

Calculation Cover Sheet

1. Document Title: <div style="text-align: center; font-weight: bold;">Shielded Container Thermal Analysis</div>		2. System Number: <div style="text-align: center; font-weight: bold;">PT01</div>
3. Document Number: <div style="text-align: center; font-weight: bold;">SCA-CAL-0002</div>	4. Document Revision: <div style="text-align: center; font-weight: bold;">0</div>	5. Page: <div style="text-align: center; font-weight: bold;">1 of 117</div>
6. Summary Description		
<p>This analysis models the newly designed Shielded Containers (SCs) for the regulatory Normal Conditions of Transport (NCT) thermal performance requirements delineated in 10 CFR 71. The payload designs covered by this analysis are the SC-30G2, SC-30G3, SC-55G1, and SC-55G2. The results of this analysis confirm that the aforementioned new SC payload designs meet all of the respective component temperature limits when subjected to the regulatory thermal conditions prescribed in 10 CFR 71.</p> <p>This analysis also presents the maximum and average payload temperatures as a function of decay heat for MNOP calculations.</p>		
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0	All	New Issue

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1.0 INTRODUCTION

The HalfPACT package [Ref. 1] is a U.S. Nuclear Regulatory Commission (NRC) approved Type B package (Docket No. 71-9279) for the transport of radioactive waste. It is designed for use by the U.S. Department of Energy (DOE) for the transport of Contact Handled Transuranic (CH-TRU) radioactive waste to the Waste Isolation Pilot Plant (WIPP). The HalfPACT package is depicted in a quarter cutout view, with various components of interest labeled, in Figure 1-1.

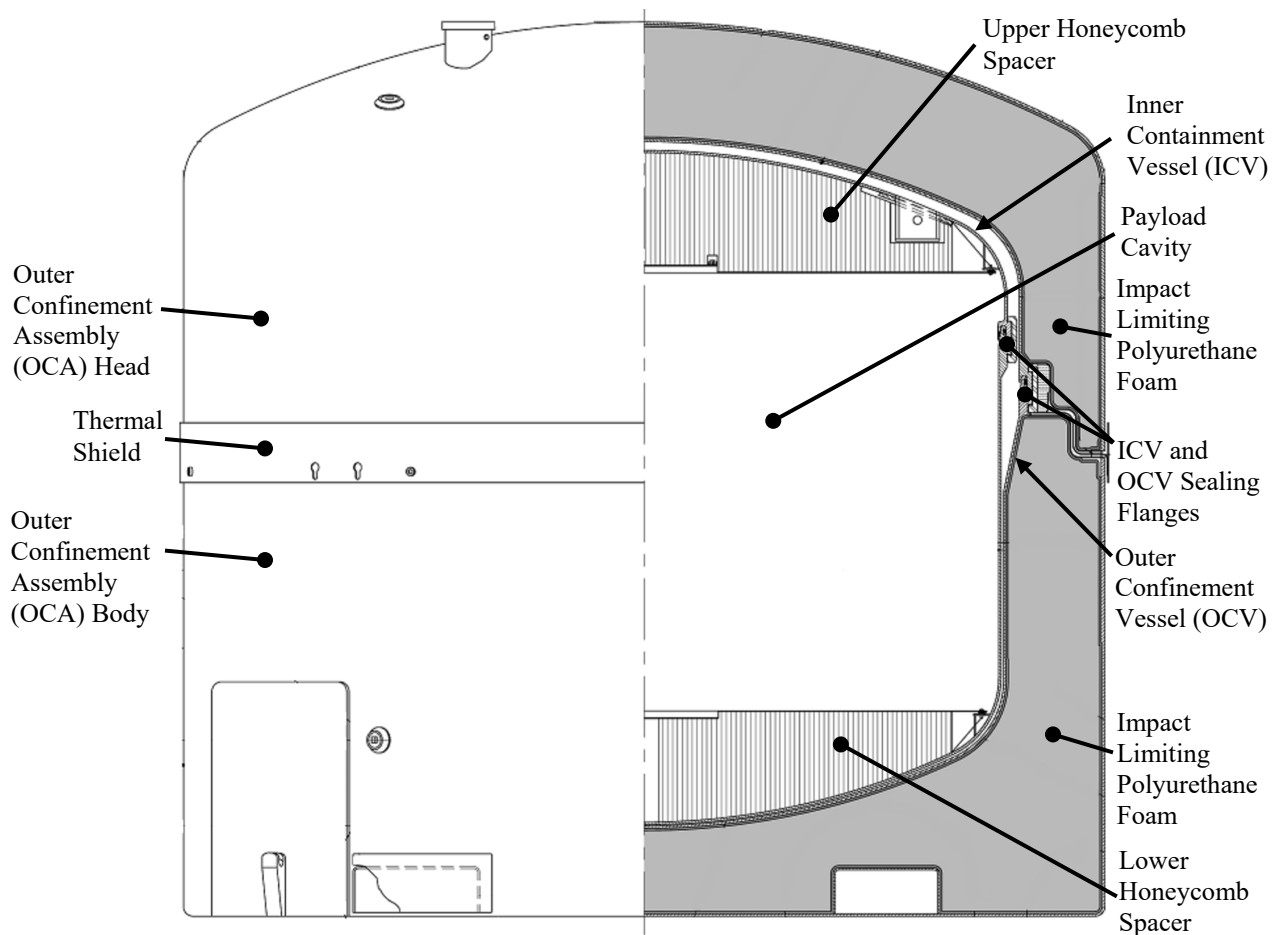


Figure 1-1 HalfPACT Packaging without Payload

The HalfPACT packaging was designed to be lightweight in order to maximize the mass of the payload contents. The relatively low thermal loading of the waste transported in the HalfPACT allows for a design that maximizes payload content mass and impact attenuation, at the expense of low maximum thermal loads due to the use of insulating foam material. The package design consists of the outer confinement assembly (OCA), which includes the outer confinement vessel (OCV), and the inner containment vessel (ICV). The OCV is classified as a confining boundary without credit for leak tightness. The main function of the OCA as a whole is to provide

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protection for the ICV from regulatory accident testing conditions. The ICV is credited for providing a leak tight containment boundary to the payload contents.

The HalfPACT OCA design utilizes relatively thin shells of Type 304 stainless steel surrounding 8.25 lb/ft³ impact attenuating and thermally-insulating polyurethane foam. The inner cavity of the OCA shell is also lined with ¼-inch thick ceramic fiber paper that acts as a high temperature capable insulating barrier between the foam and shell. The ICV also utilizes thin shells of Type 304 stainless steel and relies on the protective features of the OCA to attenuate impact loads and thermal transients. In the effort to minimize packaging weight and maximize payload mass, the ICV utilizes aluminum components with hexagonally shaped extruded cells (honeycomb spacers) to adapt the upper and lower torispherical heads of the ICV into flat surfaces and accommodate the payload contents. The result is a Type B package design with a total maximum weight of 18,100 pounds, of which 7,600 pounds is the total allowable payload weight.

The HalfPACT package is designed to carry a variety of payloads within its payload cavity. Those payloads include seven 55-gallon drums, four 85-gallon drums, three 100-gallon drums, seven pipe overpacks (POCs), seven criticality control overpacks (CCOs), a standard waste box (SWB), or three shielded container assemblies (SCAs). See the Contact Handled Transuranic Waste Authorized Methods for Payload Control (CH-TRAMPAC) [Ref. 3], Section 2.0, for further discussion and high level figures depicting the various approved payload containers. There are two general classifications of waste accepted for disposal at the WIPP within these approved payload containers, CH-TRU and Remote Handled Transuranic (RH-TRU). The defining trait that distinguishes CH from RH payload containers is the surface dose rate at the payload container itself, where CH is limited 200 millirem per hour (mrem/hr) and RH is greater than 200 mrem/hr. Due to operational limitations, the WIPP is currently not accepting RH waste for disposal, however there still exists waste in the DOE inventory that is contained in 30- or 55-gallon drums and whose dose rate at the outer surface of the containers exceeds the CH limit. Therefore, there is a present need to design overpacking payload containers with radiation shielding to lower surface dose rates to acceptable CH levels (≤ 200 mrem/hr), thereby allowing reclassification of RH-TRU payload containers as CH-TRU payload containers.

The SCA [Ref. 21] fills a portion of the aforementioned need. The SCA container and payload design are depicted in Figure 1-2 and Figure 1-3. The design is a right circular cylinder of carbon steel and lead composite construction with interior dimensions to accommodate a 30-gallon drum. The carbon steel chassis consists of a lid and body, with fifteen (15) ½-inch cap screws to fasten the lid to the body. A silicone closed cell sponge gasket is utilized between the lid and body to seal the two components and provide particulate retention of the contents within the container. A filter vent is also installed in the lid to prevent pressurization of the overpacked contents, completing the confinement boundary of the design. The shielding features of the SCA are provided by a thick carbon steel lid and base, and a 0.88-inch thick minimum void space within the wall of the chassis body that is filled with lead. A lead shield cap is also installed in the lid to prevent radiation shine through the locally thin region of lid material near the filter vent.

The SCA payload design consists of three (3) SCAs and impact attenuating dunnage material. The impact attenuating dunnage consists of the radial and axial dunnage assemblies. The radial

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and axial dunnage assemblies are polyurethane foam wrapped in thin aluminum skin. The remaining dunnage components are not credited with respect to impact attenuation, but are optionally included to assist the handling of the waste. This includes the pallet, slip sheet, and reinforcing plate.

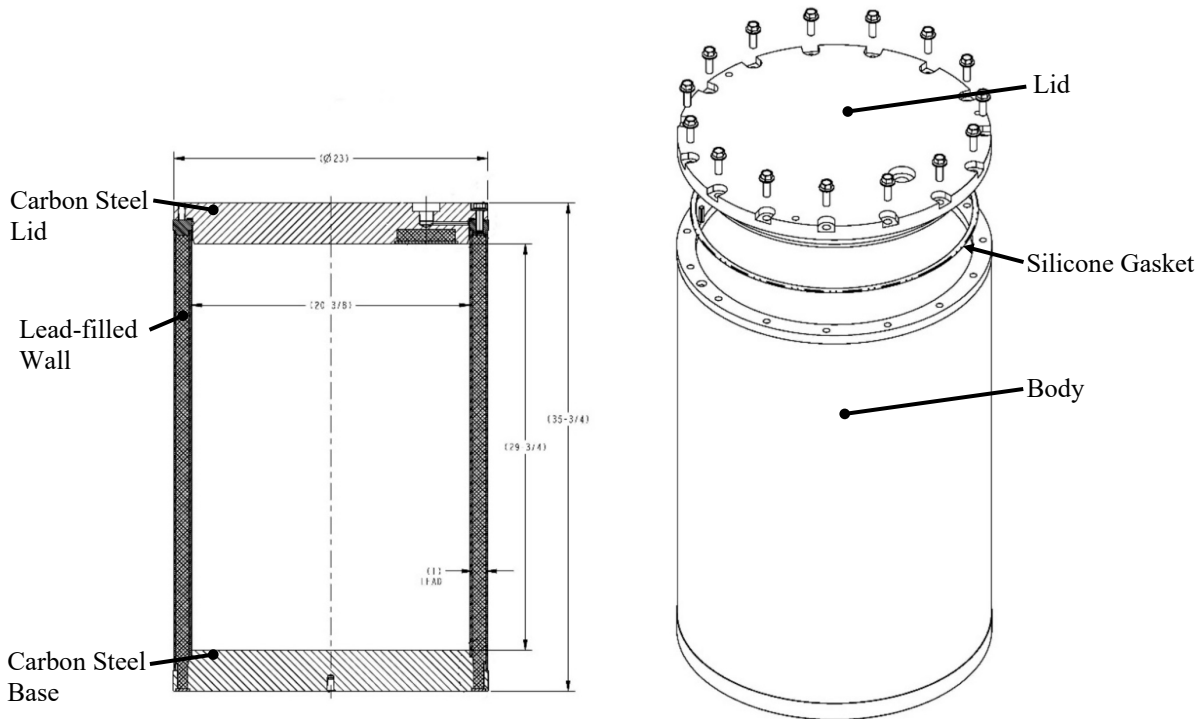


Figure 1-2 Original SCA Container Design

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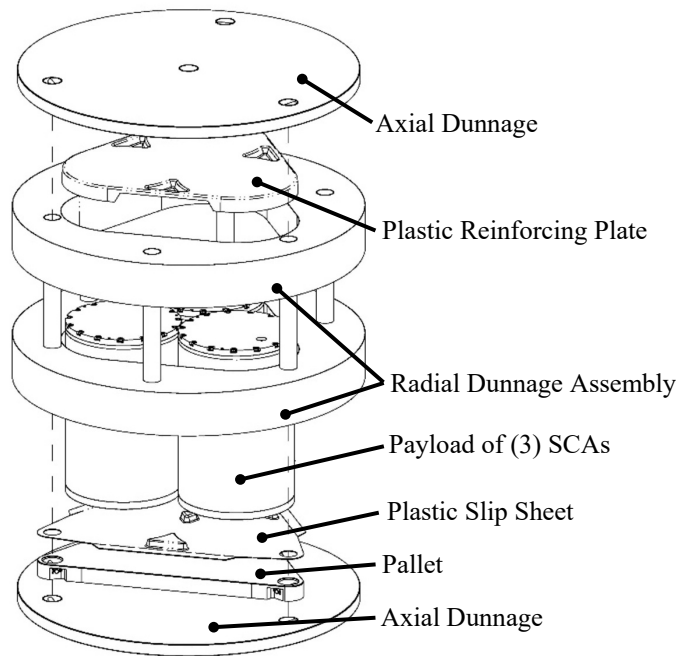


Figure 1-3 Original SCA Payload Design

The SCA is designed to overpack a 30-gallon drum and provides gamma ray shielding through use of approximately 1-inch lead equivalent thickness in the radial and axial directions. However, the SCA design does not provide enough shielding to attenuate radiation levels down to acceptable CH levels for some of the future inventory of 30-gallon drums, and physically cannot overpack the larger 55-gallon drums. Therefore, there is still a need for shielded container designs to overpack 30-gallon drums with additional gamma ray shielding, and designs with larger interior dimensions in which a 55-gallon drum can fit within its cavity.

The result is the expansion of the originally approved SCA design into a line of Shielded Container (SC) designs of various sizes and shielding levels. The original SCA is now renamed using a new nomenclature to distinguish the various SC types. The original SCA is hereafter referred to as the SC-30G1 (that is a Shielded Container, overpacking a 30-gallon drum, and designed to shield Gamma rays through approximately 1-inch equivalent of lead). The additional new SC designs are the SC-30G2, SC-30G3, SC-55G1 and SC-55G2, with each container and payload design depicted in Figure 1-4 through Figure 1-11.

The new container designs are derivatives of the SC-30G1, that is a right circular cylinder with a carbon steel chassis. Varying degrees of gamma shielding are provided by the thickness of the carbon steel chassis material itself (SC-55G1), or the carbon steel chassis thickness in combination with lead-filled cavities (SC-30G2, SC-30G3, and SC-55G2). The new SCs are designed to overpack 30- or 55-gallon drums. Gamma shielding is provided through approximately 1-, 2-, or 3-inch equivalent thickness of lead. They utilize the same materials as the original SC-30G1, including low carbon steel with fine grain practice controls, lead, and a closed cell silicon sponge sealing gasket.

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The new SC payload designs utilize similar materials as the SC-30G1 payload design, but differ in configuration and type. Where the SC-30G1 payload is configured to accommodate three (3) SC-30G1s, the physically larger SC-30G2s, SC-30G3s, SC-55G1s, and SC-55G2s are designed with a reduced payload container quantity. The SC-30G2 and SC-55G1 payload designs each accommodate two (2) payload containers. The SC-30G3 and SC-55G2 are larger yet, and their payload designs only accommodate a single payload container. The SC-30G2 and SC-55G1 are transported in the upright orientation, that is the payload containers cylindrical axis is aligned with the HalfPACTs. The overall heights of the SC-30G3 and SC-55G2 are such that transport in the upright orientation within the HalfPACT is not possible. Instead, the SC-30G3 and SC-55G2 are transported with their main cylindrical axis orthogonal to the HalfPACTs (i.e. sideways).

All dunnage assembly designs are relatively similar to that of the SC-30G1, i.e. impact attenuating foam material with optional plastic payload handling sheets. All dunnage assemblies include polyurethane foam, wrapped in a thin aluminum skin, to provide alignment in the payload cavity during normal conditions and impact attenuation during accidents. The dunnage designs of the SC-30G2 and SC-55G1 are similar to that of the SC-30G1, which includes radial and axial dunnage assemblies. The SC-30G2 dunnage design includes a top axial dunnage assembly to attenuate vertical impact loads into the top honeycomb, similar to the SC-30G1. The SC-55G1 deviates from the SC-30G1's design approach slightly through incorporation of a thick aluminum top sheet on its radial dunnage assembly, intended to distribute, rather than attenuate, axial impact loads against the top honeycomb. Both the SC-30G2 and SC-55G1 dunnage designs omit the use of a bottom axial dunnage assembly, and instead rely on the pallet design to distribute axial impact loads into the lower honeycomb. Due to the lateral shipment orientation, the SC-30G3 and SC-55G2 utilize a pair of "clam shell" assembled lateral dunnage assembly designs that deviate from the radial/axial assembly approach of the other payload designs. The upper and lower halves of this design are each intended to limit the radial and axial direction impact loads while providing support to the laterally shipped container designs. The SC-30G3 and SC-55G2 share a common lateral dunnage assembly design. However, the SC-30G3 payload design includes plastic end caps to adapt the shorter and thinner design of the SC-30G3 container to the dunnage.

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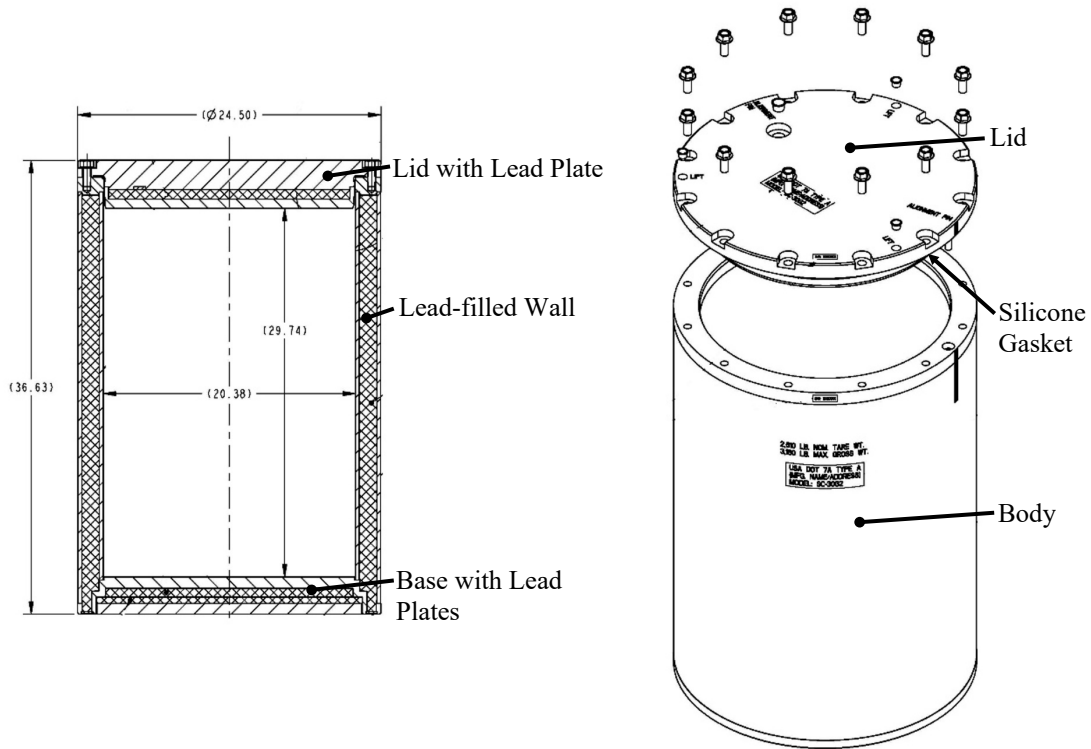


Figure 1-4 SC-30G2 Container Design

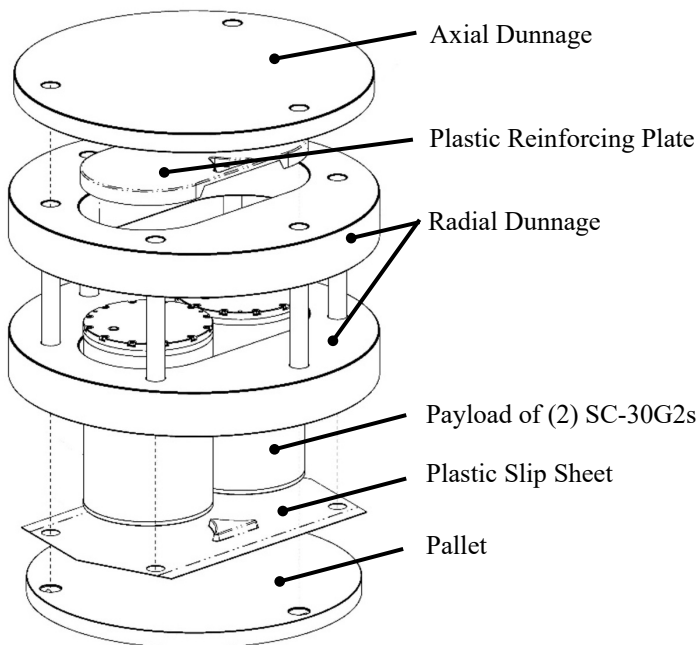


Figure 1-5 SC-30G2 Payload Design

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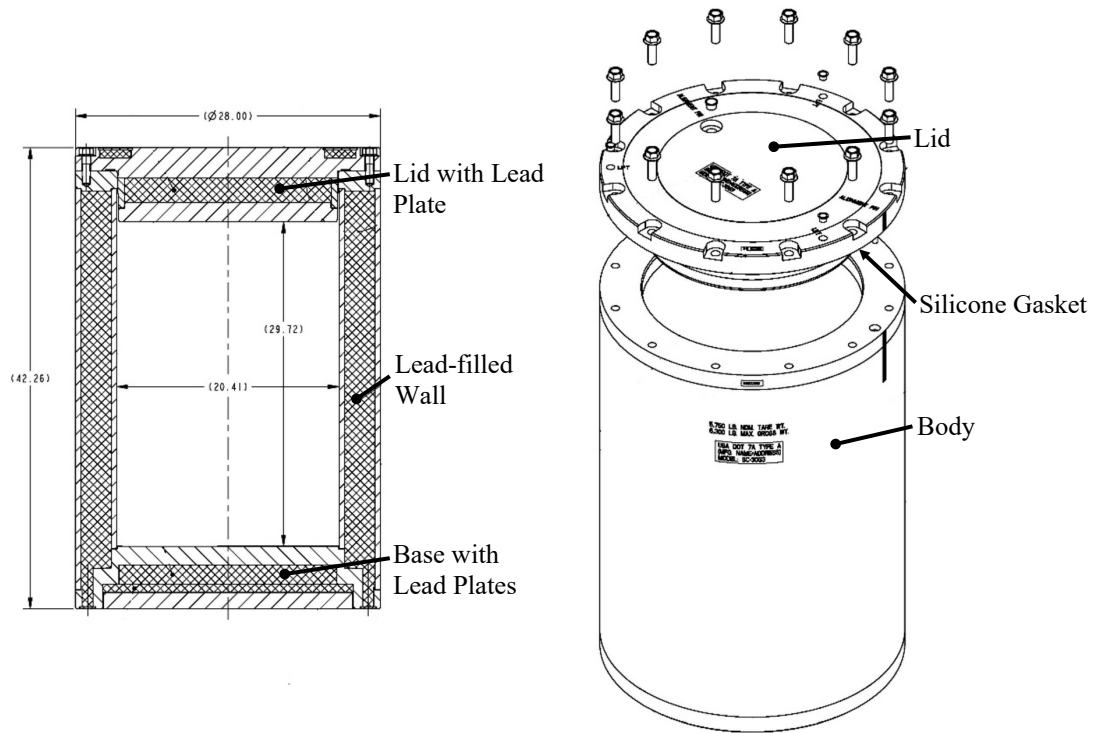


Figure 1-6 SC-30G3 Container Design

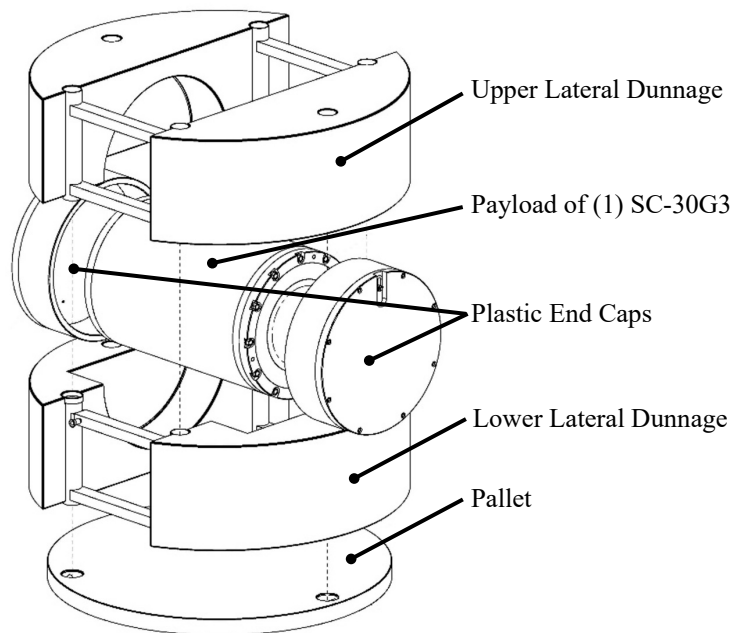


Figure 1-7 SC-30G3 Payload Design

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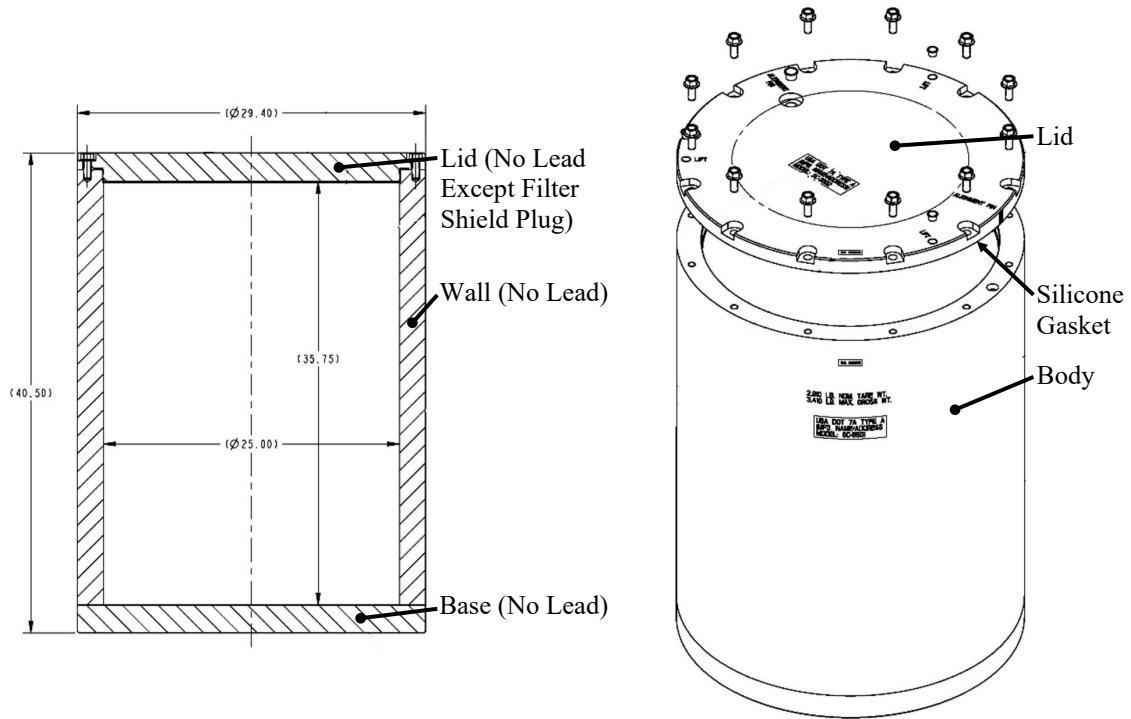


Figure 1-8 SC-55G1 Container Design

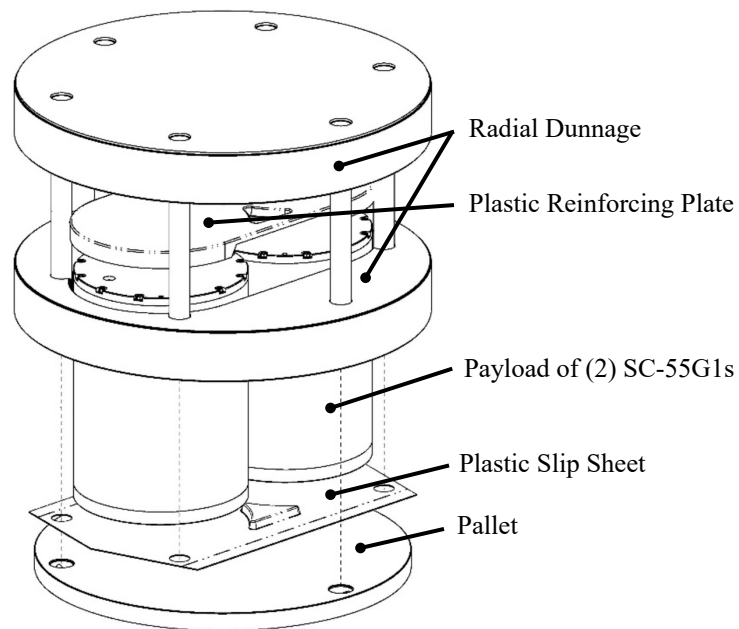


Figure 1-9 SC-55G1 Payload Design

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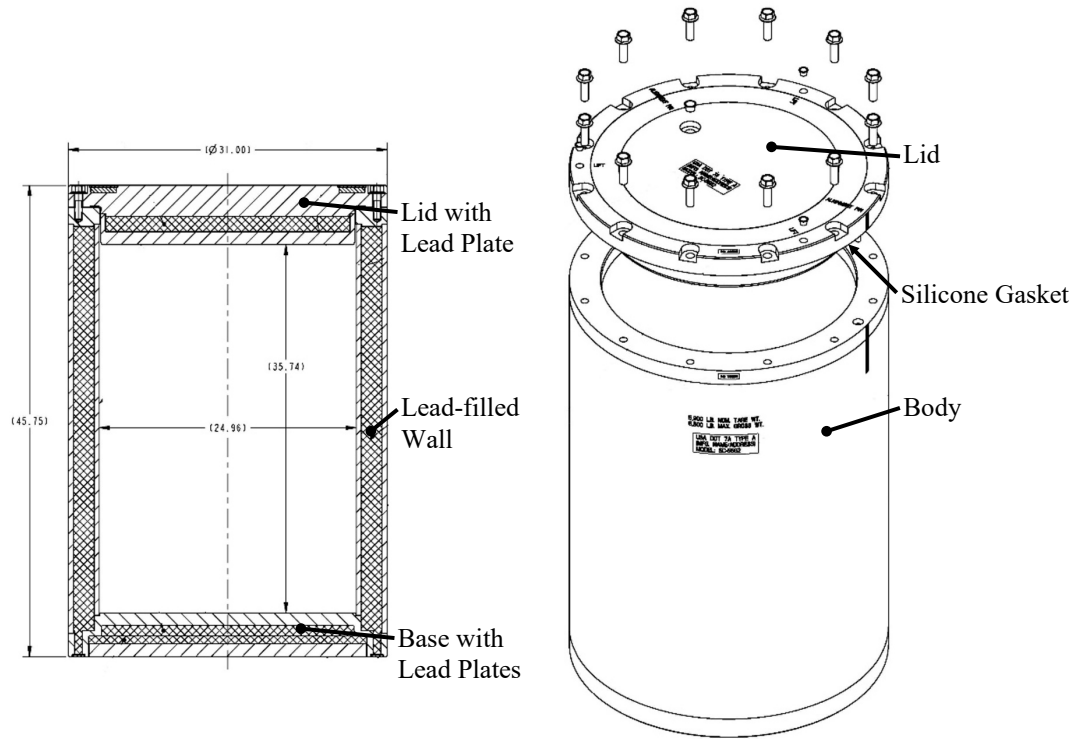


Figure 1-10 SC-55G2 Container Design

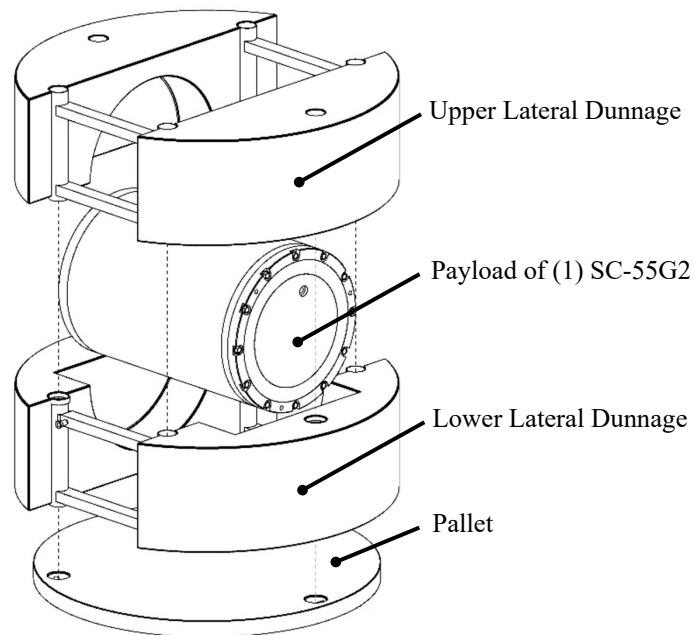


Figure 1-11 SC-55G2 Payload Design

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<p>The purpose of this analysis is to evaluate the new SC designs for compliance with the thermal requirements delineated in 10 CFR 71. The analysis also supports input to downstream maximum normal operating pressure (MNOP) analysis.</p>		

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2.0 THERMAL EVALUATION

The purpose of this section of the report is to provide a convenient means of regulatory review by referencing the sections of the thermal report that address the topics of interest to the reviewer. This section is structured and named utilizing the standard format and content guidelines provided in Section 3, Thermal Evaluation, of Regulatory Guide 7.9 [Ref. 14]. Each subsection provides discussion, data, and reference to the remainder of the report as appropriate for more detailed discussions on the thermal analysis performed.

The thermal evaluation of the HalfPACT package with the SC-30G2, SC-30G3, SC-55G1, or SC-55G2 payload designs can be briefly described as only requiring the explicit thermal analysis of the regulatory NCT Heat conditions. In addition, the thermal evaluation of the package to the NCT Heat conditions is focused mainly on the temperature results of the newly designed SC payloads, with packaging temperatures presented for posterity. This is the result of the screening evaluation of the applicable thermal cases to be analyzed in Section 3.1.1. In short, the new SC payload designs do not impact any of the HalfPACT thermal design features due to compliance with previously established package weight and decay heat limits. Additionally, the new SC payload designs utilize materials of construction and design features consistent with previously reviewed and approved payload designs. As a result, the HalfPACT package with the new SC designs are considered bounded by previous thermal evaluations with regard to NCT Cold conditions (10 CFR §71.71(c)(2)), HAC conditions (10 CFR §71.73(c)(4)), and exclusive use temperature limitations (10 CFR §71.43(g)). Please see the logic and screening of thermal evaluation cases discussed in Section 3.1.1 for more detail.

2.1 Description of Thermal Design

2.1.1 Design Features

2.1.1.1 Packaging

The HalfPACT packaging's thermal design features have been evaluated and discussed at length in several previous thermal evaluations. Those include the generic payload case thermal evaluation in Chapter 3 of the HalfPACT SAR [Ref. 1], and the SC-30G1 and Criticality Control Overpack (CCO) thermal evaluations in Section 4.5.4 and 4.6.4, respectively, of the CH-TRU Payload Appendices [Ref. 2]. The design of the new SC payloads do not impact or alter the HalfPACT packaging's thermal design features in any way. As such, the previous thermal design feature discussions of the HalfPACT packaging remain applicable. The thermal design feature discussion provided in Chapter 3.1.1 of the HalfPACT SAR is repeated herein for convenience.

The HalfPACT packaging is designed with a totally passive thermal system. As illustrated in Figure 1.1-1 and Figure 1.1-2 from Section 1.1, Introduction, the principal thermal characteristic of the HalfPACT package is that it does not contain the relatively thick steel shells and lead shielding typical of other shipping packages. Instead, the HalfPACT packaging utilizes a relatively thin containment and confinement vessel with shell thicknesses of 1/4 and 3/16 inch,

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respectively. Use of the thin shells means that the thermal response of the packaging shells to transient heat input is more rapid than for conventional, heavy walled packages. This characteristic is significantly offset by the unusually large, insulating capability of the polyurethane foam tending to isolate, or decouple, interior responses from temperature variations due to exterior transients. The outer surface of these shells may be painted. The analyses herein use unpainted surface (i.e., bare stainless steel) thermal properties. Since painted surfaces have higher emissivities that allow for better decay heat rejection than unpainted surfaces, the use of unpainted surface thermal properties is conservative.

Both the inner containment vessel (ICV) and the outer confinement vessel (OCV) are constructed of Type 304 stainless steel. As discussed in [Section 1.2, Package Description](#), the ICV has a 72-5/8-inch inside diameter, and the OCV has a 73-5/8-inch inside diameter and is completely encased in polyurethane foam with a density of approximately 8¼ lb/ft³. The foam provides impact protection for the NCT and HAC drop events, and thermal protection during the subsequent HAC thermal event. The 1/4-to-3/8-inch thick outer shell of the outer confinement assembly (OCA) is comprised of Type 304 stainless steel that serves to protect the polyurethane foam from damage encountered during normal handling and shipping operations.

2.1.1.2 Payload

The new SC payload designs, including the designs of the SC's themselves, are introduced and generally discussed in Section 1.0. See the new SC payload designs depicted with major components labeled in Figure 1-4 through Figure 1-11. In short, the designs are extensions of the original SC-30G1 in which variations in the magnitude of gamma shielding and internal cavity sizes are provided by the new designs. The original SC-30G1 design is depicted in Figure 1-2 and Figure 1-3. The majority of discussion pertaining to the thermal design features of the SC-30G1 provided in Section 4.5.2 and 4.5.4 of the CH-TRU Payload Appendices [Ref. 2] are applicable to the new SC designs. However, since there are variations between the designs, the thermal design features are discussed herein. For detailed discussion pertaining to the modeling methods and assumptions related to the thermal features of the designs and how they are captured in the analysis, see Sections 3.1, 3.3, and 4.0.

In general, the HalfPACT payloads are all designed to passively exchange heat with the packaging components for dissipation to the environment. The design of the SCs is that of a right circular cylinder of either solid carbon steel construction (SC-55G1), or carbon steel and lead composite construction (SC-30G1, SC-30G2, SC-30G3, and SC-55G2). All exposed carbon steel surfaces are painted to protect from environmental conditions. A closed-cell silicone sponge gasket is used to provide a particulate confining seal between the lid and body. Impact-limiting polyurethane foam dunnage encased in thin aluminum shells are used to provide geometric positioning of the SCs within the payload cavity of the HalfPACT ICV. The impact limiter assemblies include up to a maximum 1/8-inch gap between the shell and the foam. The impact limiters are designed to balance the needs of impact attenuation during an accident event, while maximizing the optical view between the SCs and ICV for radiation heat exchange. The polyurethane foam is otherwise a thermal insulating material. The SC-30G3 also contains High Density Polyethylene (HDPE) end caps used to adapt the SC to the load bearing cavity of the SC-30G3/SC-55G2 lateral dunnage design. These end caps are designed to maintain the

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unobstructed view of the SC with the rest of the ICV payload cavity for radiation exchange. Each SC is designed to overpack a 30- or 55-gallon drum with waste contents inside. The drums are of thin gauge carbon steel construction and are also painted to protect from environmental conditions.

The aforementioned thermal design features are captured by modeling heat exchange through radiation and conduction between components of the payload. A mixture of solid and surface elements are utilized in the model. Surface elements are used where temperature gradients through the thickness of a material are of no interest (i.e. thin shells of highly conductive material). Convection exchange within the HalfPACT package and payload is conservatively ignored. All surfaces, similar to the HalfPACT packaging, are conservatively assumed clean, smooth, and unpainted with regard to optical properties. This translates to no credit being taken for the higher emissivity provided by painted or passively oxidized surface conditions. Gaps between the lead shielding in the carbon steel chassis of the SC designs are also included and modeled with both air conduction and radiation exchange. Any air gaps larger than 0.25 inch are treated as void, i.e. no conduction and only radiation heat exchange. The waste contents are modeled as a solid right circular cylinder with a conservative combination of surrogate low conductivity loosely packed paper waste with the maximum decay heat applied uniformly in the volume.

2.1.2 Content's Decay Heat

The maximum HalfPACT packaging design content's decay heat is 30 W per Section 3 of the SAR [Ref. 1]. The HalfPACT package with any of the payload configurations, including the new SC payload designs, maintains this maximum decay heat limit. Therefore, all thermal models within this report simulate uniform decay heat at 0 W and 30 W in distributed (as appropriate) and concentrated forms within a conservative low conductivity and low density simulated waste volume. See Sections 3.1.1 and 4.2.7.3 for discussion on the derivation and justification of the thermal modeling cases simulated for each package design. See Section 3.2.2 for discussion and justification on the material properties utilized for the simulation of the waste contents.

2.1.3 Summary Tables of Temperatures

The results of the NCT Heat analysis are presented in summarized tables of maximum, minimum, and average temperatures for various components of interest throughout the model during the pseudo-steady-state analysis. See the discussion on the post-processing utilized to extract results in Section 4.2.8 for clarity on the data provided in this section. The data are also tabularized by SC design and run case. See the discussion provided in Section 3.1.1 for the logic and structure behind the run cases analyzed. And finally, see Section 3.4 for a summary of the temperature limits and their logic for use in this analysis.

Table 2-1 summarizes the results for the HalfPACT package with the SC-30G2 payload design, Table 2-2 summarizes the results for the package with the SC-30G3 payload design, Table 2-3 summarizes the results for the package with the SC-55G1 payload design, and Table 2-4 summarizes the results for the package with the SC-55G2 payload design. All temperature

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results displayed are the maximum values to occur over the full time-history of the run for that respective post-processed value (generally occurs over the last 24 hours of the simulation).

Table 2-1 – SC-30G2 NCT with Insolation Temperature Results (°F)

Model Region	Location	0W	30W Distributed	30W Concentrated	Limits
SC30G2-1	Waste Max	121.8	231.6	325.9	402
	Waste Centerline Avg	121.7	207.0	276.7	N/A
	Waste Bulk Avg	121.8	174.1	210.9	302
	Drum Shell Max	121.8	148.2	158.9	212
	Drum Shell Avg	121.8	146.0	154.6	212
	SC30G2 Max	121.9	139.6	142.3	212
	SC30G2 Avg	121.8	139.2	141.4	212
SC30G2-2	Waste Max	121.8	231.6	137.6	402
	Waste Centerline Avg	121.7	207.0	136.9	302
	Waste Bulk Avg	121.8	174.1	137.0	302
	Drum Shell Max	121.8	148.2	137.6	212
	Drum Shell Avg	121.8	146.0	137.0	212
	SC30G2 Max	121.9	139.6	139.0	212
	SC30G2 Avg	121.8	139.2	137.1	212
Payload	Dunnage Foam Max	122.3	138.7	140.5	N/A
	Dunnage Foam Avg	122.1	136.0	136.0	140
ICV	Air Cavity Avg	122.3	135.5	135.5	N/A
	Shell Max	124.2	133.3	133.8	160
	Shell Avg	122.6	131.7	131.7	160
	Shell Min	121.3	130.2	130.2	160
	O-ring Max	123.5	132.0	132.2	225
OCV	Shell Max	130.5	134.3	134.5	160
	Shell Avg	124.3	131.3	131.3	160
	O-ring Max	130.5	134.3	134.5	225
OCA	Poly Foam Max	150.9	151.0	151.0	300
	Poly Foam Avg	128.0	131.2	131.3	300
	Shell Max	150.9	150.9	150.9	160

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Table 2-2 – SC-30G3 NCT with Insolation Temperature Results (°F)

Model Region	Location	0W	30W	Limits
SC30G3	Waste Max	122.0	326.2	402
	Waste Centerline Avg	122.0	276.9	N/A
	Waste Bulk Avg	122.0	212.7	302
	Drum Shell Max	122.0	158.9	212
	Drum Shell Avg	122.0	154.8	212
	SC30G3 Max	122.1	141.9	212
	SC30G3 Avg	122.1	141.5	212
Payload	Dunnage Foam Max	122.4	137.6	N/A
	Dunnage Foam Avg	122.2	134.8	140
	End Cap Max	122.2	140.4	170
	End Cap Avg	122.1	139.3	N/A
ICV	Air Cavity Avg	122.6	133.9	N/A
	Shell Max	124.4	133.0	160
	Shell Avg	122.7	130.6	160
	Shell Min	121.5	129.9	160
	O-ring Max	123.6	132.2	225
OCV	Shell Max	130.6	133.7	160
	Shell Avg	124.4	130.3	160
	O-ring Max	130.6	133.7	225
OCA	Poly Foam Max	150.9	151.0	300
	Poly Foam Avg	128.1	130.8	300
	Shell Max	150.9	150.9	160

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Table 2-3 – SC-55G1 NCT with Insolation Temperature Results (°F)

Model Region	Location	0W	30W Distributed	30W Concentrated	Limits
SC55G1-1	Waste Max	121.9	210.4	286.0	402
	Waste Centerline Avg	121.7	190.2	245.5	N/A
	Waste Bulk Avg	121.8	163.9	192.8	302
	Drum Shell Max	121.9	142.5	149.6	212
	Drum Shell Avg	121.9	140.8	146.5	212
	SC55G1 Max	122.0	136.5	137.8	212
	SC55G1 Avg	121.9	136.3	137.5	212
SC55G1-2	Waste Max	121.9	210.5	135.6	402
	Waste Centerline Avg	121.7	190.2	134.8	302
	Waste Bulk Avg	121.8	163.9	135.0	302
	Drum Shell Max	121.9	142.5	135.6	212
	Drum Shell Avg	121.9	140.8	135.1	212
	SC55G1 Max	122.0	136.5	136.5	212
	SC55G1 Avg	121.9	136.3	135.2	212
Payload	Dunnage Foam Max	122.1	136.1	137.3	N/A
	Dunnage Foam Avg	122.0	135.5	135.6	140
ICV	Air Cavity Avg	122.2	134.7	134.8	N/A
	Shell Max	124.2	132.7	133.1	160
	Shell Avg	122.6	131.2	131.3	160
	Shell Min	121.3	130.3	130.3	160
	O-ring Max	123.5	131.8	132.3	225
OCV	Shell Max	130.6	134.1	134.2	160
	Shell Avg	124.3	130.8	130.9	160
	O-ring Max	130.6	134.1	134.2	225
OCA	Poly Foam Max	150.9	151.0	151.0	300
	Poly Foam Avg	128.0	131.0	131.0	300
	Shell Max	150.9	150.9	150.9	160

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Table 2-4 – SC-55G2 NCT with Insolation Temperature Results (°F)

Model Region	Location	0W	30W	Limits
SC55G2	Waste Max	121.9	292.8	402
	Waste Centerline Avg	121.7	252.2	N/A
	Waste Bulk Avg	121.8	198.5	302
	Drum Shell Max	121.9	156.1	212
	Drum Shell Avg	121.9	153.2	212
	SC55G2 Max	122.0	144.7	212
	SC55G2 Avg	122.0	144.2	212
Payload	Dunnage Foam Max	122.4	138.7	N/A
	Dunnage Foam Avg	122.1	136.2	140
ICV	Air Cavity Avg	122.5	135.0	N/A
	Shell Max	124.4	134.4	160
	Shell Avg	122.7	131.7	160
	Shell Min	121.4	131.0	160
	O-ring Max	123.5	133.5	225
OCV	Shell Max	130.6	134.2	160
	Shell Avg	124.4	131.2	160
	O-ring Max	130.6	134.2	225
OCA	Poly Foam Max	150.9	151.0	300
	Poly Foam Avg	128.0	131.2	300
	Shell Max	150.9	150.9	160

2.1.4 Summary Tables of Maximum Pressures

As discussed in Section 2.3.2, the maximum pressure of the containment system during transport is outside the scope of this analysis. Instead, linear coefficients of the temperature as a function of decay heat for downstream maximum normal operating pressure (MNOP) calculations are provided in Table 2-5 for all four SC payload designs analyzed. These coefficients are utilized in the following equations to predict temperature as a function of decay heat as follows:

$$T(Q) = bQ + T_0$$

$$b = \frac{T_{30} - T_0}{30W}$$

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See the discussion on the post-processing utilized to extract results in Section 4.2.8 for clarity on the data provided in this section. The data are also tabularized by SC design and run case. See the discussion provided in Section 3.1.1 for the logic and structure behind the run cases analyzed.

Table 2-5 – MNOP Linear Curve Coefficients

SC-30G2 (Distributed)				
Location	T₀ (°F)	T₃₀ (°F)	a (°F)	b (°F/W)
Waste Bulk Avg	121.8	174.1	121.8	1.75
ICV Air Cavity Avg	122.3	135.5	122.3	0.44
ICV Shell Min	121.3	130.2	121.3	0.30
SC-30G2 (Concentrated)				
Location	T₀ (°F)	T₃₀ (°F)	a (°F)	b (°F/W)
Waste Bulk Avg	121.8	210.9	121.8	2.97
ICV Air Cavity Avg	122.3	135.5	122.3	0.44
ICV Shell Min	121.3	130.2	121.3	0.30
SC-30G3				
Location	T₀ (°F)	T₃₀ (°F)	a (°F)	b (°F/W)
Waste Bulk Avg	122.0	212.7	122.0	3.02
ICV Air Cavity Avg	122.6	133.9	122.6	0.38
ICV Shell Min	121.5	129.9	121.5	0.28
SC-55G1 (Distributed)				
Location	T₀ (°F)	T₃₀ (°F)	a (°F)	b (°F/W)
Waste Bulk Avg	121.8	163.9	121.8	1.40
ICV Air Cavity Avg	122.2	134.7	122.2	0.42
ICV Shell Min	121.3	130.3	121.3	0.30
SC-55G1 (Concentrated)				
Location	T₀ (°F)	T₃₀ (°F)	a (°F)	b (°F/W)
Waste Bulk Avg	121.8	192.8	121.8	2.37
ICV Air Cavity Avg	122.2	134.8	122.2	0.42
ICV Shell Min	121.3	130.3	121.3	0.30
SC-55G2				
Location	T₀ (°F)	T₃₀ (°F)	a (°F)	b (°F/W)
Waste Bulk Avg	121.8	198.5	121.8	2.55
ICV Air Cavity Avg	122.5	135.0	122.5	0.42
ICV Shell Min	121.4	131.0	121.4	0.32

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2.2 Material Properties and Component Specifications

2.2.1 Material Properties

The thermophysical and optical properties utilized in the thermal analysis of the HalfPACT package with new SC payload designs are included in Section 3.2.2, Table 3-1 through Table 3-12. The thermophysical and optical properties utilized in this thermal analysis are largely recycled from previously NRC reviewed and accepted thermal analyses. These analyses include the Criticality Control Overpack thermal analysis [Ref. 4] (an approved payload design for the TRUPACT-II and HalfPACT packages) and the RH-TRU 72-B thermal analysis [Ref. 5]. For instances in which these sources did not contain the thermophysical or optical properties necessary for this analysis, vendor or thermal handbook properties are utilized and cited.

2.2.2 Component Specifications

Component specifications for the thermal analysis are split between the design specifications and corresponding material temperature limits. The design specifications consist of the design drawings utilized as input to model the HalfPACT packaging and SC payloads discussed and listed in Section 3.2.1. The drawings detail the geometry, fabrication requirements, and materials of construction for the HalfPACT packaging and SC payload designs.

The material temperature limits are listed in Table 3-13 and discussed in Section 3.4. Each temperature limit is accompanied by an appropriate justification based on material, function, and any credit for previous analysis. The temperature limits form the acceptance criteria utilized in determining the acceptability of the NCT Heat temperature results presented in Section 2.1.3. Since the SC payload designs are determined to be bounded by previous thermal analyses with regard to NCT Cold, exclusive use, and HAC conditions, only NCT Heat temperature limits are addressed in Section 2.1.3.

2.3 Thermal Evaluation Under Normal Conditions of Transport

2.3.1 Heat and Cold

The HalfPACT package with new SC payload designs are modeled within this report for the effects of the regulatory NCT Heat conditions (10 CFR §71.71(c)(1)). The NCT Cold (10 CFR §71.71(c)(2)) and exclusive use (10 CFR §71.43(g)) conditions are justified in Section 3.1.1 as bounded by previous HalfPACT package thermal analyses. The following bulleted list provides the topics of interest within the report relative to the content guidance of Section 3.3 and 3.3.1 of Regulatory Guide 7.9 [Ref. 14]:

- The methodology, including the thermal cases screened for analysis, are included in Section 3.1.
- The analysis inputs, such as geometry, materials, and boundary conditions, are included in Section 3.2.
- Any significant assumptions employed in the analysis are listed in Section 3.3.

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- The temperature limits for the analysis are listed and justified in Section 3.4.
- Detailed discussion on the geometry of the thermal models is in Section 4.1.
- Detailed discussion on the thermal FEA models, including symmetry constraints, mesh, connections, analysis settings, boundary conditions, and post-processing of results are included in Section 4.2.
- References are subdivided and listed in Section 5.0.
- Computer runs and associated file names are included in Section 6.0.
- A mesh sensitivity study is included in Appendix A.1.

This thermal evaluation confirms that the HalfPACT package with the SC-30G2, SC-30G3, SC-55G1, and SC-55G2 payload designs comply with the respective component temperature limits while subjected to the NCT Heat and Cold conditions of 10 CFR §71.71. It also confirms that the HalfPACT package with the SC-30G2, SC-30G3, SC-55G1, and SC-55G2 payload designs comply with the exclusive use requirements of 10 CFR §71.43(g).

2.3.2 Maximum Normal Operating Pressure

The design maximum pressure in the ICV under NCT is 50 psig. The major factors affecting the ICV internal pressure are radiolytic gas generation (radiolysis), thermal expansion of gases, and the vapor pressure of water within the ICV cavity. The determination of MNOP is not within the scope of this analysis. Instead, the temperatures of key areas of interest from the model are provided as a function of decay heat. See Section 2.1.4 for the linear coefficients for each SC payload design. See Section 4.2.8 for discussion on the post-processing of the aforementioned temperatures.

2.4 Thermal Evaluation under Hypothetical Accident Conditions

The HAC thermal conditions are justified in Section 3.1.1 as bounded by the previous HalfPACT package with SC-30G1 payload HAC thermal evaluation. This thermal evaluation confirms that the HalfPACT package with the SC-30G2, SC-30G3, SC-55G1, and SC-55G2 payload designs comply with the HAC thermal requirements 10 CFR §71.73.

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3.0 METHODOLOGY

3.1 Method

The overall method employed within this analysis is largely consistent with the two most recent thermal analyses performed in support of NRC licensing applications (i.e., CCO [Ref. 4] and RH-TRU 72-B [Ref. 5]). That is transient thermal analysis models with a long enough run time such that reported temperatures have reached equilibrium with a cyclically applied input (pseudo-steady-state analysis). Previously derived and cited temperature-dependent material properties (see Section 3.2.2) and modeling assumptions are employed. External passive heat dissipation from the package is modeled through natural convection and radiation exchange to the environment. Heat exchange within internal annuli of the package and payload are almost exclusively transferred through radiation exchange (i.e. assumed void), with small (≤ 0.25 -inch) gaps having additional still air conduction modeled. Internal convection, natural or forced, is not included. Regulatory thermal insolation (see Section 3.2.3) is applied to the exterior of the packaging as a 12-hour-averaged, step-applied heat flux rate, with the subsequent 12-hour step in a 24-hour day modeled without applied heat (on/off heat flux cycling). The waste is modeled as a solid, right circular cylinder of paper-based, low density and low conductivity surrogate waste material to maximize simulated waste temperatures. All temperatures reported are the maximum values over the time-history for each respective component, location, and temperature type.

The method for simulation of the thermal response of the new SC payload designs is the finite element analysis (FEA) method. The FEA method involves the discretizing of complex geometry into a large number of small, simplified elements. Each element is mathematically represented by equations that are shape and physics dependent. The computer then solves the governing equations for the physics of the analysis type and the results are post-processed. The model results are then summarized for comparison to respective material or component limits, or are provided for downstream analysis.

The aforementioned previous thermal analyses for the CCO [Ref. 4] and RH-TRU 72-B [Ref. 5] employ a combination of finite element and finite difference methods. These previous analyses were executed using a thermal analysis specific computer code called SINDA, through a graphical interface called Thermal Desktop. This analysis utilizes ANSYS Structural [Ref. 29] products, which include the ANSYS Parametric Design Language (Mechanical APDL) solver code with the ANSYS Mechanical and Workbench graphical interfaces. The ANSYS Mechanical APDL code uses the finite element method exclusively. The code contains thermal analysis specific elements utilized to model the exchange of heat between solid, surface, and line bodies. The ANSYS thermal analysis capabilities are able to properly model the new SC payload designs within the HalfPACT packaging, which includes:

- Transient thermal analysis,
- Solid and surface element conduction,
- Contact conduction,
- Non-linear temperature-dependent convective heat exchange to the environment,
- Radiation heat exchange between surfaces, and
- Non-linear temperature-dependent material properties.

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3.1.1 Thermal Cases

U.S. Federal law requires that packages designed to carry radioactive material meet specific regulatory thermal conditions. Regulatory requirements for the packaging and transportation of radioactive material over public roads and in Type B quantities are delineated in 10 CFR 71 [Ref. 12]. In addition, Regulatory Guide 7.9 [Ref. 14] and Regulatory Guide 7.8 [Ref. 15] provide content guidance and interpretation of these requirements, as applicable. In general, the requirements for thermal performance can be split into two conditions of analysis, those are normal conditions of transport (NCT) and hypothetical accident conditions (HAC).

NCT conditions are tests intended to subject the package to hypothetical loads expected to occur as a result of normal, everyday transport without significant impact to the packages nominal function. The package must be designed for NCT conditions such that there would be “no loss or dispersal of radioactive contents, no significant increase in external surface radiation levels, and no substantial reduction in the effectiveness of the packaging” [Ref. 12]. HAC conditions are those tests intended to subject the package to a set of hypothetical worst case accident loads. The package must be designed for HAC conditions such that there would be “no escape of krypton-85 exceeding 10 A₂ in 1 week, no escape of other radioactive material exceeding a total amount A₂ in 1 week, and no external radiation dose rate exceeding 10 mSv/h (1 rem/h) at 1 m (40 in) from the external surface of the package” [Ref. 12].

The thermal cases necessary for analysis to show compliance with these requirements can be summarized by the following, with input from the guidance provided by Table 1 of Reg Guide 7.8 [Ref. 15]:

- NCT Heat (10 CFR §71.71 [Ref. 12])
 - 100°F ambient conditions
 - Maximum applied decay heat
 - Regulatory external insolation applied (See discussion in Section 3.2.3)
- NCT Cold (10 CFR §71.71 [Ref. 12])
 - -40°F ambient conditions
 - Zero applied decay heat
 - No external insolation applied
- HAC (10 CFR §71.73 [Ref. 12])
 - Initial NCT Heat conditions to produce maximum initial package temperatures.
 - Damage from free drop and puncture tests must be present.
 - A fully engulfed fire accident simulation as prescribed in 10 CFR §71.73(c)(4).

The NCT Cold thermal case has been previously analyzed and justified for the original SC-30G1 design in Section 4.5.4.1 of the CH-TRU Payload Appendices [Ref. 2]. It is also in the original generic payload thermal analysis in Section 3.4.3 of the HalfPACT SAR [Ref. 1]. This thermal case has been regarded as trivial since the steady state conditions prescribed with no internal heat load would eventually result in a complete package equilibrium temperature of -40°F. All components and materials credited within the package design for compliance with the regulatory requirements have allowable operating temperature ranges that allow for operation at -40°F. The new SC designs utilize the same types of materials of construction as the original SC-30G1 (see

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Section 3.2.2 and 3.4). Therefore, the new SC designs meet the NCT Cold requirements of 10 CFR 71 and require no further analysis for this condition.

The HAC thermal case was originally analyzed through testing of surrogate prototype units of the HalfPACT package with a generic payload. The analysis and testing are discussed in Section 3.5 of the HalfPACT SAR [Ref. 1]. The original SC-30G1 HAC analysis is provided in Section 4.5.4.2 of the CH-TRU Payload Appendices [Ref. 2]. The analysis provides justification for how the SC-30G1 design is bounded by the results of the HAC testing performed on the HalfPACT package with a generic payload. For posterity, that justification is repeated as follows:

1. The level of heat input into the HalfPACT package during the HAC event is a function of the package's exterior surface area, the thermal mass of the package components, etc., which is essentially unaffected by the makeup of the payload.
2. The temperature response within the payload is a function of its thermal mass and the amount of heat passed to it by the HalfPACT packaging.
3. Since the heat input to the HalfPACT packaging during the HAC event is essentially the same between a package containing a base payload evaluated in the HalfPACT SAR and a package containing a payload of three shielded containers, the thermal HAC response of the HalfPACT package will be bounded by that presented in the HalfPACT SAR.
4. Given a similar temperature response for the ICV shell under HAC conditions for either the base payload or the shielded container payload, the thermal response of the shielded container will be inversely proportional to the thermal mass and directly proportional to the surface area of the shielded container payload versus that existing for the base payload. The maximum payload mass (i.e., the packaging contents which includes the payload containers, waste contents, dunnage, pallets, etc.) of the shielded container payload is identical to the maximum base payload mass. However, the combined surface area of the shielded container payload is lower than the combined surface area of the base drum payload. As such, the rate of heat transfer between the ICV and shielded containers will be lower under HAC conditions than seen with the base payload due to the lower area for radiation and convection/conduction heat transfer. A lower rate of heat transfer combined with an equal payload mass means the temperature rise experienced by the shielded container payload will be bounded by that experienced by the base payload.

The justification provided above is also applicable to the new SC designs. The new SC designs were designed to remain within the total mass limit of 7,600 pounds for the payload of the HalfPACT package design. The total surface area of the exterior of the new SCs is also bounded by the surface area of the generic drum based payload. The materials of construction for the new SCs are identical to those used for the original SC-30G1, and identical to or less sensitive than the generic payload designs. To summarize, the total thermal mass of the new SC payload designs is essentially unchanged, the temperature rise of the new SCs are expected to be bounded by the generic drum based payload, and the materials of construction are either the same or less sensitive than those utilized in payload designs already qualified for use. Therefore, the new SC designs are bounded by the HAC analysis for the HalfPACT package with a generic payload and no further analysis is required.

In addition to the requirements of NCT and HAC, 10 CFR §71.43(g) delineates special external surface temperature limits for packages. These limits are dependent on whether the package

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during transport is classified as a nonexclusive use or exclusive use shipment. See discussion and definitions on exclusive use provided in 10 CFR 71 [Ref. 12]. As analyzed in the HalfPACT SAR [Ref. 1], the HalfPACT package is transported as an exclusive use shipment. The requirement for an exclusive use shipment is that accessible surface temperatures of the package not exceed 185°F when subjected to 100°F ambient conditions, no insolation, and maximum decay heat. Previous results of the HalfPACT package in Table 3.5-1 of the SAR reveal that under the prescribed conditions the accessible surface temperatures result in large margin with respect to this requirement (<102°F). This is due to the relatively low total decay heat limit for the package design and the large external surface area with which heat is passively dissipated to the ambient. The new SC designs are subject to the maximum package decay heat limit of 30 W for the HalfPACT package. Therefore, no change in the accessible surface temperatures under the prescribed conditions is expected. As a result, the HalfPACT package with the new SC payload designs comply with requirements of 10 CFR §71.43(g) and no further analysis of this condition is required.

Previous thermal analyses for the HalfPACT (Section 3 of the SAR [Ref. 1]) and the CCO [Ref. 4] split the NCT Heat case into several subcases to support downstream analysis and ensure the capture of maximum temperatures for payload components. For the support of maximum normal operating pressure (MNOP) analysis, the NCT Heat case is split into the zero decay heat and maximum decay heat cases. This is based on the observation that the relatively low maximum decay heat results in an approximately linear relationship between payload temperatures and decay heat from no load to maximum. The maximum decay heat case is further split into two cases, one in which the decay heat is evenly distributed between the payload containers, for designs with more than one (1) payload container, and one in which all decay heat is concentrated in a single container. The split of the maximum decay heat cases into both distributed and concentrated cases ensures that the maximum component temperatures are captured. It also allows for the specification of decay heat limits on a per payload container basis, should the concentrated case be identified as limited by payload temperatures (see the CCO thermal analysis [Ref. 4] for an example of this case). The low maximum decay heat limit of the HalfPACT package and relatively unobstructed heat exchange between the overpacked drum and SC, and the SC and ICV wall is such that this level of decay heat load control is unnecessary (see the results presented in Section 2.1.3).

Based on the discussion provided above, the thermal cases analyzed within this report are broken down by payload design as follows:

- SC-30G2 (2 payload container design)
 - NCT Heat conditions with 0W decay heat
 - NCT Heat conditions with 30W decay heat, evenly distributed.
 - NCT Heat conditions with 30W decay heat, concentrated.
- SC-30G3 (1 payload container design)
 - NCT Heat conditions with 0W decay heat
 - NCT Heat conditions with 30W decay heat, concentrated.
- SC-55G1 (2 payload container design)
 - NCT Heat conditions with 0W decay heat
 - NCT Heat conditions with 30W decay heat, evenly distributed.

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- NCT Heat conditions with 30W decay heat, concentrated.
- SC-55G2 (1 payload container design)
 - NCT Heat conditions with 0W decay heat
 - NCT Heat conditions with 30W decay heat, concentrated.

3.2 Inputs

3.2.1 Geometry

The geometric inputs utilized in modeling the HalfPACT packaging components and various SC payloads come from the respective SAR or vendor drawings. Nominal dimensions within the tolerance ranges were utilized to represent each geometry. Each component and corresponding geometric input is summarized as follows:

- HalfPACT Packaging Components – SAR drawing 707-SAR [Ref. 20]
- Original SCA (SC-30G1) Payload Design – SAR Drawing 163-008 [Ref. 21]
- SC-30G2 Payload Design – SAR Drawing 163-010 [Ref. 22]
- SC-30G3 Payload Design – SAR Drawing 163-011 [Ref. 23]
- SC-55G1 Payload Design – SAR Drawing 163-012 [Ref. 24]
- SC-55G2 Payload Design – SAR Drawing 163-013 [Ref. 25]
- 30-Gallon Drum – Vendor Supplied Drawing CQ3007 [Ref. 26]
- 55-Gallon Drum – Vendor Supplied Drawing CQ5506 [Ref. 27]
- Drum Internal Waste Volumes – Calculation Report PLD-CAL-0001 [Ref. 8]

3.2.2 Materials

Thermophysical properties are the properties utilized to simulate the conduction and convection heat exchange in the thermal model. The optical properties are the properties utilized in the modeling of radiation heat exchange between gray diffuse surfaces. The majority of the material properties are recycled from the most recent CH-TRU payload based thermal analysis, which is Section 2.0 of the CCO thermal analysis [Ref. 4]. In a few instances where the CCO analysis does not provide the necessary input, other sources are utilized.

The material properties that are taken directly from previously published thermal analyses supporting recent SAR revisions are summarized in the following list with reference citations:

- Table 3-1 – Thermophysical Properties of Type 304 Stainless Steel [Ref. 4]
- Table 3-2 – Thermophysical Properties of Carbon Steel [Ref. 4]
- Table 3-3 – Thermophysical Properties of Lead [Ref. 5]
- Table 3-4 – Thermophysical Properties of 6061-T6 Aluminum [Ref. 4]
- Table 3-5 – Thermophysical Properties of 5052 Aluminum [Ref. 4]
- Table 3-7 – Thermophysical Properties of 8.25 lb/ft³ Polyurethane Foam [Ref. 4]
- Table 3-9 – Thermophysical Properties of High-Density Polyethylene (HDPE) [Ref. 4]
- Table 3-10 – Thermophysical Properties of Paper-Based Payload [Ref. 4]

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For other material properties utilized in this analysis, further discussion is necessary. The aluminum honeycomb spacers used in the ICV payload cavity of the HalfPACT are designed to adapt the torispherical heads of the ICV into flat surfaces for accommodation of the typical payload geometry. The honeycomb spacers are fabricated from 5052 aluminum with a repeating array of hexagonally shaped cells aligned in the axial direction. The CCO thermal analysis [Ref. 4] provides the density of the honeycomb structure, which is 3.6 lb/ft³, and the derivation of the orthotropic conductivity in the Appendix of the analysis. The result is that proportional to solid aluminum 5052, the honeycomb spacers are modeled with conductivity scaling factors of 0.008 in the radial and 0.0213 in the axial directions. The solid 5052 aluminum conductivity and honeycomb conductivity factors are utilized in deriving the directionally dependent honeycomb conductive properties provided in Table 3-6.

The material properties for SC payload dunnage foam are provided in Table 3-8 for 6 lb/ft³ density foam. Per the drawings listed in Section 3.2.1, the polyurethane foam for the various SC payload designs (including the original SC-30G1) ranges from 6 lb/ft³ to 20 lb/ft³ in nominal density, with more than one density employed within some of the payload designs. Nominal polyurethane material property data is provided by a technical data sheet from the vendor [Ref. 18]. The foam data shows a positive correlation between density and conductivity. To bound the NCT thermal response of the temperature sensitive components for any foam density utilized in the SC payload designs, the material properties for 6 lb/ft³ are utilized for all dunnage foam properties.

The material properties for the simulated waste volume in Table 3-10 are those of the paper-based surrogate waste contents from the CCO thermal analysis [Ref. 4]. This is the same set of conservative material properties applied to simulated waste volumes in previous CH SAR analyses [Ref. 1 and 4]. The combination of loosely-packed paper thermophysical properties, and maximum decay heat loading for the package, conservatively maximizes the predicted waste temperatures in the models. Realistically, payloads with high decay heat waste contents are expected to contain inorganic (metallic or similar) waste with a combination of higher thermal decomposition temperatures, higher thermal mass, and/or higher effective conductivities. However, organic material such as paper-based waste is typically limited to a lower decay heat limit to prevent a flammable mixture of hydrogen gas and air from forming in the innermost confinement layer of the waste due to radiation-induced hydrogen gas generation (radiolysis). Generally, only payloads of waste forms with low hydrogen gas generation potential (inorganic) are able to challenge the total decay heat limit of the package without being limited first by the hydrogen gas concentration limit. See the discussion, values, and example calculations provided in CH-TRU Payload Appendix 2.3, 3.1, and 3.2 [Ref. 2] for clarity on this discussion and the competing decay heat limitations.

The properties for dry air at one atmosphere of pressure are provided in Table 3-11. These properties differ from the air properties provided in the CCO [Ref. 4] and 72-B [Ref. 5] thermal analyses in that density and specific heat are not provided. This is due to the modeling method in which air is not explicitly modeled with finite elements as discussed in Section 4.1. Rather, air gaps are modeled as either void, or use manually-specified conductance values, which only require conductivity and the appropriate geometric gap (i.e. zero thermal mass). However, fluid properties are necessary to support the convective film coefficients derived in Section 4.2.7.2.

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These properties are the kinematic viscosity, conductivity, thermal diffusivity, and Prandtl number for air. Table 3-11 provides these properties for a range of temperatures from 300°K to 900°K (80.33°F to 1,160.33°F) for dry air at one atmosphere of pressure from Table A.4 of the Fundamentals of Heat and Mass Transfer [Ref. 9].

The optical properties utilized in the analysis for the simulation of gray diffuse surface radiation heat exchange is provided in Table 3-12. Values for both emissivity (thermal spectrum) and absorptivity (solar spectrum) are provided. The exterior of the HalfPACT package design is fabricated completely of Type 304 stainless steel, hence the only value for solar absorption provided is for clean, smooth, and unpainted Type 304 stainless steel. Similarly, interior surfaces fabricated from Type 304 stainless steel, alloy 6061-T6 aluminum, High-Density Polyethylene (HDPE), and carbon steel are assumed clean, smooth, and unpainted. All optical values, except for carbon steel and lead, come from Table 2-12 of the CCO thermal analysis [Ref. 4]. The emissivity for carbon steel comes from Table 2-9 of the RH-TRU 72-B thermal analysis [Ref. 5] for an unpainted, clean, and smooth surface condition.

Note that the optical properties provided in Table 3-12 for Type 304 stainless steel, alloy 6061-T6 aluminum, and carbon steel are all based on clean, smooth, and unpainted surfaces. These surfaces are associated with components whose realistic condition in service is either in a passively oxidized state (Type 304 stainless steel and 6061 aluminum) or painted (optional exterior painted Type 304 stainless steel and carbon steel payload containers) to protect it from the environment. When compared to clean, smooth, and unpainted surfaces, oxidized or painted surfaces generally have higher thermal spectrum emissivity values. The use of clean, smooth, and unpainted surface properties for these materials is conservative.

The emissivity for lead comes from Table A.7.1 of the Handbook of Heat Transfer [Ref. 10] for gray oxidized lead. The analyses within this document assume the presence of air gaps between the lead shields and carbon steel shells, rather than intimate contact. As such, the thermal exchange across these gaps utilizes the insulating effects of still air conduction and radiation exchange. The presence of air in these spaces will result in the oxidation of both the interfacing carbon steel and lead. In addition, chemistry fundamentals dictate that chemical reaction rates are dependent upon the activation energy for the reaction and the temperature (see Section 14.4 of General Chemistry [Ref. 11]). The fabrication of the SC is such that elevated temperatures of 650°F and beyond due to the lead pour process [Ref. 7] or the welding shut of the lid or base shielding cavities, is expected. The assumed presence of air gaps between the lead and carbon steel surfaces, in combination with the increased oxidation reaction rates of elevated fabrication temperatures, will result in oxidized lead and carbon steel surfaces for radiation heat exchange in these gaps. The assumed use of an oxidized lead surface emissivity is therefore appropriate, while the use of clean, smooth, unpainted carbon steel remains conservative.

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Table 3-1 – Thermophysical Properties of Type 304 Stainless Steel

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
-100	0.2871	0.6211	0.1037
-40	0.2868	0.6547	0.1079
0	0.2865	0.6762	0.1105
70	0.2860	0.7167	0.1152
100	0.2858	0.7250	0.1159
150	0.2854	0.7500	0.1185
200	0.2850	0.7750	0.1210
250	0.2846	0.8000	0.1235
300	0.2842	0.8167	0.1247
350	0.2838	0.8417	0.1271
400	0.2833	0.8667	0.1287
450	0.2829	0.8833	0.1298
500	0.2825	0.9083	0.1314
550	0.2820	0.8250	0.1324
600	0.2816	0.9417	0.1335
650	0.2811	0.9667	0.1349
700	0.2807	0.9833	0.1359
750	0.2802	1.0000	0.1369
800	0.2798	1.0167	0.1372
850	0.2793	1.0417	0.1392
900	0.2789	1.0583	0.1394
950	0.2784	1.0750	0.1404
1,000	0.2779	1.1000	0.1417

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Table 3-2 – Thermophysical Properties of Carbon Steel

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
-100	0.2849	3.0575	0.0909
-40	0.2846	3.0137	0.0952
0	0.2844	2.9819	0.0981
70	0.2840	2.9250	0.1029
100	0.2838	2.8917	0.1050
150	0.2836	2.8417	0.1079
200	0.2833	2.8000	0.1120
250	0.2830	2.7417	0.1150
300	0.2827	2.6917	0.1179
350	0.2823	2.6333	0.1213
400	0.2820	2.5750	0.1238
450	0.2817	2.5250	0.1258
500	0.2813	2.4583	0.1286
550	0.2810	2.4000	0.1309
600	0.2807	2.3333	0.1333
650	0.2803	2.2750	0.1361
700	0.2800	2.2167	0.1396
750	0.2796	2.1583	0.1433
800	0.2792	2.1000	0.1471
850	0.2788	2.0417	0.1518
900	0.2785	1.9833	0.1560
950	0.2781	1.9250	0.1597
1,000	0.2777	1.8667	0.1655

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Table 3-3 – Thermophysical Properties of Lead

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
70	0.4095	1.6979	0.0308
100	-	1.6891	0.0309
150	-	1.6733	0.0311
200	-	1.6538	0.0313
250	-	1.6318	0.0315
300	-	1.6118	0.0317
350	-	1.5942	0.0320
400	-	1.5779	0.0323
450	-	1.5617	0.0327
500	-	1.5448	0.0330
550	-	1.5273	0.0334
600	-	1.5095	0.0338
620.33	-	1.5023	0.0339

Table 3-4 – Thermophysical Properties of 6061-T6 Aluminum

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
-100	0.0986	6.4000	0.1750
-40	0.0984	6.7750	0.1890
0	0.0983	6.9833	0.1970
70	0.0980	7.2917	0.2090
100	0.0979	7.4083	0.2130
150	0.0977	7.5750	0.2180
200	0.0975	7.7417	0.2230
250	0.0973	7.9167	0.2270
300	0.0971	8.0750	0.2310
350	0.0969	8.2083	0.2340
400	0.0967	8.3250	0.2370
450	0.0965	8.4167	0.2400
500	0.0963	8.4917	0.2430
550	0.0960	8.5667	0.2450
600	0.0958	8.6250	0.2470

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Table 3-5 – Thermophysical Properties of 5052 Aluminum

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
-100	0.0976	6.0209	0.2017
-40	0.0974	6.2493	0.2062
0	0.0972	6.3953	0.2091
70	0.0970	6.6333	0.2139
100	0.0969	6.7333	0.2164
150	0.0967	6.8917	0.2200
200	0.0965	7.0333	0.2230
250	0.0963	7.1583	0.2264
300	0.0961	7.2667	0.2293
350	0.0959	7.3667	0.2319
400	0.0957	7.4667	0.2356
450	0.0955	7.5544	0.2383
500	0.0953	7.6381	0.2411
550	0.0950	7.7172	0.2439
600	0.0948	7.7923	0.2466

Table 3-6 – Thermophysical Properties of Honeycomb Spacers

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)		Specific Heat (Btu/lb-°F)
		Axial	Radial	
-100	-	0.1282	0.0482	0.2017
-40	-	0.1331	0.0500	0.2062
0	-	0.1362	0.0512	0.2091
70	2.083E-3	0.1413	0.0531	0.2139
100	-	0.1434	0.0539	0.2164
150	-	0.1468	0.0551	0.2200
200	-	0.1498	0.0563	0.2230
250	-	0.1525	0.0573	0.2264
300	-	0.1548	0.0581	0.2293
350	-	0.1569	0.0589	0.2319
400	-	0.1590	0.0597	0.2356
450	-	0.1609	0.0604	0.2383
500	-	0.1627	0.0611	0.2411
550	-	0.1644	0.0617	0.2439
600	-	0.1660	0.0623	0.2466

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Table 3-7 – Thermophysical Properties of 8.25 lb/ft³ Polyurethane Foam

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
All	4.7743E-3	1.6083E-3	0.3530

Table 3-8 – Thermophysical Properties of 6 lb/ft³ Polyurethane Foam

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
All	3.4722E-3	1.5694E-3	0.3530

Table 3-9 – Thermophysical Properties of High-Density Polyethylene (HDPE)

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
-100	-	1.4252E-2	0.2554
-40	-	1.5374E-2	0.3089
0	-	1.5875E-2	0.3482
70	0.03431	1.6363E-2	0.4133
100	-	1.6475E-2	0.4445
150	-	1.6663E-2	0.5107
200	-	1.6667E-2	0.5761
250	-	1.6667E-2	0.9772

Table 3-10 – Thermophysical Properties of Paper-Based Payload

Temperature (°F)	Density (lb/in ³)	Conductivity (Btu/hr-in-°F)	Specific Heat (Btu/lb-°F)
All	2.3148E-2	1.6667E-3	0.3201

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Table 3-11 – Thermophysical Properties of Dry Air at One Atmosphere

Temperature (°K)	Kinematic Viscosity (m ² /s)	Conductivity (W/m-°K)	Thermal Diffusivity (m ² /s)	Prandtl Number (unitless)
300	15.89E-6	26.3E-3	22.5E-6	0.707
350	20.92E-6	30.0E-3	29.9E-6	0.700
400	26.41E-6	33.8E-3	38.3E-6	0.690
450	32.39E-6	37.3E-3	47.2E-6	0.686
500	38.79E-6	40.7E-3	56.7E-6	0.684
550	45.57E-6	43.9E-3	66.7E-6	0.683
600	52.69E-6	46.9E-3	76.9E-6	0.685
650	60.21E-6	49.7E-3	87.3E-6	0.690
700	68.10E-6	52.4E-3	98.0E-6	0.695
750	76.37E-6	54.9E-3	109E-6	0.702
800	84.93E-6	57.3E-3	120E-6	0.709
850	93.80E-6	59.6E-3	131E-6	0.716
900	102.9E-6	62.0E-3	143E-6	0.720

Table 3-12 – Optical Properties of Packaging and Payload Surfaces

Surface	Emissivity (ε)	Absorptivity (α)
Type 304 SS	0.25	0.50
6061-T6 Aluminum	0.15	-
HDPE	0.92	-
Carbon Steel	0.50	-
Lead	0.28	-

3.2.3 Boundary Conditions

Boundary conditions (thermal loads) are applied to the simulation of the HalfPACT package with the new SC payload designs. Those include the regulatory insulation energy fluxes specified in 10 CFR 71 [Ref. 12], the maximum decay heat loading of the internally packaged waste, and the ambient temperature of the surrounding environment. As discussed in Section 3.1.1, the regulatory ambient condition for NCT Heat conditions is 100°F still air and the maximum decay heat load for the HalfPACT package is 30 W.

The regulatory thermal insulation for NCT Heat conditions are prescribed in 10 CFR §71.71(c)(1) [Ref. 12] and are summarized as follows:

- Insulation applied over a 12-hour period as follows:
 - Flat surfaces transported horizontally – downward facing – N/A
 - Flat surfaces transported horizontally – upward facing – 800 gcal/cm²
 - Flat surfaces not transported horizontally (e.g. vertical) – 200 gcal/cm²
 - Curved surfaces – 400 gcal/cm².

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The precedence for interpretation of the applied regulatory insolation for the HalfPACT package is contained in the generic payload thermal analysis (Section 3 of the SAR [Ref. 1]), the SC-30G1 thermal analysis (Section 4.5.4 of the CH-TRU Payload Appendices [Ref. 2]), and the CCO thermal analysis [Ref. 4]. That interpretation is repeated herein as follows:

- The torispherical head of the outer OCA shell is treated as a curved surface with insolation of 400 gcal/cm² applied.
- The outer cylindrical surface of the OCA shell, including the thermal shield, is treated as a vertical surface with insolation of 200 gcal/cm² applied.
- The bottom flat surface of the OCA shell is treated as a flat downward facing surface with no insolation applied.

3.3 Significant Assumptions

The significant assumptions employed in this analysis are summarized in the following bulleted list. All assumptions are conservative unless otherwise noted.

Methodology

- The analyses in this calculation report utilize transient simulations with a 40-day run time for the models to reach pseudo-steady state conditions with cyclic regulatory boundary conditions. This is the same simulation run time utilized in the most recent CH related thermal analysis [Ref. 4], and is verified as appropriate based on the time-history responses summarized in Section 4.2.8. Therefore, this modeling assumption is appropriate.
- The space within the payload cavity (within the ICV and external to the SCs and dunnage) is assumed void. Modeling this cavity as void means that conductive and convective heat exchange is ignored, and only radiation heat exchange is modeled. Ignoring parallel heat exchange mechanisms results in higher temperature gradients to transport the internally generated decay heat to the outer package surface for dissipation to the environment. Therefore, this modeling assumption is conservative.
- The new SC payload designs under exclusive use and HAC thermal modeling conditions are assumed to be bound by the results of the generic payload thermal analysis for the HalfPACT package (Section 3 of the SAR [Ref. 1]). Only NCT thermal modeling conditions are evaluated in this analysis. This assumption is justified as appropriate in Section 3.1.1.
- Regulatory insolation is applied to the HalfPACT package such that the torispherical head is treated as a curved surface and the cylindrical surface is treated as a vertical surface. These assumptions match previous thermal modeling precedence for the HalfPACT package. These assumptions are justified as appropriate in Section 3.2.3.

Material Properties

- The orthotropic conductivity properties of the honeycomb spacers are based on the material of construction, alloy 5052 aluminum, with factors applied as derived in Appendix 6.1 of the CCO thermal analysis [Ref. 4]. As discussed in the source, derivation of the effective directional conductivity provides values that are lower than

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provided by the manufacturer. The values utilized herein match those conservatively derived in the CCO thermal analysis.

- The thermophysical properties applied to all SC payload dunnage foam designs is that of 6 lb/ft³ polyurethane foam. This is the lowest nominal density foam specified for any SC payload dunnage design, which correspondingly has the lowest conductivity and fastest thermal response to transient heat input. This assumption is justified as conservative in Section 3.2.2.
- The conductivity for the waste contents inside the payload containers is modeled as that of loosely packed paper. As discussed in Section 3.2.2, this assumption of waste material thermal properties is combined with the highest level of decay heat for the packaging design. Given the other competing decay heat limitation driven by the hydrogen gas generation rates of organic materials due to radiolysis, and the limitations on hydrogen gas concentration within the waste confinement layers, this is a conservative assumption.
- The optical properties provided in Table 3-12 for Type 304 stainless steel, alloy 6061-T6 aluminum, and carbon steel are all based on clean, smooth, and unpainted surfaces. The use of clean, smooth, and unpainted surface properties is justified in Section 3.2.2 as conservative.
- The optical property provided in Table 3-12 for lead is for a gray, oxidized surface condition. The discussion provided in Section 3.2.2 justifies this assumption is appropriate for the analysis.

Geometry

- Various simplifying techniques that do not impact the thermal response of the HalfPACT package with the SC payload design are employed in each model. That includes the modeling as 180° half symmetry, omission of small features, and utilizing surface bodies where through thickness temperature gradients are negligible. These modeling assumptions are justified as appropriate and discussed in more detail in Section 4.1.
- The 1/4-inch thick ceramic fiber paper that lines the inside of the OCA shell cavity, between the shell and polyurethane foam, is not explicitly modeled. Instead, the combined volume of polyurethane foam and ceramic fiber paper within the OCA cavity is modeled uniformly using the thermophysical properties of polyurethane foam. The CCO thermal analysis [Ref. 4] determined that the conductivities of the two materials are so close that modeling completely as polyurethane foam is appropriate. This analysis utilizes the same modeling assumption.
- The pallet used to load the SC payload into the package is not explicitly modeled. Instead it is abstracted by elevating the payload components 3.125-inches from the lower honeycomb top sheet and includes radiation exchange between the slip sheet or top sheet, depending on design, and the lower honeycomb. This modeling assumption is justified as conservative and discussed in more detail in Section 4.1.
- A plastic top reinforcing plate is optionally used on the upright SC payload designs, the SC-30G2 and SC-55G1. It is not modeled in this thermal analysis. This modeling assumption is justified as appropriate and discussed in more detail in Section 4.1.

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Connections

- Air gaps between interfacing surfaces larger than 0.25-inch are assumed void such that conduction heat exchange is excluded from those regions of each model. The void regions only model radiation heat exchange. This is a conservative assumption.
- Air gaps are modeled between the lead shielding and carbon steel chassis of each applicable SC design to maximize thermal resistance to inner decay heat dissipation. Further, the radial air gaps in the lead poured walls are maximized by not crediting inner carbon steel shell support during cool down contraction, nor the lead fill process. These modeling assumptions are conservative and discussed in more detail in Section 4.1.
- The maximum allowed fabrication gap between the payload dunnage foam and aluminum skin is 0.125-inch. The thermal resistance of this air gap is included in the model to maximize predicted waste and SC temperatures. This modeling assumption is conservative and discussed in more detail in Section 4.1.

Radiation

- For the modeling of the slip sheet in the SC-30G2 and SC-55G1 payload designs, a single surface body is intended to represent both the plastic slip sheet and aluminum pallet top sheet. The more conservative aluminum emissivity is applied to both sides of this surface body. This modeling assumption is conservative and discussed in more detail in Section 4.2.7.4.

3.4 Acceptance Criteria

The acceptance criteria for this analysis is driven by the temperature limits of the various components in the model. For NCT conditions, these temperature limits are those that allow for the continuous operation and normal function of the component and material. In some cases, multiple temperature limits exist for a given component as the component is comprised of a sub-assembly of components with differing temperature limitations. In the cases where an assembly may be limited to multiple temperatures, the most limiting of the temperatures is applied.

For the components comprising the HalfPACT packaging, temperature limits are subdivided into the OCA, OCV, and ICV structures, and are further split into the sealing o-rings located within the sealing flanges, the impact attenuating polyurethane foam within the OCA, and the Type 304 stainless steel construction. The Type 304 stainless steel structure of the HalfPACT is limited to 160°F. This is based on the assumption in the NCT structural analysis in Section 2.6.1.1 of the HalfPACT SAR [Ref. 1] in which a uniform bounding NCT temperature of 160°F is utilized for the NCT structural analysis of the packaging. The structure of the HalfPACT could likely endure much higher temperatures with regard to NCT structural qualification. However, to avoid invalidating the previous NCT structural qualification, this analysis limits the HalfPACT structural (OCA, OCV, and ICV shell) temperatures to 160°F.

The HalfPACT sealing O-rings are fabricated of butyl rubber using Rainier Rubber compound R0405-70. Performance tests for this sealing material are discussed in Appendix 2.10.2 of the HalfPACT SAR [Ref. 1]. The result is a conservative long-term allowable temperature range of

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-40°F to 225°F. As discussed in Section 3.3 of the SAR, this temperature range conservatively bounds industry standard data for the operating temperatures of butyl rubber.

The polyurethane foam construction within the OCA is also temperature sensitive. Per the discussion in Section 3.3 of the SAR, the structural temperature range for impact loadings is -20°F to 300°F. In addition, temperature excursions to -40°F will not degrade the performance of the foam.

For the ICV cavity, average air temperatures within the cavity are provided to support the calculation of MNOP. The temperature of the air within the ICV cavity is indirectly limited by the design pressure limit of 50 psig per Section 3.4.4.1 of the SAR. However, this pressure is dependent not only on the temperature of the air in the ICV cavity, but also the partial pressure due to any water vapor in the air of the cavity and the buildup of hydrogen gases generated by radiolysis in the waste. For this reason, a temperature limit for the ICV cavity air is not explicitly applied at this stage in the analysis. Acceptability of the ICV cavity air temperatures will be assured through downstream MNOP analysis.

Note that up to this point, the NCT temperature limits cited above are for packaging components. These components have been analyzed multiple times in previous analyses, including the HalfPACT generic payload thermal analysis (Section 3 of the SAR [Ref. 1]), the original SC-30G1 thermal analysis (Section 4.5.4 of the CH-TRU Payload Appendices [Ref. 2]), and the CCO thermal analysis (Section 4.6.4 of the CH-TRU Payload Appendices [Ref. 2]). These previous NCT analyses utilized identical regulatory loading conditions with the same HalfPACT packaging design. Since the total package decay heat, packaging, and regulatory boundary conditions remain unchanged, the NCT thermal analysis in this document is not expected to challenge any temperature limits for the packaging. The temperature limits for the packaging components are largely being provided for posterity and ease of comparison.

For the new SC payload designs, the main temperature-sensitive components are the impact limiting polyurethane foam of the dunnage designs, and the HDPE end caps of the SC-30G3. The polyurethane foam utilized in the dunnage is similar to that used in the SC-30G1 and OCA of the HalfPACT. The nominal density of the foam utilized in the dunnage designs of the SCs, including the SC-30G1 payload design, ranges from 6 lb/ft³ to 20 lb/ft³. The data provided by the manufacturer [Ref. 18] indicates that the foam has a maximum use temperature of 260°F. However, due to the highly non-linear dependency of temperature on crush strength, this thermal analysis is conservatively limiting the NCT temperature for the payload dunnage foam to 140°F to facilitate downstream structural analysis. The average temperature limit for NCT conditions of the dunnage foam for all SC payload designs is therefore 140°F.

For the HDPE end caps, a temperature limit of 170°F is used from the RH-TRU 72-B thermal analysis [Ref. 5]. As discussed in the 72-B analysis, the limit corresponds with a strength reduction factor from room temperature of 0.28, which was deemed structurally acceptable for the HDPE neutron shield insert used in the NS15 and NS30 payload canister designs. A similar determination is made for this analysis. The end caps sole function is to radially and axially adapt the support cavities of the dual use SC-30G3/SC-55G2 lateral dunnage (see Figure 1-7 and Figure 1-11). During normal transport, the end caps provide radial support against the weight of the SC-30G3 to position it relative to the lateral dunnage. Per the drawings listed in Section

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3.2.1, the outer diameter of the SC-30G3 is 28 inches and the axial length of the end cap skirts that radially support the weight of the SC-30G3 is 8 inches. The resulting projected bearing area is $2 \times 28 \text{ in} \times 8 \text{ in} = 448 \text{ in}^2$. The maximum weight of the SC-30G3 is 6,300 lbs. The resulting bearing pressure is $6,300 \text{ lbs} / 448 \text{ in}^2 = 14.06 \text{ psi}$. The MatWeb® material database [Ref. 19] reports a conservative lower bound for HDPE compressive yield strength of 580 psi. Applying the 170°F strength reduction factor of 0.28 results in a limiting compressive pressure of $580 \text{ psi} \times 0.28 = 162.4 \text{ psi}$. The margin of safety relative to a lower bound compressive strength is $(162.4 \text{ psi} / 14.06 \text{ psi}) - 1 = 10.5$. As a result, the 170°F temperature limit is conservatively applied to the HDPE end caps. Note that the simplistic assessment of bearing pressure provided above does not account for the concentrated contact area between the HDPE end caps and SC-30G3 due to the loose fit of the components. The large margin of safety in the calculated pressure, and use of a lower bound compressive yield strength, are judged to envelope the non-conservatism in the assumption.

For the SC designs, the main temperature-sensitive component is the filter vent. The filter vent minimum requirements are delineated in Section 2.5 of the CH-TRAMPAC [Ref. 3]. The upper operating temperature limit required of any filter vent installed on a payload container within the HalfPACT is 212°F. The next limiting temperature-sensitive material used on a SC would be the silicone sponge gasket. Per the general guidelines of the Parker O-Ring Handbook [Ref. 17], silicone rubber has an upper operating temperature limit of 400°F. The remaining materials for the SC designs are carbon steel and lead shielding, both of which have upper operating temperature limits even further beyond the temperatures discussed. As a result, the limiting temperature applied to the payload containers is 212°F.

Thermal decomposition temperature limits for the waste material itself are discussed at length in CH-TRU Payload Appendix 6.6 [Ref. 3]. The discussion provides the basis for establishing conservative temperature limits for the waste material, driven by the limitations on organic materials and their threshold for thermal decomposition and subsequent gas generation. Inorganics are largely thermally inert, and are therefore only briefly addressed. For organics, the partial pressures generated through radiolysis, vapor pressure of water, and vapor pressure of organic solvents are already controlled through the various payload requirements of the CH-TRAMPAC [Ref. 3]. Various common organic waste materials and their lowest threshold for thermal decomposition in air, based on testing, are provided in Table 6.6-1 of the CH-TRU Payload Appendices. The resulting lowest threshold temperature for detectable thermal decomposition provided is 150°C (302°F) for Pylox gloves (PVC). Further, it is clarified that even at temperatures up to 100°F above the onset of detectable thermal decomposition, gas generation is still negligible. The previous CCO thermal analysis [Ref. 4] and the RH-TRU 72-B thermal analysis [Ref. 5] interpreted these observations by limiting the maximum waste temperature to 402°F and the bulk average waste temperature to 302°F. These waste temperature limits are carried through to this analysis as well. Note that the waste centerline average temperature is provided to support downstream MNOP analysis. Similar to the average air cavity temperature, it is not explicitly limited in this analysis.

Table 3-13 summarizes the temperature limit acceptance criteria for the SC NCT thermal analysis in this report.

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Table 3-13 – Summary of Package Temperature Limits for NCT

Location	Limit (°F)
Waste Max	402
Waste Avg	302
Drum Shell Max	212
SC Shell Max	212
Dunnage Foam Avg	140
End Cap Max	170
ICV Shell Max	160
ICV O-Ring Max	225
OCV Shell Max	160
OCV O-Ring Max	225
OCA Foam Max	300
OCA Shell Max	160

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4.0 ANALYSIS

4.1 Geometry

The geometry for the thermal models in this analysis are developed using the SpaceClaim® CAD software, which is included as a part of the ANSYS® Structural software package [Ref. 29]. SpaceClaim® is a direct modeling CAD software, which means that unlike parametric design modeling software there are no geometric histories or dependencies required of the geometry created. The advantages to this style of modeling is the ease of importing geometry models from other CAD software packages, and the ability to easily defeature and prepare the model for FEA simulation. ANSYS utilizes the SpaceClaim software as the primary CAD system for modeling and importing geometry into the ANSYS® Mechanical software for further FEA pre-processing.

The geometry models used to represent the HalfPACT and SC payload designs utilizes the document referencing tool for an assembly in SpaceClaim®. This means that assemblies with reference to other assemblies and components will automatically update whenever the upstream assembly or component is changed or updated. This ensures control and consistency between shared geometry in the model. The relative hierarchy to the packaging assembly CAD models for the HalfPACT package with SC payload designs is as follows:

- HalfPACT Package with SC Payload Design
 - HalfPACT Packaging Assembly
 - SC Payload Assembly
 - SC(s)
 - SC Dunnage Assembly

The thermal models in this analysis employ several techniques to simplify the analysis, thus providing additional computation resources to focus on areas of interest in each model. One such technique is the use of 3-D 180° half-symmetry models. This method of modeling takes advantage of the symmetry of both the HalfPACT packaging along with the SC payload designs. It reduces the mathematical representation of the thermal model in half without sacrificing accuracy or detail. The modeling of the package as a half-symmetry model also allows for the modeling of both distributed and concentrated decay heat within the payloads, as required by the thermal cases summarized in Section 3.1.1.

Another technique is the use of surface bodies in lieu of solid bodies for certain regions of the model where through-thickness temperature gradients are negligibly small. Solids are utilized in regions of the model where temperature gradients through the thickness of the material are significant (thick sections of low conductivity material), or where the surface areas of a radiating solid body varies significantly from side-to-side. Examples of solids with through-thickness gradients of interest are the polyurethane foam of the HalfPACT OCA and the payload dunnage. Examples of solids with large differences in surfaces areas between radiation heat exchanging surfaces are the SC carbon steel and lead shielding shells. Note that the OCV and ICV flanges are modeled as solid monolithic blocks, as done previously in the CCO thermal analysis [Ref. 4]. The close coupling and high conductivity of the mating upper and lower flanges are such that a

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simplified monolithic block representation of each flange is sufficient for the purposes of modeling heat transfer in this region.

By contrast, surface bodies are used in regions of the model where temperature gradients through the thickness are considered negligible (thin materials with high conductivity). Surface bodies allow for the modeling of significant thermal diffusion along the conducting surface relative to underlying low conductivity material, without the need to include the additional nodes of a solid. Examples of surface bodies include the thin shells of the OCA, OCV, ICV, and payload dunnage skin.

Table 4-1 presents a summary of the thermal model bodies captured in the CAD model, and the type of representation used based on the aforementioned logic.

Table 4-1 – Summary of Package Component CAD Representations

Component	CAD Representation
OCA	
Polyurethane Foam	Solid
Shell	Surface
Thermal Shield	Surface
OCV	
Flange	Solid
Shell	Surface
Z Flange	Surface
ICV	
Flange	Solid
Shell	Surface
Honeycomb Spacers	Solid
Honeycomb Top Sheets	Surface
Payload Dunnage	
Dunnage Foam	Solid
Dunnage Skin	Surface
Slip Sheet	Surface
Pallet Top Sheet	Surface
End Caps	Solid
Payload Containers	
SC Chassis	Solid
SC Shielding	Solid
Waste	Solid

The final simplifying technique is the elimination of geometric details that are largely irrelevant to the thermal behavior of the package (defeaturing). The features omitted from the HalfPACT packaging thermal model include caps screws, small holes, chamfers, radii, seal test ports, fork lift pockets, etc. The knuckles at the corners of the torispherical heads are also omitted from the model to facilitate clean meshing. The thermal shield and connecting Z-flange are included in the model to capture the heat input and dissipation to the OCV flange from the broad surface of the thermal shield. However, the fiberglass insulation located outside of the locking ring and

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intended to provide protection of the OCV flange from direct flame impingement during a HAC fire event, is omitted.

The defeaturing technique is also employed to simplify the thermal model representation of the payload design. The small diameter aluminum tubes used to connect the upper and lower halves of the radial dunnage for the SC-30G2 and SC-55G1 payload designs, and each half of the upper and lower lateral dunnage assemblies for the SC-30G3 and SC-55G2 payload designs, are omitted. The axial dunnage for the SC-30G2 is simplified by merging with the upper radial dunnage. The combined upper radial and axial dunnage are modeled as a single polyurethane foam block wrapped by a thin aluminum skin, effectively omitting the aluminum plates at the interface between the two dunnage assemblies. Similarly, the upper and lower halves of the lateral dunnage assemblies for the SC-30G3 and SC-55G2 are also combined into a single foam block for each side of the payload, all wrapped by a thin aluminum skin.

Slip sheets are modeled for the purposes of providing an optical barrier to the SC containers in the axial direction. Slip sheets are used on the SC designs shipped in the upright orientation, the SC-30G2 and SC-55G1, whereas the designs shipped in a lateral orientation, the SC-30G3 and SC-55G2, do not include a plastic slip sheet. The slip sheet is a thin (0.15-in thick) rigid plastic (HDPE) sheet used to aid in the handling of the waste payload containers. They are simplified by modeling as a surface along the lower axial opening of the lower radial dunnage for the SC-30G2 and SC-55G1. Any additional slip sheet material that extends laterally beyond that lower opening is irrelevant for the purposes of thermal modeling and is omitted.

For the SC designs that are shipped in an upright orientation, the SC-30G2 and SC-55G1, there is also the option to ship with a plastic reinforcing plate on top of both SC designs. This component would reside on the tops of the SCs, and just below the bottom surface of the axial dunnage. The preliminary design of the plastic reinforcing plate for each design is similar to that of the original SC-30G1 [Ref. 21], i.e. HDPE material, 0.15-inch thick construction throughout, with 3.00-inch skirts extending down the outer edges. The thickness of this component is such that temperature gradients through the thickness are negligible. When combined with the relatively high thermal spectrum emissivity for HDPE (see Table 3-12), modeling the presence of a reinforcing plate in intimate contact with the tops of the SCs would result in improved radiation exchange with the dunnage skin. The short skirts that extend down the edges of the reinforcing plates would act as an optical barrier radially between the SC and dunnage. However, the aluminum skin of the dunnage is already modeled with a conservative, highly reflective emissivity and a low conductivity underlying foam. Modeling of the reinforcing plates is then considered negligible at best and non-conservative at worst. For the purposes of the thermal models, the reinforcing plates are omitted from the geometry of the model to instead maximize the conductive resistance of the air gap between the SC tops and the axial dunnage skin.

The pallet for all payload configuration models is conservatively omitted. The design can be summarized as that of a tubular spaceframe type construction, 3 inches thick, with a thin aluminum top sheet 0.125 inches thick resulting in approximately 3.125 inches of overall pallet height. From a thermal analysis point of view, the majority of the cross section in the axial direction, which is the main heat flow path away from the heat source in the payload cavity, is air space. In reality, some heat is exchanged through conduction in the thin square tube walls of the

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spaceframe while the rest is exchanged through radiation between the bottom surface of the thin aluminum pallet top sheet and the top surface of the honeycomb top sheet. Rather than explicitly analyze the pallet for both modes of heat transfer, the pallet is conservatively captured by “floating” the payload 3.125 inches above the top surface of the lower honeycomb and modeled as radiation exchange only between the slip sheet and honeycomb top sheet. The emissivity properties of aluminum are applied to the slip sheet for the SC-30G2 and SC-55G1 to emulate the aluminum top sheet of the pallet, while the thermophysical properties of HPDE are retained. For the payload designs shipped laterally that do not utilize a slip sheet, the SC-30G3 and SC-55G2, a surface body representing the top aluminum sheet of the pallet is included with the appropriate aluminum thermophysical and optical properties applied. Conduction through the thin square tube walls of the spaceframe design is conservatively ignored.

For the SCs themselves, they are modeled with small features such as cap screws, filtration ports, filter vents, gaskets, small radii, chamfered edges, etc. all omitted. The design aspects that are explicitly modeled to ensure accurate thermal representation are the geometries of the carbon steel chassis, lead shielding (if utilized), and air gaps approximated between interfacing lead and steel surfaces. The SC-55G1 presents the trivial modeling case since the design is that of thick, uniform, carbon steel construction, rather than the composite construction of the other three designs. It is modeled with a thick solid base, wall, and lid. The SC-30G2, SC-30G3, and SC-55G2, which are the lead shielded designs, are modeled as composite solid structures with the lead shielding and conservatively-derived lead to steel gaps included (see Section 4.2.5 for derivation). The lid and base each include fabricated lead plates as solids, and the walls include a lead-poured solid. Air gaps are modeled at these interfaces to provide thermal resistance to the expelling of interior-generated decay heat. The lid and wall are each modeled with a single air gap since the lid only contains a single lead plate, and the wall air gap is driven by the difference in thermal differential expansion of lead and steel during the cool-down process after lead pour. The base is modeled with two air gaps, both above and below the lead plates, due to the double lead plate construction and the stack up of various tolerances (discussed further in Section 4.2.5). Flanges at the top and bottom of the SC bodies are simplified into rectangular sectioned bodies for simplicity and to facilitate a clean mesh.

The 30- or 55-gallon drum overpacked in the SC is modeled as a solid right cylinder without the thin carbon steel exterior shell (approximately 0.040 to 0.060-inch thick). The dimensions are based on the computed internal drum volumes in PLD-CAL-0001 [Ref. 8], which includes the volume of the lower domed shell of each drum design. The inner diameters are as specified in the vendor supplied drum drawings [Ref. 26 and 27]. The simulated axial height is then solved for by using the total waste volumes and the internal drum diameters. The result is a cylinder diameter of 18.25 inches and height of 27.294 inches for the 30-gallon drum, and a cylinder diameter of 22.50 inches and height of 33.151 inches for the 55-gallon drum. For the SC-30G2 and SC-55G1, each modeled drum is “floated” above the bottom inner surface of each SC to account for the rolled bottom edges of the drum not explicitly modeled. For the SC-30G3 and SC-55G2, each drum, SC, and end caps (for the 30G3), are axially and radially floated to conservatively simplify the model. Similar to the SC, small features such as filter ports, filter vents, gaskets, rolled hoops, rolled edges, closure rings, etc. are all omitted from the drum model.

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The geometry in the CAD model is also organized such that bodies are split along the appropriate edges and surfaces, and then recombined into groups of bodies with shared topology. Sharing topology amongst geometric bodies is a modeling technique that simplifies downstream pre-processing of the FEA model. In SpaceClaim, this is accomplished through use of components in which bodies that are combined into a component can have overlapping surfaces and edges shared through specification of shared topology within the properties of each component. The mesher in ANSYS® Mechanical will recognize the bodies of components with overlapping surfaces and edges, if shared topology is specified, and synchronize the mesh at interfacing edges or surfaces. The elements within each mesh will share nodes along the shared interface, thereby modeling intimate contact. This modeling technique is computationally less expensive and a more accurate method of modeling intimate contact than using explicit contact elements. A drawback of this technique is that small gaps or similar small features can drive a nearby synchronized mesh into “sliver” like element shapes, which are regarded as degenerate and have poor accuracy while being computationally expensive to model. Another drawback is that overlapping surfaces cannot be used to model radiation heat exchange (i.e. thin shells must be offset from underlying solids as a result).

The result is that the majority of the model employs shared topology where overlapping edges and surfaces are present, in order to simplify the task of connecting the model through manually specified contact. An exception is in the modeling of the lead solids within the composite structures of the SC-30G2, SC-30G3, and SC-55G2. The lead solids are intentionally segregated from the components sharing topology for the rest of the carbon steel chassis. This allows for the explicit modeling of air gap conduction and radiation exchange between the lead and carbon steel surfaces. It also prevents the introduction of “sliver” elements into the carbon steel structure due to the explicitly modeled air gaps. For the rest of the model, thin shells are offset from nearby contacting solids in order to avoid the limitations of the software in modeling radiation heat exchange.

Each HalfPACT package CAD model with corresponding payload is graphically depicted in Figure 4-1 through Figure 4-4. The color scheme for the depicted CAD models is to utilize white for metallic non-lead structures, i.e. stainless steel, aluminum, and carbon steel. Lead is represented by light gray to help contrast against the carbon steel of the composite structure of the SCs. Polyurethane foam is represented by dark gray. HDPE, where utilized, is represented by black. Waste volumes are represented by red. Surface bodies are displayed as semitransparent, where solid bodies are completely opaque.

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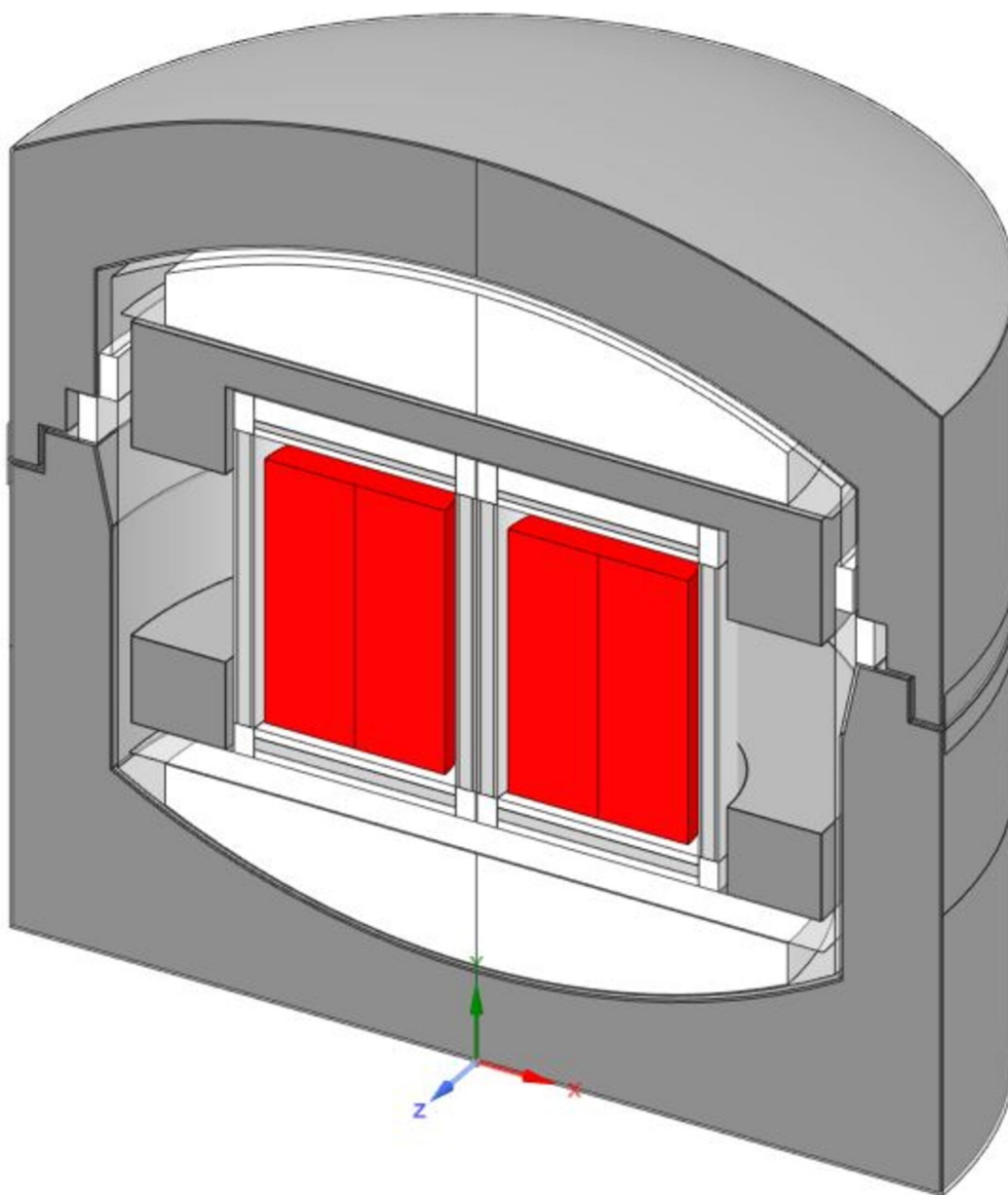


Figure 4-1 HalfPACT Package with SC-30G2 CAD Model

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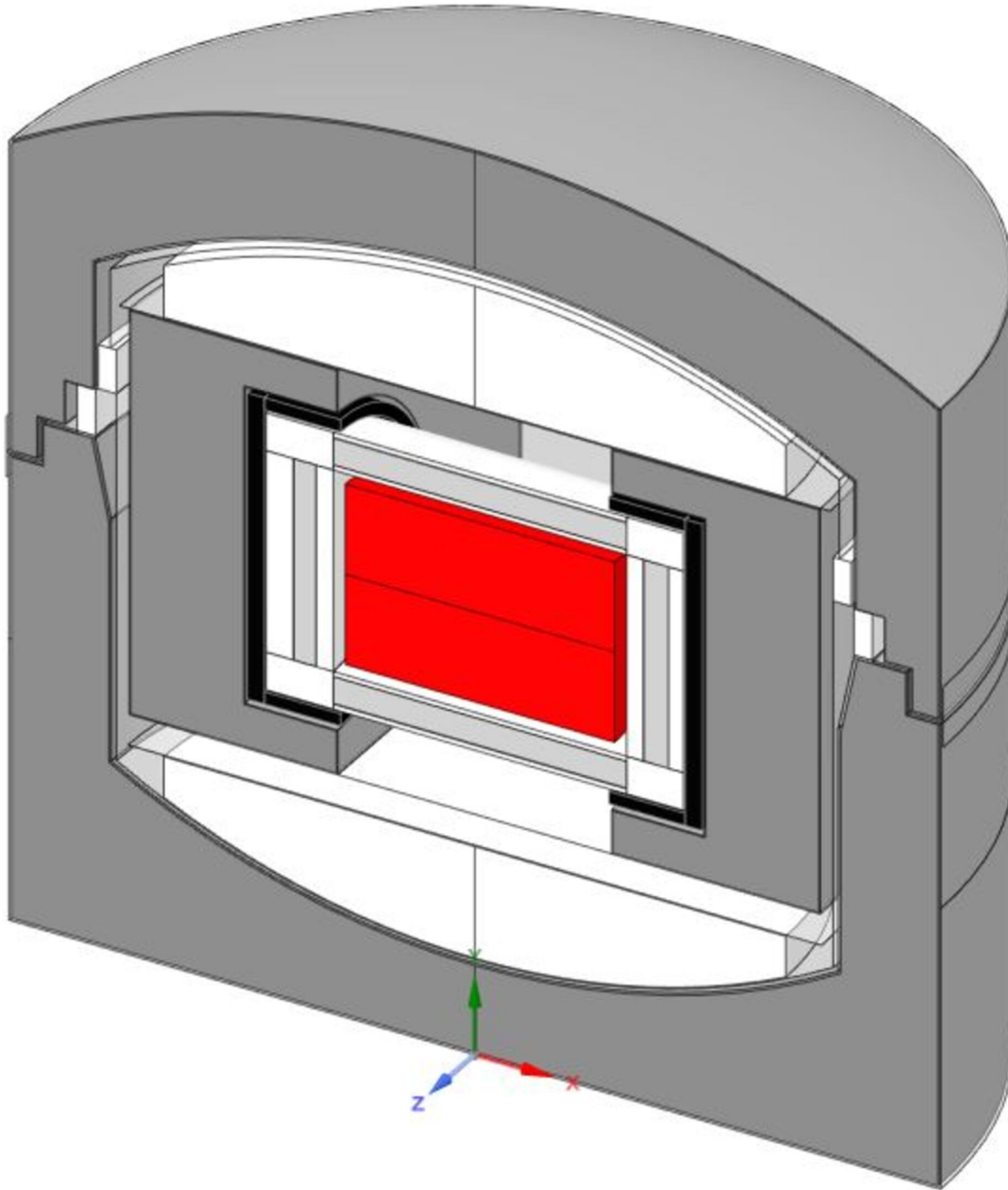


Figure 4-2 HalfPACT Package with SC-30G3 CAD Model

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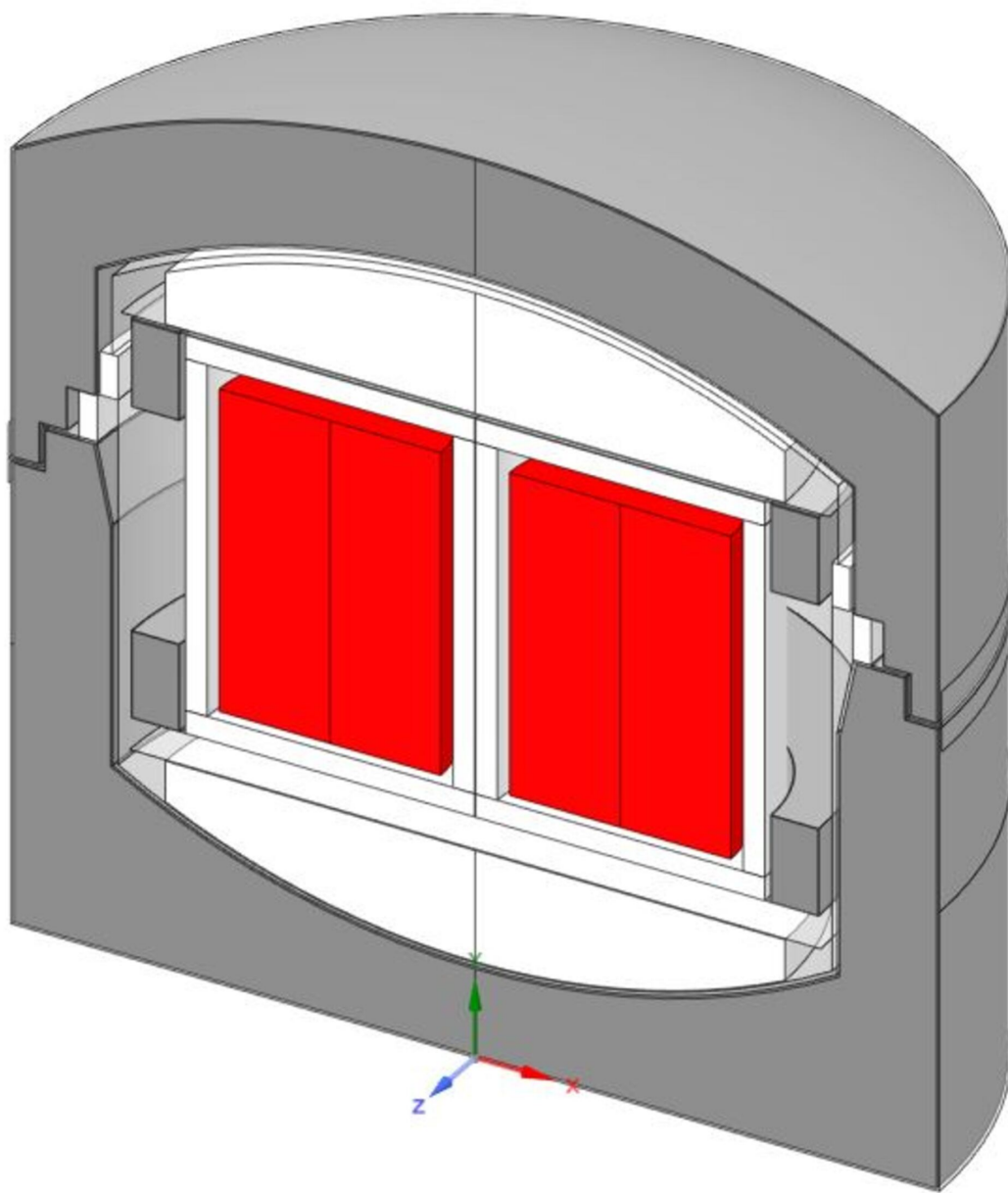


Figure 4-3 HalfPACT Package with SC-55G1 CAD Model

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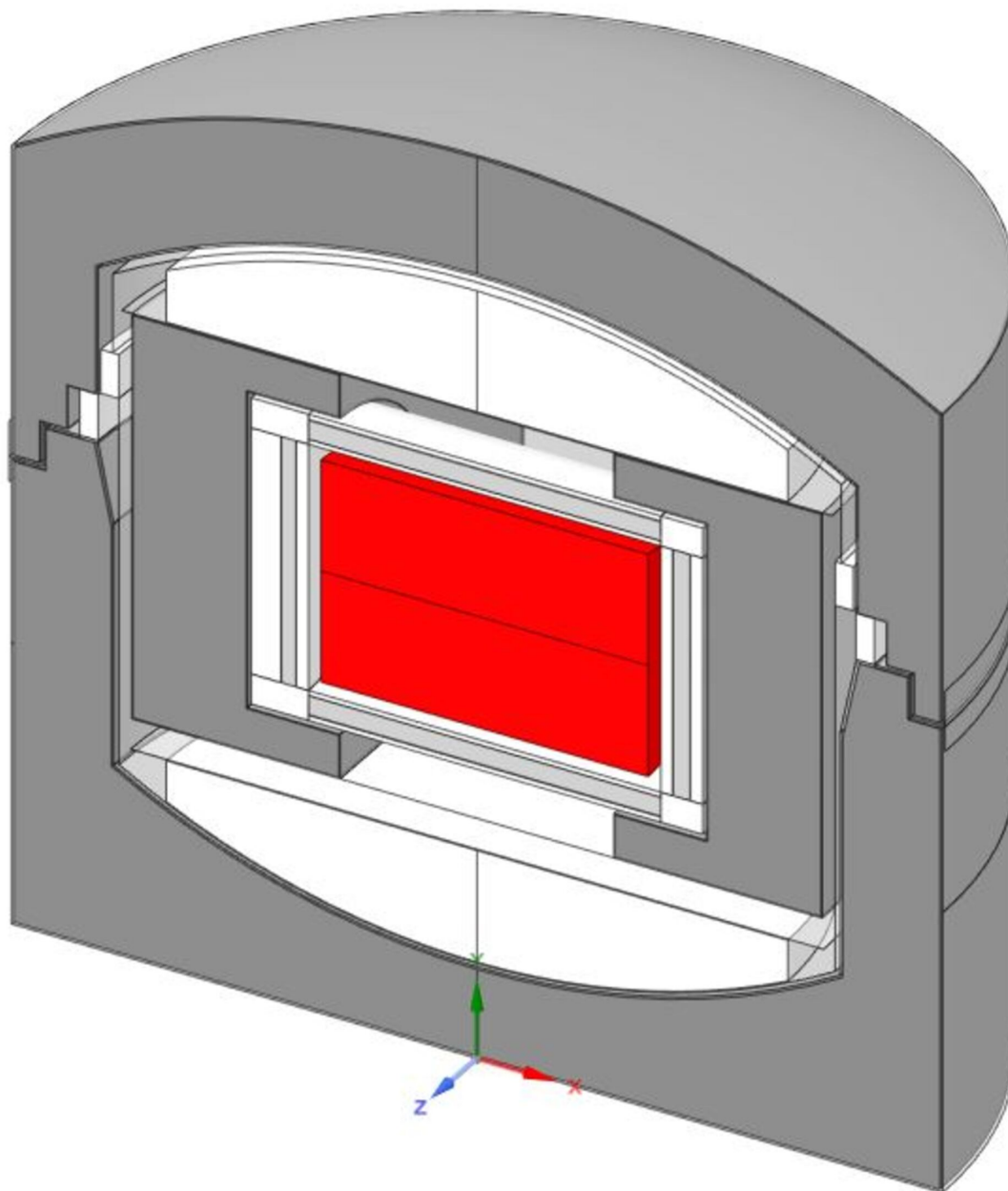


Figure 4-4 HalfPACT Package with SC-55G2 CAD Model

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4.2 NCT Thermal Models

With the geometry of the models discussed, the remaining pre-processing, execution, and post-processing of the models is covered in this subsection. The process flow in this section is structured to mimic the ANSYS® Mechanical process flow to create and execute a simulation. That is the specification of engineering data (i.e. material properties), symmetry (boundary constraints for applied symmetry), meshing (transformation of CAD geometry into discrete elements), contact (conduction contact between surfaces and edges), analysis settings (solution controls, solution steps, substep controls, etc.), boundary conditions (model constraints and loads), and results (post-processing).

The structure of the thermal models, for the purposes of file management and data sharing between simulations and projects, is controlled via the ANSYS® Workbench software. Four (4) project files are created (“wbpj” files), each representing one of the new SC designs and named accordingly. Those files are attached to this document in the Workbench archive file format (“wbpz” files) in the electronic document management system. Within each project, multiple simulations exist to cover the range of thermal cases outlined in Section 3.1.1. They include a 0W decay heat case, a 30W concentrated decay heat case, and, where appropriate, a 30W distributed decay heat case. Each project also includes an additional mesh sensitivity case, called “High Res.” Each case includes links to share the engineering data, geometry, and model (mesh data) cells between each thermal case simulation to ensure consistency between the models. The remaining cells of each simulation include data that is unique to each case (e.g. boundary conditions and solutions results), and is therefore unshared.

One exception to the above generalization is the mesh study “High Res” cases for each project. Those cases only share engineering data and geometry cell information with the other simulations. This is due to the higher resolution mesh utilized in those models, which differentiates them from other simulations. They are largely carbon copies of each project's nominal “concentrated” simulation case, with higher mesh resolution controls specified. This was achieved using the “duplicate” feature within Workbench, in which a simulation can be duplicated to create an exact copy of the simulation to serve as a starting point for further modification.

The discussions following this section make reference to various features and processes contained within the ANSYS® Workbench, Mechanical, or Mechanical APDL software. Please see the documentation provided online by ANSYS for each applicable software product for familiarization and further information [Ref. 29].

4.2.1 Engineering Data

The engineering data for each model is accessed via the ANSYS® Workbench user interface. Workbench is utilized by the software package to organize the file structure of, and manage the simulations within, a project. The engineering data is where material properties are specified for the simulation within a project. The material properties include structural, thermal, and other properties depending on the simulation to be run. For a thermal analysis, the material properties to be specified are the conductivity, density, and specific heat for each material. The density and specific heat are only necessary for time integrated simulations (transient). Steady state analyses

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only require conductivity be specified. However, since this analysis employs the pseudo-steady-state method of analysis (transient analysis), all three thermal properties are specific for each material.

Each simulation can also share engineering data in order to avoid specifying redundant properties for multiple simulations within a project and ensure consistency. The Workbench software stores the property data specified in the engineering data cell in “xml” files local to each simulation. For the purposes of sharing engineering data outside of the project, material libraries (“xml” files) can be created and referenced by projects as a common source of material data. Since the modeling of the new SC designs will utilize individual Workbench projects for each design, and each design will share material properties, a common material library file was created called “Material Properties Thermal (CH-SAR).xml”. Within this file, all of the thermal material properties for the thermal analyses in this report are stored and shared amongst the SC projects and simulations.

The material properties discussed in Section 3.2.2 and tabularized in Table 3-1 through Table 3-10 are then copied verbatim into the aforementioned material data library file. The material data library file is then referenced in each Workbench project, providing a single source of thermal material properties as input data. Engineering data cells are also linked to share material data properties between each simulation within a project, ensuring a single source of material property data. See Section 3.2.2 for tabularized material property data utilized in the thermal simulations executed in this analysis.

4.2.2 Geometry

The discussion of the geometry cells for each project is relatively trivial but included for posterity. Each project models a unique HalfPACT package with a new SC payload design, of which there are four (4). The geometry cells for each project and simulation is where the package geometry discussed in Section 4.1 are imported. Geometry cells within each project includes links to share geometry data amongst all of the simulations. The geometry is then imported into each simulation for further pre-processing in the ANSYS® Mechanical user interface.

The remainder of discussions on pre-processing, execution, and post-processing of the thermal simulations in this report are performed in the ANSYS® Mechanical software.

4.2.3 Symmetry

As discussed in Section 3.1 and Section 4.1, and depicted in Figure 4-1 through Figure 4-4 regarding the modeling method, the models are 180° half-symmetry models. Symmetry is modeled as an adiabatic boundary in which heat cannot pass across the plane of symmetry. In Mechanical, symmetry for a thermal model is implicit if thermal loads such as conduction, convection, and heat flux are not applied to the model edges and surfaces along the symmetry plane. Without thermal loads applied to those surfaces, they are treated as adiabatic since heat cannot flow out of the applicable edge or surface. However, in order for the solver to respect

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symmetry during the calculation of radiation view factors for radiation exchange, symmetry must be explicitly specified.

The symmetry plane utilized for all models in this report is the global XY-plane (Z-normal). Two symmetry objects are added to each model, one for scoping to surfaces and one for scoping to edges. The scoping of multiple types of geometry within a single symmetry object is not allowed. The global coordinate system is cited as the source for symmetry direction, and the symmetry-normal direction is selected as the z-axis.

4.2.4 Mesh

While out of order with the Mechanical workflow depicted in the project tree, the next topic of discussion is the mesh. This is because the topic that proceeds the mesh is contact, and contact is dependent on mesh. The Mechanical APDL solver will utilize the resulting mesh to create an array of discrete thermal elements to represent the geometry of the model. Those geometric thermal elements will then be coated with contact and surface-loading elements to model the various connections and boundary condition loads applied to the model and discussed later in the report. Therefore, it seems logical to discuss the mesh prior to discussing the remainder of the model.

The mesh controls employed in these models were selected to result in meshes similar to the CCO thermal model [Ref. 4] with regard to node and element count. Feedback via mesh quality metrics and the thermal error post-processor were also utilized to refine the mesh. The overall strategy for the mesh is to globally relax the mesh, and then target areas for added resolution and refinement where needed. This strategy ensures that computational resources are focused where needed, which is necessary when modeling non-linear transient models of this magnitude and complexity (structural, thermal, or otherwise).

The mesh quality metric employed is the skewness metric. The skewness metric is a measure of how close the element's shape is to ideal (1:1 aspect ratio). A skewness value of 1 indicates a degenerate element shape ("sliver"), while a value of 0 indicates an equilateral shape (perfect). Per the guidance provided in the ANSYS documentation [Ref. 29], element quality is regarded as excellent for values of less than 0.25, good for values ranging from 0.50 to 0.25, and fair for values ranging from 0.75 to 0.50.

Thermal error post-processing is also utilized as a form of mesh quality feedback. The thermal error post-processor approximates thermal error through integration of the element volume to the proportion of heat flux to conductivity (i.e. proportion of heat flux to conductance), as explained in the Mechanical APDL theory reference manual [Ref. 29]. Regions of the model with elements of low conductivity, large volume, and high heat flux result in the prediction of high thermal error. By contrast, regions of the model with elements of high conductivity, small volume, and low heat flux result in the prediction of low thermal error. Since this mesh feedback tool is a post-processor that requires model execution to attain a solution, it is an iterative process that involves executing the model, updating the mesh, and then re-executing the model. The areas of the model identified by the thermal error post-processor for refinement are a couple of local regions of the OCA foam, and the entire decay heat generating waste volume. Given the

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definition of the thermal error provided, the regions of the model identified for the most modeling error are intuitive.

Mesh controls are then applied to refine the mesh, based on the quality measures and feedback controls discussed. The first mesh control to discuss is the element order control. The element order can be selected as either linear or quadratic. Linear elements are elements which do not contain midside nodes, where quadratic elements are elements which contain midside nodes. Per the guidance and discussion provided in the Mechanical APDL Modeling and Meshing Guide [Ref. 29], linear elements are selected and judged as appropriate for the non-linear transient thermal models in this analysis. An advantage of the quadratic element is their ability to subdivide rounded geometric faces into two facets per element, rather than one, thereby providing a truer representation of a round surface without increasing element count. However, as provided in the guide, linear elements are better suited for non-linear models as they provide better accuracy and are less computationally expensive on the system. There are also a list of solution accuracy limitations with regard to quadratic elements in the guide that are not associated with linear elements (see the aforementioned Modeling and Meshing Guide for more in-depth discussion). As a result, the linear element order is specified for the elements of all thermal models in this analysis, with added resolution controls applied to round geometry to overcome the only limitation to this element type provided in the guidance documentation.

For the control of total element quantity within the mesh, a global mesh size limit of 6-inches is specified. Mesh method and sizing controls are then used in targeted areas for refinement. The hexahedron dominant method is specifically utilized in regions where the default settings of the mesher results in a tetrahedral mesh that could otherwise be represented by hexahedrons. Although the Modeling and Meshing Guide notes that triangles and tetrahedrons generally produce accurate results for non-structural analyses, it is good ANSYS FEA modeling practice to minimize the use of these elements shapes when possible.

The sweep method is used to force swept meshing wherever sweepable bodies exist to improve the mesh quality statistics and shape. A swept mesh is one in which a source and target face of a solid are identified and the initial mesh pattern is dictated by the free mesh created on the source face. The mesh is then swept (extruded) in the direction of the target face producing relatively uniform hexahedron and wedge shaped elements along the path. Sweep mesh controls are applied to the OCA foam and SC chassis and shielding. For the OCA foam, the application of a circumferentially swept mesh effectively eliminates tetrahedron elements from the solid. For the SC, use of sweep mesh controls synchronizes the elements in the composite wall in the circumferential direction such that element face penetration is avoided. A penetrating element face can result in solution errors or inaccurate results where radiation modeling is present due to erroneous view factor calculations.

The multizone method is used on bodies whose geometry, if subdivided, are otherwise sweepable. This method decomposes the geometry into simplistic shapes and then meshes using predominantly hexahedral shaped elements. The multizone method is useful for decomposing geometry that could otherwise be “sliced” into simple shapes for clean meshing at the geometry construction phase of the process, but is applied at the meshing phase. This mesh control method is applied to the SC-30G3 and SC-55G2 payload designs for the foam dunnage and HDPE end caps (SC-30G3) to enforce hexahedral shaped elements and improve mesh quality.

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The final mesh control utilized is body sizing control applied to the modeled waste volume. As discussed above, regions in the model predicted to have the highest error are those in which the elements have high heat flux in combination with low conductance. Because of the conservatively low conductivity of the paper-based material property applied to the modeled waste volume, in combination with applied volumetric heat generation due to the waste decay heat, the waste volume is identified as the likeliest source of error by the thermal error post-processor. Therefore an iterative process was utilized to refine the maximum size of the elements in the waste volume until acceptably low error is predicted. The resulting maximum body size mesh control applied is 4 inches.

The resulting nominal mesh statistics for each of the package models are summarized in Table 4-2. The statistics included are the node and element totals along with the mesh quality statistics using the skewness mesh metric discussed above. Overall, while the mesh for each geometric model is unique, the mesh metrics can be summarized as an average skewness of 0.20, with an average standard deviation of 0.18. Thus approximately 84% (upper bound for 1 standard deviation) of the element population in each model ranges in quality from excellent to good (see skewness definitions provided in the discussion above), and approximately 98% (upper bound for 2 standard deviations) of the element population in each model ranges in quality from excellent to fair.

Note that a mesh sensitivity analysis is also provided for each package model and is discussed in Appendix A.1 of this report. The result is that the nominal mesh is deemed acceptable, particularly given the large temperature margins to the acceptance criteria presented in the results in Section 2.1.3.

Table 4-2 – Summary of Mesh Metrics by Model

Mesh Metric	SC-30G2	SC-30G3	SC-55G1	SC-55G2
Node Total	8,717	6,738	7,164	6,110
Element Total	6,458	5,151	5,469	4,696
Skewness Avg	0.19	0.21	0.19	0.21
Skewness Std Dev	0.16	0.20	0.17	0.19

4.2.5 Connections

Connections are modeled in the SC thermal analyses in two ways, shared topology and bonded contact. The shared topology method and strategy was discussed in Section 4.1. Shared topology is applied at the CAD geometry level with forethought as to which regions of the model will be represented by intimate-contact conduction. Those regions of overlapping surfaces and edges at the meshing stage of the model are synchronized to share nodes between adjacent elements. The method is computational efficient by reducing the number of contact elements needed to explicitly model contact, which reduces the size of the mathematical model.

As with any method, drawbacks exist and are noted in the geometry discussion. Regions of the model with intimate contact that otherwise could not be modeled with shared topology utilize manually applied bonded contact. Applied contact allows for the finite control over the regions of the model to include contact. Manually applied contact also allows for the independent

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meshing of bodies within the model to prevent undesirable mesh outcomes (degenerate shapes such as slivers near complex geometric transitions). Finally, manual contact application allows for the direct specification of contact conductance if something other than perfect contact is to be modeled.

Multiple formulations exist for the modeling of contact. Those formulations can be summarized as penalty-based methods (pure penalty, LaGrange, etc.) and the multi-point constraint method (MPC). The MPC method is computationally efficient and simple as the formulation creates constraint equations between the nodes of scoped surfaces, edges, or vertices and effectively “ties” their degrees of freedom together. For a thermal analysis, the only degree of freedom for each node is temperature, which means the MPC formulation effectively “ties” the nodal temperatures of scoped contact pairs together. By contrast, the penalty-based methods coat the scoped entities with contact elements and “connect” them through application of stiffness based equations. The analog to stiffness is conductance in thermal simulations (i.e. Heat Flow = Conductance x Temperature Gradient). Since a finite conductance must be applied for the solver to function, bonded intimate contact is handled by the APDL solver by first identifying the element within the model with the highest conductance and scaling that value up by an internally predefined fixed amount. The scaled artificially high conductance value is then applied as the conductance to all bonded contact elements with a penalty-based formulation. By ensuring that the conductance value applied is higher than the highest element conductance in the model, introducing artificial temperature gradients in regions with modeled bonded contact is minimized.

Of the two methods for modeling bonded contact, the penalty-based method that is the default is utilized. While the MPC method is theoretically more efficient, other aspects of the model calculation are more computationally expensive (radiation exchange) to the overall solution than the contact calculations. Early modelling tested the sensitivity of the two contact methods and it was found that the solutions times and results were largely identical between the two. However, MPC presented some drawbacks in its sensitivity to pinball radius (control for contact detection) and the potential to over constrain certain areas of the model. This can be avoided through manual specification of the pinball radius of each contact location, effectively tuning each model. However, any perturbation in the mesh size and corresponding element size results in the need for retuning of the pinball radius, if manually specified. Since the default penalty-based contact formulation, coupled with default pinball radius settings, appeared both insensitive to mesh settings and produced equivalent results and computation times as modeling with MPC based contact, default contact settings are utilized. As a result, the default penalty-based method for all contact is employed.

Regions of the model where low-conductivity solids are wrapped in high-conductivity skin, or where manual control of contact interfaces are desired in order to capture air gap conduction, are modeled with bonded contact. The regions of the model with bonded contact that are intended to model perfect contact are left with default settings that approximate ideal contact as discussed above. For areas of the model where air gap conduction is captured, manual calculation of the air gap conductance is required. General linear conductance through a fixed cross section is $K \cdot A / L$, where K is the conductivity of the conducting medium, A is the cross sectional area, and L is the length in the direction of heat flow. Per the ANSYS® Mechanical documentation, the

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solver uses the area of the contact element for the computation of conductance. Therefore, conductance is specified within Mechanical as K/L.

The conductivity of air at 300°K (80.33°F) per Table 3-11 is utilized for all approximations of air gap conductance. This is a conservative approximation given that all modeled temperatures are a minimum of 100°F, and that air conductivity increases with increasing temperature. The length for each air gap is then approximated. Air gaps in the model can be summarized as modeled in three distinct regions; the lead shielding to carbon steel chassis of the SCs (excluding the SC-55G1 design), the SC to dunnage assemblies, and the ICV to OCV radial and axial gaps. Note that all air gaps greater than 0.25-inch are assumed void and air conduction is therefore not modeled. Only radiation exchange exists at these interfaces.

For the approximation of lead shielding to carbon steel chassis gaps, it is further split into two types of air gaps. Those are the axial air gaps between the lead plates and the carbon steel bodies of the base and lid, and the radial air gaps between lead-poured shielding and the outer carbon steel shells of each wall. For the radial air gaps, they are conservatively approximated using the coefficients of thermal expansion for lead and carbon steel, and assume the unrestrained contraction of the lead from the outer carbon steel wall, from the lead melting temperature of 620°F to room temperature. This is a conservative approach that does not credit the pour process specified in the fabrication specification [Ref. 7], which specifies the continuous pouring of lead as the lead solidifies to fill in any gaps formed during the cool-down process. It also does not credit the radial support provided by the inner carbon steel shell, which restrains the lead from the contraction.

The thermal coefficients of expansion for low-alloy carbon steel come from the material properties provided in Table TE-1 of the ASME Boiler and Pressure Vessel Code (BPVC) [Ref. 13]. The thermal coefficients of expansion for lead are from Appendix A of NUREG/CR-0481 [Ref. 16]. They are each computed as the average coefficient of expansion from room temperature to 620°F as follows:

$$\alpha_{CS} = \left(\frac{7.5 - 7.4}{650 - 600} * (620 - 600) + 7.4 \right) * 10^{-6} \frac{\text{in}}{\text{in} * ^\circ\text{F}} = 7.44 * 10^{-6} \frac{\text{in}}{\text{in} * ^\circ\text{F}}$$

$$\alpha_{Lead} = \left(\frac{36.7 + 28.9}{2} \right) * 10^{-6} \frac{\text{m}}{\text{m} * ^\circ\text{C}} * \frac{5\Delta^\circ\text{C}}{9\Delta^\circ\text{F}} = 18.22 * 10^{-6} \frac{\text{in}}{\text{in} * ^\circ\text{F}}$$

Each radial air gap and corresponding air conductance is then computed using the following formulae:

$$Gap = \frac{D}{2} * (\alpha_{Lead} - \alpha_{CS})(T_{Melt} - T_{RT})$$

$$C = \frac{k_{air}}{Gap}$$

The variables T_{Melt} and T_{RT} are the lead melting temperature at 620°F and room temperature at 70°F, respectively. The variable k_{air} is the conductivity of air at 300°K of 3.518E-7 Btu/s-in-°F (26.3E-3 W/m-K), as defined in Table 3-11. The variable D is the inner diameter of the outer shell for each SC design from the drawings summarized in Section 3.2.1. The resulting radial wall gaps and conductance values for SCs with lead shielding are tabulated in Table 4-3.

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For the SC axial lead air gaps in the lid and base of each design, the gaps are modeled as a result of nominal dimension gaps rather than thermal expansion differences. This is due to the fabrication technique in which lead plates are press fit into a cavity in the lid and base, rather than poured in the liquid state. Each assembly is then completed by welding a carbon steel plate to close the cavity, sealing the lead plate into the assembly. Each lid is designed with only a single lead plate pressed into the cavity. Each base is designed with two (2) lead plates pressed into a step designed cavity. The assumption used to determine the number of axial air gaps modeled is based on the fabrication technique. A single gap is modeled in the lids with the assumption that the fabricator will either press the lead plate to the bottom prior to final assembly, or press the lead plate with the carbon steel plate together onto the assembly. In either case, intimate contact on one surface of the lead plate is maintained while the other contains an air gap. For the base, a similar assumption regarding assembly is made and results in two (2) gaps.

The drawings summarized in Section 3.2.1 are utilized to determine the nominal dimensions for the geometry of the carbon steel plates, flanges, and lead plates of the lid and base for each lead shielded SC design. The various nominal dimensions are stacked together in deriving the modeled gaps. The process is relatively simple and not explicitly detailed herein. Instead, the total computed axial air gaps, with their corresponding conductance, are presented in Table 4-3. Air gap conductance is computed using the same formula for conductance based on air conductivity as presented above. Two values are provided for the lead gaps in each base as the nominal dimensions result in slightly different upper and lower gaps for that assembly.

Table 4-3 – SC Lead Air Gaps and Conductance Values

Design	Location	Gap (in)	Conductance (Btu/s-in ² -°F)
SC-30G2	Wall	0.071	4.972E-6
	Lid	0.055	6.396E-6
	Base	0.040/0.045	8.794E-6/7.817E-6
SC-30G3	Wall	0.080	4.394E-6
	Lid	0.070	5.025E-6
	Base	0.040/0.045	8.794E-6/7.817E-6
SC-55G2	Wall	0.089	3.954E-6
	Lid	0.055	6.396E-6
	Base	0.040/0.045	8.794E-6/7.817E-6

The axial and radial air gaps between the SC and dunnage surfaces are similarly calculated by stacking the nominal dimensions provided by the drawings in Section 3.2.1. For the SC-30G2 and SC-55G1, only the axial air gaps between the tops of the SCs and the bottom surface of the top dunnage aluminum sheet are modeled. For the SC-30G3, the design is radially and axially “floated” such that axial and radial air gaps are modeled between the SC, HDPE end caps, and aluminum dunnage skin. Note that the radial gap between the HDPE end caps and aluminum dunnage skin is larger than 0.250-inch and therefore not modeled. For the SC-55G2 that is also radially and axially “floated”, the axial and radial air gaps between the SC and aluminum dunnage skin are also larger than 0.250-inch and are not modeled. Using the room temperature

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conductivity of air, as used in the calculations above, the resulting axial and radial SC to dunnage air gaps and conductance values are provided in Table 4-4.

Table 4-4 – SC to Dunnage Air Gaps and Conductance Values

Design	Type	Gap (in)	Conductance (Btu/s-in ² -°F)
SC-30G2	Top Axial	0.221	1.590E-6
SC-30G3	Radial	0.25	1.407E-6
SC-30G3	Axial	0.185	1.901E-6
SC-55G1	Top Axial	0.031	1.126E-5

Foam dunnage for the various SC payload designs are constructed by fabricating the dunnage shapes from stock material. Each foam shape is then encased in thin aluminum sheets that are welded together at the seams. To facilitate the variability in allowed tolerances and fabrication imperfections, each design allows up to a 0.125-inch gap between the dunnage foam and aluminum skin. To conservatively maximize the SC and waste temperatures, the 0.125-inch air gap conductance is included in the models. Using the formulae and room temperature air conduction cited above, the dunnage foam to aluminum skin air gap conductance is summarized in Table 4-5.

Table 4-5 – Dunnage Foam to Aluminum Skin Air Gap and Conductance Value

Gap (in)	Conductance (Btu/s-in ² -°F)
0.125	2.814E-6

The final air gap conductance values to compute are those associated with the gap between the ICV and OCV shells. As assumed in CCO thermal analysis [Ref. 4], the silicon wear pad between the lower ICV and OCV domes is omitted and instead modeled with air conduction. Utilizing the HP SAR drawing listed in Section 3.2.1, the ICV to OCV nominal axial gap between the lower torispherical heads is 0.125-in. and the nominal radial gap between the lower body shells is 0.250-in. The air gap conduction between the upper cylindrical shells (2.438-in) and upper torispherical heads (0.875-in) are not modeled. The ICV to OCV air gaps and conductance values are summarized in Table 4-6.

Table 4-6 – ICV to OCV Air Gaps and Conductance Values

Type	Gap (in)	Conductance (Btu/s-in ² -°F)
Axial	0.125	2.814E-6
Radial	0.250	1.407E-6

With the air gap conductance values computed, Table 4-7 summarizes all of the contact pairs utilized in the thermal models discussed in this report, along with their specified conductance value, if applicable. The “Default” conductance is the default value for conductance to model intimate contact within ANSYS® Mechanical, as discussed above. Note that for brevity,

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repetitive contact pairs with otherwise identical contact specified are consolidated as presented on Table 4-7.

Table 4-7 – Thermal Model Contact Pairs and Conductance Settings

Contact Pair	Conductance (Btu/s-in²-°F)
OCA Head Foam to Various OCA and OCV Heads	Default
OCA Body Foam to Various OCA and OCV Body Shells	Default
ICV Lower Shell to OCV Body Shell Air Gap	2.814E-6
ICV Lower Shell to OCV Body Lower Head Air Gap	1.407E-6
Lower Honeycomb to ICV Lower Shell	Default
Honeycombs to Aluminum Top Sheets	Default
SC-30G2	
SC Bottoms to Slip Sheet	Default
SC Tops to Upper Shell Air Gap	1.590E-6
Lead Wall to Body Inner Shell	Default
Lead Wall to Body Outer Shell Air Gap	4.972E-6
Base Lead Plates to Base Inner Plate Air Gap	8.794E-6
Base Lead Plates to Base Outer Plate Air Gap	7.817E-6
Lid Lead Plate to Lid Inner Shell	Default
Lid Lead Plate to Lid Outer Shell Air Gap	6.396E-6
SC to End Cap/End Cap to Dunnage Skin Axial Air Gap	1.901E-6
SC to End Cap Radial Air Gap	1.407E-6
Dunnage Foam to Shell	2.814E-6
SC-30G3	
Lead Wall to Body Inner Shell	Default
Lead Wall to Body Outer Shell Air Gap	4.394E-6
Base Lead Plates to Base Inner Plate Air Gap	8.794E-6
Base Lead Plates to Base Outer Plate Air Gap	7.817E-6
Lid Lead Plate to Lid Inner Shell	Default
Lid Lead Plate to Lid Outer Shell Air Gap	5.025E-6
Dunnage f Foam to Shell	2.814E-6
SC-55G1	
SC Bottoms to Slip Sheet	Default
SC Tops to Upper Shell Air Gap	1.126E-5
Dunnage Foam to Shell	2.814E-6
SC-55G2	
Lead Wall to Body Inner Shell	Default
Lead Wall to Body Outer Shell Air Gap	3.954E-6
Base Lead Plates to Base Inner Plate Air Gap	8.794E-6
Base Lead Plates to Base Outer Plate Air Gap	7.817E-6
Lid Lead Plate to Lid Inner Shell	Default
Lid Lead Plate to Lid Outer Shell Air Gap	6.396E-6
Dunnage Foam to Shell	2.814E-6

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4.2.6 Analysis Settings

The analysis settings within the ANSYS® Mechanical software is where the solution controls reside. The solution controls include control settings related to the solving of the model, such as the number of solution steps to solve, substep control, radiosity method (see additional discussion on this method in Section 4.2.7.4) solver controls and convergence criteria, nonlinear iterative convergence criteria, output data control, and more. The ANSYS® Mechanical documentation [Ref. 29], in parallel with several scoping runs, were used to study the effects of these controls and determine the acceptability of the default settings. Overall, the default settings were determined to produce acceptable results that were largely insensitive to small changes. The only exceptions were the need for additional outputs to support some post processors of interest and the manual specification of the number of solution steps. Therefore, the analysis settings are largely left to their default status.

For the number of solution steps, the models employ a 12-hour on/12-hour off stepped regulatory insolation boundary condition. The models are simulated through 40 days of the transient solution. The previous CCO thermal analysis [Ref. 4] determined this length of run time as sufficient to reach pseudo-steady-state model behavior with the HalfPACT packaging design. To determine the validity of a 40-day simulation period for the SC payload designs, the maximum time-history waste temperatures are interrogated since the simulated waste is the slowest to respond in each model. The time-histories of interest are plotted in Figure 4-14, Figure 4-18, Figure 4-22, and Figure 4-27 through Figure 4-31. As visually depicted, the waste temperatures have reached pseudo-steady-state equilibrium, with a range in peak-to-peak maximum waste temperatures over the last 48 hours of less than 0.1°F. As a result, 40 days of simulation is deemed appropriate and acceptable for reaching pseudo-steady-state conditions for the SC payload designs.

Since the simulations are modeled over 40 days with two insolation states applied per day, each model is specified with 80 solution steps. Each step is 12 hours in length. Time within the ANSYS solver is measured in seconds. Therefore, each step is 43,200 seconds in length.

4.2.7 Boundary Conditions

The boundary conditions of the model include the various thermal loads discussed in the subsequent subsections. For the initial conditions, the initial temperature is set to 100°F and is applied uniformly in the model. Since the regulatory NCT Heat conditions (Section 3.1.1) specify 100°F ambient conditions with additional thermal loading applied, the minimum expected temperature for any component is greater than 100°F. Therefore, a uniform initial temperature of 100°F is appropriate.

4.2.7.1 Regulatory Insolation

The regulatory insolation to apply to the thermal models is discussed in Section 3.1.1 and Section 3.2.3. It is summarized as the curved surface insolation of 400 gcal/cm² applied to the torispherical head of the OCA exterior shell, and the vertical surface insolation of 200 gcal/cm²

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applied to the cylindrical OCA exterior shell (including thermal shield). Both values represent the total energy flux to apply to these exterior surfaces over a 12-hour period.

As done in previous thermal analyses for CH and RH package designs (Ref. 1, 4, and 5], the regulatory solar insolation is converted into a constant heat flux rate applied periodically to the exterior of the model. In addition, the energy flux values are treated as the solar energy incidence for surfaces that are optically black in the solar spectrum. To convert the energy fluxes into heat flux rates that also account for the solar spectrum absorptivity of the exterior packaging surfaces of 0.50 from Table 3-12, the heat fluxes are computed as follows:

$$q' = \alpha * \frac{q}{12 \text{ hr}} * \frac{1 \text{ Btu}}{252.164 \text{ gcal}} * \frac{1 \text{ hr}}{3600 \text{ sec}} * \frac{6.452 \text{ cm}^2}{1 \text{ in}^2}$$

The variable α is the solar spectrum absorptivity of clean, smooth, unpainted stainless steel as specified in Table 3-12, q and q' are the heat flux and heat flux rate, respectively, and the remaining values are unit conversion constants. The heat flux rates applied to the model during the 12-hour on cycle are summarized in Table 4-8.

Table 4-8 – Regulatory Insolation Heat Flux Rates

Insolation Surface	Heat Flux (Btu/s-in²)
Curved	1.185E-4
Vertical	5.926E-5

Within the ANSYS® Mechanical user interface, the regulatory insolation is applied using the heat flux thermal load conditions to appropriately scoped surfaces in the model, as depicted in Figure 4-5. Each heat flux is specified with the corresponding values provided in Table 4-8 as a constant magnitude. To control the stepped cycling of the applied heat flux, the tabular data tab of each heat flux object is used to manually deactivate the applied load for every second load step. The software interprets this input, during the eventual APDL solver input file creation, by switching the applied heat flux on and off in the solution processor of each load step prior to solving the model.

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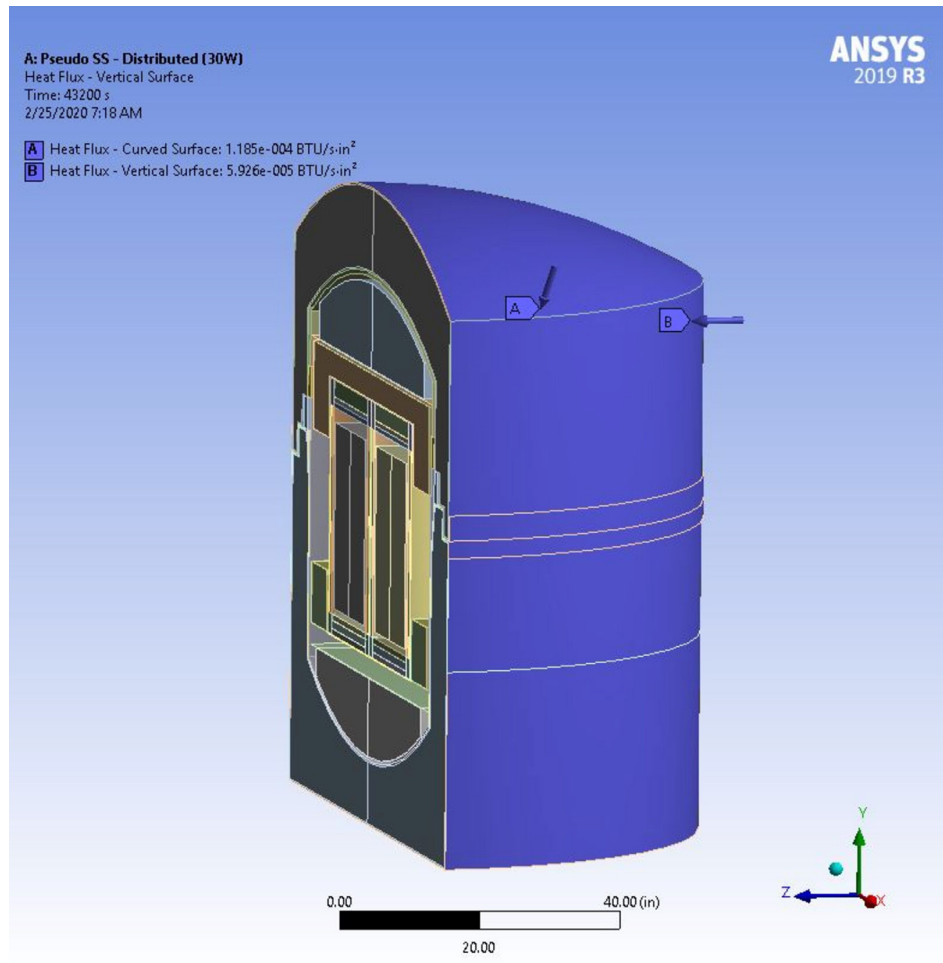


Figure 4-5 Applied Insolation Surface Loads

4.2.7.2 Natural Convection

The HalfPACT packaging is designed to passively dissipate heat to the environment (i.e. no forced convection sources or heat exchangers are utilized by the design). The passive heat dissipation is modeled by the application of both radiation heat exchange (Section 4.2.7.4) and natural convection. Natural convection is a phenomenon in which a hot or cool (relative) surface develops a film of fluid near the surface whose temperature is either elevated or reduced, relative to ambient conditions. The fluid film temperature difference generates fluid film motion due to the buoyancy of the fluid relative to the ambient conditions.

As done in previous thermal analyses [Ref. 1, 4, and 5], the bottom, side, and top surfaces of the packaging are modeled with natural convection loads applied. This is due to the HalfPACT transportation trailer interface design, which is intended for fastening to two trailer beams in an open style transport trailer with the HalfPACT in an upright orientation. Therefore, the top and side surfaces of the HalfPACT are unobstructed for the purposes of developing a full convective film boundary layer. The bottom surface is partially blocked by the two trailer beams, which would partially impede the development of a full film convective boundary layer on the bottom

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of the packaging. However, the trailer beams are also not credited for the conductive heat sink properties that they would provide if explicitly modeled in the analysis. For simplicity and conservatism, the HalfPACT packaging is assumed to be fully immersed in ambient air and the beams are ignored. Therefore, natural convection with a fully developed convective film boundary layer is also applied to the bottom surface.

Convection loads in the ANSYS® Mechanical software provide a multitude of settings to model various convective loading situations. Film coefficients can be specified as constant, tabulated, or specified as a function of internal parameters. For tabulated input, they can be specified as either temperature or time dependent. And within temperature-dependent film coefficients, they can be surface, film average, bulk average, or temperature difference dependent. Ambient temperature can also be specified as constant, tabulated with respect to time, or a function of an internal parameter. For this analysis, the natural convection film coefficients are specified as tabulated input that is a function of surface temperature, with a constant ambient temperature of 100°F. The software applies a single convective film coefficient to all surfaces scoped to a single convective surface load that is based on the average surface temperature of the scoped surfaces. This lends itself well to the use of empirical convective film coefficients derived in heat transfer handbooks.

The natural convective film coefficients are computed using the empirical correlations provided in Chapter 4 of the Handbook of Heat Transfer [Ref. 10]. The correlations provided in the handbook include both the correlations themselves, along with plots comparing the predicted film coefficients of the correlations to controlled test data of various fluid mediums and Rayleigh numbers. Nusselt number correlations are provided for the effects of laminar and turbulent flow, with equations to combine the contributions of the two flow types and compensate for the transition of flow. The only exception is for the heated downward facing plate in which the direction of film flow is into, and then subsequently around the surface perimeter. In this case, only a laminar correlation is provided since the flow stays laminar even at relatively high Rayleigh numbers. All film coefficients computed assume an isothermal surface and are computed as an average coefficient for the entire surface.

The calculation of the surface temperature-dependent film coefficients is handled by a Mathcad sheet titled “HP_Free_Convection_Coefficients.xmcd”. The Mathcad sheet is included in Appendix A.2 and attached to this document in the document management system. The remainder of the discussion pertaining to the calculation of the convective film coefficients references the calculations in the Mathcad sheet. The Mathcad sheet begins by defining variables to be utilized throughout the analysis. The first the variable “Air” is a matrix that contains the dry air properties defined in Table 3-11 for interpolation later in the sheet. Characteristic variables “L” and “D” are then defined as the height (74.594-in) and diameter (94.375-in) of the OCA cylindrical shell, respectively. With that, the “L/D” aspect ratio for calculation of the short vertical cylindrical shell coefficients for the HalfPACT is computed as 0.79. For the calculation of upward and downward isothermal flat plate coefficients, another characteristic dimension is the surface area to perimeter ratio, defined as “L_{star}”. To compensate for the added surface area of the torispherical head, the surface area provided in the CCO thermal analysis of 8,421.02 in² is utilized and results in an “L_{star}” value of 28.403 in²/in. For the bottom flat surface, the “L_{star}” variable is computed as 23.594 in²/in. Finally, a range variable “T_{surf}” is

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created to provide a range of target surface temperature values to compute film coefficients. The surface temperature variable is specified as an array that spans from 1,500°F to 100°F, with a range resolution of 1,001 values. This is done to compute the convective coefficients for cooling the exterior surfaces over a range that envelopes the temperatures expected for modeling HAC and NCT. Note that HAC is not modeled in this thermal analysis, and that this large range of convective film coefficients is for potential future use.

Three external natural convection cases from Chapter 4 of the Handbook of Heat Transfer [Ref. 10] are utilized to model the temperature-dependent film coefficients of the exterior surfaces of the HalfPACT. The cases utilized are for a short vertical circular cylinder with square ends (Table 4.3a), a heated upward facing flat plate (page 4.16), and a heated downward facing flat plate (page 4.17). The short vertical circular cylinder with square ends is used to model the convective film coefficients of the outer cylindrical OCA shell and thermal shield. The heated upward facing and downward facing flat plate cases model the convective film coefficients of the top torispherical head of the OCA and the bottom flat head of the OCA, respectively. The outer cylindrical surfaces are modeled as a short vertical cylinder in lieu of a vertical plate or long vertical cylinder to capture the effects of a small aspect ratio (i.e. an L/D ratio of 4 or less) on the convective coefficients.

For the calculation of the short vertical circular cylinder coefficients, the derivation of a few additional correlation constants is necessary. Per Table 4.3a, a table of constants are provided as a function of the L/D aspect ratio derived above. The tabulated values are copied into a Mathcad matrix variable “Table43a”. Each column of constants is then linearly interpolated to the L/D ratio of 0.79 for the HalfPACT outer cylindrical shell and stored in a variable to call later in the calculation.

At this point in the Mathcad sheet, each convective film coefficient is calculated in a similar fashion using correlation-case-specific equations. Each is computed in a program loop that cycles through each defined target surface temperature in the array variable “T_{surf}”. First the average film temperature is computed as the average between the target surface temperature and a constant 100°F ambient temperature. The film temperature is then used to linearly interpolate the columns of air properties defined in the “Air” matrix variable to solve for each air property value at the current film temperature. The Rayleigh number, correlation constants, and Nusselt numbers are then computed using the current cycles surface temperature and air properties. With the Nusselt number derived, the equivalent convective film coefficient is computed and stored along with the associated surface temperature. The program then restarts at the beginning of the cycle and solves for the next surface temperature in the array. The output of each program is a 2x1,001 matrix of surface temperatures and film coefficients in SI units (°K and W/m²-°C). Note that the use of SI units in the calculation of convective film coefficients is for convenience. The ANSYS® Mechanical interface allows for the switching of units on-the-fly such that inputs can be specified in any of the software’s available unit systems, and values will be converted as appropriate.

The values are then exported as a table of values into each convection load tabulated data field. The surfaces scoped for applied convection loads are depicted in Figure 4-6.

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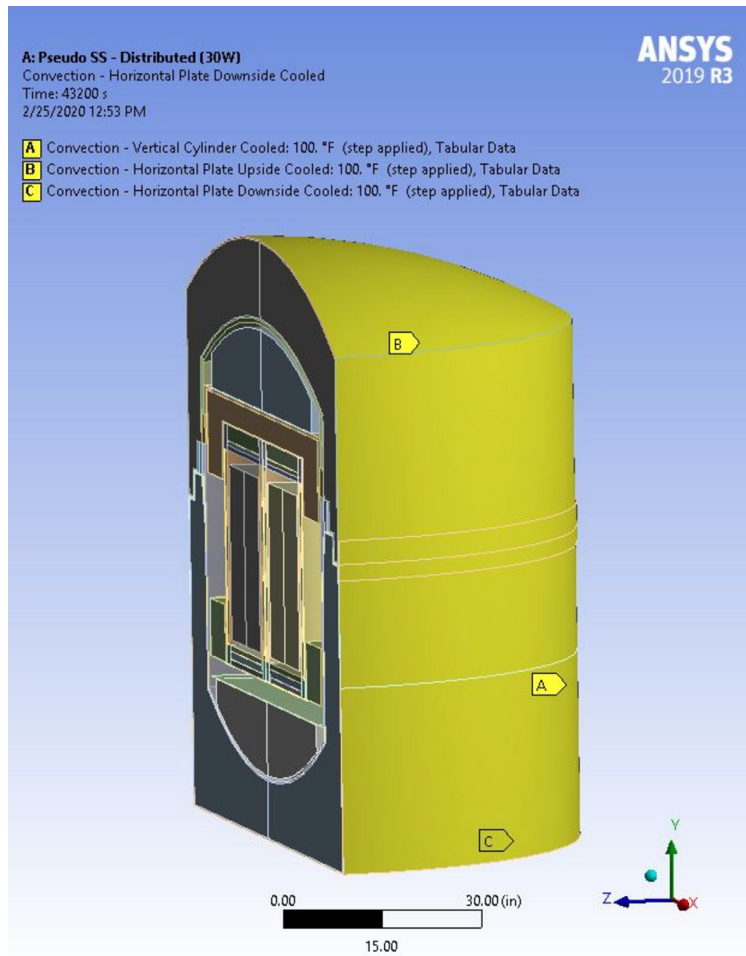


Figure 4-6 Applied Natural Convection Surface Loads

4.2.7.3 Internal Heat Generation

The heat generated by the decay of the radionuclides in the waste is modeled using the internal heat generation load in the ANSYS® Mechanical software. This type of loading is a volumetric heat generation load applied uniformly to the elements of scoped bodies. The load is therefore applied homogenously to the modeled waste volume of the SC payload contents.

The thermal cases to be analyzed, as discussed in Section 3.1.1, are a 0 W, a 30 W concentrated, and, if applicable, a 30 W distributed decay heat load case. For the trivial 0 W decay heat load case, no internal heat generation load is applied. For the 30 W cases, the volumetric heat generation rate is dependent on the concentration of decay heat, and the total volume to model the uniform heat source. For the distributed cases, the decay heat is evenly distributed in the two simulated waste volumes (the SC-30G2 and SC-55G1 payload designs) at 15 W each. For concentrated cases, all 30 W of total decay heat is concentrated in a single simulated waste volume.

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Two different simulated waste volumes are modeled based on the SC payload design. As discussed and depicted in Section 1.0, the SC-30G2 and SC-30G3 each contain a single 30-gallon drum within the SC cavity. The SC-55G1 and SC-55G2 designs each contain a single 55-gallon drum within the SC cavity. To account both for the concentration of heat and the volume of the heat generating source, each volumetric heat load magnitude is computed as follows:

$$q' = \frac{Q'}{V_{drum}}$$

The variable V is the simulated waste volume, Q' is the total decay heat rate, and q' is the volumetric heat rate. The values utilized as the internal drum volume come from the values provided in PLD-CAL-0001 [Ref. 8] for a 30-gallon and 55-gallon drum. The values for volumetric heat generation rate of the simulated 30-gallon and 55-gallon drums, both in concentrated and distributed cases, are summarized in Table 4-9. An example depiction of the scoped solid bodies for applied heat generation rate load of a 30-gallon distributed case is also provided in Figure 4-7.

Table 4-9 – Internal Volumetric Heat Generation Rates

Volume	Distributed Heat Rate (Btu/s-in³)	Concentrated Heat Rate (Btu/s-in³)
30-Gallon	1.991E-6	3.983E-6
55-Gallon	1.079E-6	2.157E-6

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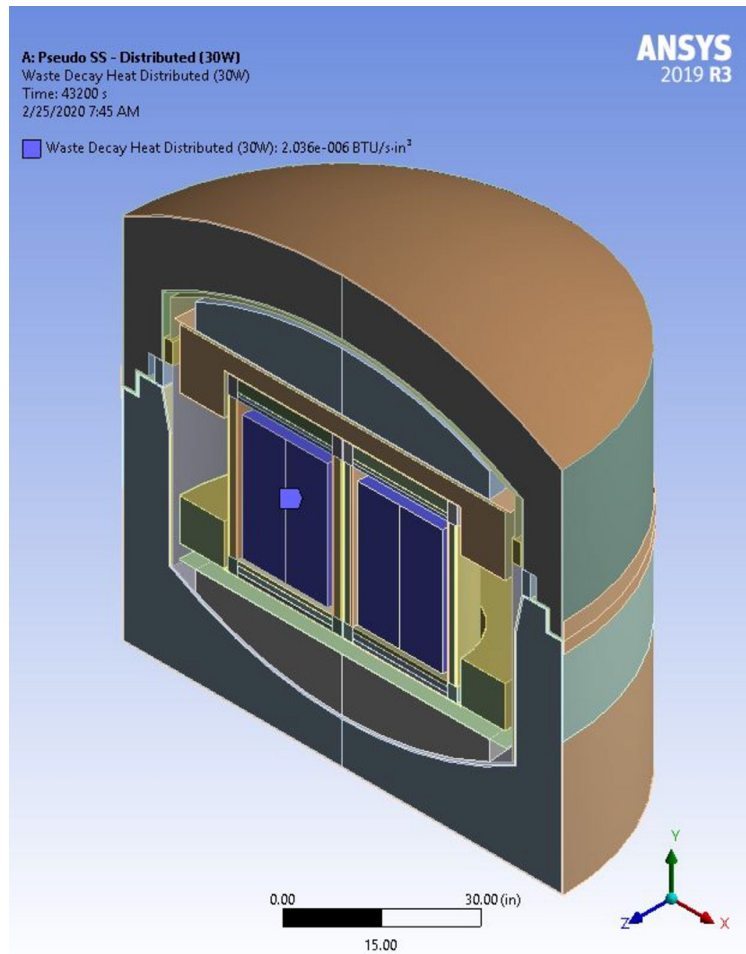


Figure 4-7 Applied 30-Gallon Distributed Decay Heat Load

4.2.7.4 Radiation

As discussed in Section 3.1, the dominant means of heat transfer between the various surfaces of the internal annuli of the packaging and payload components is radiation heat exchange. This includes the interior surfaces of the OCV, interior and exterior surfaces of the ICV, exterior surfaces of the honeycomb spacers and payload dunnage components, exterior and interior surfaces of the SCs, exterior surfaces of the waste volumes, and the applicable surfaces of the lead shielding and carbon steel within each SC. Radiation heat exchange is also included on the exterior surfaces of the OCA to the ambient as a means of passive heat dissipation.

Radiation in the ANSYS® Mechanical and APDL software codes utilizes the Radiosity Solver method. The Radiosity Solver method is essentially a discretized form of classic hand calculated gray body diffuse radiation heat exchange. It requires the user input of the surface emissivity values, the calculation of view factors between radiating surfaces, and the calculation of average faceted surface temperatures, which are then used to compute the radiation-induced heat flux between participating surfaces. Per the ANSYS documentation [Ref. 29], the Radiosity Solver method is described as the calculation of outgoing radiative heat flux for each surface, that then

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provide boundary conditions to the FEA model for conduction calculations. Radiation exchange is driven by the fourth order difference in surface temperatures, and conduction heat exchange is driven by first order temperature gradients. This makes the overall process iterative, in which each update to the conduction model results in new surface temperatures, and new surface temperatures result in new radiative heat fluxes, new radiative heat fluxes result in new boundary conditions applied to the conduction model, and so on, until the solvers convergence criteria is met for that step.

View factors in 3-D models are computed using the Hemi-Cube method. See the ANSYS APDL Theory Reference Manual [Ref. 29] for more detailed discussion. The Hemi-Cube method can be visualized as a pixelated half cube, placed over each faceted surface with radiation exchange, and is utilized to approximate that surfaces “view” of other surfaces in the model. Each surface “viewed” through a Hemi-Cube pixel is summed and then divided by the total sum of pixels to derive an approximate view factor. The Hemi-Cube method also respects symmetry, in which the edge of a surface with symmetry applied will restrict the Hemi-Cube method to only view factors within the symmetry plane. The Hemi-Cube method is visually depicted in Figure 4-8, courtesy of the ANSYS APDL Theory Reference Manual.

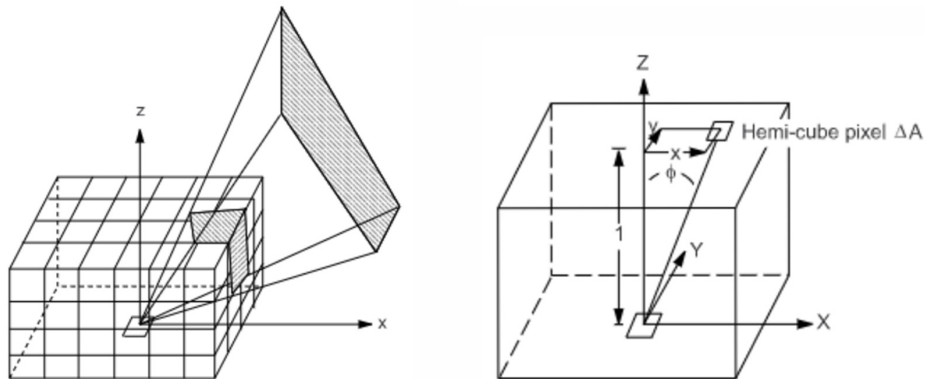


Figure 4-8 Visualization of ANSYS Hemi-Cube Method [Ref. 29]

Radiation is applied in the ANSYS® Mechanical software using the radiation thermal load object. Each of the objects are scoped to applicable surface geometry with the surface emissivity, as specified in Table 3-12, applied to each surface. Ambient temperature for each radiation object is set to a constant magnitude of 100°F. Correlations for each radiation exchange can be set as “To Ambient” or “Surface to Surface”. To ambient correlation assumes all radiation heat is being exchanged with the ambient for the scoped surfaces, and therefore view factors are not computed. In contrast, surface to surface correlation explicitly computes view factors using the Hemi-Cube method described above for the selected surfaces. Total summed view factors of less than unity result in the remaining view factor being treated as To ambient. To ambient correlation should be less computationally expensive than modeling surface to surface exchange for the exterior surface of the model, when the flat or convex surfaces of the exterior essentially exchanges with only the ambient. However, in practice the difference was negligible, and so for consistency all radiation objects are specified with “Surface to Surface” correlation.

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The radiation objects control the subdivision of radiation exchange through use of “Enclosures”. Enclosures are identified by a unique number (i.e. Enclosure 1, Enclosure 2, etc.). Each enclosure identifies a group of radiating surfaces that are actively participating in radiation exchange with each other in the model. Radiating surfaces do not participate in radiation exchange with surfaces of differing enclosure numbers. In practice, all radiating surfaces within the model can be identified under a single enclosure number with surface to surface correlation specified, so as long as optical barriers are placed and selected to prevent erroneous exchanged with the environment in perfectly closed systems. However, enclosure numbers provide a means of finite control of radiating surfaces that simplifies the task of quality controlling the model, along with troubleshooting errors should any occur. Given the complexity of the model and number of radiating surfaces and enclosures, enclosures are utilized for this purpose.

In addition, each enclosure can be further controlled by defining its “Enclosure Type”. An enclosure type is either “Open” or “Perfect”. A perfect enclosure is one in which surface to surface exchange is the only intended means of radiation exchange, with no exchange to the ambient modeled. The solver employs the ANSYS APDL command “VFSM”, which adjusts the view factor matrix for a given enclosure if the view factors do not sum up to 1 (a perfectly closed radiation enclosure). By contrast, an open enclosure type allows for the view factor matrix to sum up to less than 1, as this is indicative of a partial or full view of the ambient. Note that a limitation of the software is such that a surface cannot be modeled in two different enclosures, even if two different sides of a surface are participating in two different radiation enclosure exchanges. If a surface is specified with radiation exchange on both sides of the surface, a single enclosure number must be specified for that surface and the open enclosure type must be utilized. This is the case with the modeling of enclosure 2 with both sides of the ICV shell active in the radiation exchange. The enclosure is otherwise a perfectly closed enclosure.

Table 4-10 summarizes the enclosures, enclosure types, and emissivity values specified for various surfaces in the model. The emissivity values applied are largely trivial, as they are defined by the values delineated Table 3-12 and the material of the surface. One region of the model in which this is an exception is the slip sheet (SC-30G2 and SC-55G1) or pallet top sheet (SC-30G3 and SC-55G2), depending on payload design. As discussed in the geometry modeling section, Section 3.2.1, the pallet that normally resides between the slip sheet and honeycomb top sheet of the payload within the ICV cavity is omitted from explicit modeling. Instead, for the SC-30G2 and SC-55G1, the thin aluminum top sheet of the pallet that is in intimate contact with the slip sheet is abstractly modeled as a single surface body representing both sheets. Because of a modeling limitation of the software, both sides of the surface body must be modeled with the same emissivity properties. Aluminum is conservatively applied to both the top and bottom surfaces. For the SC-30G3 and SC-55G2, a slip sheet is not utilized in the payload design, so instead the aluminum top sheet of the pallet is included as an optical barrier with the optical properties of aluminum applied to both top and bottom surfaces.

Note that the HalfPACT exterior to ambient and HalfPACT interior to payload exterior enclosure numbers are the same for each SC payload design. The enclosure numbering scheme for the surfaces within the payload designs themselves, however, are unique to each design and broken down by SC payload design type.

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Table 4-10 – Radiation Surfaces, Emissivity Values, Enclosure Numbers, and Enclosure Types

Surfaces	Emissivity	Enclosure #	Enclosure Type
OCA Outer Shells, including Thermal Shield (Type 304 SS)	0.25	1	Open
OCV and ICV Flange and Shells (Type 304 SS)	0.25	2	Open
Honeycombs, including Top Sheets (Aluminum)	0.15	2	Open
SC Dunnage Skin (Aluminum)	0.15	2	Open
SC Exterior (Carbon Steel)	0.50	2	Open
SC-30G2 and SC-55G1			
Slip Sheet (Aluminum)	0.15	2	Open
SC Interior and Waste Exterior (Carbon Steel) (First Container)	0.50	3	Perfect
SC Interior and Waste Exterior (Carbon Steel) (Second Container)	0.50	4	Perfect
SC-30G2 (Cont.)			
SC Inner Cavity Air Gaps (Carbon Steel) (First Container)	0.50	5-8	Perfect
SC Inner Cavity Air Gaps (Lead) (First Container)	0.28	5-8	Perfect
SC Inner Cavity Air Gaps (Carbon Steel) (Second Container)	0.50	9-12	Perfect
SC Inner Cavity Air Gaps (Lead) (Second Container)	0.28	9-12	Perfect
SC-30G3 and SC-55G2			
Pallet Top Sheet (Aluminum)	0.15	2	Open
SC Interior and Waste Exterior (Carbon Steel)	0.50	3	Perfect
SC Inner Cavity Air Gaps (Carbon Steel)	0.50	4-7	Perfect
SC Inner Cavity Air Gaps (Lead)	0.28	4-7	Perfect
SC-30G3 (Cont.)			
Plastic End Caps (HDPE)	0.92	2	Open

4.2.8 Results

The post-processing of the thermal models is accomplished through use of the result tools provided in the ANSYS® Mechanical user interface. The result tools are generally split into two types, thermal results and probe results. Thermal results contain tools for the extraction of common node and element results, such as temperature and heat flux. The results can be calculated for the full time-history, and are summarized as tabular data and graphically displayed in plots. Probes are used to interrogate similar results at specific load steps, along with the extraction of abstract results from the model such as reactions at applied boundary conditions (heat flow due to contact conduction, convection, radiation, etc.).

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<p>The majority of results post-processed from the model are temperature based time-histories. This provides the data necessary for comparison to the acceptance criteria outlined in Section 3.4 and delineated in Table 3-13. In short, the selection of the temperatures for comparison to the limits in Table 3-13 are intended to duplicate the temperatures commonly compared in previous CH thermal analyses [Ref. 1 and 4]. Justification for each limit is provided in the discussion in Section 3.4.</p> <p>The temperatures extracted from the model are each scoped to the appropriate geometry applicable to the temperature limit being compared. Each maximum, average, or minimum temperature is representative of the node temperatures of the underlying elements of the scoped geometry in the model. Maximum or minimum temperatures are the maximum or minimum node temperature to occur over the selected geometry at each load step. Average temperatures represent the arithmetic mean of the node temperatures of the selected geometry at each load step.</p> <p>The scoped solids, surfaces, or edges for each temperature result correspond to each temperature name and description, and are otherwise self-evident. One exception to this generalization is the ICV Air Cavity temperature result. The ICV air cavity is within the ICV payload cavity of the HalfPACT and surrounds the SC payload surfaces. It is not explicitly modeled with finite elements. The result is instead abstracted by extracting the average temperatures of the surfaces in contact with the majority of the payload cavity air volume. See Figure 4-9 for a visual example of the surfaces selected to extract the average air temperature of the payload cavity. The average temperature of the cavity air volume is expected to be accurately represented by the average temperature of the surfaces in contact with the cavity air volume.</p>		

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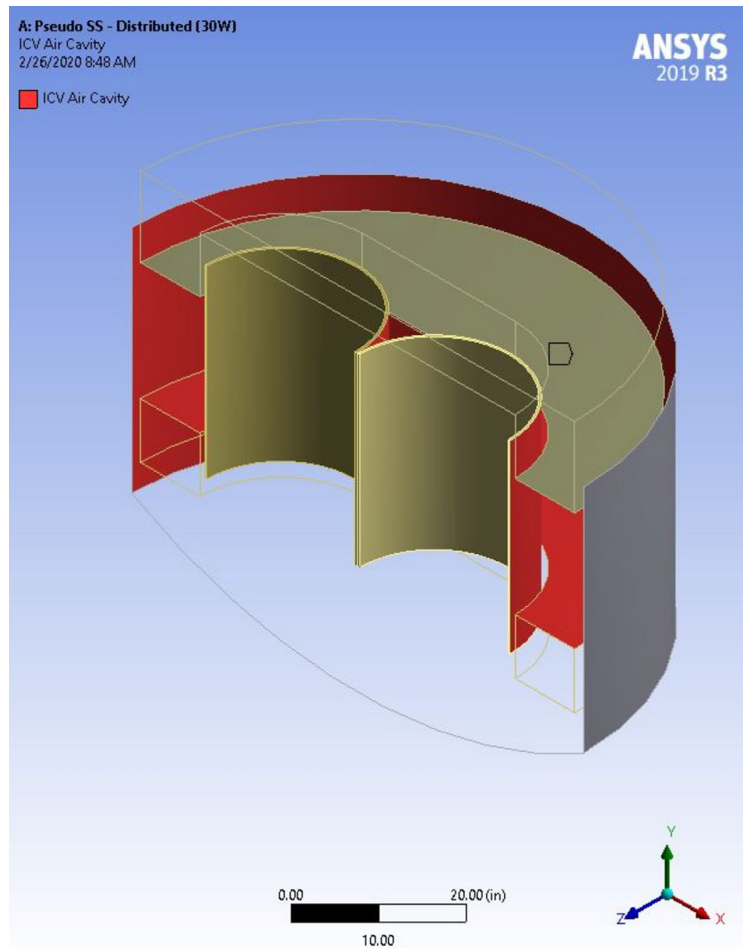


Figure 4-9 Payload Air Cavity Average Temperature Surface Selection for SC-30G2 Model

The values reported in the temperature result tables in Section 2.1.3 are the maximum values to occur over the temperature time-histories for that scoped solid, surface, or edge. Excel data sheets, attached to this document in the document management system, are used to organize and identify the maximum value in each set of time-history temperature data. See the summary of temperature data provided in the tables in Section 2.1.3 for the maximum time-history temperature values for each model and case.

In addition to the maximum time-history temperatures, linear temperature coefficients are provided in Section 2.1.4. The coefficients are provided in support of downstream MNOP calculations. The MNOP calculations utilize the waste centerline average temperature to conservatively compute the gas generation rate of the waste, the average ICV cavity air temperature to compute the ideal gas pressure increase of the cavity volume, and the minimum ICV wall temperature to compute the partial pressure of water vapor condensing against the coolest surface of the ICV structure. They provide coefficients for a linear correlation of temperature as a function of decay heat. The generic linear correlation equation is of the form:

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$$T(Q) = bQ + T_0$$

$$b = \frac{T_{30} - T_0}{30W}$$

The function T(Q) is the temperature as a function of decay heat, the variable b is the slope of the linear curve (°F/W), Q is the decay heat (W), and T₃₀ and T₀ are the applicable temperatures (°F) at 30W and 0W, respectively. The values of temperature for each model's coefficients come from the results summarized in Table 2-1 through Table 2-4. For the payload designs with both distributed and concentrated run cases (SC-30G2 and SC-55G1), the maximum temperature value of either run case is utilized to conservatively maximize temperatures predicted by the linear correlation.

The remainder of the discussion in this section is focused on the data processed from the models that do not pertain to the maximum time-history temperatures and linear coefficients reported in Section 2.1.3 and 2.1.4, respectively. That includes contour plots of the maximum temperatures of each packaging configuration, plots of time-history temperature behaviors, and plots of convective and radiation time-history heat reactions. The aforementioned Excel sheets are also utilized to plot this time-history data. The data is utilized for quality control purposes to study the heat flow within the model and validate the behavior of each model.

Figure 4-10 through Figure 4-13 provide temperature contour plots of each HalfPACT package with the corresponding SC payload design. The SC-30G2 and SC-55G1 plots are each depicting the distributed 30 W case, while the SC-30G3 and SC-55G2 are each depicting the 30 W case which is concentrated due to the single-unit payload assemblies. The time step chosen for the plotted data is the last step of applied regulatory insolation of the last 24-hour cycle of the 40-day simulation (39.5-days). This time step occurs just prior to the last 12-hours of the simulation in which regulatory insolation heat flux is turned off, and the exterior of the package begins to rapidly cool. Note that the packaging and payload components, from the OCV and inward, respond out of phase with the externally applied regulatory insolation heat flux. This is due to the thermal insulating effects of the polyurethane foam and the thermal mass within the package. The maximum temperatures for these components can occur after the regulatory insolation cycle has turned off. However, as depicted in the remaining plots in this section, these components have reached pseudo-steady-state after 39.5 days of simulation. Therefore, for the purposes of capturing overall maximum temperature contour plots, the temperature results at the 39.5 day time step are appropriate.

Figure 4-14 through Figure 4-31 provide plots of the temperature as a function of time in the SC models. The figures confirm that the temperature response of the model at the payload cavity level and inward is effectively decoupled from the cyclic perturbations of the applied regulatory insolation loading. This finding mimics the previous CH thermal analysis transient modeling work [Ref. 4], with the observed time-history data showing a similar decoupled response from the payload cavity and inward. It also reconfirms that the 40-day run time is sufficiently long to produce pseudo-steady-state results. Note that all plots generated for the HalfPACT package with the SC-30G2 payload design are provided in the figures. However, for other payload designs, the temperature time histories for the packaging components are effectively identical

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regardless of package payload design. For the sake of brevity, only the payload design specific temperature time-histories are provided for the remaining designs.

Figure 4-32 and Figure 4-33 provide time-history external convection, radiation, and total heat dissipation reactions for the HalfPACT package with the SC-30G2 payload package design. The convection reactions are those of the natural convection loads applied to the exterior surface of the OCA. The radiation reactions are the net outgoing (emitted + reflected – incident) radiation of the exterior surfaces of the OCA and the interior surfaces of the SC cavity. The net outgoing radiation at the interior SC cavity surfaces is intended to provide a quality check on the total amount of simulated waste decay heat being transferred from the waste volume to the SC for dissipation. The OCA thermal reaction time-history plots are combined in the figures to provide clarity on the relative magnitudes of heat dissipation from convection, radiation, and total to the ambient. These plots also visualize the lack of temperature sensitivity of the packaging components to payload sourced decay heat loading. The majority of heat dissipated by the package is due to the externally applied regulatory insolation heat flux. The peak magnitude of total heat dissipation from the package is on the order of ~1,600W, 30 of which comes from the maximum internal decay heat loading. Therefore, at maximum heat dissipating conditions, less than 2% of the total heat is attributed to the internal decay heat.

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A: Pseudo SS - Distributed (30W)

Temperature

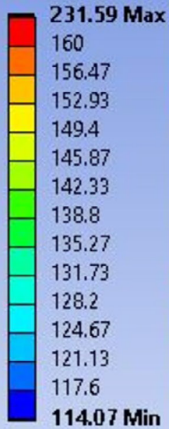
Type: Temperature

Unit: °F

Time: 3412800

3/23/2020 8:20 AM

ANSYS
2019 R3



0.00 40.00 (in)
20.00

Figure 4-10 Temperature Contour Plot for SC-30G2 Distributed 30W Case at 39.5-Days

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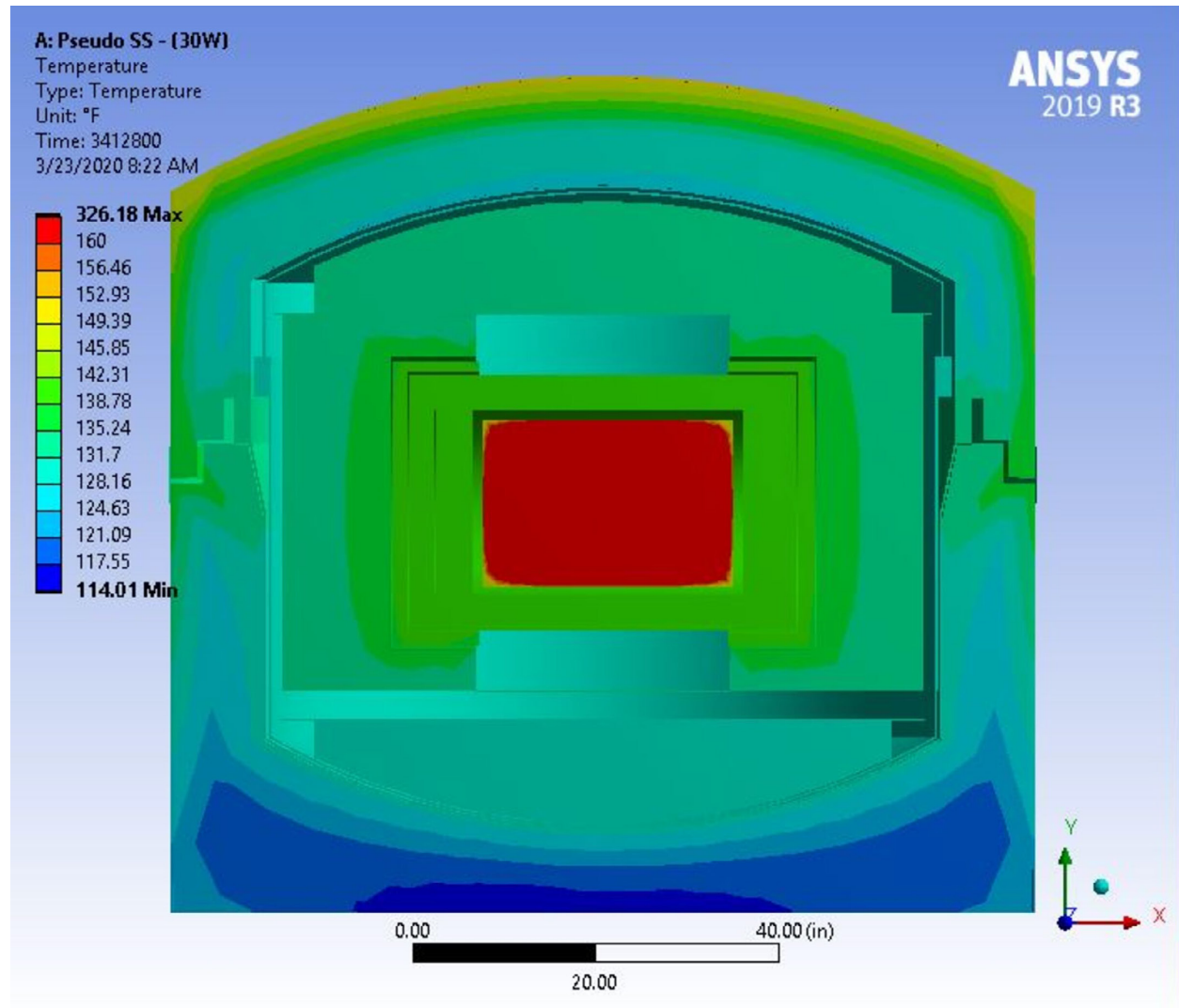


Figure 4-11 Temperature Contour Plot for SC-30G3 30W Case at 39.5-Days

Calculation Continuation Sheet

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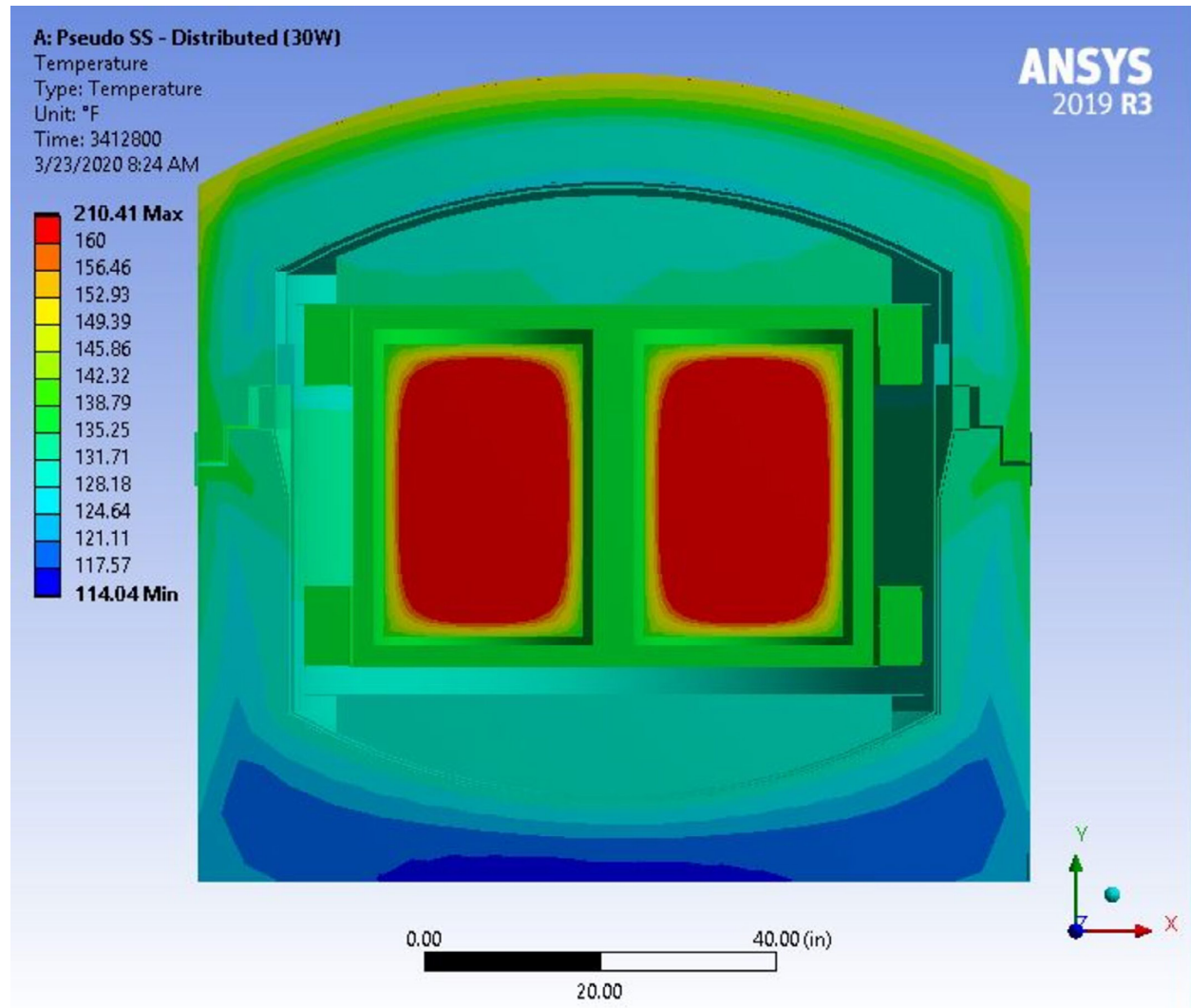


Figure 4-12 Temperature Contour Plot for SC-55G1 Distributed 30W Case at 39.5-Days

Calculation Continuation Sheet

1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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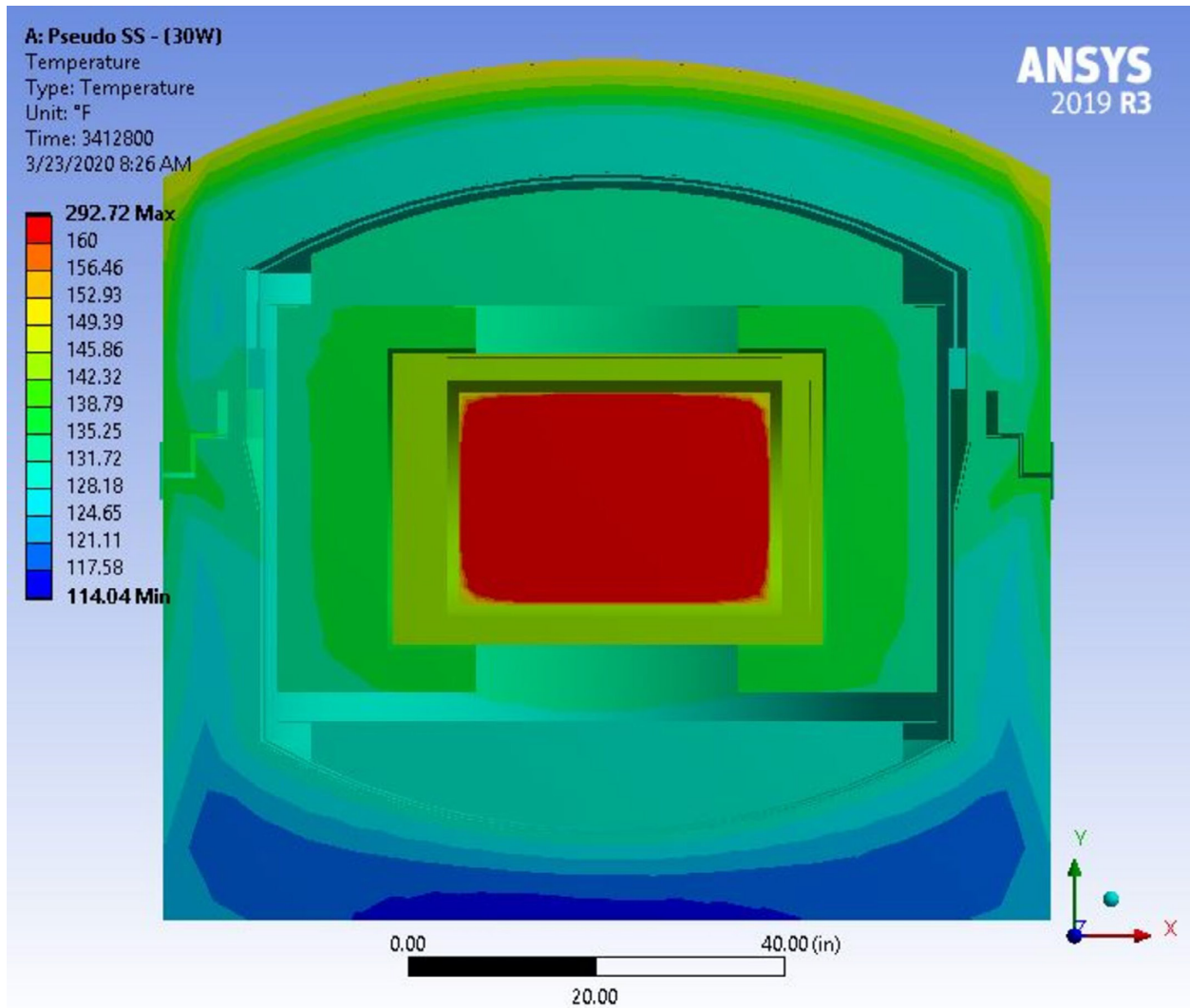


Figure 4-13 Temperature Contour Plot for SC-55G2 30W Case at 39.5-Days

Calculation Continuation Sheet

1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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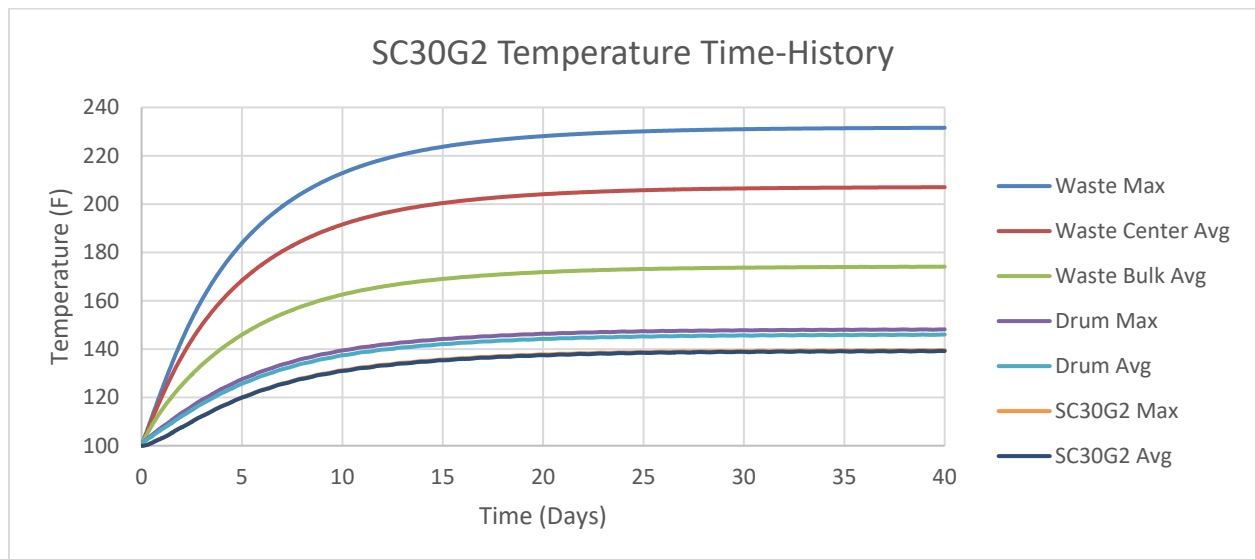


Figure 4-14 Payload Temperature Time-Histories for SC-30G2 Distributed 30W Case

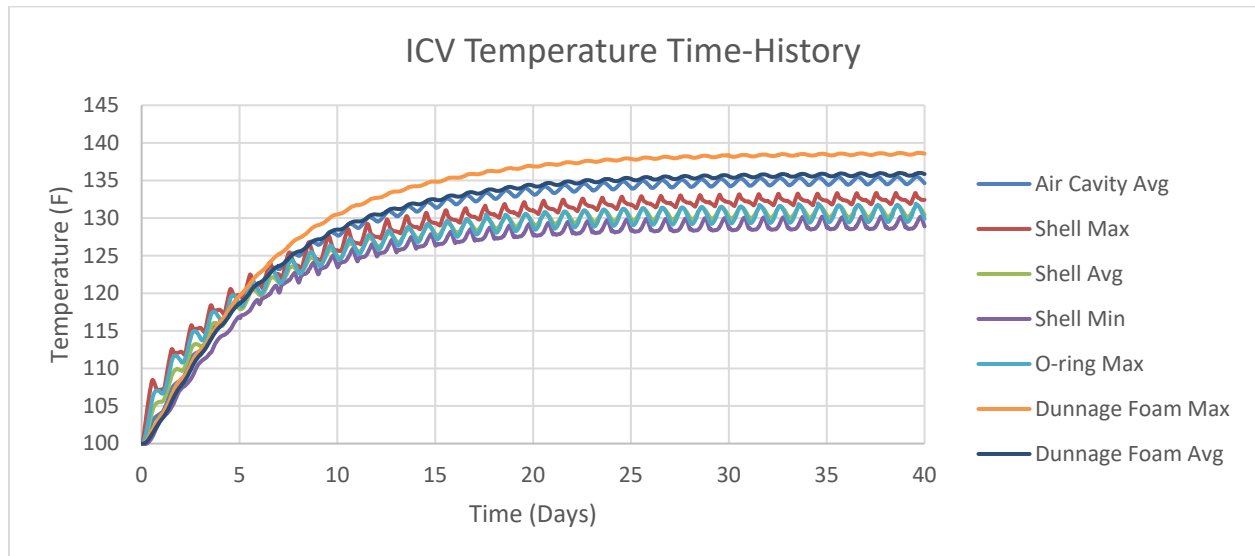


Figure 4-15 ICV and Dunnage Temperature Time-Histories for SC-30G2 Distributed 30W Case

Calculation Continuation Sheet

1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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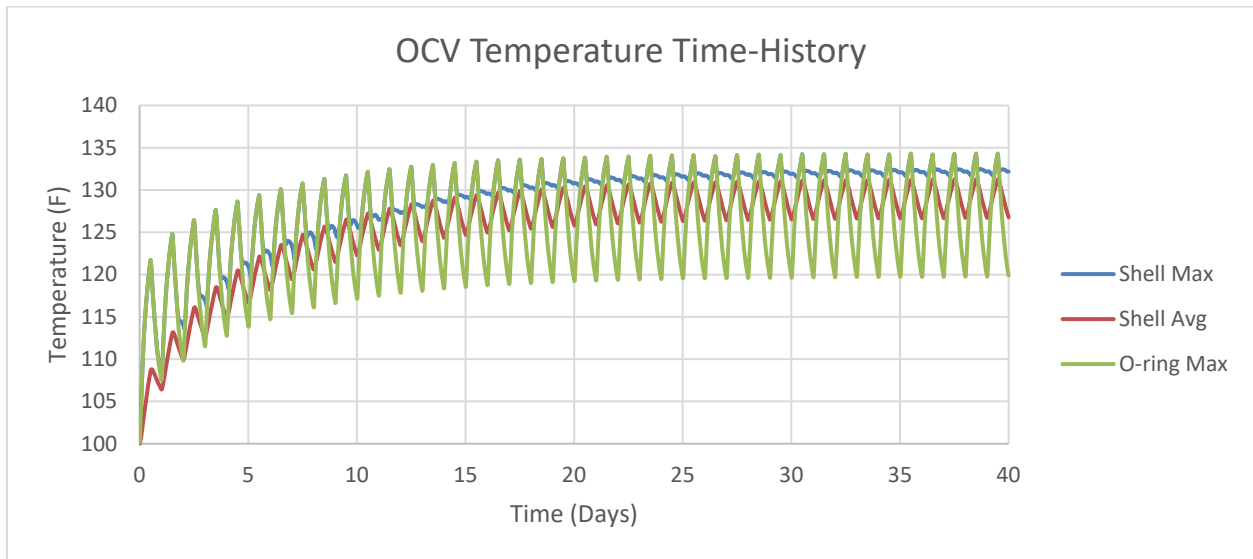


Figure 4-16 OCV Temperature Time-Histories for SC-30G2 Distributed 30W Case

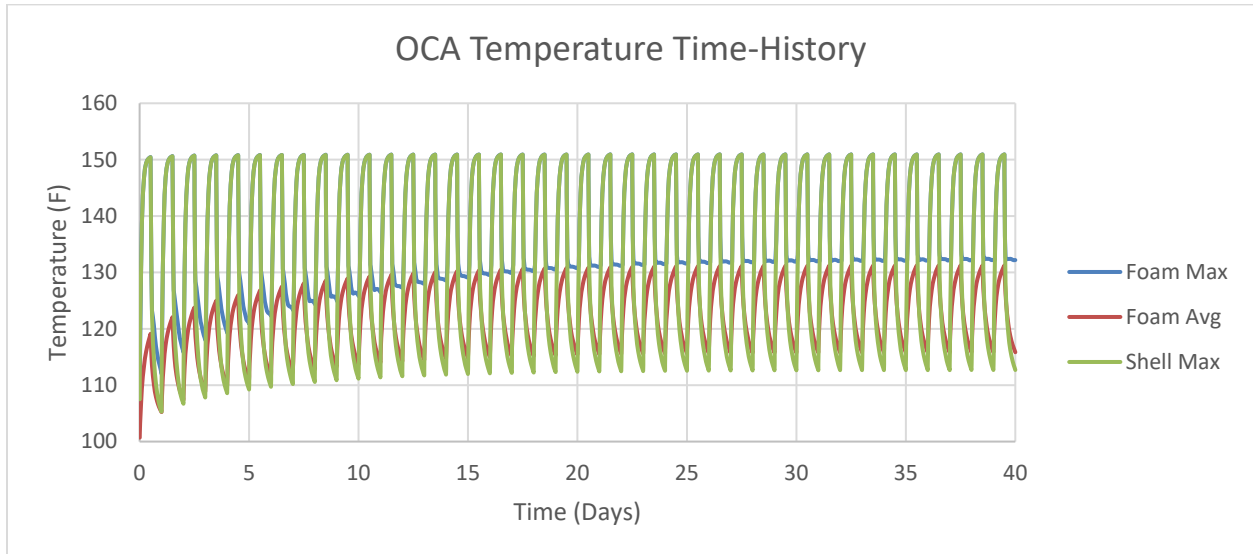


Figure 4-17 OCA Temperature Time-Histories for SC-30G2 Distributed 30W Case

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1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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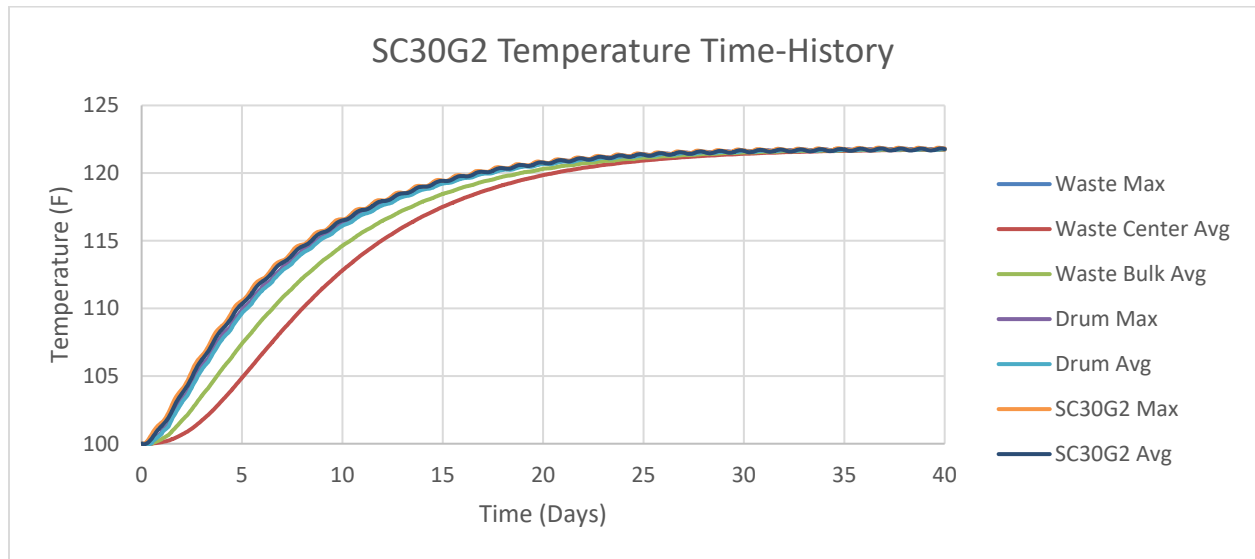


Figure 4-18 Payload Temperature Time-Histories for SC-30G2 0W Case

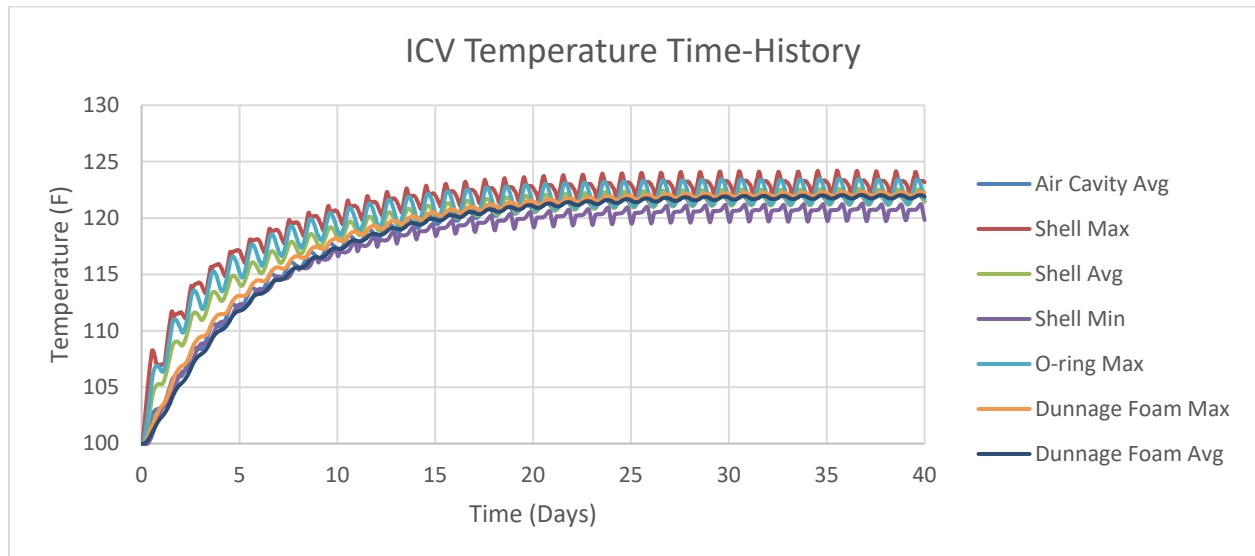


Figure 4-19 ICV and Dunnage Temperature Time-Histories for SC-30G2 0W Case

Calculation Continuation Sheet

1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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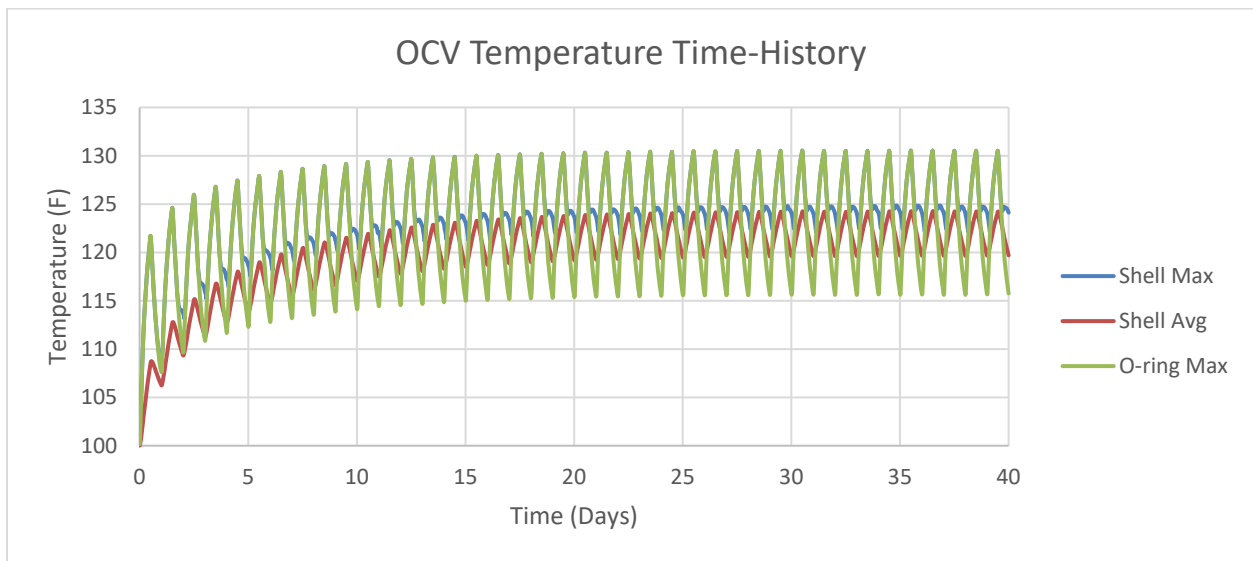


Figure 4-20 OCV Temperature Time-Histories for SC-30G2 0W Case

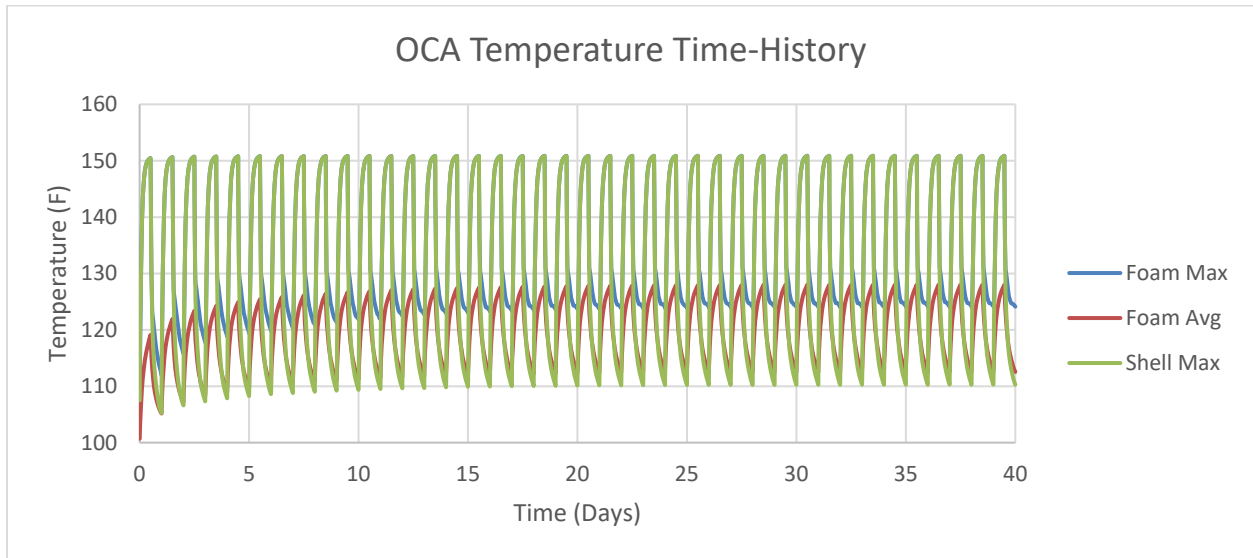


Figure 4-21 OCA Temperature Time-Histories for SC-30G2 0W Case

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1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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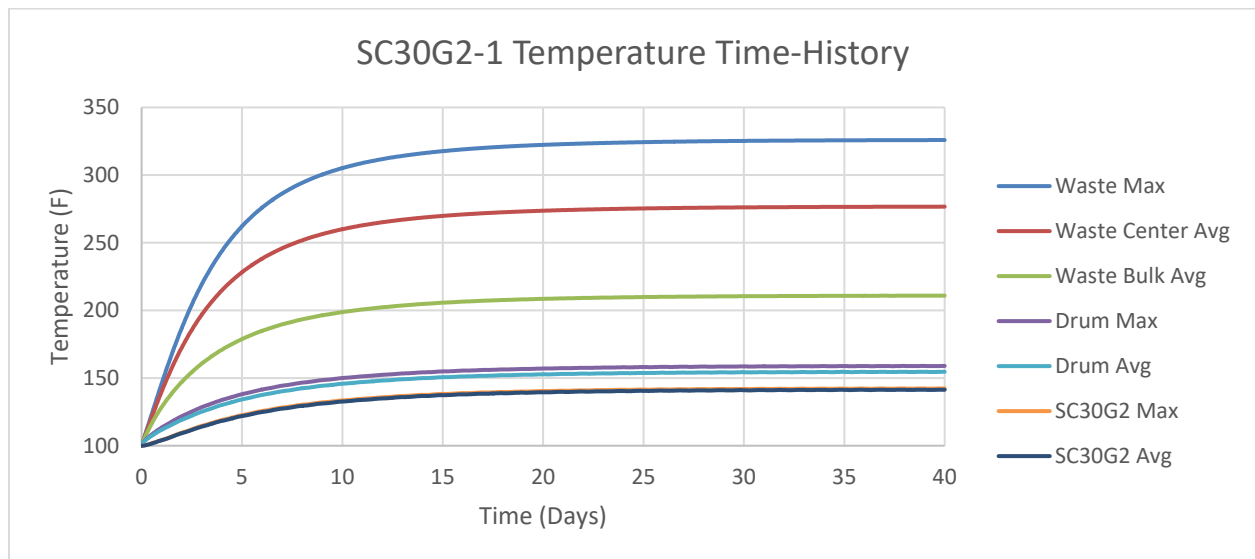


Figure 4-22 Payload (Heated) Temperature Time-Histories for SC-30G2 Concentrated 30W Case

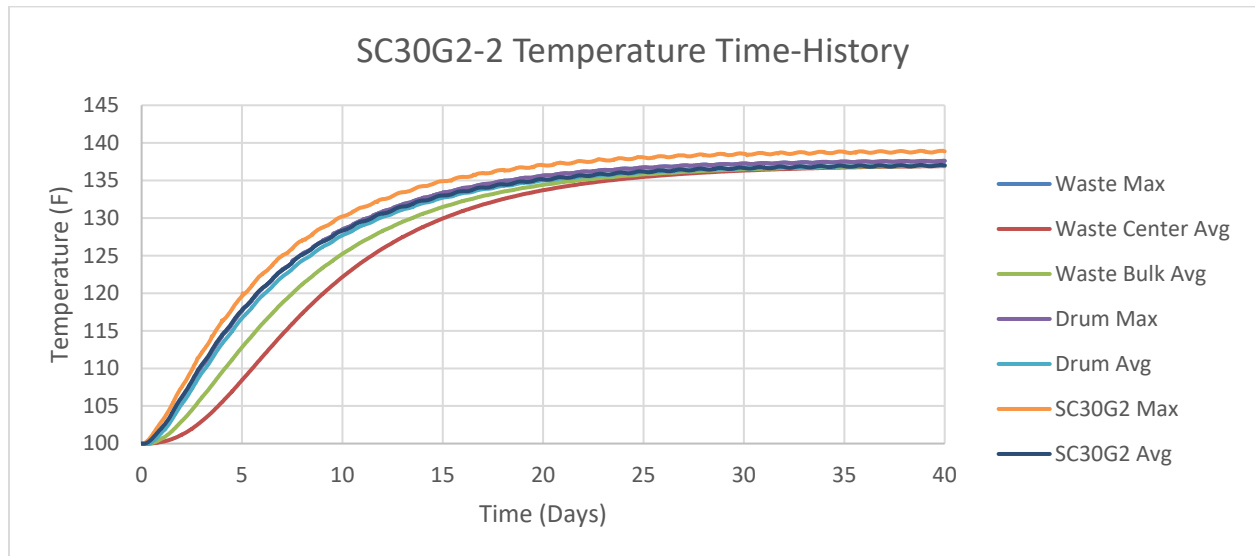


Figure 4-23 Payload (Un-Heated) Temperature Time-Histories for SC-30G2 Concentrated 30W Case

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1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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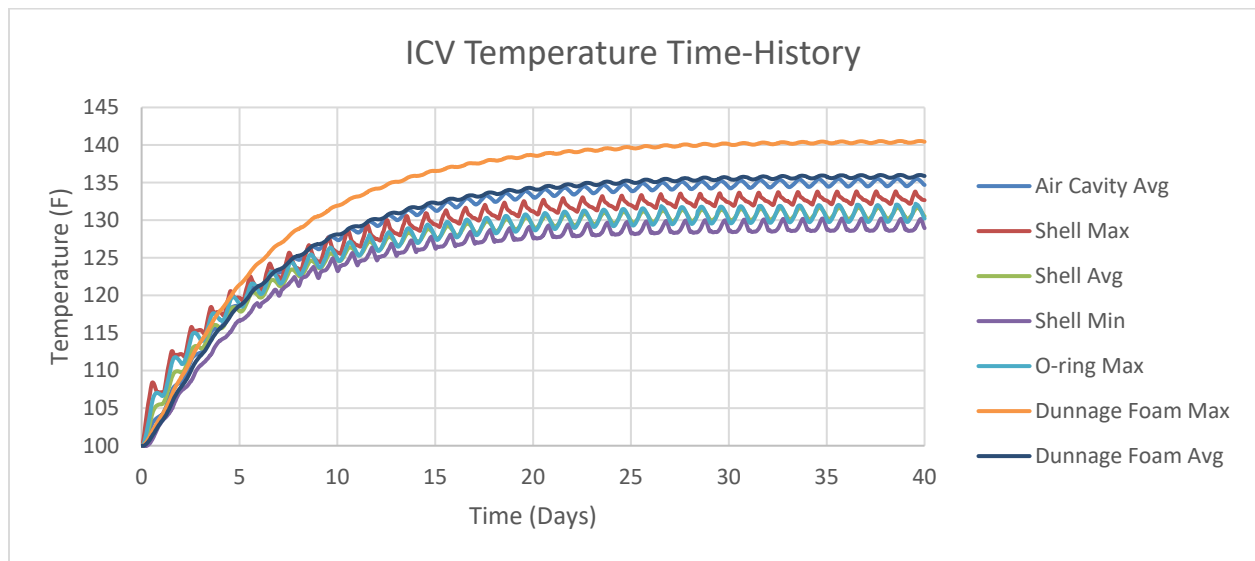


Figure 4-24 ICV and Dunnage Temperature Time-Histories for SC-30G2 Concentrated 30W Case

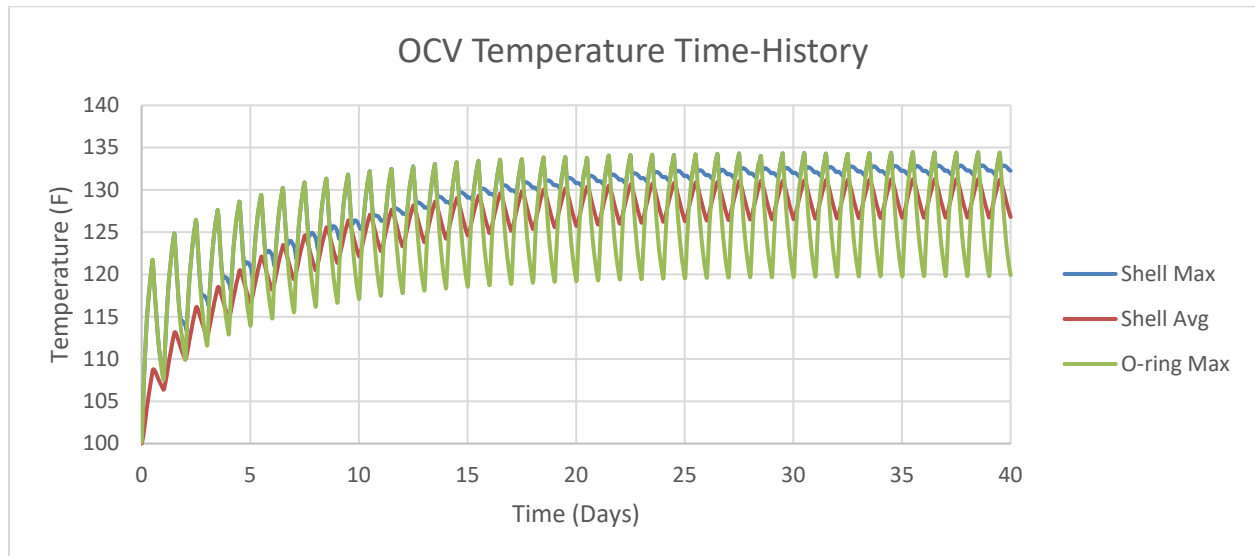


Figure 4-25 OCV Temperature Time-Histories for SC-30G2 Concentrated 30W Case

Calculation Continuation Sheet

1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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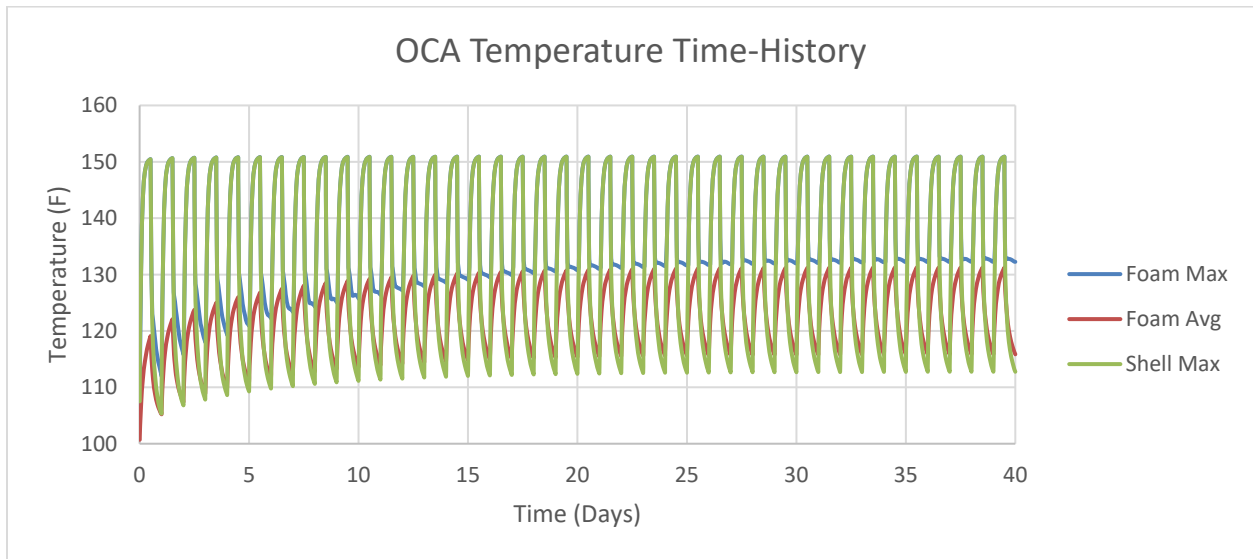


Figure 4-26 OCA Temperature Time-Histories for SC-30G2 Concentrated 30W Case

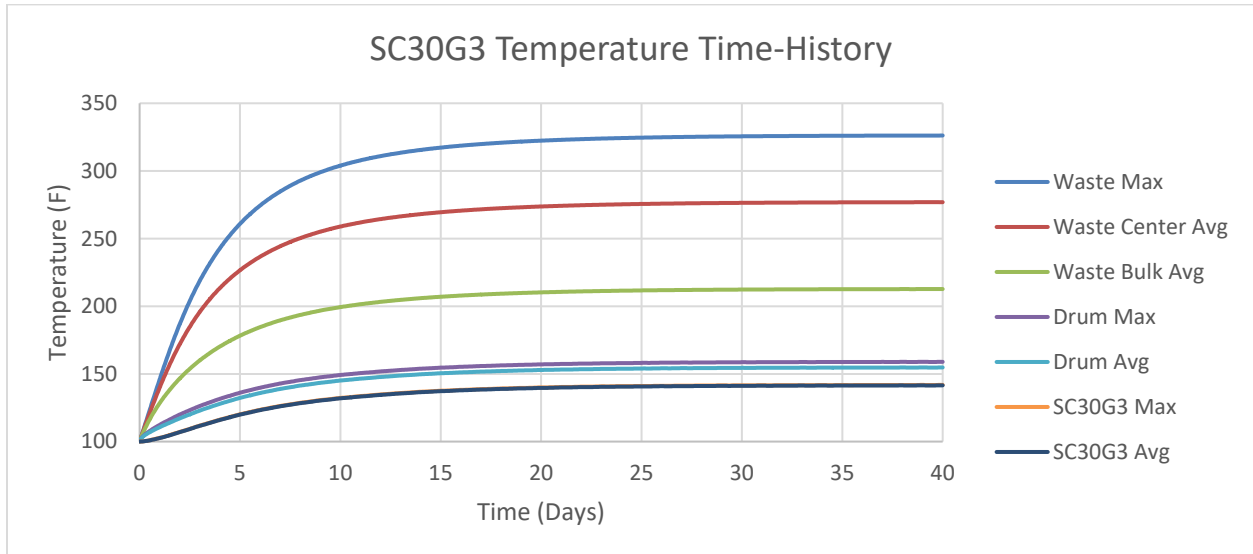


Figure 4-27 Payload Temperature Time-Histories for SC-30G3 30W Case

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1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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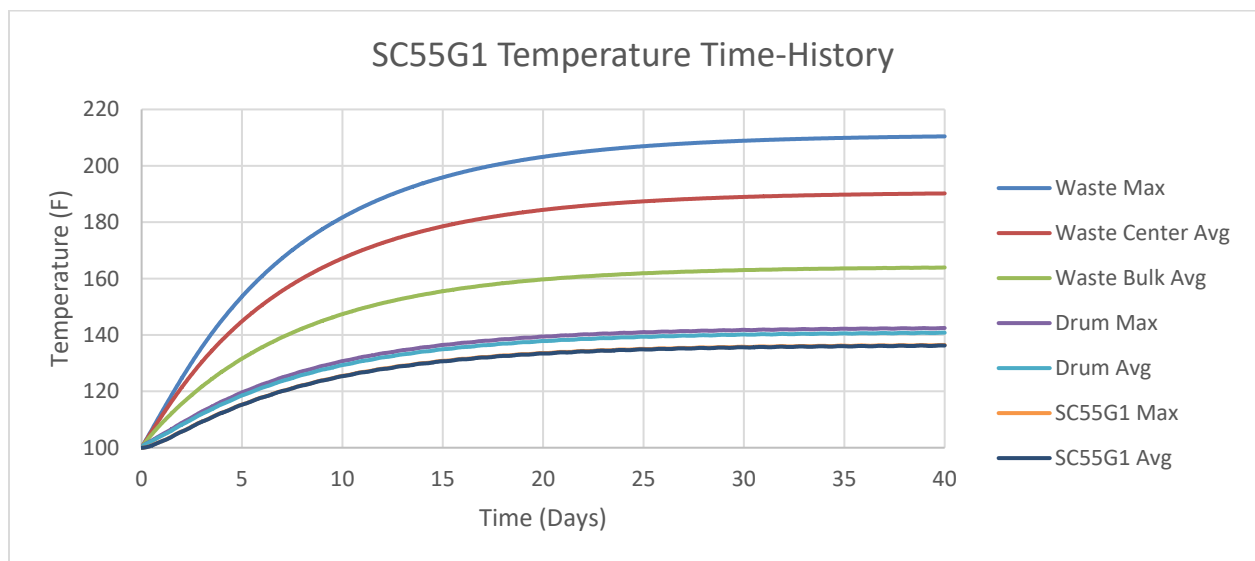


Figure 4-28 Payload Temperature Time-Histories for SC-55G1 Distributed 30W Case

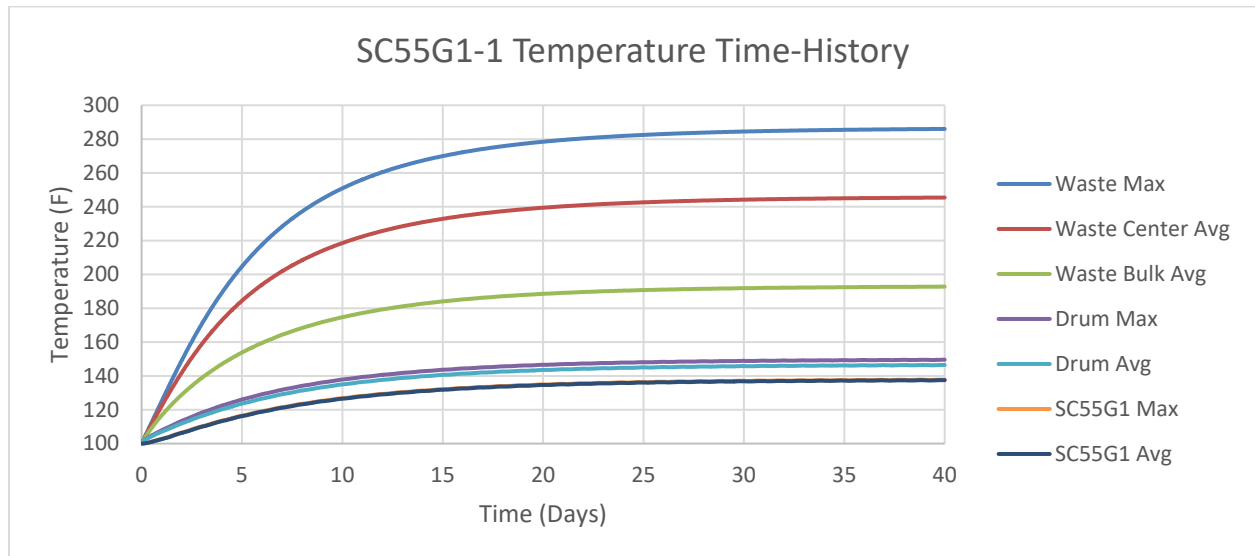


Figure 4-29 Payload (Heated) Temperature Time-Histories for SC-55G1 Concentrated 30W Case

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1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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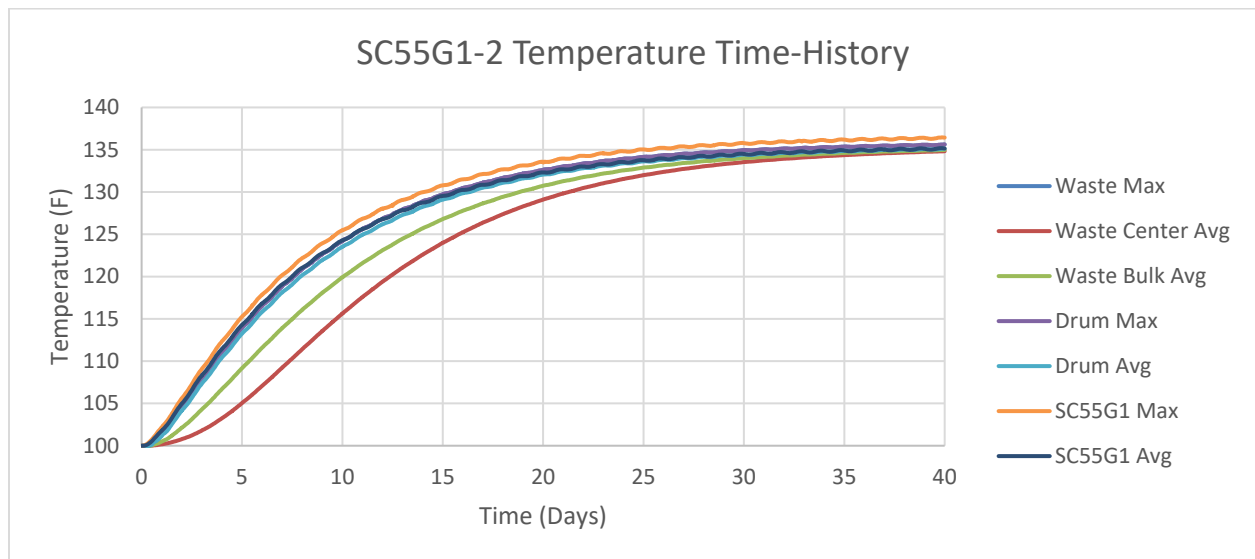


Figure 4-30 Payload (Un-Heated) Temperature Time-Histories for SC-55G1 Concentrated 30W Case

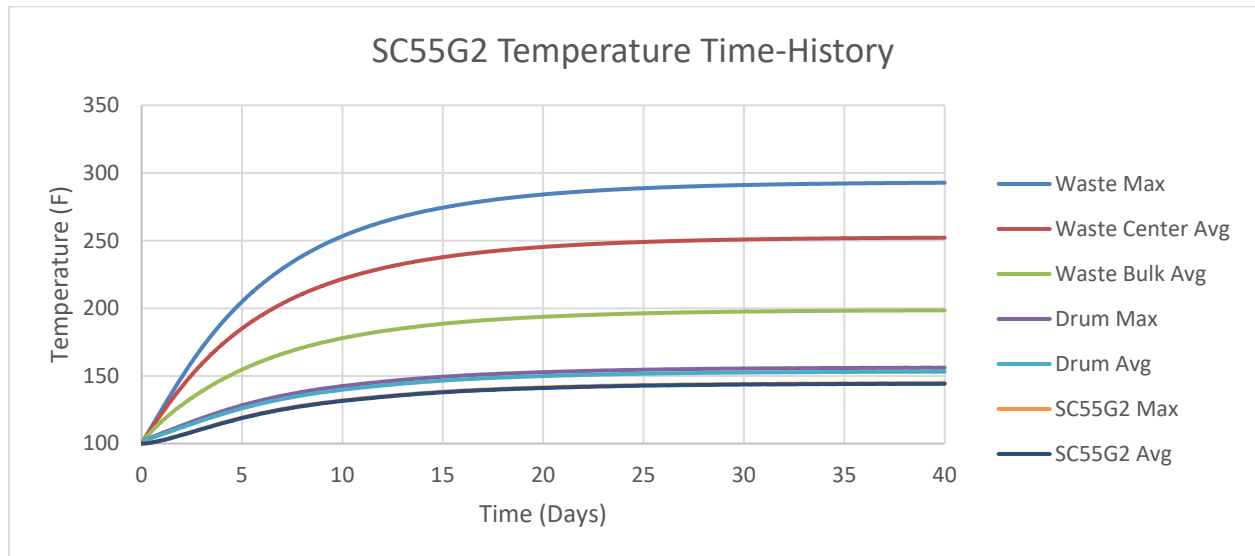


Figure 4-31 Payload Temperature Time-Histories for SC-55G2 30W Case

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1. Document Title: Shielded Container Thermal Analysis		2. System Number: PT01
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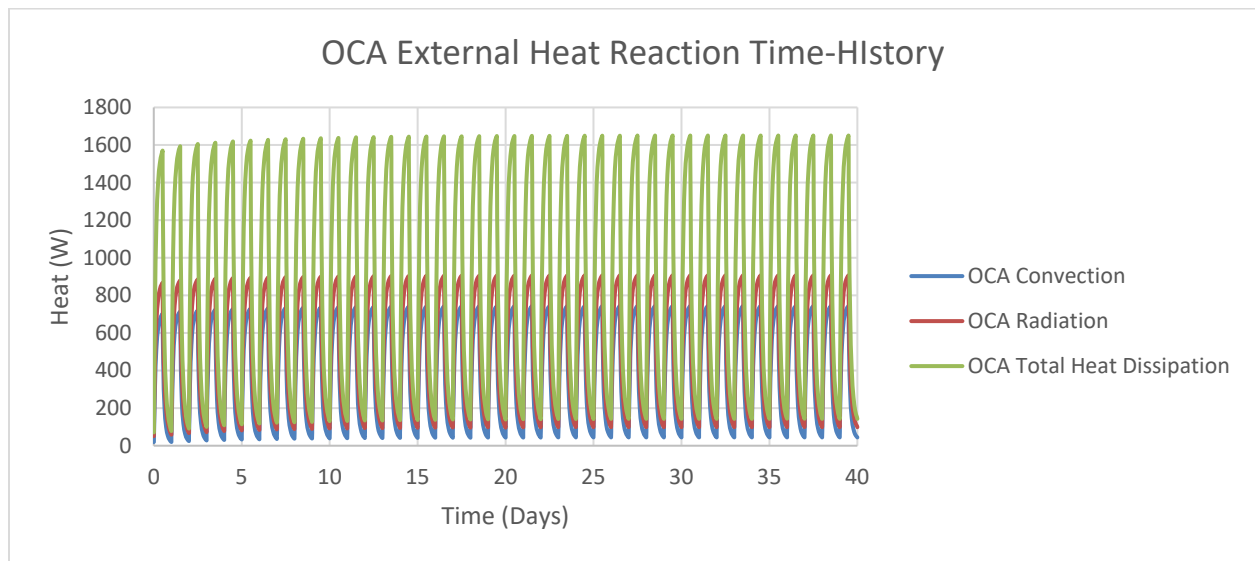


Figure 4-32 OCA External Heat Dissipation Reaction Time-Histories for SC-30G2 Distributed 30W Case

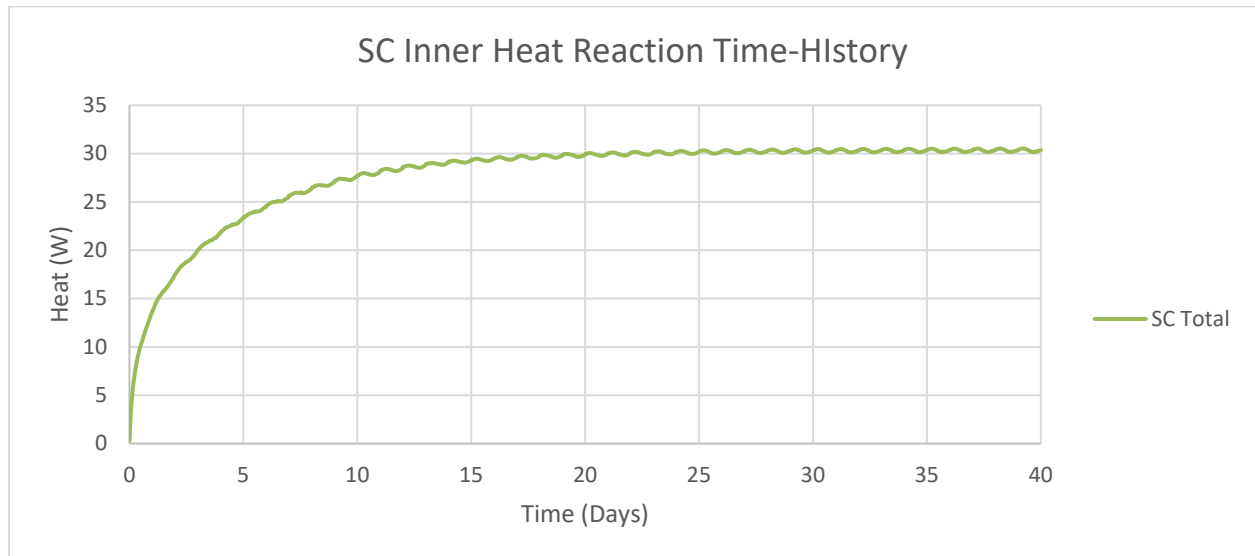


Figure 4-33 SC Internal Radiation Total Heat Reaction Time-History for SC-30G2 Distributed 30W Case

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6.0 COMPUTER RUNS

Table 6-1 – Computer Run Listing¹

Software	Name/Description/Run Time and Date/Machine Name	File Type	File Name
ANSYS	The NCT thermal analysis for the HalfPACT package with the SC-30G2 payload design. Run cases include 0W, 30W distributed, 30W concentrated, and 30W concentrated high resolution. See the solve.out file associated with each run for run time and date. The machine name for all ANSYS runs is S025847L, and the associated V&V package is provided in Reference 28.	ANSYS Archive	SC-30G2_NCT.wbpz
ANSYS	The NCT thermal analysis for the HalfPACT package with the SC-30G3 payload design. Run cases include 0W, 30W, 30W high resolution. See the solve.out file associated with each run for run time and date.	ANSYS Archive	SC-30G3_NCT.wbpz
ANSYS	The NCT thermal analysis for the HalfPACT package with the SC-55G1 payload design. Run cases include 0W, 30W distributed, 30W concentrated, and 30W concentrated high resolution. See the solve.out file associated with each run for run time and date.	ANSYS Archive	SC-55G1_NCT.wbpz
ANSYS	The NCT thermal analysis for the HalfPACT package with the SC-55G2 payload design. Run cases include 0W, 30W, and 30W high resolution. See the solve.out file associated with each run for run time and date.	ANSYS Archive	SC-55G2_NCT.wbpz
Mathcad	The calculation of HalfPACT specific external natural convection film coefficients, as discussed in Section 4.2.7.2. There is no run time and date provided by the software as it is treated as a math focused scripting software that continuously solves the mathematical expressions provided. The associated V&V package is provided in Reference 30.	Mathcad	HP_Free_Convection_Coefficients.xmed
ANSYS	The NCT thermal analysis for the HalfPACT package with the SC-30G1 payload design. The project includes a single run case, 30W concentrated. See the solve.out file associated with each run for run time and date.	ANSYS Archive	SC-30G1_NCT.wbpz

¹ The files listed in this table are electronically attached to this document in the document management system.

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APPENDIX A

A.1 Mesh Sensitivity Study

The purpose of this appendix is to study the sensitivity of each models nominal mesh with regard to the temperature results provided in Section 2.1.3. A mesh sensitivity study is a common method of determining nominal mesh acceptability. It is a process by which the nominal mesh resolution of the model is perturbed and the results are interrogated for changes. All mesh perturbations cause a change to the results of a model, with finer mesh densities generally converging on a “true” solution for the model. The intent of a mesh study is to perturb the nominal models mesh to determine if the results are near the converged end of the mesh density spectrum (insensitive), or susceptible to large changes in results (sensitive).

For this purpose, each HalPACT package with a unique SC payload design is modeled with a high mesh resolution model (“High Res”) for comparison. As discussed in Section 4.2.4, the thermal error post processor predicts the regions of the model with the highest error based on the relative conductance and heat flux of each underlying element. A mixture of low conductance and high heat flux results in the prediction of high error. As a result, the “High Res” models are duplicates of the 30W concentrated cases for the SC-30G2 and SC-55G1 models, and the 30W cases for the SC-30G3 and SC-55G2 models. All else being equal, these models are expected to contain elements with the largest potential error since heat flux is otherwise maximized.

The mesh for each “High Res” model is increased in density throughout. This is done by reducing maximum allowed elements sizes and increasing sweep division where specified. The combination of mesh resolution increases results in the mesh statics provided in Table A-1 for the “High Res” models. Note that the values for the nominal mesh from Table 4-2 are provided in Table A-1 for convenience of comparison.

Table A-1 – Comparison of Nominal and High Resolution Mesh Metrics by Model

Mesh Metric	SC-30G2		SC-30G3	
	Nominal	High Res	Nominal	High Res
Node Total	8,717	17,907	6,738	13,682
Element Total	6,458	13,906	5,151	10,994
Skewness Avg	0.19	0.16	0.21	0.19
Skewness Std Dev	0.16	0.14	0.20	0.19
Mesh Metric	SC-55G1		SC-55G2	
	Nominal	High Res	Nominal	High Res
Node Total	7,164	13,860	6,110	12,021
Element Total	5,469	10,988	4,696	9,616
Skewness Avg	0.19	0.18	0.21	0.18
Skewness Std Dev	0.17	0.16	0.19	0.17

A comparison of the temperatures of interest for each HalfPACT package with new SC payload design is provided in Table A-2 through Table A-5. Overall, the differences in temperatures are acceptable and within the range of the software’s default convergence tolerances. The largest

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differences are the temperatures reported in the vicinity of the heat generating waste and the heat flux applied outer OCA shell. A temperature difference of up to 2.7°F is observed in these areas of the model. As a result, further interrogation of these modeling regions and accompanying discussion is provided.

For the simulated waste volume, the average bulk and centerline temperatures are the main offenders. This is to be expected given that the average reported temperatures represent the arithmetic mean of the underlying node temperatures of the selected solids. Per the heat transfer fundamentals [Ref. 9], heat generating bodies with internal conduction result in non-linear temperature distributions. Therefore the larger the population of evenly distributed nodes within the solid body, the closer to a true representation of the average temperature. Given the large margins reported in Section 2.1.3 with regard to waste temperatures, these differences in average waste temperature are deemed acceptable.

For the OCA outer shell and corresponding foam temperatures, the maximum temperatures are the main offenders. In interrogating the model, the maximum OCA shell temperature occurs in the torispherical head. The torispherical head is where the highest regulatory solar insolation is applied in the model. Heat in the torispherical head is either exchanged via conduction into the package through the foam, conducts circumferentially along the shell, convects out to the environment, or radiates to the environment. Due to the low conductivity of the underlying foam, a significant portion of the heat applied to the OCA head shell travels circumferentially to the cooler outer cylindrical shell for dissipation, creating a circumferential temperature gradient. Similar to the waste temperature distribution above, a non-linear temperature distribution exists along the OCA torispherical head. However, given the repeated previous thermal analyses that all show compliance with the 160°F NCT structural analysis limit, and the relative insensitivity to internal decay heat observed in Section 4.2.8, this difference in maximum temperatures is acceptable.

Therefore, the nominal mesh for each HalfPACT package with new SC payload design is deemed acceptable.

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Table A-2 – SC-30G2 NCT 30W Concentrated Case Mesh Sensitivity Temperature Comparison (°F)

Model Region	Location	30W Nominal	30W High Res	Diff
SC30G2-1	Waste Max	325.9	325.5	-0.4
	Waste Centerline Avg	276.7	278.0	+1.3
	Waste Bulk Avg	210.9	213.5	+2.6
	Drum Shell Max	158.9	158.5	-0.4
	Drum Shell Avg	154.6	154.4	-0.3
	SC30G2 Max	142.3	141.9	-0.5
	SC30G2 Avg	141.4	141.0	-0.4
SC30G2-2	Waste Max	137.6	136.5	-1.1
	Waste Centerline Avg	136.9	135.9	-1.0
	Waste Bulk Avg	137.0	136.0	-1.0
	Drum Shell Max	137.6	136.5	-1.1
	Drum Shell Avg	137.0	136.0	-1.0
	SC30G2 Max	139.0	137.5	-1.5
	SC30G2 Avg	137.1	136.1	-1.0
Payload	Dunnage Foam Max	140.5	140.1	-0.4
	Dunnage Foam Avg	136.0	135.1	-0.9
ICV	Air Cavity Avg	135.5	134.9	-0.6
	Shell Max	133.8	133.5	-0.3
	Shell Avg	131.7	131.3	-0.4
	Shell Min	130.2	129.4	-0.8
	O-ring Max	132.2	131.4	-0.8
OCV	Shell Max	134.5	133.8	-0.7
	Shell Avg	131.3	130.9	-0.4
	O-ring Max	134.5	133.8	-0.7
OCA	Poly Foam Max	151.0	152.6	+1.6
	Poly Foam Avg	131.3	130.4	-0.9
	Shell Max	150.9	152.4	+1.5

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Table A-3– SC-30G3 NCT 30W Case Mesh Sensitivity Temperature Comparison (°F)

Model Region	Location	30W Nominal	30W High Res	Diff
SC30G3	Waste Max	326.2	326.6	+0.4
	Waste Centerline Avg	276.9	279.6	+2.7
	Waste Bulk Avg	212.7	215.2	+2.5
	Drum Shell Max	158.9	160.0	+1.1
	Drum Shell Avg	154.8	155.8	+1.0
	SC30G3 Max	141.9	143.1	+1.2
	SC30G3 Avg	141.5	142.6	+1.1
Payload	Dunnage Foam Max	137.6	138.6	+1.0
	Dunnage Foam Avg	134.8	135.8	+1.0
	End Cap Max	140.4	141.4	+1.0
	End Cap Avg	139.3	140.4	+1.0
ICV	Air Cavity Avg	133.9	134.6	+0.7
	Shell Max	133.0	133.8	+0.8
	Shell Avg	130.6	131.2	+0.6
	Shell Min	129.9	130.5	+0.6
	O-ring Max	132.2	132.8	+0.6
OCV	Shell Max	133.7	133.6	-0.1
	Shell Avg	130.3	130.7	+0.4
	O-ring Max	133.7	133.7	0.0
OCA	Poly Foam Max	151.0	152.6	+1.6
	Poly Foam Avg	130.8	130.3	-0.5
	Shell Max	150.9	152.4	+1.5

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Table A-4– SC-55G1 NCT 30W Concentrated Case Mesh Sensitivity Temperature Comparison (°F)

Model Region	Location	30W Nominal	30W High Res	Diff
SC55G1-1	Waste Max	286.0	286.5	+0.5
	Waste Centerline Avg	245.5	247.1	+1.6
	Waste Bulk Avg	192.8	192.9	+0.1
	Drum Shell Max	149.6	150.0	+0.4
	Drum Shell Avg	146.5	146.7	+0.2
	SC55G1 Max	137.8	138.1	+0.3
	SC55G1 Avg	137.5	137.8	+0.3
SC55G1-2	Waste Max	135.6	135.9	+0.3
	Waste Centerline Avg	134.8	135.0	+0.2
	Waste Bulk Avg	135.0	135.2	+0.2
	Drum Shell Max	135.6	135.9	+0.3
	Drum Shell Avg	135.1	135.3	+0.2
	SC55G1 Max	136.5	136.6	+0.1
	SC55G1 Avg	135.2	135.4	+0.2
Payload	Dunnage Foam Max	137.3	137.6	+0.3
	Dunnage Foam Avg	135.6	135.8	+0.2
ICV	Air Cavity Avg	134.8	134.8	0.0
	Shell Max	133.1	133.2	+0.1
	Shell Avg	131.3	131.4	+0.1
	Shell Min	130.3	130.4	+0.1
	O-ring Max	132.3	132.1	-0.2
OCV	Shell Max	134.2	133.9	-0.3
	Shell Avg	130.9	130.9	0.0
	O-ring Max	134.2	133.9	-0.3
OCA	Poly Foam Max	151.0	152.6	+1.6
	Poly Foam Avg	131.0	130.4	-0.6
	Shell Max	150.9	152.5	+1.6

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Table A-5– SC-55G2 NCT 30W Case Mesh Sensitivity Temperature Comparison (°F)

Model Region	Location	30W Nominal	30W High Res	Diff
SC55G2	Waste Max	292.8	292.2	-0.4
	Waste Centerline Avg	252.2	252.9	+0.7
	Waste Bulk Avg	198.5	201.0	+2.5
	Drum Shell Max	156.1	155.7	-0.4
	Drum Shell Avg	153.2	152.6	-0.6
	SC55G2 Max	144.7	144.2	-0.5
	SC55G2 Avg	144.2	143.7	-0.5
Payload	Dunnage Foam Max	138.7	138.4	-0.3
	Dunnage Foam Avg	136.2	136.0	-0.2
ICV	Air Cavity Avg	135.0	134.9	-0.1
	Shell Max	134.4	134.3	-0.1
	Shell Avg	131.7	131.6	-0.1
	Shell Min	131.0	130.8	-0.2
	O-ring Max	133.5	133.4	-0.1
OCV	Shell Max	134.2	133.3	-0.9
	Shell Avg	131.2	130.9	-0.3
	O-ring Max	134.2	133.5	-0.7
OCA	Poly Foam Max	151.0	152.0	+1.0
	Poly Foam Avg	131.2	130.6	-0.6
	Shell Max	150.9	152.0	+1.1

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A.2 Natural Convection Mathcad Sheet Listing

Properties of Air. Columns are as follows: Temperature (K), Kinematic Viscosity (m^2/s), Conductivity ($\text{W}/\text{m}\cdot\text{K}$), Thermal Diffusivity (m^2/s), and Prandtl Number (unitless). Note that Volumetric Thermal Expansion Coefficient for an ideal gas is the inverse of the absolute temperature. Air properties come from the Fundamentals of Heat and Mass Transfer, 5th Edition.

Air :=	300	$15.89 \cdot 10^{-6}$	$26.3 \cdot 10^{-3}$	$22.5 \cdot 10^{-6}$	0.707
	350	$20.92 \cdot 10^{-6}$	$30.0 \cdot 10^{-3}$	$29.9 \cdot 10^{-6}$	0.700
	400	$26.41 \cdot 10^{-6}$	$33.8 \cdot 10^{-3}$	$38.3 \cdot 10^{-6}$	0.690
	450	$32.39 \cdot 10^{-6}$	$37.3 \cdot 10^{-3}$	$47.2 \cdot 10^{-6}$	0.686
	500	$38.79 \cdot 10^{-6}$	$40.7 \cdot 10^{-3}$	$56.7 \cdot 10^{-6}$	0.684
	550	$45.57 \cdot 10^{-6}$	$43.9 \cdot 10^{-3}$	$66.7 \cdot 10^{-6}$	0.683
	600	$52.69 \cdot 10^{-6}$	$46.9 \cdot 10^{-3}$	$76.9 \cdot 10^{-6}$	0.685
	650	$60.21 \cdot 10^{-6}$	$49.7 \cdot 10^{-3}$	$87.3 \cdot 10^{-6}$	0.690
	700	$68.10 \cdot 10^{-6}$	$52.4 \cdot 10^{-3}$	$98.0 \cdot 10^{-6}$	0.695
	750	$76.37 \cdot 10^{-6}$	$54.9 \cdot 10^{-3}$	$109 \cdot 10^{-6}$	0.702
	800	$84.93 \cdot 10^{-6}$	$57.3 \cdot 10^{-3}$	$120 \cdot 10^{-6}$	0.709
	850	$93.80 \cdot 10^{-6}$	$59.6 \cdot 10^{-3}$	$131 \cdot 10^{-6}$	0.716
	900	$102.9 \cdot 10^{-6}$	$62.0 \cdot 10^{-3}$	$143 \cdot 10^{-6}$	0.720

The following empirical correlations for natural convection film coefficients come from the Handbook of Heat Transfer, 3rd Edition.

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Vertical heated short cylindrical shell. Ambient temp of 100F with surface temp range of 100F - 1500F.

$$L_w := \left[91.5 - \left(16 + \frac{17}{32} + \frac{3}{8} \right) \right] \text{in} = 74.594 \text{ in}$$

$$D := 94.375 \text{ in}$$

$$\frac{L}{D} = 0.79$$

$$n := 1000$$

$$i := 0 \dots n$$

$$T_{\text{surf}_i} := \left[100 + \left(\frac{1500 - 100}{n} \right) \cdot i \right] \quad \text{Surface temperature array divided into 1000 values from 100F to 1500F.}$$

Empirical constants provided by the data for short vertical circular cylinders in Table 4.3a in Handbook of Heat Transfer, 3rd Edition. The columns are as follows and in order from left to right; L/D ratios, Nu_{cond}, G, n, C_t, and m. To prevent the constants from redefining Mathcad built in units, they've been specified as "C sub letter" where necessary. These constants are used in the follow on equations to compute the convective coefficients.

$$\text{Table43a} := \begin{pmatrix} 0.5 & 1.93 & 0.792 & 1.07 & 0.087 & 10 \\ 1.0 & 1.59 & 0.839 & 1.11 & 0.092 & 10 \\ 2.0 & 1.26 & 0.733 & 1.07 & 0.096 & 10 \end{pmatrix}$$

$$\text{Nu}_{\text{cond}} := \text{linterp} \left(\text{Table43a}^{(0)}, \text{Table43a}^{(1)}, \frac{L}{D} \right) = 1.733$$

$$C_G := \text{linterp} \left(\text{Table43a}^{(0)}, \text{Table43a}^{(2)}, \frac{L}{D} \right) = 0.819$$

$$C_n := \text{linterp} \left(\text{Table43a}^{(0)}, \text{Table43a}^{(3)}, \frac{L}{D} \right) = 1.093$$

$$C_t := \text{linterp} \left(\text{Table43a}^{(0)}, \text{Table43a}^{(4)}, \frac{L}{D} \right) = 0.09$$

$$C_m := \text{linterp} \left(\text{Table43a}^{(0)}, \text{Table43a}^{(5)}, \frac{L}{D} \right) = 10$$

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$h_{cyl} :=$ for $i \in 0..length(T_{surf}) - 1$

$T_s \leftarrow T_{surf_i}$

$T_f \leftarrow \left[\frac{(T_s + 100)}{2} + 459.67 \right] \cdot \frac{5}{9}$

$\nu \leftarrow \text{linterp}(Air^{(0)}, Air^{(1)}, T_f)$

$k \leftarrow \text{linterp}(Air^{(0)}, Air^{(2)}, T_f)$

$\alpha \leftarrow \text{linterp}(Air^{(0)}, Air^{(3)}, T_f)$

$Pr \leftarrow \text{linterp}(Air^{(0)}, Air^{(4)}, T_f)$

$\beta \leftarrow (T_f)^{-1}$

$Ra \leftarrow \frac{(9.807) \cdot \beta \cdot \left[(T_s - 100) \cdot \frac{5}{9} \right] \cdot \left(\frac{D \cdot 25.4}{1000 \cdot \text{in}} \right)^3}{\nu \cdot \alpha}$

$C_1 \leftarrow \frac{0.671}{\left[1 + \left(\frac{0.492}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}}$

$Nu_T \leftarrow C_G \cdot C_1 \cdot Ra^{\frac{1}{4}}$

$Nu_l \leftarrow \left(Nu_{cond}^{C_n} + Nu_T^{C_n} \right)^{\frac{1}{C_n}}$

$Nu_t \leftarrow C_t \cdot Ra^{\frac{1}{3}}$

	0	1
0	310.928	0.02
1	311.706	0.972
2	312.483	1.213
3	313.261	1.383
4	314.039	1.518
5	314.817	1.632
6	315.594	1.731
7	316.372	1.82
8	317.15	1.9
9	317.928	1.974
10	318.706	2.042
11	319.483	2.106
12	320.261	2.165
13	321.039	2.222
14	321.817	2.275
15	322.594	...

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The diagram shows a vertical pipe with several labels and equations. On the left side, there are two vertical lines representing the pipe walls. To the right of the pipe, the following equations are listed from top to bottom:

- $Nu \leftarrow \left(Nu_l^{C_m} + Nu_t^{C_m} \right)^{\frac{1}{C_m}}$
- $Out_{i,0} \leftarrow (T_s + 459.67) \cdot \frac{5}{9}$
- $Out_{i,1} \leftarrow \frac{Nu \cdot k}{\left(\frac{D \cdot 25.4}{1000 \cdot in} \right)}$

At the very bottom of the pipe, the word "Out" is written.

Flat heated horizontal plate upward facing using equations 4.39. The area is provided from the CCO Thermal Desktop model (CCO-CAL-0003) for the OCA head natural convection conductor. The value is noted as based on the area of the torispherical head modeled in AutoCAD. Same assumptions as above otherwise.

$D := 94.375in = 94.375in$

$P := \pi \cdot D = 296.488in$

$A := 8421.02in^2$

$L_{star} := \frac{A}{P} = 28.403in$

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$h_{top} :=$ for $i \in 0..length(T_{surf}) - 1$

$$T_s \leftarrow T_{surf_i}$$

$$T_f \leftarrow \left[\frac{(T_s + 100)}{2} + 459.67 \right] \cdot \frac{5}{9}$$

$$\nu \leftarrow \text{linterp}(Air^{(0)}, Air^{(1)}, T_f)$$

$$k \leftarrow \text{linterp}(Air^{(0)}, Air^{(2)}, T_f)$$

$$\alpha \leftarrow \text{linterp}(Air^{(0)}, Air^{(3)}, T_f)$$

$$Pr \leftarrow \text{linterp}(Air^{(0)}, Air^{(4)}, T_f)$$

$$\beta \leftarrow (T_f)^{-1}$$

$$Ra \leftarrow \frac{(9.807) \cdot \beta \cdot \left[(T_s - 100) \cdot \frac{5}{9} \right] \cdot \left(\frac{L_{star} \cdot 25.4}{1000 \cdot in} \right)^3}{\nu \cdot \alpha}$$

$$C_1 \leftarrow \frac{0.671}{\frac{4}{9}}$$

$$\left[1 + \left(\frac{0.492}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{1}{4}}$$

$$Nu_T \leftarrow (0.835) \cdot C_1 \cdot Ra^{\frac{1}{4}}$$

$$Nu_l \leftarrow \begin{cases} 0 & \text{if } Ra = 0 \\ \frac{1.4}{\ln \left(1 + \frac{1.4}{Nu_T} \right)} & \text{otherwise} \end{cases}$$

$$C_{Ut} \leftarrow 0.14 \cdot \left(\frac{1 + 0.0107 \cdot Pr}{1 + 0.01 \cdot Pr} \right)$$

	0	1
0	310.928	0
1	311.706	1.494
2	312.483	1.875
3	313.261	2.142
4	314.039	2.354
5	314.817	2.533
6	315.594	2.689
7	316.372	2.827
8	317.15	2.953
9	317.928	3.068
10	318.706	3.175
11	319.483	3.274
12	320.261	3.367
13	321.039	3.455
14	321.817	3.538
15	322.594	...

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$$\begin{aligned} \text{Nu}_t &\leftarrow C_{Ut} \cdot Ra^{\frac{1}{3}} \\ \text{Nu} &\leftarrow \left(\text{Nu}_l^{10} + \text{Nu}_t^{10} \right)^{\frac{1}{10}} \\ \text{Out}_{1,0} &\leftarrow (T_s + 459.67) \cdot \frac{5}{9} \\ \text{Out}_{1,1} &\leftarrow \frac{\text{Nu} \cdot k}{\left(\frac{L_{star} \cdot 25.4}{1000 \cdot \text{in}} \right)} \end{aligned}$$

Out

Flat heated horizontal plate downward facing using equations 4.40. Area and Lstar are recalculated using the area of the bottom flat OCA surface. Same assumptions as above otherwise.

$$A := \frac{\pi}{4} \cdot D^2 = 6.995 \times 10^3 \text{ in}^2$$
$$L_{star} := \frac{A}{P} = 23.594 \text{ in}$$

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$h_{\text{bottom}} :=$ for $i \in 0 .. \text{length}(T_{\text{surf}}) - 1$

$T_s \leftarrow T_{\text{surf}_i}$

$T_f \leftarrow \left[\frac{(T_s + 100)}{2} + 459.67 \right] \cdot \frac{5}{9}$

$\nu \leftarrow \text{linterp}(Air^{(0)}, Air^{(1)}, T_f)$

$k \leftarrow \text{linterp}(Air^{(0)}, Air^{(2)}, T_f)$

$\alpha \leftarrow \text{linterp}(Air^{(0)}, Air^{(3)}, T_f)$

$Pr \leftarrow \text{linterp}(Air^{(0)}, Air^{(4)}, T_f)$

$\beta \leftarrow (T_f)^{-1}$

$Ra \leftarrow \frac{(9.807) \cdot \beta \cdot \left[(T_s - 100) \cdot \frac{5}{9} \right] \cdot \left(\frac{L_{\text{star}} \cdot 25.4}{1000 \cdot \text{in}} \right)^3}{\nu \cdot \alpha}$

$Nu_T \leftarrow \frac{0.527}{\frac{2}{9}} \cdot Ra^{\frac{1}{5}}$

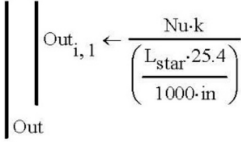
$Nu_l \leftarrow \begin{cases} 0 & \text{if } Ra = 0 \\ \frac{2.5}{\ln \left(1 + \frac{2.5}{Nu_T} \right)} & \text{otherwise} \end{cases}$

$Nu \leftarrow Nu_l$

$Out_{i,0} \leftarrow (T_s + 459.67) \cdot \frac{5}{9}$

	0	1
0	310.928	0
1	311.706	0.533
2	312.483	0.605
3	313.261	0.651
4	314.039	0.687
5	314.817	0.715
6	315.594	0.74
7	316.372	0.761
8	317.15	0.781
9	317.928	0.798
10	318.706	0.814
11	319.483	0.828
12	320.261	0.842
13	321.039	0.854
14	321.817	0.866
15	322.594	...

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A.3 SC-30G1 NCT Model for Baseline Comparison

The thermal analysis for the SC-30G1 is documented in Section 4.5.4 of the CH-TRU Payload Appendices [Ref. 2]. The source for the analysis is contained in the AREVA design analysis report P04F.M2.02-03 [Ref. 6]. Although largely similar to the analysis performed in this report, there are differences in the methodology that result in relatively minor differences in simulation outputs. The purpose of this appendix is to perform a simulation of the HalfPACT package with the SC-30G1 payload design, using the methodology and modeling techniques employed in this analysis on the new SC payload designs. This analysis serves as a baseline comparison to confirm that the original thermal analysis is conservative and appropriate, maintaining the original SC-30G1 thermal analysis as the basis for regulatory compliance.

From a high level, the original SC-30G1 thermal model utilized the Thermal Desktop software and SINDA code to simulate the thermal response of the HalfPACT package and payload design. The model utilized the original 2-D lumped parameter representation of the original HalfPACT package generic payload thermal model from Section 3 of the HalfPACT SAR [Ref. 1] to represent the HalfPACT packaging. The model is connected to a 3-D half symmetry representation of the SC-30G1 payload. The original model was simulated using a steady state thermal analysis technique that averaged the regulatory insolation over a 24-hour period to report temperatures at the OCV and inward (credited thermal response decoupling of HalfPACT package), while regulatory insolation averaged over a 12-hour period was used for reporting OCA foam and shell temperatures. Air conduction and radiation exchange were modeled between annular spaces in the package. Convection and radiation exchange were used to model passive heat dissipation from the exterior of the package to the environment.

The thermal modeling techniques employed for the new SC payload designs are discussed at length in this report. See Sections 3.0 and 4.0 for more detail. In short, the models are constructed and executed in the ANSYS® Structural software suite. The models are full 3-D half symmetry models. They utilize a transient modeling method to simulate the pseudo steady-state response of the package to the regulatory insolation averaged over a 12-hour period and applied as a stepped loading. Radiation exchange is modeled between all annular spaces in the package, where air conduction is modeled for gaps ≤ 0.25 -inch with the rest assumed void (no conduction). Convection and radiation exchange were also used to model passive heat dissipation from the exterior of the package to the environment.

The following bulleted list details the differences (and similarities) in the thermal modeling techniques employed in the original SC-30G1 analysis and the current techniques employed within this report.

Summary of Modeling Differences Between Original SC-30G1 and Current

- The original analysis utilized the Thermal Desktop® software and SINDA code. This analysis utilizes the ANSYS® Structural software products. Both sets of software packages contain thermal analysis specific elements, tools, and features that can simulate the thermal heat exchange required.
- The original analysis was modeled as 3-D half symmetry using six (6) of the original HalfPACT packaging 2-D 30° lumped parameter segments. Each segment was connected circumferentially to create a pseudo solid half symmetry model of the

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packaging. The SC-30G1 payload was explicitly modeled as a 3-D half symmetry model using a mixture of solid and surface elements. This analysis explicitly models both the HalfPACT packaging and SC payload designs as 3-D half symmetry using a mixture of solid and surface elements.

- The original analysis models the thermal response using a steady state analysis technique with 24-hour averaged insolation applied for OCV and inward temperature reporting, and 12-hour averaged insolation applied for OCA foam and shell temperature reporting. The original analysis effectively credits the thermal response isolating effects of the package design due to the low conductance polyurethane foam construction of the OCA, the thin high conductance OCA outer shell, and the large internal thermal mass of the ICV and payload contents. This analysis utilizes a transient analysis technique with 12-hour averaged insolation step applied over 24-hour cycles to all models and the maximum time-history temperatures are reported.
- Both analyses model the passive heat dissipation of the package external surfaces through radiation exchange and natural convection to the environment. Both analyses also model annular radiation heat exchange. The original analysis also modeled annular heat exchange with air conduction, both explicitly through the use of air elements or abstractly through conductors. This analysis does not explicitly model air element conduction and only includes air conductance applied in annular regions of a 0.25-inch gap or less. Annular regions with larger gaps are treated as void with only radiation heat exchange.
- The material properties between the two analyses are largely similar, although not identical. Since the citations for the various thermophysical material properties vary in both source and publication year, small differences are expected. The differences are judged to be small and considered negligible.
- The optical properties used in this analysis are either equivalent or more conservative than used in the original. Differences between the original optical properties and current include the painted carbon steel (0.85) vs. clean, smooth, and unpainted carbon steel (0.50), heavily oxidized lead (0.60) vs. lightly oxidized lead (0.28), and rough oxidized aluminum for the honeycomb (0.25) vs. bright surface condition (0.15).
- The original analysis explicitly modeled the payload pallet for its impact on conduction and radiation exchange between the bottoms of the SCs and the lower honeycomb. This analysis abstracts the payload pallet by modeling the radiation exchange between the top sheet of the pallet and the honeycomb. Conduction exchange is conservatively omitted.
- Both analyses model an annular gap between the lead shielding in the wall and carbon steel shell of the SC. This analysis conservatively assumes that the thermal differential contraction of the lead is unrestrained, effectively maximizing the gap and corresponding thermal resistance for each model. The result is the original model assumed an annular gap of 0.007-inch, while this analysis assumes an annular gap of 0.067-inch.
- Both analyses radially center and axially “float” the modeled waste drum within the SC to maximize simulated waste temperatures.
- The original analysis used 13 lb/ft³ and 6 lb/ft³ polyurethane foam properties for the radial and axial foam dunnage of the SC payload, respectively. The original analysis also applied a 15% reduction in density to the applied properties to conservatively bound the expected thermal behavior. In this analysis, 6 lb/ft³ polyurethane foam properties are

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applied to all foam dunnage properties to conservatively bound the expected thermal behavior.

The SC-30G1 thermal model built and executed for this comparison mimics the methodology covered in this report (see Sections 3.0 and 4.0 for detailed discussion). The methodology, assumptions, and development logic are not repeated herein. Instead, any differences or modeling methods unique to this model are discussed. The following bulleted list summarizes those unique characteristics.

Summary of Modeling Differences Between New SC Design Models and SC-30G1

- The SC-30G1 payload design has a three (3) SCs. The half symmetry model therefore contains 1 and ½ SCs. See Figure A-1 for a visual depiction of the CAD geometry of the model.
- The SC-30G1 payload design dunnage includes, from bottom to top, axial dunnage, pallet, radial dunnage, and another axial dunnage (see Figure 1-3). The pallet in this analysis is still omitted and abstractly modeled by including the radiation exchange between interfacing surfaces. However, the additional axial dunnage at the bottom of the payload is included in the model as a separate solid with thin aluminum skin.
- Similar to the SC-30G2 dunnage, the SC-30G1 top axial dunnage is merged into the top radial dunnage as a single solid body encased in thin aluminum skin.
- The SC-30G1 carbon steel chassis is designed with relatively thin wall inner and outer shells (7 gauge and 11 gauge, respectively). Instead of modeling as solid, the SC-30G1 shells are modeled as surfaces with negligible through thickness temperature gradients. The lead within the wall cavity is still modeled as a solid.
- Since the wall shells are modeled as surfaces, edge sizing controls are used to control mesh density in the circumferential direction to maintain the appropriate surface gap between the swept mesh of the lead and outer shell elements.
- Contact is modeled as bonded between the bottom surface of the lower axial dunnage and the top of the honeycomb. The axial air gap between the tops of the SCs and the bottom surface of the upper axial dunnage is nominally 0.25-inch. This air gap translate to an axial air gap conductance of $1.407\text{E-}6 \text{ BTU/s/in}^2/\text{°F}$. The radial air gap between the lead wall and outer shell 0.067-inch nominally, assuming unrestrained thermal contraction of the lead (see methodology and properties used in Section 4.2.5). This equates to an air gap conductance of $5.212\text{E-}6 \text{ BTU/s/in}^2/\text{°F}$. Since the lid and base are solid carbon steel for this design, no additional contact is defined for the SC.
- Due to the software limitation related to radiation enclosures and emissive property specification of surface bodies discussed in Section 4.2.7.4, the radiation exchange in the lead to outer shell annulus is included in enclosure 2 rather than a separate enclosure. The carbon steel outer shell is specified with both the inner and outer sides of the surface body active for radiation exchange. Enclosure 3 and 4 are maintained as perfectly enclosed radiation exchange between the waste drum and inner surfaces of the modeled SCs.

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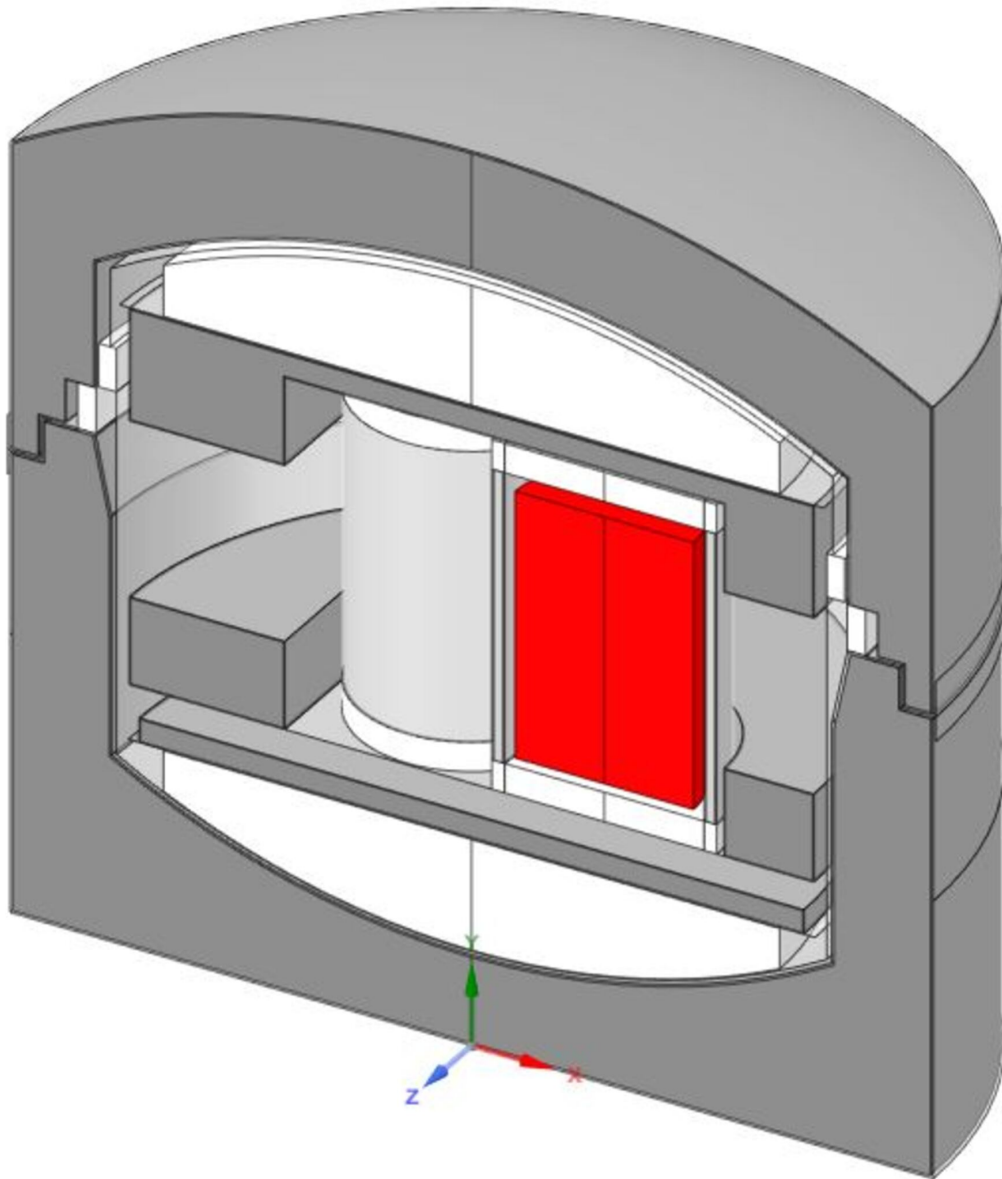


Figure A-1 Geometry of HalfPACT Package with SC-30G1 Payload

The model executed for comparative purposes is the NCT Heat condition with 30W concentrated in a single SC model. This modeling case was chosen since it produces the largest temperature gradients and is the bounding case for any SC design with regard to maximum temperatures. The maximum time history temperature results are presented in Table A-6. Included for comparison purposes are the corresponding temperatures for the SC-30G1 from Table 4.5-2 of the original thermal analysis [Ref. 2].

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Additionally included are the packaging temperatures from Case 2 of Table 4.6-4 of the CCO thermal analysis [Ref. 2]. The CCO temperature results for the payload components are omitted since they are irrelevant for comparison purposes to a different payload design. However, the packaging temperatures are provided for comparison since that model utilizes the same transient, pseudo steady state modeling technique employed in this analysis. The CCO case that is judged to be the most similar to the concentrated SC-30G1 model is case 2.

Table A-6– SC-30G1 NCT 30W Concentrated Case Temperature Comparison (°F)

Model Region	Location	Original SC-30G1 Results	New SC-30G1 Results	CCO Case 2 Results
SC30G1 (Heated)	Waste Max	342	324.9	
	Waste Centerline Avg		275.6	
	Waste Bulk Avg	224	211.9	
	Drum Shell Max		158.6	
	Drum Shell Avg		153.7	
	SC30G3 Max	158	141.9	
	SC30G3 Avg		140.5	
Payload	Dunnage Foam Max		139.3	
	Dunnage Foam Avg		134.4	
ICV	Air Cavity Avg	154	135.5	138.1
	Shell Max	150	133.1	137.6
	Shell Avg	149	131.0	134.8
	Shell Min	148	130.0	133.0
	O-ring Max	148	131.9	135.4
OCV	Shell Max	149	133.9	136.0
	Shell Avg	147	130.7	133.3
	O-ring Max	147	133.9	133.4
OCA	Poly Foam Max	152	150.9	150.7
	Poly Foam Avg	128	131.0	129.8
	Shell Max	152	150.9	150.7

The results presented in Table A-6 illustrate the conservative modeling techniques and corresponding conservative results of the original SC-30G1 thermal analysis. Large temperature differences in packaging components exist between the original and new model, illuminating the impact that the modeling differences have on the simulated results. The difference in average ICV shell temperatures is 18°F. If that temperature difference is used to scale the payload temperatures and approximately normalize for the differences in packaging temperatures, the

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payload temperature results are in relative close agreement. Thus, aside from the modeling differences and their impact on packaging temperatures, the models yield similar results at the payload level.

Further, the CCO thermal results for Case 2 are presented to provide packaging component temperature comparison to another HalfPACT package thermal model with similar boundary conditions. Both models utilize cyclically applied boundary conditions and are solved for pseudo steady state results. The packaging temperatures of the CCO model are in close agreement with the new SC-30G1 model. They are within the expected tolerance window given the small differences in modeling assumptions (difference in carbon steel emissivity and air cavities modeling), solver codes (SINDA vs ANSYS), and corresponding internal solver code tolerances.

The current modeling methodology employed by the thermal analysis in this report is conservative. Specification of the conservatisms and their respective justifications for the current modelling methodology are discussed at length in the body of the report. The baseline comparative analysis provided in this appendix and summarized in Table A-6 illustrates that the original thermal analysis methodology is even more conservative than the current practice. The original thermal analysis for the SC-30G1 is therefore judged to be conservative and still appropriate for use as the compliance basis for the thermal conditions prescribed in 10 CFR 71.