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THERMAL ANALYSIS OF A 9977 PACKAGE DURING A KAC FIRE ACCIDENT

Dr. David Tamburello[1], Mr. Matthew Kesterson, Mr. Andrew Escobar
Savannah River National Laboratory
Aiken, SC, USA

ABSTRACT

The 9977 is a US Department of Energy (DOE) shipping package used 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 storage facility fire, which is longer and hotter than the regulatory transportation fire, is evaluated to ensure radioactive material containment is maintained. A sensitivity analysis of 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 options were considered to conservatively simulate the potential foam reduction possibilities due to aging during storage. Note that the foam insulation thermal properties were limited to their beginning of life or "as built" property values. A minimum foam thickness needed to maintain containment during the hypothetical facility fire 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

CV	Containment Vessel
DOE	Department of Energy
DOT	Department of Transportation
Foam	Last-A-Foam® FR-3716 Insulation
FFA	Facility Fire Accident
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

The Model 9977 shipping package was designed as a replacement for the Department of Transportation (DOT) Fissile Specification 6M package, consisting of the following:

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

In support of expanding its applicability to additional DOE missions, the 9977 shipping package has been reanalyzed for additional content configurations. A schematic of the 9977 shipping package[2] with a 6-inch CV and two SAVY-4000 containers are shown in **Figure 1**. The SAVY containers are placed within the CV using spacers, which is 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 9977-SAVY shipping package are outlined in M-CLC-A-00665[3] for the 9977-3013 shipping package and in M-CLC-K-00788[4] and M-CLC-K-00789[5] for the 9975 shipping package.

1.0 MODEL INPUTS AND ASSUMPTIONS

The inputs consist of package geometry, material thermal properties, thermal loading, and boundary conditions. These

[1] Contact author: david.tamburello@srnl.doe.gov

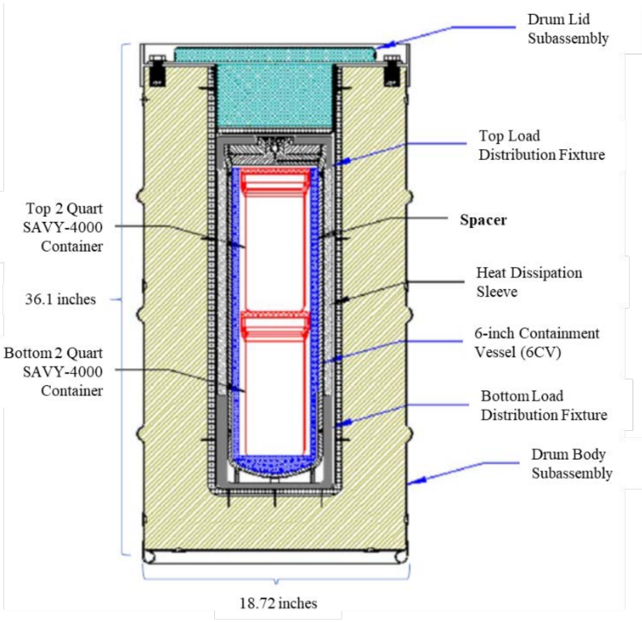

FIGURE 1: Schematic of a Typical Dual-SAVY Container Configuration in the 9977 Shipping Package.

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. References M-CLC-A-00563[6] and M-CLC-A-00558[7] provide additional thermal model explanations of the 9977 shipping package. 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. The drum has vent holes plugged with plastic Caplugs® (not included in the computational model) that prevent rainwater entry during NCS. These fusible Caplugs® are consumed during the HAC-fire events and allow the drum to vent gases generated from thermal decomposition of the Last-A-Foam® insulation[8] (referred to as Foam). A cylindrical drum liner constructed of 18-gauge 304L SS is concentrically located within the drum. The drum liner is closed using eight 5/8-inch bolts to secure the lid to the drum flange. 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 sides and bottom of the drum liner. Initially, the Fiberfrax® blanket is 1-inch thick, but is compressed during the fabrication process by the Foam insulating material. Foam is a rigid polyurethane foam that expands to a density of approximately 16 lbm/ft^3 as it cures made by General Plastics Manufacturing. 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

The 9977 shipping geometry was developed into a 2-dimensional axisymmetric model and analyzed using COMSOL Multiphysics®, version 5.2a. **Figure 2** shows the material representation of the 9977 package thermal model. Note that any variations from this geometry will be explained below. Within the package, heat is transferred by conduction and radiation. Natural convection is neglected within the internal gas spaces, while only thermal radiation and conduction heat transfer are applied 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[2]	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[3]	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.

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

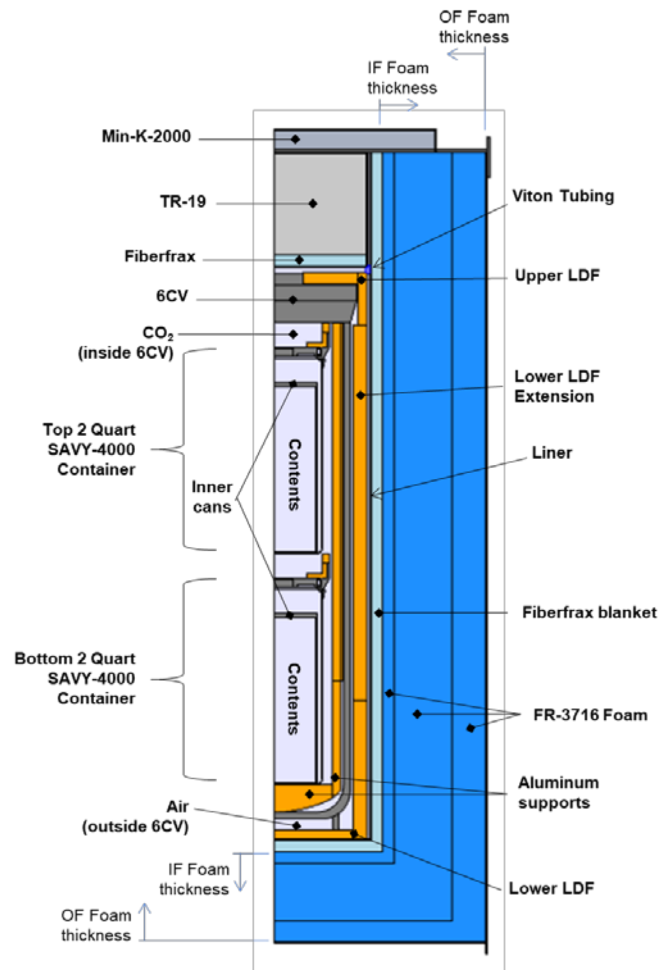

FIGURE 2: Material representation of the 9977 package thermal model.

The surface emissivity values are for the gray and diffuse surfaces. The values assumed in **Table 3** are the same as the values used in other similar analyses[2-7]. The 6CV and the SAVY 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 post-fire cooldown, respectively. The drum emissivity during NCS is based on the detailed analysis for different types of drum surfaces[10]. The fire and post-fire emissivity values are specified in the 10CFR part 71.73. Note that a lower drum surface emissivity value results in higher component temperatures during the fire and post-fire cooldown. The aluminum surfaces are assumed oxidized.

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

1.3 Thermal Models

The 9977 shipping package models described in this report have a heat source located in one of the two SAVY-4000 containers and heat source magnitudes up to 25W. The SAVY-4000 container assemblies consist of an outer container, an inner container, and a product can. 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 [ºF]	
	NCS	HAC
6-inch CV	300	500
Upper LDF	300	800
Lower LDF	300	800
O-Rings	400	700*, 400[16]

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

NCS Model Conditions:

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 listed in reference [7]).
5. The ambient temperature is 104ºF.
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 fire accident (FFA) thermal models consist of three sequential phases corresponding to the pre-fire, 90-minute fire, and post-fire conditions, respectively. 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 1832 ºF fire. 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 three phases are modeled using the COMSOL Multiphysics® software. The package component thermal limits (**Table 4**) are used to evaluate the thermal model results, while the 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 FFA is equivalent to the NCS thermal model above. The second phase of the HAC FFA fire thermal model is a 90-minute all engulfing fire performed under the following conditions.

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 1832ºF 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 1832 ºF fire.
5. There is forced convection heat transfer from the top, bottom, and sides of the drum to the ambient 1832 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.
8. The insulation does not char during the fire and maintains its thermal properties for the duration of the HAC, which is a conservative assumption[18].

The third and final phase of the HAC FFA thermal model is the post-fire or cooldown phase after the 90-minute 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 90-minute Fire phase model.
2. The ambient temperature and duration are 104 ºF and a minimum of 12-hours, respectively.
3. The drum is in an upright position.
4. The bottom drum surface is adiabatic.
5. There is radiative heat transfer from the top and sides of the drum to the ambient.
6. There is natural convection heat transfer from the top and sides of the drum to the ambient.
7. Unless otherwise stated, a total of 25W of decay heat power is uniformly distributed within the contents.
8. The insulation does not char during the fire and maintains its thermal properties for the duration of the HAC, which is a conservative assumption[18].

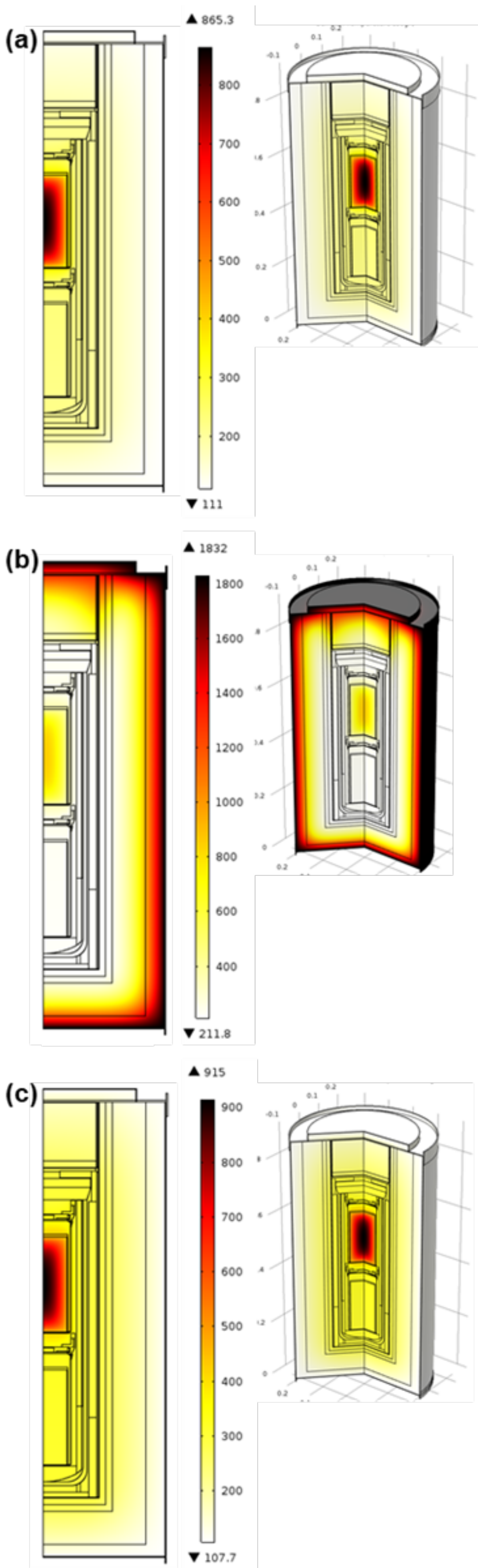

FIGURE 3: Temperature Contours (^{o}F) for the 9977-SAVY Shipping Package with a single 25W heat source and as-built, full insulation: a) during NCS, b) after 90-min fire, and c) 720-min post-fire.

9. 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 full as-built insulation and a 25W evenly distributed heat source located in the upper SAVY container was examined first. **Figure 3** shows temperature contours during NCS, after the 90-minute fire, and 12 hours into the cooldown post-fire. 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**. After 12 hours of cooldown post-fire, the temperature contours have begun to approach the pre-fire NCS distribution. The maximum component temperatures throughout the HAC FFA for selected components of the as-built, fully insulated 9977-SAVY package as shown in **Figure 4**. The maximum component temperature plots of **Figure 4** shows that no component temperature approaches its HAC temperature limits as listed in the SARP[1] during either the 90-minute fire phase or the post-fire cooldown phase. Note that Time = 0 at the end of NCS when the 90-minute fire begins.

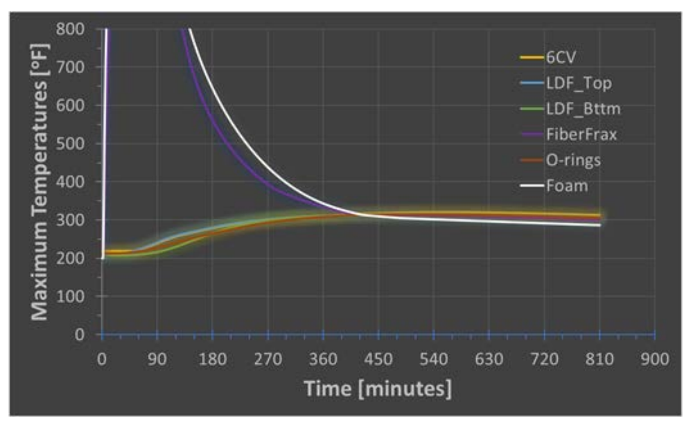

FIGURE 4: Maximum Component Temperatures throughout the HAC FFA for Selected 9977-SAVY Package Components with Full, As-Built Last-A-Foam® FR-3716 Insulation and a 25W Evenly Distributed Heat Source in the Upper SAVY Container.

2.2 No Insulation, 25W Source

Unlike the fully-insulated, as-built 9977-SAVY shipping package model examined in the previous section, this examines the 9977-SAVY shipping package model at the other extreme with no insulation within the as-designed / as-built configuration.

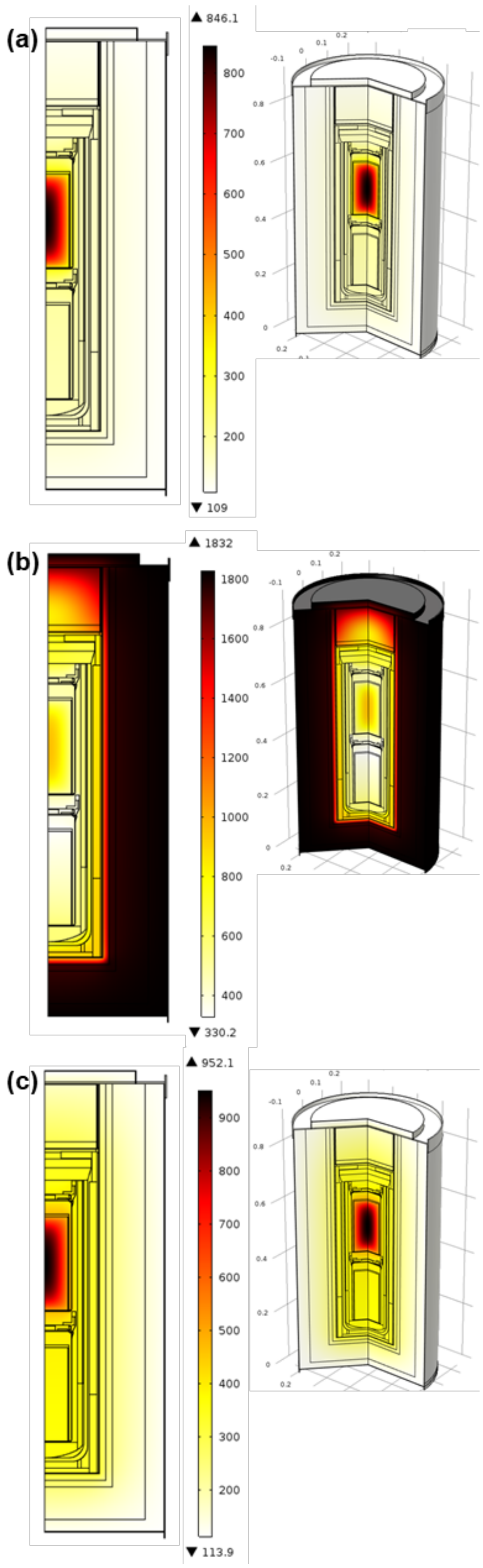

FIGURE 5: Temperature Contours (ºF) for the 9977-SAVY Shipping Package with a single 25W Heat Source and No Insulation: a) during NCS, b) after 90-min fire, and c) 720-min post-fire.

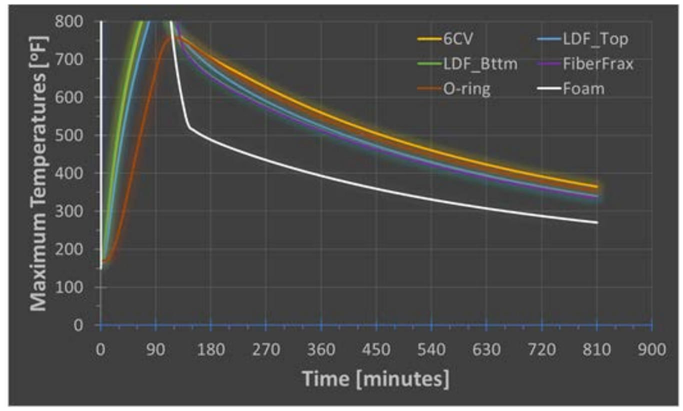

FIGURE 6: Maximum Component Temperatures throughout the HAC FFA for Selected 9977-SAVY Package Components with No Insulation and a 25W Evenly Distributed Heat Source.

Note that the Fiberfrax is still installed and *compressed*, while the package cavity is full of air instead of insulation. Natural convection is ignored and the air only experiences conduction and radiation heat transfer. Note that it is assumed that nothing shifts/moves within the 9977 shipping package as a result of the insulation removal. The heat source for this model is evenly distributed within the upper SAVY container with a magnitude of 25W.

Temperature contours for the 9977-SAVY shipping package with no insulation during NCS, after the 90-minute fire, and 12 hours into the post-fire cooldown are shown in **Figure 5**. The maximum component temperatures throughout the HAC FFA for selected package components are shown in **Figure 6**, with the maximum temperatures for each HAC FFA phase provided in **Table 5** with their corresponding temperature limits. Note that the Package Contents as listed in **Table 5** include everything within the 6CV. With no insulation, all of the 9977-SAVY shipping package components exceed their HAC temperature limits as listed in the SARP[1] during both the 90-minute fire phase and the post-fire cooldown phase.

TABLE 5: Maximum 9977-SAVY Shipping Package Component Temperatures During Each Phase of the HAC FFA for an Evenly Distributed 25W Source in the Upper SAVY with No Insulation.

Component	Pre-Fire [ºF]	90-min Fire [ºF]	Post-Fire [ºF]	Temp. Lim[1] [ºF]
Package Contents	594	826	1001	N/A
6CV	174	**911**	**911**	500
Upper LDF	162	**843**	**855**	800
Lower LDF	161	**921**	**921**	800
O-Rings	167	**658**	**746**	700*, 400[16]

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

2.3 Inner Foam Insulation Thickness Variation, 25W Source

The preceding sections showed the extremes of as-built, fully installed Last-A-Foam® FR-3716 Insulation and no insulation (except for Fiberfrax®). This section seeks to show the insulation thickness necessary to remain below the 9977-SAVY package component temperature limits as listed in the SARP[1].

Note that the Inner Foam insulation thickness is measured from the outside of the Fiberfrax along the drum liner cavity outward toward the inner wall of the drum body, as shown in **Figure 2** previously.

Several inner foam insulation thicknesses were examined for the 9977-SAVY shipping package with a 25W evenly distributed heat source. A plot of the maximum 9977-SAVY shipping package component temperatures as a function of the inner foam insulation thickness throughout the HAC FFA is shown in **Figure 7a**, with the comparable 9977-3013 shipping package[18] provided in **Figure 7b** for reference. **Table 6** provides the corresponding maximum 9977-SAVY shipping package component temperatures versus inner foam insulation thickness. The two critical components are shown to be the 6CV and the O-rings, which have temperature limits of 500 ºF and 400 ºF, respectively.

By analyzing the curve fits of **Figure 7a**, a minimum Inner Foam insulation thickness of 1.46 inches is needed to maintain all package components above their respective temperature limits, as measured from outward from the Fiberfrax and assuming the O-ring temperature limit is 400 ºF. This is a similar Inner Foam insulation thickness as measured for the 9977-3013 shipping package reported in M-CLC-A-00649[18], which had a minimum Inner Foam thickness of 1.43 inches.

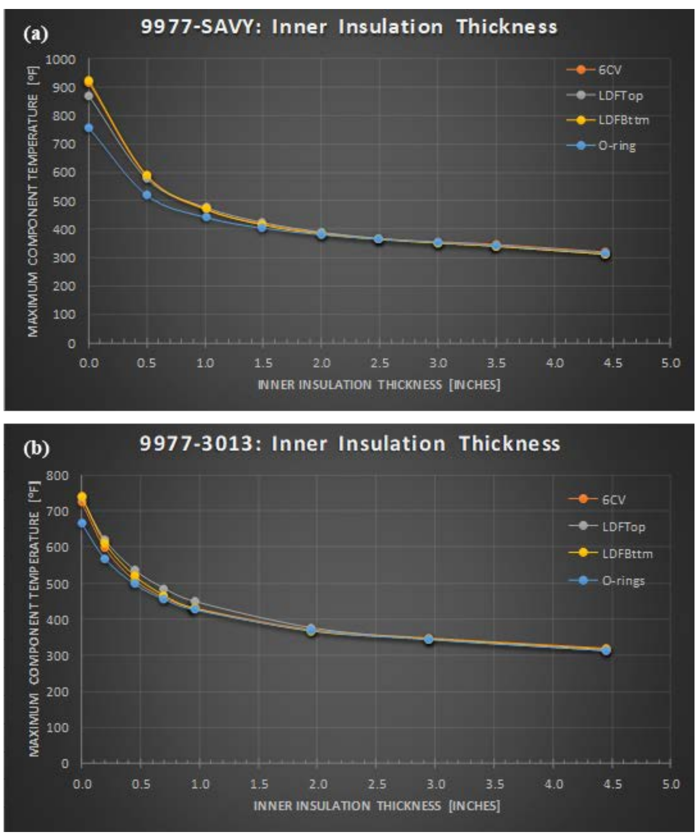

FIGURE 7: Maximum Component Temperatures throughout the HAC FFA for Selected (a) 9977-SAVY and (b) 9977-3013 Package Components with a 25W Evenly Distributed Heat Source and Various Inner Foam Insulation Thicknesses.

TABLE 6: Maximum 9977 Package Component Temperatures During the HAC FFA for an Evenly Distributed 25W Heat Source in the Upper SAVY Container for Various Inner Foam Insulation Thicknesses.

Insulation Thickness [in]	Package Content [ºF]	6-inch CV [ºF]	Upper LDF [ºF]	Lower LDF [ºF]	O-Rings [ºF]
0.0	1001	911	855	921	746
0.5	822	583	569	589	512
1.0	770	468	469	471	435
1.5	747	410	414	411	397
2.0	733	380	382	380	374
2.5	724	361	360	361	359
3.0	717	351	346	348	347
3.5	710	342	334	338	337
4.45	692	318	308	312	312
Limits	**N/A**	**500**	**800**	**800**	**700[1], 400[16]**

2.4 Outer Foam Insulation Thickness Variation, 25W Source

The preceding section examined Inner Foam insulation thickness, while this section will examine the Outer Foam insulation thickness necessary to remain below the 9977-SAVY package component temperature limits as listed in the SARP[1] during the HAC FFA. Note that the Outer Foam insulation thickness is measured from the interior wall of the drum body inward toward the drum centerline, as shown in **Figure 2** previously.

As in the previous section, various Outer Foam Last-A-Foam® FR-3716 insulation thicknesses were examined for the 9977-SAVY shipping package with a 25W evenly distributed heat source. **Figure 8a** shows the maximum component temperature versus the Outer Foam insulation thickness, with the comparable Outer Foam thickness for the 9977-3013 shipping package[18] provided in **Figure 8b** for reference. The maximum temperatures corresponding to **Figure 9a** are provided in **Table 7**. Analyzing the curve fits as before, a minimum Outer Foam insulation thickness of 2.37 inches is needed to maintain all 9977-SAVY package above their temperature limits, as measured inward from the interior wall of the drum wall and assuming the O-ring temperature limit is 400 ºF. This is approximately 20% higher than the comparable Outer Foam insulation thickness of the 9977-3013 package reported in M-CLC-A-00649[19], which had a minimum Outer Foam thickness of 2.03 inches.

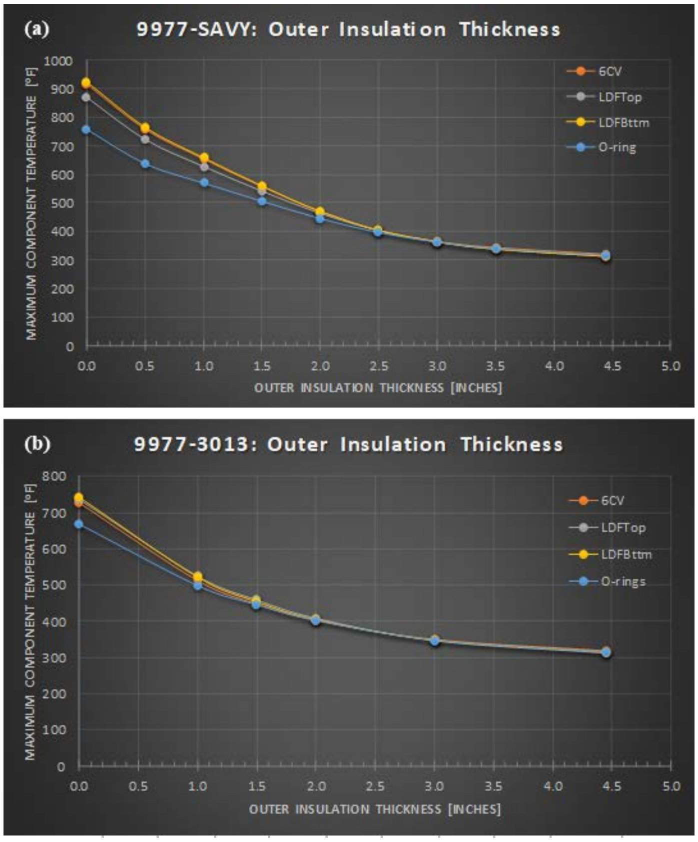

FIGURE 8: Maximum Component Temperatures throughout the HAC FFA for Selected (a) 9977-SAVY and (b) 9977-3013 Package Components with a 25W Evenly Distributed Heat Source and Various Outer Foam Insulation Thicknesses.

TABLE 7: Maximum 9977 Package Component Temperatures During the HAC FFA for an Evenly Distributed 25W Heat Source in the Upper SAVY Container for Various Outer Foam Insulation Thicknesses.

Insulation Thickness [in]	Package Content [ºF]	6-inch CV [ºF]	Upper LDF [ºF]	Lower LDF [ºF]	O-Rings [ºF]
0.0	1001	**911**	**855**	**921**	**746**
0.5	912	**754**	709	762	**629**
1.0	866	**649**	616	655	**563**
1.5	824	**552**	531	555	**500**
2.0	782	467	456	469	**440**
2.5	743	397	390	398	385
3.0	720	357	351	357	352
3.5	705	336	327	332	330
4.45	692	318	308	312	312
Limits	**N/A**	**500**	**800**	**800**	**700[1], 400[16]**

2.5 Inner and Outer Foam Variation, 19W Source

The 9977 shipping package analyses in the preceding sections all examined 25W heat sources. This section examines the effects of lowering the heat source to 19W on the insulation thickness variations. **Tables 8** and **9** provide the maximum 9977-SAVY shipping package component temperatures for various Inner Foam and Outer Foam insulation thicknesses, respectively. As identified previously, the 6CV and O-rings are the critical components, and the reduced temperature limit of 400 ºF is used for the O-rings being the most critical. Based on the reduced O-ring component temperature limit, the minimum Inner Foam and Outer Foam insulation thicknesses needed are 1.31 inches and 2.12 inches, respectively, in order to maintain all components of the 9977-SAVY shipping package above their temperature limits.

TABLE 8: Maximum 9977 Package Component Temperatures During the HAC FFA for an Evenly Distributed 19W Heat Source in the Upper SAVY Container for Various Inner Foam Insulation Thicknesses.

Insulation Thickness [in]	Package Content [ºF]	6-inch CV [ºF]	Upper LDF [ºF]	Lower LDF [ºF]	O-Rings [ºF]
0.0	922	**907**	**860**	**917**	**746**
0.5	733	**574**	564	580	**505**
1.0	677	457	461	460	**425**
1.5	651	401	405	400	384
2.0	636	368	370	367	360
2.5	626	346	347	347	343
3.0	618	334	331	333	331
3.5	611	324	319	322	321
4.45	586	293	286	290	289
Limits	**N/A**	**500**	**800**	**800**	**700[1], 400[16]**

TABLE 9: Maximum 9977 Package Component Temperatures During the HAC FFA for an Evenly Distributed 19W Heat Source in the Upper SAVY Container for Various Outer Foam Insulation Thicknesses.

Insulation Thickness [in]	Package Content [ºF]	6-inch CV [ºF]	Upper LDF [ºF]	Lower LDF [ºF]	O-Rings [ºF]
0.0	922	**907**	**860**	**917**	**746**
0.5	809	**727**	682	735	**602**
1.0	760	**619**	585	624	**531**
1.5	717	**522**	502	526	**469**
2.0	677	441	429	442	**412**
2.5	639	374	366	374	360
3.0	617	337	332	338	331
3.5	601	312	306	311	308
4.45	586	293	286	290	289
Limits	**N/A**	**500**	**800**	**800**	**700[1], 400[16]**

Figures 9 and **10** show the maximum component temperatures for selected 9977 shipping package components with a 19W heat source for variations in Inner Foam and Outer Foam Insulation thickness, respectively. Note that **Figures 9a** and **10a** show the 9977-SAVY package temperature profiles, while **Figures 9b** and **10b** provide the comparable 9977-3013 package[18] temperature profiles. The 9977-3013 shipping package results are taken from M-CLC-A-00649[19] and show that the minimum Inner Foam and Outer Foam insulations thicknesses are 1.13 inches and 1.83 inches, respectively, for the

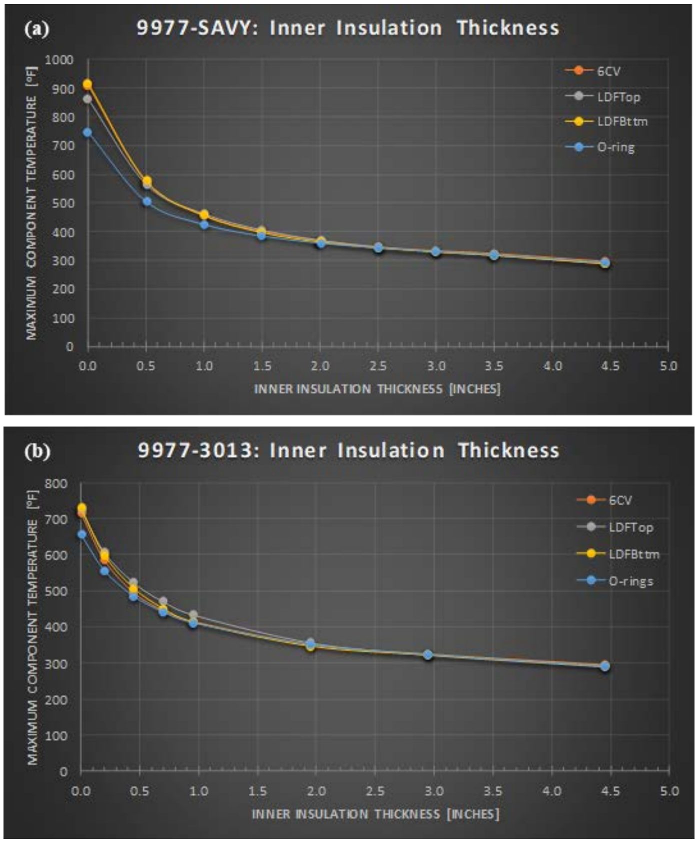

FIGURE 9: Maximum Component Temperatures throughout the HAC FFA for Selected (a) 9977-SAVY and (b) 9977-3013 Package Components with a 19W Evenly Distributed Heat Source and Various Inner Foam Insulation Thicknesses.

evenly distributed 19W heat source. These values are approximately 13.5% lower than the corresponding 9977-SAVY shipping package minimum insulation thicknesses.

By comparing the temperature plots for 25W and 19W heat sources with Inner Foam and Outer Foam insulation variations, the plots for the 9977-SAVY and 9977-3013 shipping packages are similar with only small variations in magnitudes. This can be attributed to the differences in conductive heat transfer through the 9977 package design variations to accommodate the 3013 or SAVY containers. Specifically, these are the differences within the 6CV that hold the 3013 or SAVY containers, including the size and shape of the aluminum spacers, the volume and type of gas within the 6CV, the volume of the heat source within the 3013 or SAVY container, and the amounts of stainless steel that make up the 3013 or SAVY containers. Note that decreasing the heat source magnitude does decrease the maximum component temperatures for each package, but does not significantly change the curves of the maximum component temperature plots.

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 51,000 to 112,500. The HAC FFA for a 25W heat

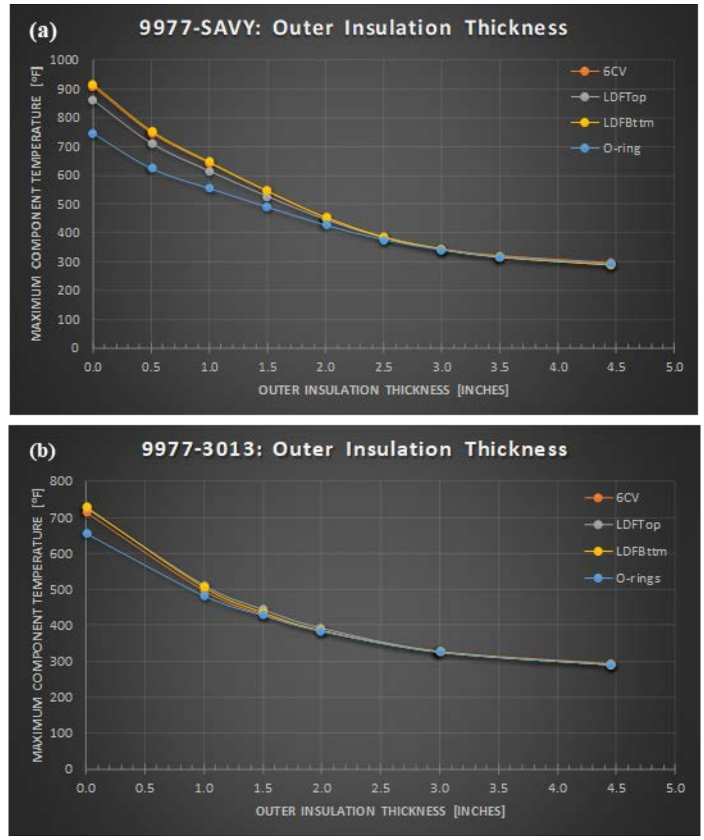

FIGURE 10: Maximum Component Temperatures throughout the HAC FFA for Selected (a) 9977-SAVY and (b) 9977-3013 Package Components with a 19W Evenly Distributed Heat Source and Various Outer Foam Insulation Thicknesses.

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 0.0254%. Therefore, the results reported in this calculation are based on models with about 51,000 elements.

3.0 CONCLUSIONS

The above thermal analyses examined the HAC FFA of the 9977-SAVY shipping package with various heat source magnitudes (25W and 19W) and various insulation thicknesses. The present calculation assumes that the 9977-SAVY shipping package materials are new with as-built material 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 shipping package remains below the component temperature limits, as listed in the SARP[1], throughout HAC FFA. With no insulation between the Fiberfrax at the drum liner cavity and the drum body, the 9977-SAVY package component maximum temperatures exceed their component temperature limits. Various insulation thickness as measured from the Fiberfrax outward (Inner Foam) and from the drum body inward (Outer Foam) were also examined. A summary of the minimum required insulation thickness to maintain all 9977 shipping package components below their temperature limits is provided here in **Table 10**.

TABLE 10: Minimum Last-A-Foam® FR-3716 Foam Insulation Thickness Needed to Maintain All 9977 Shipping Package Components Below Their Temperature Limits.

	9977-SAVY Package		9977-3013 Package[18]	
	Inner Foam	**Outer Foam**	**Inner Foam**	**Outer Foam**
19W	1.31 in.	2.12 in.	1.13 in.	1.83 in.
25W	1.46 in.	2.37 in.	1.43 in.	2.03 in.

ACKNOWLEDGEMENTS

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