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THERMAL ANALYSIS OF 9977 RADIOACTIVE MATERIAL PACKAGE

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ABSTRACT

The 9977 package is a certified Type B transportation packaging that was designed to transport radioactive materials with a decay heat load of up to 19 W. The packaging was recently modified to accommodate increased content heat load (up to 38 W) by employing an aluminum heat-dissipating sleeve outside the containment vessel (CV), as well as an aluminum spacer inside the CV holding two 3013 containers. This paper provides highlights of thermal analyses of the modified 9977 package that were performed to evaluate its compliance with the 10 CFR 71 regulatory safety requirements. Parametric studies were also performed to examine effects of (1) surface properties, e.g., light absorptivity and emissivity, of the packaging; (2) total decay heat loads, ranging from 18 to 38 W; and (3) distribution of decay heat load inside the CV on the temperature of the Viton O-ring seal. The results of thermal analyses show that for the normal condition of transport with insolation, increasing absorptivity and decreasing emissivity increase the temperature of the O-ring; decreasing heat load decreases the temperature of the O-ring, whereas changing heat load distribution has little effect on the temperature of the O-ring. Likewise, changing the thermal conductivity of the spacer inside the CV has little effect on the temperature of the O-ring. Future study will examine the temperature of the O-ring under extended storage conditions.

INTRODUCTION

The Model 9977 package was originally designed to replace the U.S. Department of Transportation (DOT) Specification 6M package. The 9977 package is a Type B transportation package [1] certified by the U.S. Department of Energy Packaging Certification Program for the transportation of fissile and radioactive materials. Various contents and payload configurations were added to the Certificate of Compliance (CoC) via addenda requests during the last few years. The most recent contents addition, Addendum 7 [2], involved a design modification of the packaging to accommodate a substantial increase in the contents decay heat load from 19 to 38 W. The new contents are two 3013 containers, and the design modifications involve the incorporation of an external aluminum sleeve and an internal aluminum spacer for enhanced heat transfer, as described in detail in the next section.

This paper describes the thermal analyses conducted for the modified 9977 package as part of the certification review and independent confirmatory evaluation of the package for compliance with the regulatory safety requirements. Because of the doubling of the decay heat load, particular attention was paid to the calculated temperature of the Viton O-rings that provide the sealing function of the package against any release of radioactivity. The ANSYS/Mechanical software was used in the confirmatory evaluation.

Modified 9977 Packaging

The original 9977 packaging consists of a single 15.24-cm (6-inch) diameter CV, a drum overpack filled with rigid polyurethane foam, and a bolted closure lid that has two layers of insulation. The original 9977 packaging has been designed for contents decay heat load of up to 19 W in a single DOE-STD-3013 container. The modified 9977 design, as shown in Figure 1, includes two 3013 containers and a 3013 spacer (6061-T6 Al) inside the CV, which is closed with a cone seal plug that has a set of double O-rings and a cone seal nut. The CV is loaded into a cylindrical drum liner, which is surrounded by an aluminum sleeve held in place by an upper and a lower load distributor fixture. The purpose of the design modifications is to enhance heat transfer and accommodate the increase in contents decay heat load from 19 to 38 W. The Addendum 7 request for the 9977 Safety Analysis Report for Packaging (SARP) has been approved by the DOE Headquarter Certifying Official in 2012 [3].

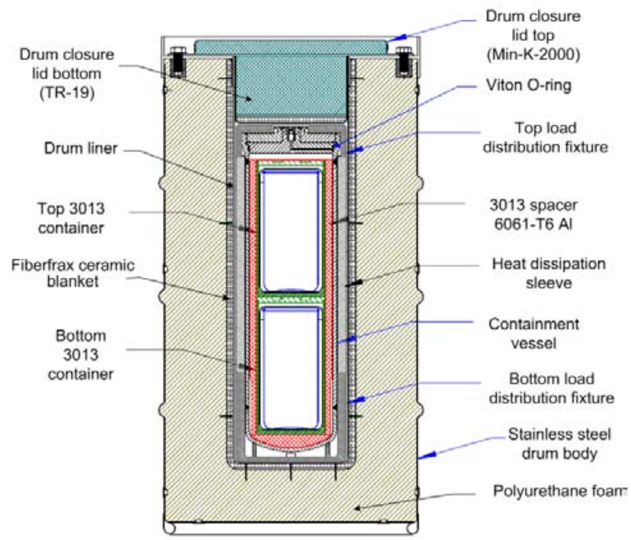


Fig. 1: Schematic of modified 9977 packaging (The contents of 3013 containers are composed of convenience can, inner can, and outer can which are not labeled).

Packaging Design and Functional Requirements

One of the major objectives in packaging design is the containment of radioactivity under the normal conditions of transport (NCT) and hypothetical accident conditions (HAC), as prescribed in 10 CFR 71.71 and 71.73, respectively. The key components that offer protection of the CV and O-rings of the 9977 package from structural damage and overheating during NCT and HAC are:

1. Polyurethane foam (Last-A-Foam from General Plastics) confined in the stainless-steel drum body, which acts as an impact limiter and provides thermal insulation.
2. Stainless-steel CV with cone seal plug and cone seal nut, which provides containment of radioactivity.
3. Viton® GLT/GLT-S O-rings, which provide the sealing function for the containment boundary of the CV.

The following features of the modified 9977 packaging design are important to thermal performance: (a) Aluminum (6061-T6 Al) sleeve surrounding the CV to enhance heat transfer; (b) CO_2 inside the CV to provide an inerting atmosphere; and (c) stainless steel 3013 container inerted inside with helium. The impacts of heat loads and heat-load distribution inside the CV on the O-rings are also investigated. The O-rings are expected to remain leak-tight for up to one year after initial closure.

Table 1 provides the temperature limits for the key components of the 9977 packaging.

Table 1: Temperature limits of key components of 9977 packaging

Component	Temperature Limits (°C/°F)
O-Rings	149/300
Containment vessel	427/800
Polyurethane foam	149/300
Accessible drum surface	50/122*

** See 10 CFR 71.43g (still air at 100°F and in shade) for a non-exclusive use shipment [4].*

THERMAL MODEL

Geometry and Thermal Physical Properties

A two dimensional (2-D) ANSYS axisymmetric model, shown in Figure 2, was constructed to simulate temperatures of the modified 9977 package under NCT. The geometrical model of the modified 9977 packaging consists of seven (7) layers of different materials, and the 3013 containers consist of three (3) layers of stainless steel for the outer, inner, and convenience can. Stainless steel is also used for the drum, liner, and CV, whereas aluminum alloy (6061-T6 Al) is used as spacer and loading fixtures for the 3013 containers, as well as heat dissipation sleeve. The polyurethane foam is the primary thermal insulating material for the CV; the ceramic fiber-Frax blanket that surrounds the liner and the top lid provides additional thermal insulation. Moreover, two ceramic thermal insulting materials, Min-k-2000 and Vermiculite TR-19, are used at the top and bottom of the lid, respectively, to provide insulation for the CV.

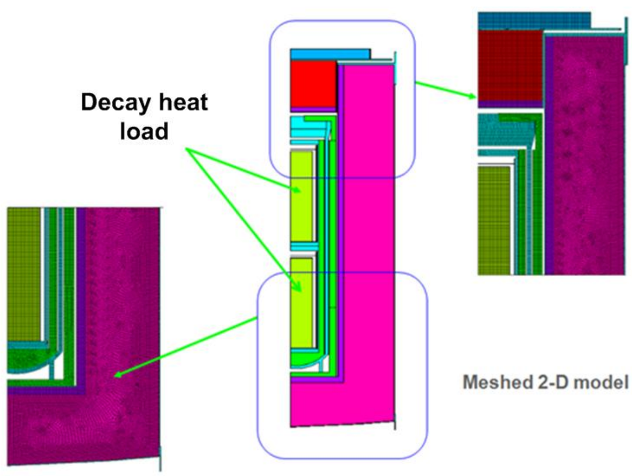


Fig. 2: ANSYS finite element model (FEM) of the 9977 package (areas of top and bottom enlarged)

Each 3013 container is filled with helium, whereas the CV is filled with CO_2-enriched (>75%) air to prevent flammable mixture and hydrogen explosion. In these gas-filled cavities, both heat conduction and radiation are simulated in the ANSYS calculations [5]. The thermal physical properties of all the materials used in the ANSYS simulations can be found in reference [2].

FEM Model and Boundary Conditions

In the ANSYS calculations, the 4-node quadrilateral PLANE 55 element is used to simulate the heat transfer of the 9977 package body. Surface element SURF 151 is applied to the drum surface to model the thermal boundary conditions (convection and radiation). In addition, contact elements, CONTA 171 and TARGE 169, are used to simulate heat transfer between two adjacent surfaces. 29,617 elements were used in the simulations. The boundary conditions for the ANSYS calculations are shown in Table 2 for NCT that includes both shade and solar insolation.

Table 2: Boundary conditions for NCT simulations

Condition	Description	Applicable Conditions: Ambient Temperature (°F)	Insolation		Decay Heat	
			Max.	Zero	Max.	Zero
1	NCT Hot	100	×		×	
2	NCT Hot (no solar)	100		×	×	
3	NCT Cold	-20		×	×	
4	NCT Cold Environment	-40		×		×

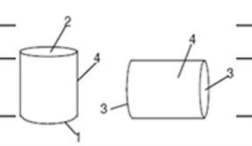
Heat Loads

Two types of heat loads are considered in the ANSYS simulations: decay heat, 38 W maximum from two 3013 containers, and solar insolation, shown in Table 3 based on 10 CFR 71 [4].

Table 3: Heat loads from solar insolation, based on 10 CFR 71 [4]

INSOLATION DATA

Form and location of surface	Total insolation for a 12-hour period (g cal/cm²)
Flat surfaces transported horizontally	
Base	None
Other surfaces	800
Flat surfaces not transported horizontally	200
Curved surfaces	400



RESULTS AND DISCUSSION

In the shade, the 38 W decay heat is modeled in three different configurations: (1) applying 19 W uniformly to the inner wall of the two 3013 cans as a surface heat flux; (2) applying 19 W to the radioactive material inside each 3013 convenience can as a body load where material is loosely packed with a bulk density of 2 g/cm^3 and thermal conductivity of 0.0795 W/m-K (0.046 Btu/h-ft-^{o}F); and (3) same as (2) except for a bulk density of 11.5 g/cm^3 and thermal conductivity of 2 W/m-K (1.16 Btu/h-ft-^{o}F) [6].

Table 4 shows the calculated maximum temperatures for the packaging components and contents for NCT in the shade. The result shows little differences in the calculated temperatures for the packaging components. 10 CFR 71 requires the accessible surface temperature of a transportation package to remain below 50°C (122°F) for non-exclusive use in the shade for an ambient temperature of 38°C (100°F) in still air. The calculated maximum temperature for the drum body surface is 43°C (110°F), which is below the regulatory requirement. For the PuO_2 contents, the calculated maximum temperatures are significantly below 426°C (800°F), the temperature of Pu/Fe eutectic reaction [7].

The following parametric analyses are based on the decay heat load configuration of 2.0 g/cc.

Table 4: Calculated maximum temperatures of packaging components and contents under three modeling configurations of heat loads (38 W total)

Components	**Max. Temperature ($^oC/^oF$)** (surface heat flux)	**Max. Temperature ($^oC/^oF$)**	
		(2.0 g/cc)	(11.5 g/cc)
Drum body	43/110	43/110	43/110
Drum lid, Min-k 2000	51/124	51/125	51/124
Drum lid, TR19	78/173	79/174	79/174
Drum lid, fiberfrex	83/182	83/182	83/182
Fiberfrex blanket, near liner	131/267	131/268	131/268
Load distributor/top	123/254	124/255	124/255
Load distributor/bottom	131/267	131/268	132/269
Heat dissipation sleeve	129/265	131/267	131/267
PU foam	124/255	124/256	124/256
Containment vessel	137/279	138/280	138/281
Viton O-ring	124/256	125/257	125/257
3013 outer can/top	149/301	149/301	151/303
3013 outer can/bottom	149/301	149/301	151/303
PuO_2 fuel (top)	N/A	247/477	155/312
PuO_2 fuel (bottom)	N/A	245/473	154/309

Maximum Temperatures of Packaging Components under Solar Insolation

Table 5 shows the calculated maximum temperatures of each packaging component obtained in the SARP and confirmatory evaluation, as well as the allowable temperature limits. The calculated maximum temperatures of packaging components in the confirmatory evaluation using the ANSYS code are consistently lower than those obtained in the SARP using the P-thermal code. However, both are lower than the allowable temperatures for the corresponding materials. The temperature limit of 149^{o}C (300°F) of the Viton$^@$ O-ring is established on the basis of O-ring fixture long-term leak performance [8], which shows that the O-ring remains leak-tight over 1000 days at 149^{o}C (300^{o}F). This period is longer than the annual leakage rate test requirement in ANSI N14.5 [9].

Effect of Packaging Surface Properties on O-ring Temperature under Solar Insolation

Figure 3 shows the effect of packaging surface properties, such as absorptivity and emissivity (ε), on the O-ring temperature under solar insolation. The calculated maximum temperature of the O-rings varies from 123°C (254°F) to 136°C (277°F), with absorptivity varying from 0.3 to 1 and ε = 0.21 or 0.5, showing little sensitivity to emissivity.

Table 5: Calculated maximum temperatures for the packaging components

Components	Max. Temperature (°C/°F)		
	SARP	Confirmatory Evaluation*	Allowable
Drum body	87/189	76/169	426/800
Drum lid, Min-k 2000	/	71/159	N/A
Drum lid, TR19	/	93/200	1,371/2,500
Drum lid, fiberfrex	/	97/207	1,760/3,200
Fiberfrex blanket, near liner	/	136/276	1,760/3,200
Load distributor/top	/	130/266	149/300
Load distributor/bottom	/	136/276	149/300
Heat dissipation sleeve	/	135/275	149/300
Polyurethane (PU) foam	**144/291**	**130/266**	**149/300**
Containment vessel	154/310	141/286	426/800
Viton O-ring	**148/299**	**131/269**	**149/300**
3013 content/top	292/559	251/484	426/800
3013 content/bottom	291/555	249/480	426/800

* drum surface absorptivity = 0.7

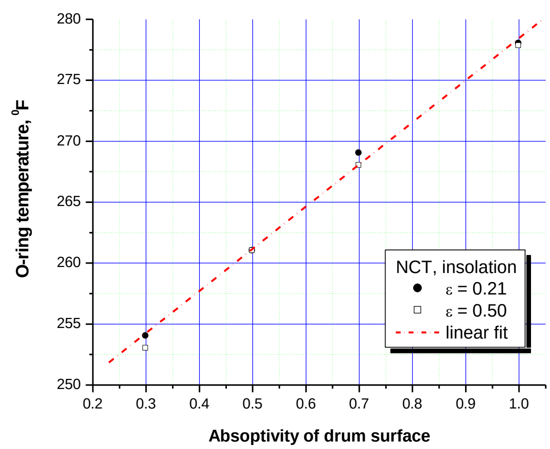


Fig. 3: Effect of packaging surface absorptivity on calculated maximum temperature of the O-ring

Effect of Decay Heat Load and Its Distribution

The Viton O-rings are part of the containment boundary of the CV. High temperature generally accelerates aging and shortens the O-ring's lifetime [10, 11]. This is a particular concern for long-term storage of radioactive materials in Type B transportation packages with high decay heat loads. Computer simulations were conducted, with decay heat load ranging from 18 to 38 W, to calculate the O-ring temperatures. In the simulations, all decay heat is evenly distributed between two 3013 containers. Both solar insolation and shade were considered.

Figure 4 shows that the calculated maximum temperature of the O-ring increases with increasing decay heat load under solar insolation, reaching 136°C (277°F) at 38 W, which is below the allowable temperature of 149°C (300°F).

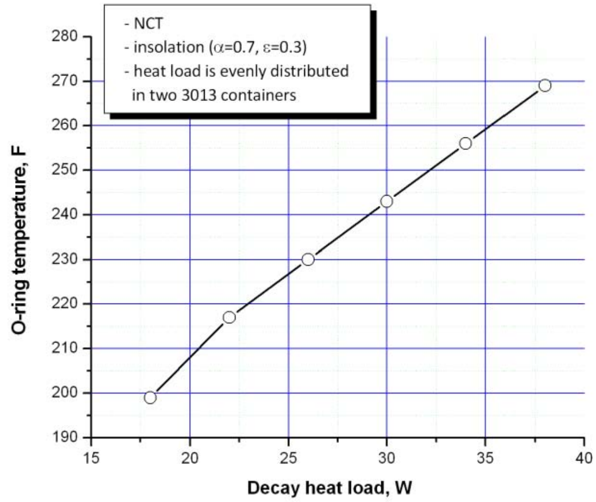


Fig. 4: Effect of decay heat load on calculated maximum temperature of the O-rings under solar insolation

The effect of decay heat load on calculated maximum temperature of the O-rings in the shade was also simulated, as well as the heat load distribution in the CV. Figure 5 shows that the calculated maximum temperatures of the O-ring in the shade, which simulates in-door storage, are always lower than those obtained under solar insolation for a given decay heat load. Heat load distributions, on the other hand, show relatively little effect on the calculated maximum temperatures of the O-ring.

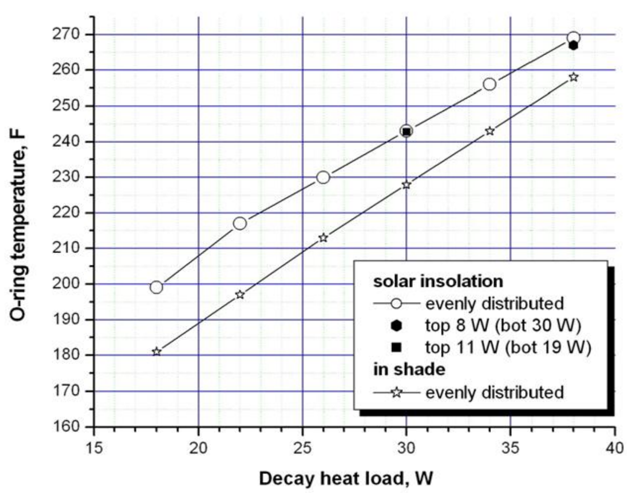


Fig. 5: Effect of heat load distribution on calculated maximum temperatures of the O-ring

Effect of Thermal Conductivity of the CV Spacer

According to Addendum 7 of the SARP [2], the 3013 spacer (6061-T6 Al) inside the CV is designed to dissipate decay heat of the modified 9977 package. Simulations were performed for the CV spacers with thermal conductivities varying over four orders of magnitudes of $*k_{x,Al}$ normalized to1 for physical value of 166.3 W/m-K (96.1 Btu/hr-ft-°F) at 21^{o}C (70°F). Figure 6 shows the calculated maximum temperatures of the O-ring; an increase of only 5.6^{o}C (10°F) is noted in the O-ring temperature for a CV spacer with a thermal conductivity of 1E-4 of that of the 3013 spacer.

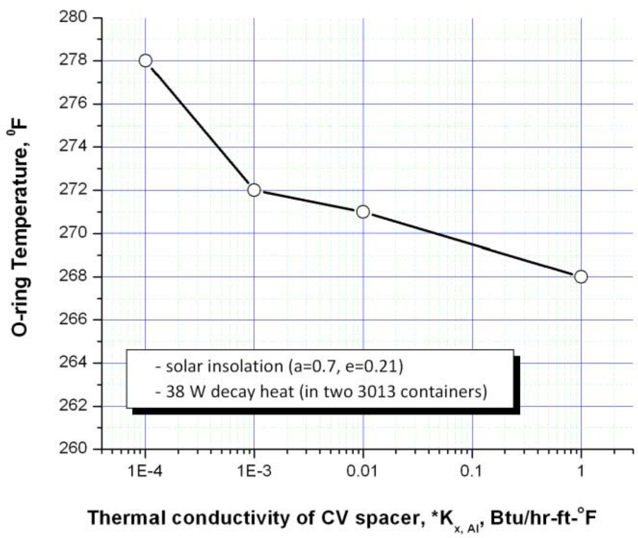


Fig. 6: Effect of thermal conductivity of CV spacer on calculated maximum temperatures of the O-ring

Since the primary heat flow of the drum is along the CV wall and the liner, the marginal increase in the calculated maximum temperatures of the O-ring is expected, because (1) the O-ring is located near the heat flow path, as shown in Figure 7, and (2) the required balance between the total heat generation of the contents and heat transfer out of the drum.

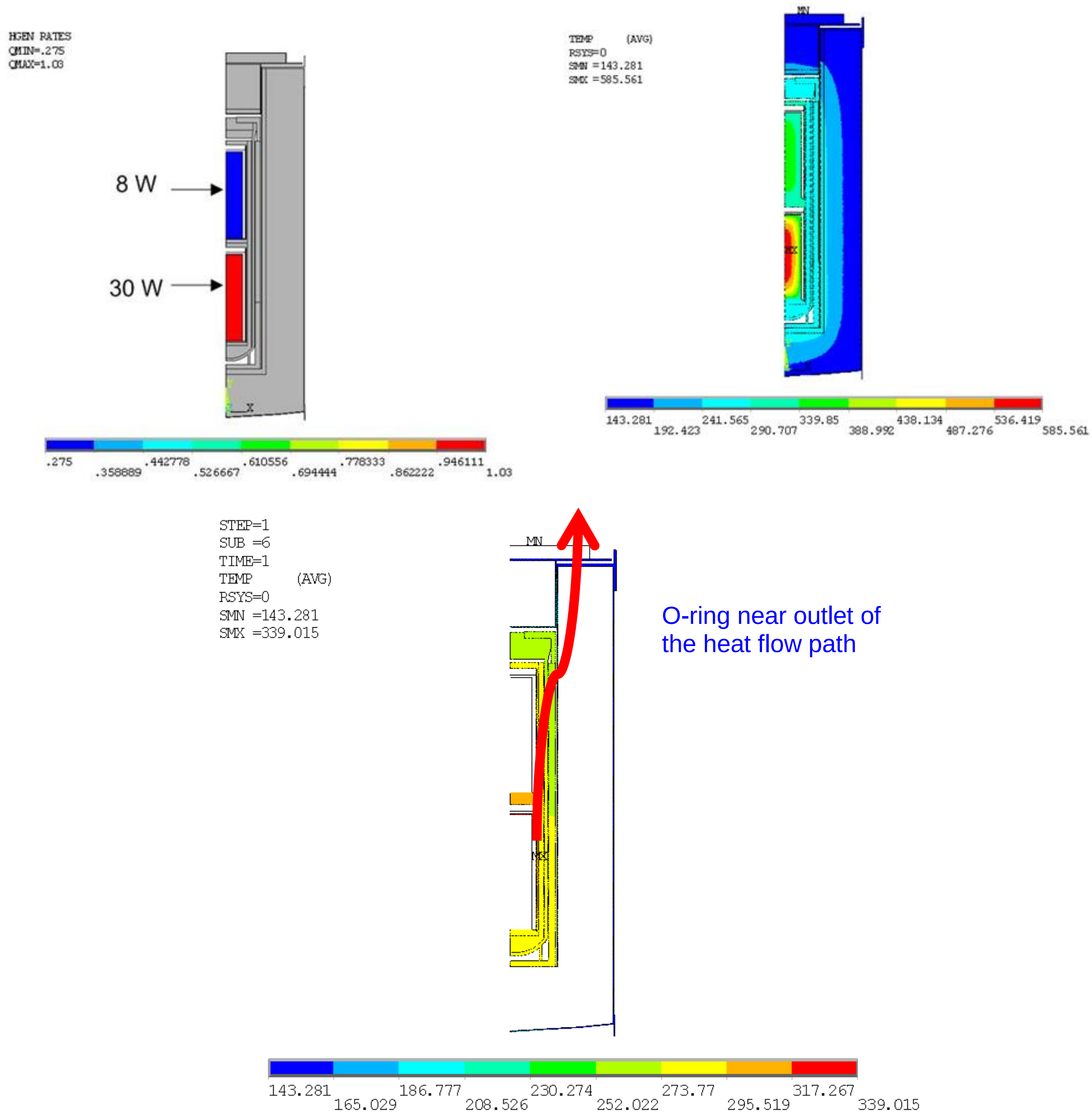


Fig. 7: Temperature profile for selected components in the 9977 package
(The thermal conductivity of the CV spacer = 1E-4 $k_{x,Al}$; 30-W is used for illustration purpose only)

CONCLUSION

ANSYS thermal analyses were performed on the modified 9977 package for two 3013 containers with a total heat load up to 38 W under normal conditions of transport. The simulation shows that the modified 9977 design satisfies the requirement of 10 CFR 71.43(g). The calculated maximum temperatures of the packaging components under solar insolation are well within the allowable temperature limits.

The results of parametric thermal analyses show that under solar insolation, increasing absorptivity and decreasing emissivity increase the O-ring temperature; decreasing heat load decreases the O-ring temperature, whereas changing heat load distribution has little effect on the O-ring temperature. Likewise, changing thermal conductivity of the CV spacer has little effect on the O-ring temperature. Future study will examine the temperature of the O-ring under extended storage conditions [12, 13].

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