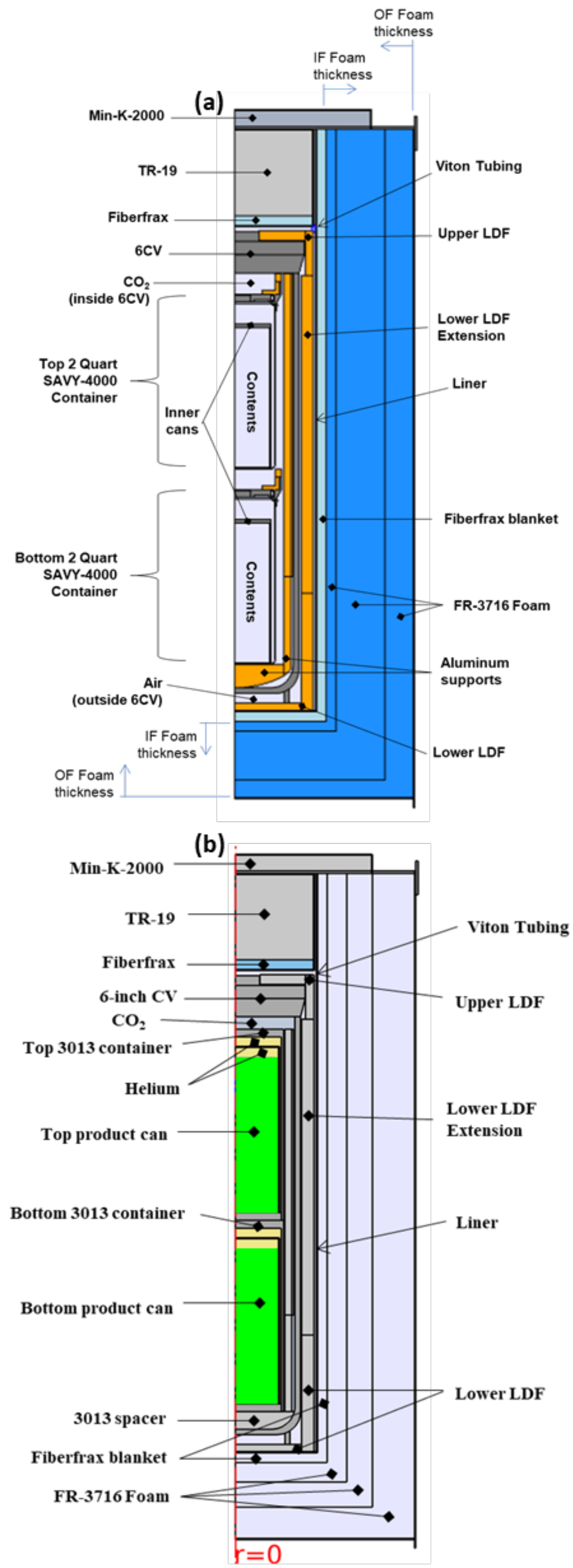

FIGURE 2: Material representations of the (a) 9977-SAVY and (b) 9977-3013 shipping package thermal models.

TABLE 2: Thermal Properties of Gaseous Components

Material	Thermal Conductivity (Btu/hr-ft-°F)	Density (lbm/ft^3)	Specific Heat (Btu/lbm-°F)
Air at 1 atm[12]	1.40E-02 @ 32°F 1.50E-02 @ 80°F 1.84E-02 @ 212°F 2.24E-02 @ 392°F 2.59E-02 @ 572°F	$\frac{1}{0.025203(T+459.67)}$ T is in °F	0.24044
Helium[12]	0.081675 @ 32°F 0.086845 @ 77°F 0.090958 @ 120°F 0.098456 @ 212°F 0.12265 @.. 392°F 0.16384 @ 932°F 0.25521 @ 2192°F	0.011049	0.124
Carbon Dioxide[12]	9.5753E-03 @ 80.33 1.1828E-02 @ 170.33 1.4220E-02 @ 260.33 1.6739E-02 @ 350.33 1.9368E-02 @ 440.33 2.2078E-02 @ 530.33 2.4909E-02 @620.33	0.1122	0.2082 @ 80.33 0.2152 @ 170.33 0.2252 @ 260.33 0.2343 @ 350.33 0.2422 @ 440.33 0.2503 @ 530.33 0.2572 @ 620.33

TABLE 3: Material Surface Emissivities

Surface	Emissivity
CV	0.30
Drum Liner	0.30
Bottom of Lid	0.30
Load Distributors	0.20
3013 Containers	0.30
Drum Exterior (NCS)	0.21
Drum Exterior (90-min Fire)	0.90
Drum Exterior (Post-Fire)	0.80

The surface emissivity values are for the gray and diffuse surfaces. The values listed in **Table 3** are the same as the values used in other similar analyses[2-7,9-10]. The 6CV, the SAVY, and the 3013 vessels are machined SS components with clean surfaces that are not polished or shiny. The drum surface is assumed *as received*, with emissivity values of 0.21, 0.90, and 0.80 for the NCS, 90-minute fire, and both the 60-minute smoldering fire and the post-fire cooldown, respectively. The drum emissivity during NCS is based on the detailed analysis for different types of drum surfaces[16]. Note that a lower drum surface emissivity value results in higher component temperatures during the fire, smolder, and post-fire cooldown. The aluminum surfaces are assumed oxidized.

1.3 Thermal Models

The 9977 shipping package models described in this report have a heat source located in top container (either SAVY-4000 or 3013 container) and heat source magnitudes of 25W unless otherwise stated. Whether the SAVY-4000 or the 3013 container, the assemblies consist of an outer container, an inner container, and a product can holding the heat source. These temperatures within the configurations are strongly dependent on the material thermal conductivity and decay rate of the heat source. The thermal conductivity (k) of the contents (assumed PuO_2) used in the models corresponds to the lowest density PuO_2 (2 g/cc) is the minimum value (k = 0.046 Btu/ft-hr-°F), while the maximum heat rate of 25W was used for a single container. Note that the heat source was decreased to 19W for several specific cases, as will be discussed in the results.

1.3.1 NCS Thermal Models

The thermal model for the NCS calculation was developed using the COMSOL Multiphysics®[17] software. The limiting components of the thermal analysis are the containment vessel (6CV), its O-ring seals, and the Upper and Lower LDFs, as listed in **Table 4** with their temperature limits as listed in the SARP[1]. For these limiting components, the predicted max temperatures are tracked for each model configuration and are compared to their thermal limits.

TABLE 4: 9977 Package Component Thermal Limits[1]

Component	Temperature Limit [°F]	
	NCS	HAC
6-inch CV	300	500
Upper LDF	300	800
Lower LDF	300	800
O-Rings	400	700*, 400[18]

*HAC Short Term, where *short term* is not specifically defined.

<u>*NCS Model Conditions:*</u>

1. The drum is in an upright position.
2. The drum bottom surface is adiabatic.
3. There is radiative heat transfer to the ambient from the top and sides of the drum (see **Table 3** for emissivities).
4. There is natural convection to the ambient heat transfer from top and sides of the drum (external natural convection coefficients are listed in several references [2-7, 9-10]).
5. The ambient temperature is 139.7 °F.
6. Unless otherwise stated, a total of 25W of decay heat power is uniformly distributed within the contents.
7. The NCS thermal model is analyzed as a steady state model.

1.3.2 KAC HAC FFA Thermal Models

The K-Area complex (KAC) hypothetical accident conditions (HAC) facility drop-fire-smolder accident thermal models consist of four sequential phases—the pre-fire, 90-minute fire, 60-minute smolder, and post-fire conditions. The pre-fire model for the NCS calculates the temperature profiles in the package prior to the HAC fire transient. The second phase is a 90-minute fire model in which the package is fully engulfed in an 1500 °F fire. The third phase is a 60-minute smolder in which a section of fiberboard on the top, bottom, or side is *on fire* at a temperature of 1400 °F. The final phase is a post-fire transient used to predict the bounding temperature of the 9977 shipping package components after the fire has been extinguished. All phases are modeled using the COMSOL Multiphysics® software. The thermal model results are evaluated by the package component thermal limits (**Table 4**). All relevant material and gas properties are listed in **Tables 1** and **2**, respectively, and surface emissivities are shown in **Tables 3**.

The pre-fire phase thermal model for the HAC facility drop-fire-smolder accident is equivalent to the NCS thermal model above. The second phase of the HAC facility drop-fire-smolder thermal model is a 90-minute all engulfing fire performed under the following conditions. Please note that the insulation does not char during the fire and maintains its thermal properties for the duration of the HAC facility drop-fire-smolder accident, which is a conservative assumption[3].

HAC Fire Phase Model Conditions:

1. Initial conditions are the final results of the steady-state Pre-Fire phase model (NCS model).
2. The fire temperature and duration are 1500 ºF and 90-minutes, respectively.
3. The drum is in an upright position.
4. There is radiative heat transfer from the top, bottom, and sides of the drum to the ambient 1500 ºF fire. See **Table 3** for surface emissivities.
5. There is forced convection heat transfer from the top, bottom, and sides of the drum to the ambient 1500 ºF fire. The convection heat transfer coefficients are based on a forced flow velocity of 20 m/s:
   a. 5.9 Btu/hr-ft^2-ºF for the drum top and bottom.
   b. 3.0 Btu/hr-ft^2-ºF for the sides of the drum.
6. Unless otherwise stated, a total of 25W of decay heat power is uniformly distributed within the contents.
7. The fire model is a transient model for 90 minutes.

The third phase of the HAC facility drop-fire-smolder accident thermal model is the 60-minute localized smoldering fire affecting fiberboard on the top, bottom, or side of the 9977 package, corresponding to the drop impact location. The smoldering fire phase is performed under the following conditions:

60-min Smoldering Fire HAC Phase Model Conditions:

1. Initial conditions are the final results of the transient 90-minute Fire phase model.
2. The smoldering temperature and duration are 1400 ºF and 60 minutes, respectively.
3. The drum is horizontal (on its side), resulting from one of three drop scenarios.
4. Top corner drop scenario:
   a. Top fiberboard and drum boundaries are set to 1400 ºF.
   b. There is natural convection heat transfer from the side and bottom of the drum to the ambient at 139.7 ºF.
5. Bottom corner drop scenario:
   a. Bottom fiberboard and drum boundaries are set to 1400 ºF.
   b. There is natural convection heat transfer from the side and top of the drum to the ambient at 139.7 ºF.
6. Side drop scenario:
   a. Section of fiberboard on the side boundary is set to 1400 ºF.
   b. There is natural convection heat transfer from the top, bottom, and side of the drum to the ambient at 139.7 ºF.
7. The ambient temperature is 139.7 ºF.
8. There is radiative heat transfer from the sides, bottom, and top of the drum to the ambient. See **Table 3** for surface emissivities.
9. Unless otherwise stated, a total of 25W of decay heat power is uniformly distributed within the contents.
10. The smoldering fire model is a transient model for 60 minutes.

The fourth and final phase of the HAC facility drop-fire-smolder accident thermal model is the post-fire or cooldown phase after the 60-minute smoldering fire phase. The cooldown phase corresponds to the time necessary for each of the 9977 package components to reach their peak (maximum) temperature and begin cooling thereafter. A minimum cooldown time of 12 hours is used to ensure that the peak temperature has been reached.

Post-Fire HAC Phase Model Conditions:

1. Initial conditions are the final results of the transient 60-minute smoldering fire phase model.
2. The ambient temperature and duration are 139.7 ºF and a minimum of 12-hours, respectively.
3. The drum is horizontal (on its side), resulting from one of the three drop scenarios.
4. There is radiative heat transfer from the top, bottom, and sides of the drum to the ambient. See **Table 3** for surface emissivities.
5. There is natural convection heat transfer from the top, bottom, and sides of the drum to the ambient.

FIGURE 4: Maximum Component Temperatures throughout the HAC FFA for Selected 9977-SAVY Package Components with Full, As-Built Last-A-Foam® FR-3716 Insulation and a 25W Evenly Distributed Heat Source in the Upper SAVY Container.

6. Unless otherwise stated, a total of 25W of decay heat power is uniformly distributed within the contents.
7. The post-fire transient is monitored to ensure that all of the 9977 package components have reached their peak (maximum) temperatures and begun decreasing.

2.0 COMPUTATIONAL ANALYSIS AND RESULTS

The following model results examine an evenly distributed 25W heat source located in the upper SAVY container within the 9977 shipping package. Note that no studies were performed with more than one heat source, while some studies examined heat sources of 19W.

2.1 Full As-Built Insulation, 25W Source

The 9977 shipping package with the as-built thermal properties, full insulation, and an evenly distributed 25W heat source located in the upper container was examined first. Figure 3 shows the temperature contours 9977-SAVY shipping package

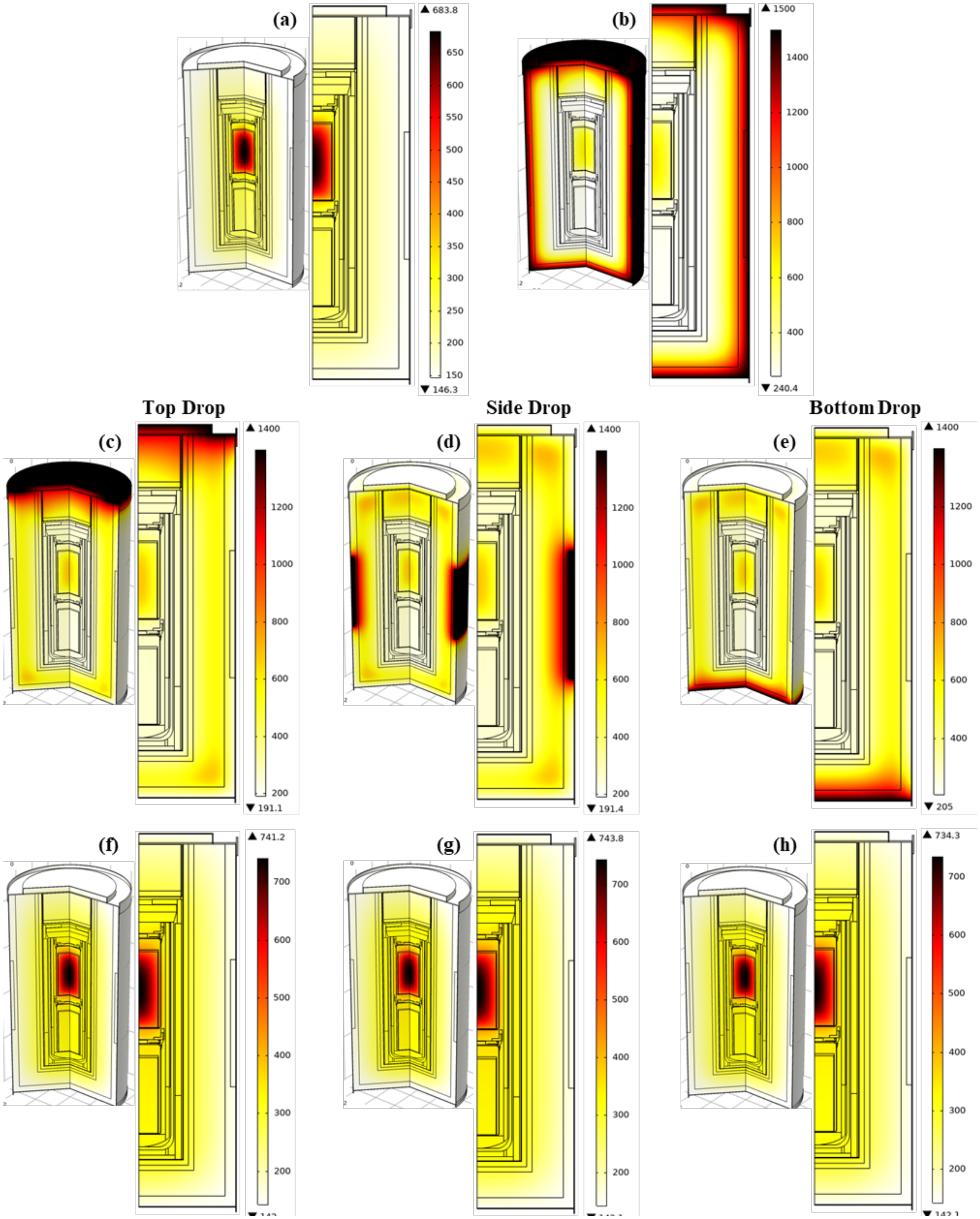

FIGURE 3: Temperature Contours (°F) for the 9977-SAVY Shipping Package with a single 25W heat source and as-built, full insulation: a) during NCS, b) after 90-min fire, c) – e) after 60-min smoldering fire, f) – g) 720-min post-fire. c) & f) Top Drop, d) & g) Side Drop, e) and h) Bottom Drop.

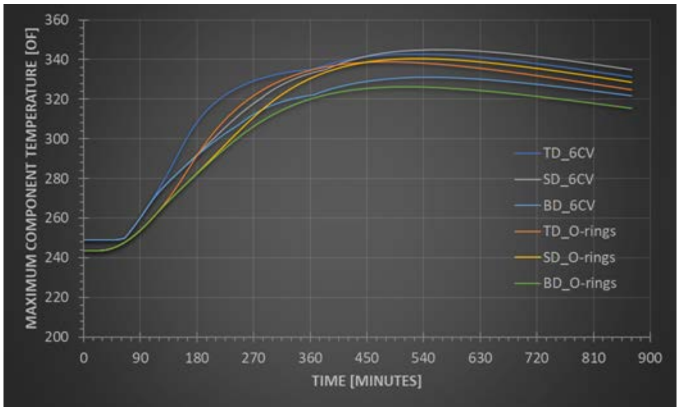

FIGURE 4: Maximum component temperatures throughout the HAC facility drop-fire-smolder accident for selected 9977-SAVY Package Components with as-built, full insulation and a 25W heat source in the upper SAVY container.

during all four phases of the HAC facility drop-fire-smolder accident for all three drop scenarios. During normal conditions of storage, all of the high temperatures are located within the heat source in the upper SAVY container. By the end of the 90-minute fire, the insulation has helped the 9977-SAVY shipping package components remain well below the component temperature limits as listed in **Table 4**. Regardless of the drop scenario, the component temperatures either continue to increase magnitude or remain the same during the 60-minute smoldering fire scenario. After 12 hours of cooldown post-fires, the temperature contours have begun to approach the pre-fire NCS distribution for each of the drop scenarios. Throughout the HAC facility drop-fire-smolder accident, the maximum component temperatures for the selected components of the as-built, fully insulated 9977-SAVY shipping package remain below their component temperature limits as shown in **Figure 4** for the maximum temperature plots of the two most critical components, the 6-inch CV and the O-rings. Previous calculations[2-7, 9-10] have shown that these two components are the first components to exceed their temperature limits during a HAC facility accident. Note that the 9977-3013 package was also examined and produced similar results with the same trends, but was not reported for brevity.

2.2 Insulation Thermal Property Variations, 25W Source

The previous section described a fully-insulated, as-built 9977 shipping package during a HAC facility drop-fire-smolder accident. However, many of these 9977 packages can be stored for decades, which can impact the thermal properties of LAST-A-FOAM® FR-3716 insulation. In a recent materials aging study[19], the Foam's thermal properties at temperatures less than 215 ºF were shown to change by as much as 15%. Unfortunately, aged Foam insulation thermal properties at elevated temperatures (> 250 ºF), such as those that would be experienced in a fire accident scenario, are unavailable. To properly bracket the potential thermal property changes that the Foam could experience, the thermal properties were examined at 50%, 100%, and 150% of the thermal conductivity, density, and specific heat values listed in the SARP[1]. **Figure 5** shows maximum temperature profiles for all three drop scenarios for the 9977-SAVY shipping package. The packages with reduced insulation thermal properties (with on 50% of the SARP[1] properties) have the highest maximum component temperatures, with very little variation shown between the three drop scenarios. Similar results were calculated for the 9977-3013, but were not shown here for brevity. Note that additional calculations were performed using many different Foam insulation thermal properties variations, but those shown in the figure provide the bounding cases

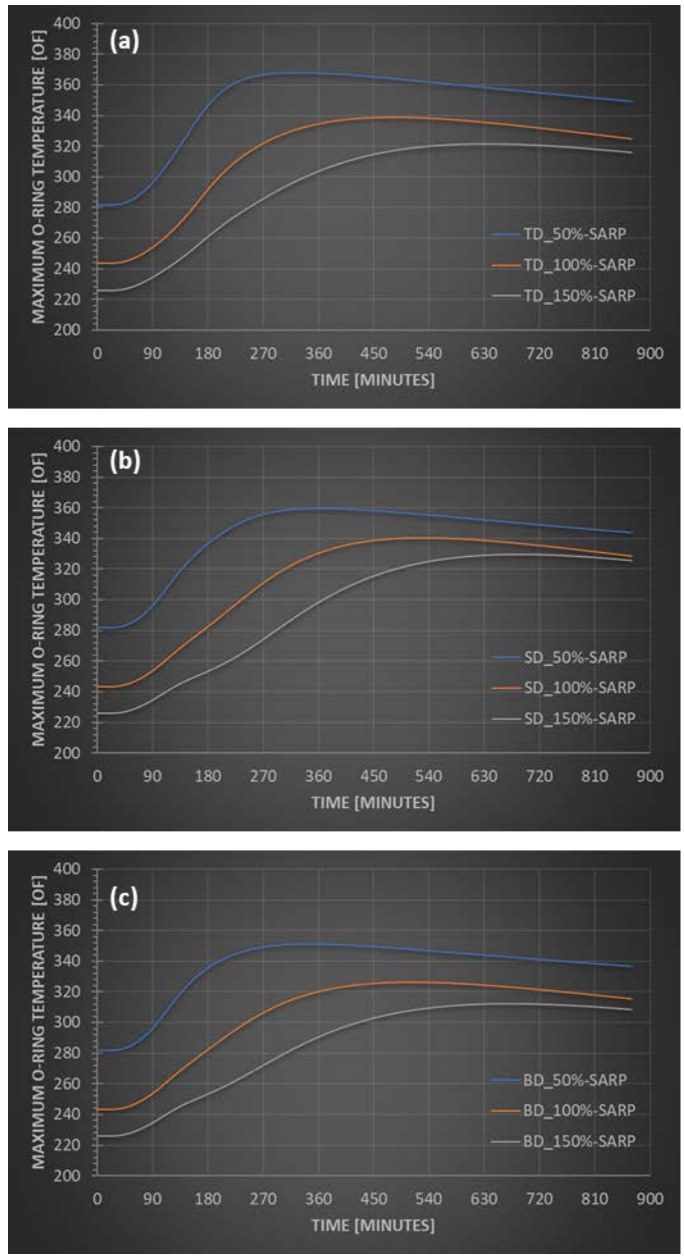

FIGURE 5: Maximum O-ring temperatures throughout the HAC facility drop-fire-smolder accident for fully insulated 9977-SAVY Package a 25W heat source in the upper SAVY container and variations in Foam insulation thermal properties: a) Top Drop,) Side Drop, and c) Bottom Drop.

3.0 Sensitivity Analysis

A mesh sensitivity analysis was performed to assess the impact of the finite element mesh quality on the package temperatures. The number of elements was increased from approximately 50,000 to 110,000. The HAC facility drop-fire-smolder accident for a 25W heat source evenly distributed in the upper SAVY container was repeated. The maximum content temperatures across all time steps in the analysis were compared between the lower and higher density meshes. Across the entire analysis space, the largest temperature difference between the two mesh densities is less than 0.03%. Therefore, the results reported in this calculation are based on models with about 50,000 elements.

3.0 CONCLUSIONS

The above thermal analyses examined the HAC facility drop-fire-smolder accident of the 9977 shipping package with either SAVY-4000 or 3013 containers. The present calculation examines both as-build package materials as well as bounding cases with aged Foam insulation thermal properties. The limiting components are the 6CV and the O-rings, which have maximum temperatures of 500 ºF and 400 ºF, respectively (as listed in **Table 4**). Note that the O-ring temperature limit as listed in the SARP[1] is 700 ºF for a short time, but this the temperature limit was lowered to 400 ºF as was referenced in M-ESR-K-00073[16] and used in M-CLC-A-00649[18].

The fully-insulated, as-built 9977-SAVY and 9977-3013 shipping packages remain below the component temperature limits, as listed in the SARP[1], throughout HAC facility drop-fire-smolder accident. With the Foam insulation thermal properties (thermal conductivity, density, and specific heat) decreased to 50% of the SARP values and increased to 150% of the SARP values, the potential effects of aging were bounded. None of these scenarios exceeded their component temperature limits.

ACKNOWLEDGEMENTS

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