SECTION THREE
THERMAL EVALUATION

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List of Tables and Figures

3 THERMAL EVALUATION

The Century Industries Versa-Pac is designed to maintain the temperatures of the payload and containment boundary within specified limits during normal transportation and hypothetical accident conditions. This section presents an evaluation of the thermal performance of the packaging.

3.1 Description of the Thermal Design

3.1.1 Design Features

The 55-gallon Versa-Pac consists of a 15" ID x 25-7/8" inside height payload cavity centered within an insulated 55-gallon drum. Drawings of the 55-gallon version Versa-Pac are provided in Appendix 1.3.1. An illustration of the packaging is provided in Figure 1-1.

The overall nominal dimensions of the 55-gallon Versa-Pac shipping container are 23-1/16" OD x 34-1/2" in height to the top of the outer drum lid without the bolt ring in place. The payload cavity is protected from water intrusion with a gasketed lid that is closed with twelve ½" diameter bolts. Exterior to the payload cavity lid, the 55-gallon drum lid is modified with a 20ga steel encapsulated polyurethane insulation plug. The gasketed drum lid is closed with four ½" diameter bolts and a standard drum ring. A gasket at the drum lid's stiffening ring provides a third barrier against water in-leakage. The 55-gallon drum is strengthened with four longitudinal stiffeners fabricated from 1-1/4" carbon steel square tubing equally spaced around the circumference of the drum. A 16ga outer liner and a 16ga inner liner provide additional radial stiffness to the drum. A ½" thick fiberglass ring is used as a thermal break at the payload cavity flange. The thermal break is sandwiched between the steel components and effectively limits the flow of heat to the payload cavity through the steel flange components. The volume between the inner liner and the 10ga containment body is filled with ceramic fiber insulation (see Appendix 1.3.4).

The 110-gallon Versa-Pac consists of a 21" ID x 29-3/4" payload cavity centered within an insulated 110-gallon drum. Drawings of the 110-gallon version Versa-Pac are provided in Appendix 1.4.1. An illustration of the packaging is provided in Figure 1-2. The overall nominal dimensions of the package are 30-7/16" OD x 42-1/2" in height to the top of the outer drum lid without the bolt ring in place. The basic design of the 110-gallon Versa-Pac is identical to that of the 55-gallon Versa-Pac, except for the larger exterior diameter and payload cavity diameter. The thickness of the walls and insulation remain the same.

3.1.2 Contents Decay Heat

The decay heat for the payload is limited to 11.4 W total for the 55-gallon and 110-gallon models, with no single item having a decay heat greater than 20 W/m^3.

3.1.3 Summary Tables of Temperatures

Table 3-1 provides a summary of the Normal and HAC temperatures for the Versa-Pac. The maximum peak content temperature occurs for the HAC fire event 22 minutes into the cool-down sequence and is 552°F at the top of payload cavity.

3.1.4 Summary Tables of Maximum Pressures

Since the Versa-Pac is not a sealed system, the maximum normal and HAC operating pressure is near atmospheric pressure. Thus, the Versa-Pac meets the requirements of 10CFR71. However, assuming a sealed system, the maximum HAC operating pressure is less than 9.8 psig (Section 2.6.1.1)

3.2 Material Properties and Component Specifications

3.2.1 Material Properties

Thermal material properties are provided in Table 3.5.1-3. Mechanical material properties, including the linear thermal expansion coefficient, are provided in Table 2-2.

The payload is a stable solid that does not undergo any physical state changes (solid to liquid or solid to gas) below 600°F. Additionally, the melting point temperature of the contents must be greater than 600°F. Water moisture may be present (standing water is not permitted); however, during the fire it is converted to steam and is allowed to escape via the package closure gaskets. Payloads that are unstable or decompose at temperatures below 600°F that further pressurize the containment shall not be shipped in the Versa-Pac. The payload is a stable solid with both the auto-ignition temperature and the melting point greater than 600°F. The allowable temperature limits for the payload of the Versa-Pac packages are 500°F for NCT and 600°F for HAC.

3.2.2 Component Specifications

The Versa-Pac is insulated to protect the containment boundary during Hypothetical Accident Conditions (HAC). The volume between the drum and the liner is filled with ceramic fiber insulation. The volume between the liner and the payload canister is also filled with ceramic fiber insulation. A fiberglass thermal break is used to limit the flow of heat to the payload cavity through the steel flange components. The relevant thermal material properties and specifications are provided in Table 3.5.1-2. These insulators have been shown by the manufacturers to perform adequately over extended periods of time, with no shrinkage, settling, or loss of insulating properties. Additionally, these insulators do not burn. The melting point of the ceramic fiber insulation and the fiberglass thermal break are well above the temperature of the 1475°F fire specified by 10CFR71.73. These insulation products are provided as fire-protection and are sacrificial components during a fire event. Steel components are serviceable to 800°F per the ASME Code, and have a melting point of about 2500°F.

The payload cavity gaskets are rated for operating temperatures between -40°F and 1800°F; however, the Versa-Pac isn't designed as a sealed system and the function of the gaskets is to prevent dispersal of the contents only. Since the system is not sealed, the internal pressure is maintained near atmospheric conditions during all conditions of transport. The nominal payload vessel internal pressure is 0 psig. As a conservative comparison and demonstration, the maximum allowable external and internal working pressure for a sealed cylinder having 0.14" walls and ends is evaluated as 15 psig, with the maximum stresses occurring at the juncture of the lid and base with the sides of the cylinder[1]. Thus, the Versa-Pac is capable of sustaining the working pressures expected without collapse.

The fiberglass thermal break is fabricated to the specification provided in Appendix 1.3.5. The fiberglass is serviceable to a temperature of 160°F and maintains its thermal properties to 525°F

3.3 Thermal Evaluation for Normal Conditions of Transport (NCT)

The Versa-Pac is designed to meet the requirements specified by the United States Code of Federal Regulations (Title 10 and 49) and IAEA Safety Standards (TS-R-1). The package was evaluated for all conditions of transport utilizing a transient quarter-symmetric finite element model as described in Appendix 3.5.1. Material properties used in the analyses are provided in Appendix 3.5.1. Table 3-2 provides a summary of the parameters analyzed for each scenario examined, including initial conditions and heat loads.

3.3.1 Heat and Cold

The absorptivity of the outer shell is conservatively assumed to be 1.0. The convection heat transfer coefficient is conservatively assumed to be 1.0 Btu/hr-F-ft^2. The decay heat is assumed to be at the maximum for normal hot conditions. The maximum temperatures for Normal Conditions of Transport occur when the conditions specified by 10CFR71.71(c)(1) are applied. The specified insolation rate of 800 g-cal/cm^2 per 12-hour period is applied to the top surface of the packaging and an insolation rate of 400 g-cal/cm^2 per 12-hour period is applied to the curved sides of the packaging. Insolation is not applied to the base of the packaging.

With these insolation rates applied for 12-hours and alternated with 12-hours without insolation, the peak daytime temperature at the external surface of the package for the normal condition of transport is 140°F (60°C) at the drum lid as illustrated in Figures 3-1 and 3-2. The peak temperature of the contents for the normal condition is 144°F (62°C), as shown in Figure 3-3.

Under normal cold conditions as specified by 10CFR71.71(c)(2), the minimum temperature of the packaging and payload, assuming zero decay heat, is -40°F. This temperature is within the limits specified in Section 3.1.

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[1] Classical equations for thin-walled cylinders with a uniformly distributed interior pressure are used, including junction discontinuity stresses at the connection between the ends and sides of the cylinder, and considering an allowable stress of 30 ksi.

3.3.2 Maximum Normal Operating Pressure

Since the Versa-Pac is not a sealed system, the maximum normal operating pressure is near atmospheric pressure.

3.4 Thermal Evaluation for Hypothetical Accident Conditions (HAC)

The Versa-Pac was evaluated for HAC using the finite element models described in Appendix 3.5.1 and under the conditions listed in Table 3-2. The maximum temperature recorded at the payload cavity during the fire event was 552^{o}F at the top of payload cavity, just below the polyurethane plug, as shown in Figure 3.1. This temperature is well below the maximum HAC allowable temperature of 600^{o}F.

3.4.1 Initial Conditions

The model imposes an initial condition of 100^{o}F on all nodes at the start of the thermal event. Damage from the mechanical tests was not simulated; however, local reductions in wall thickness were shown in the drop tests to be limited to the outer 1-1/2" of the package. Since this portion of the package quickly attains the temperature of the fire, a local reduction isn't expected to influence the temperature of the contents.

3.4.2 Fire Test Conditions

For the fire analysis, the external surface nodes were constrained to a temperature of 1475^{o}F for the 30-minute event. For the 55-gallon version, the contents are modeled with a decay heat load of 0.022 in-lb_f/s / in^3, for a conservative total package heat load of 11.4 W. The decay heat load of the 110-gallon version modeled is 0.0085 for a total of 11.4 W.

3.4.3 Cool-down Conditions

The cool-down sequence is initialized with the temperatures recorded for each node at the end of the 30 minute fire sequence. Insolation is applied using the insolation rates and 12-hours on, 12-hours off application described for the NCT evaluation. The ambient temperature is 100^{o}F. Surface temperature dependant external surface natural convection coefficients are applied at the outer surfaces of the package, with the exception of the base, which is assumed to be adiabatic[2]. The remainder of the model and specifications are identical to those used during the fire sequence. The cool-down sequence was run for a 2-hour cool-down period, with the peak payload temperatures occurring within the first hour after cessation of the fire.

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[2] An *adiabatic process* is a thermodynamic process in which there is no heat transfer into or out of the system. In this case, the surface that the package is sitting on is assumed to be a perfect insulator, and no heat can be removed from the base unless it moves through the sides of the package. This is considered to be the conservative orientation for the package during cool-down conditions.

3.4.4 Maximum HAC Temperatures and Pressures

3.4.4.1 HAC Temperatures

The maximum temperature recorded at the payload cavity during the fire event was 552°F at the top of payload cavity, just below the polyurethane plug, for the 55-gallon package as shown in Figure 3.4. The temperature distributions of the various package components are shown in Figures 3.4 through 3.14. A time dependent graph of the peak temperature locations on the payload cavity is provided in Figure 3.15. The 110-gallon package performance is bounded by that of the 55-gallon package.

3.4.4.2 HAC Pressures

Since the Versa-Pac is not a sealed system, the maximum normal operating pressure is near atmospheric pressure.

3.4.5 Maximum Thermal Stresses

The performance of the Versa-Pac with respect to thermal stresses is demonstrated through the fire tests performed for similar packages. A summary of one such test is provided in Appendix 3.5.3. The flexible construction of the connection between the payload cavity and the flange assures that thermal gradients do not impose excessive stress on the package joints. Appendix 3.5.5 provides a thermal stress evaluation of the polyurethane plug insert.

3.4.6 Accident Conditions for Fissile Material Packages for Air Transport

This section is not applicable.

3.5 List of Appendices

3.5.1. Description of the Thermal Model

3.5.2. Excerpted from ALGOR Non-Linear Thermal Transient Heat Transfer Analysis Manual, Emulation of body-to-body radiation as temperature dependent conduction

3.5.3. Excerpted from Safety Analysis Report for the Century Champion Type B Package Thermal Test

3.5.4. Schematic of Thermal Evaluation Conditions

3.5.5. Thermal Stress Evaluation of the Polyurethane Plug Insert

3.6 References

3.6.1. MatWeb material database, a division of Automation Creations, Inc. (ACI) of Blacksburg, Virginia.

3.6.2. ALGOR FEMPRO FEA Software by Autodesk, Pittsburgh, PA, version 18.1.

3.6.3. Incropera & DeWitt, *Fundamentals of Heat and Mass Transfer 3rd Edition*, John Wiley & Sons, New York, 1990.

Table 3-1 Evaluation Results

Evaluation	Component	Evaluation Result	Evaluation Criteria	Margin of Safety [Note 1]
Normal Hot Maximum Temperature	External surface	140°F	800°F	660°F
	Payload cavity gasket	130°F	1800°F	1670°F
	Payload	144°F	500°F	356°F
Normal Cold Minimum Temperature	External surface	-40°F	N/A	N/A
	Payload cavity gasket	-40°F	-40°F	0°F
	Payload	-40°F	N/A	N/A
Normal Maximum internal pressure	Payload cavity	0 psig	15 psig	15 psig
HAC Maximum Temperature	External surface	1475°F	2500°F	1025°F
	Payload cavity gasket	623°F	1800°F	1177°F
	Payload	552°F	600°F	48°F
HAC Maximum Internal Pressure	Payload cavity	0 psig	15 psig	15 psig
HAC Thermal Stress	package	Demonstrated by test as acceptable	No failure due to fire event temperature distribution	N/A

Notes on Table 3-1

1. The margin of safety is (allowable – actual)
2. Results shown are for the 55-gallon package. The 110-gallon package performance is bounded by that of the 55-gallon package.

Table 3-2 Applied Heat Loads, Heat Transfer Coefficients and Initial Conditions

Parameter	Normal Transport Hot	Normal Transport Cold	HAC Transport
Ambient Temperature, °F	100.00	-40.00	1475 for 30min, 100.00 until peak temperatures are identified
Top surface insolation, BTU/hr-ft^2, 12 hours on, 12 hours off	246.00	0.00	N/A during the fire, 246.00 during cool-down
Curved surface insolation, BTU/hr-ft^2, 12 hours on, 12 hours off	123.0	0.00	N/A during the fire, 123.00 during cool-down
Base surface insolation, BTU/hr-ft^2, 12 hours on, 12 hours off	0.00	0.00	N/A during the fire, 0.00 during cool-down
Radiological Decay Heat, 55 gal / 110 gal, W	11.4 / 11.4	0.00	11.4 / 11.4
Analysis performed	Transient	N/A	Transient
Initial Package/Content Temperature	100.00	N/A	100ºF
External surface absorptivity/emissivity	1.0	N/A	1.0
External surface convection coefficient, Btu/hr-F-ft^2	1.0	N/A	During fire transient, N/A During cool-down, see Table 3.5.1-5

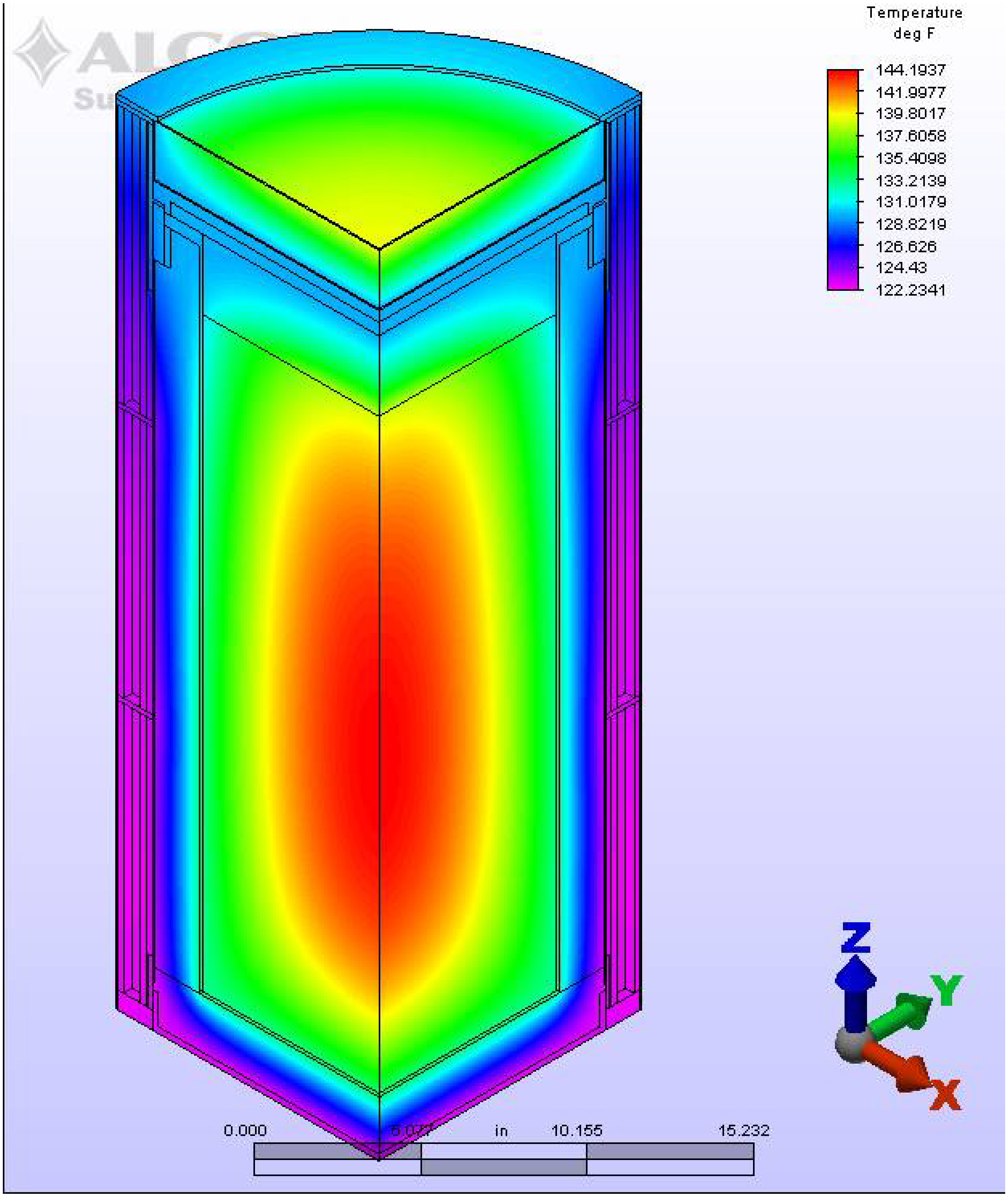

Figure 3-1 Normal Hot Package Peak Temperature Distribution, 55-gallon Versa-Pac

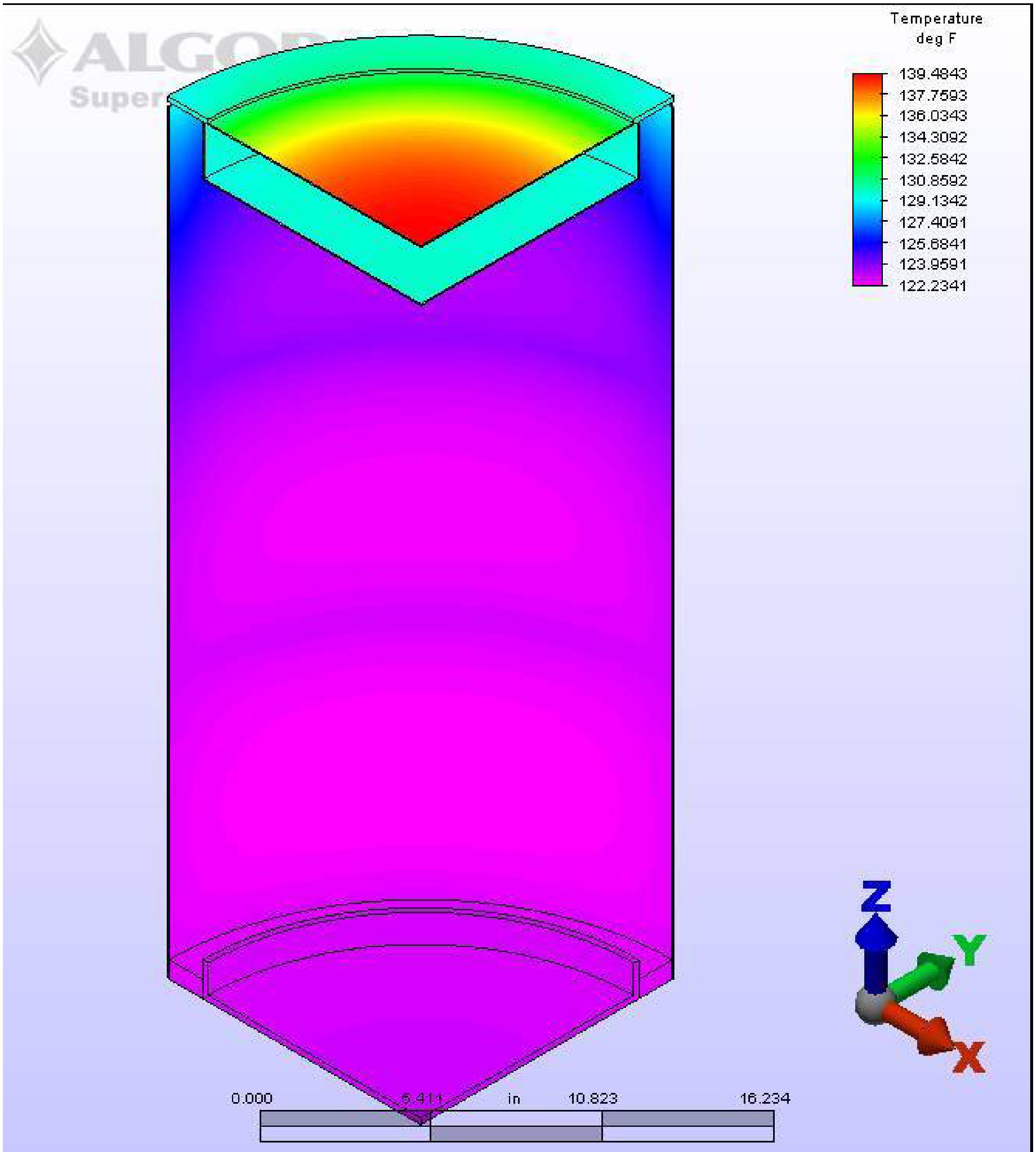

Figure 3-2 Normal Hot Outer Surface Peak Temperature Distribution, 55-gallon Versa-Pac

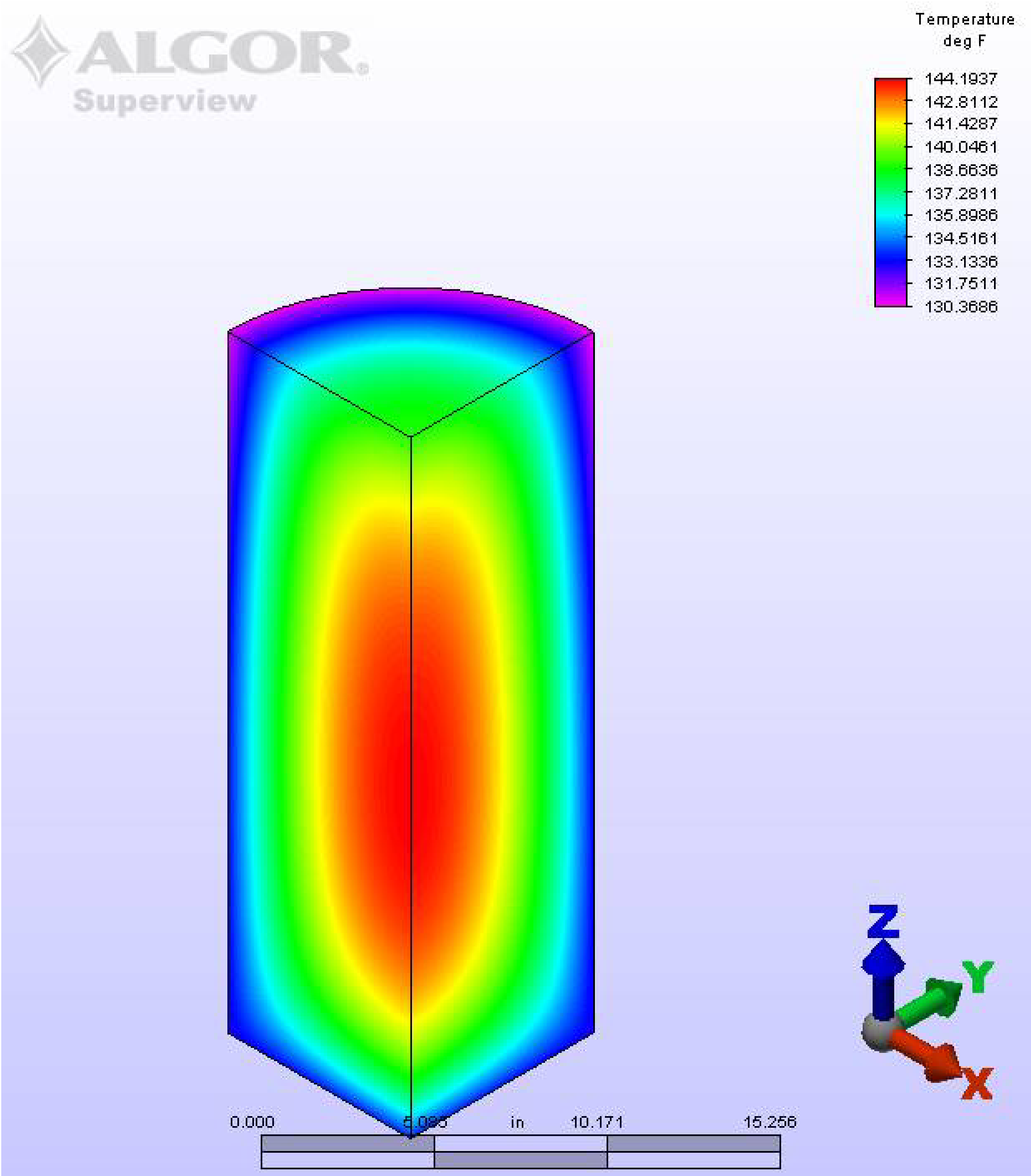

Figure 3-3 Normal Hot Contents Peak Temperature Distribution, 55-gallon Versa-Pac

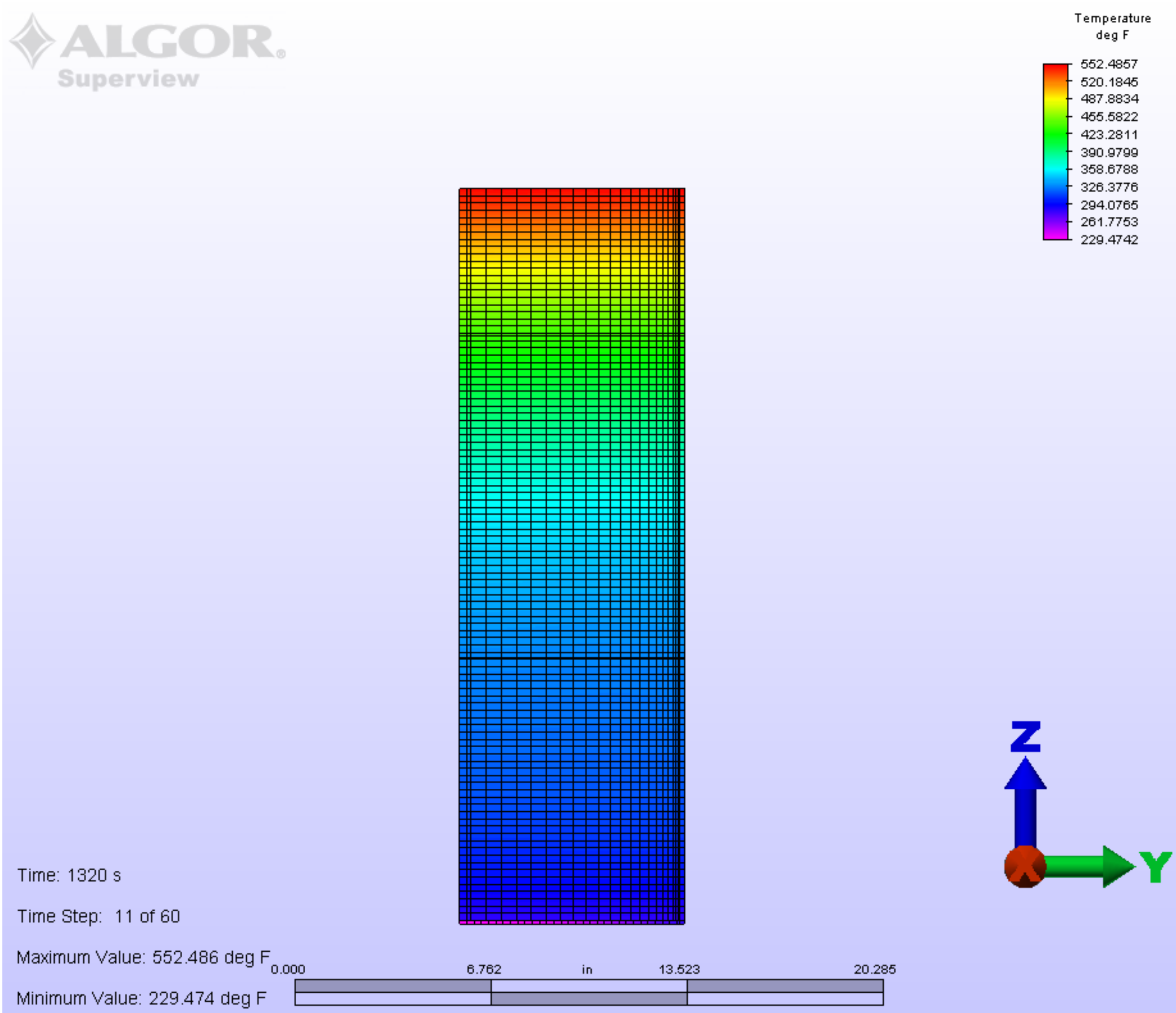

Figure 3-4 Maximum Fire Event Temperature at Cool-down Sequence, 22 minutes after Cessation of Fire, Contents

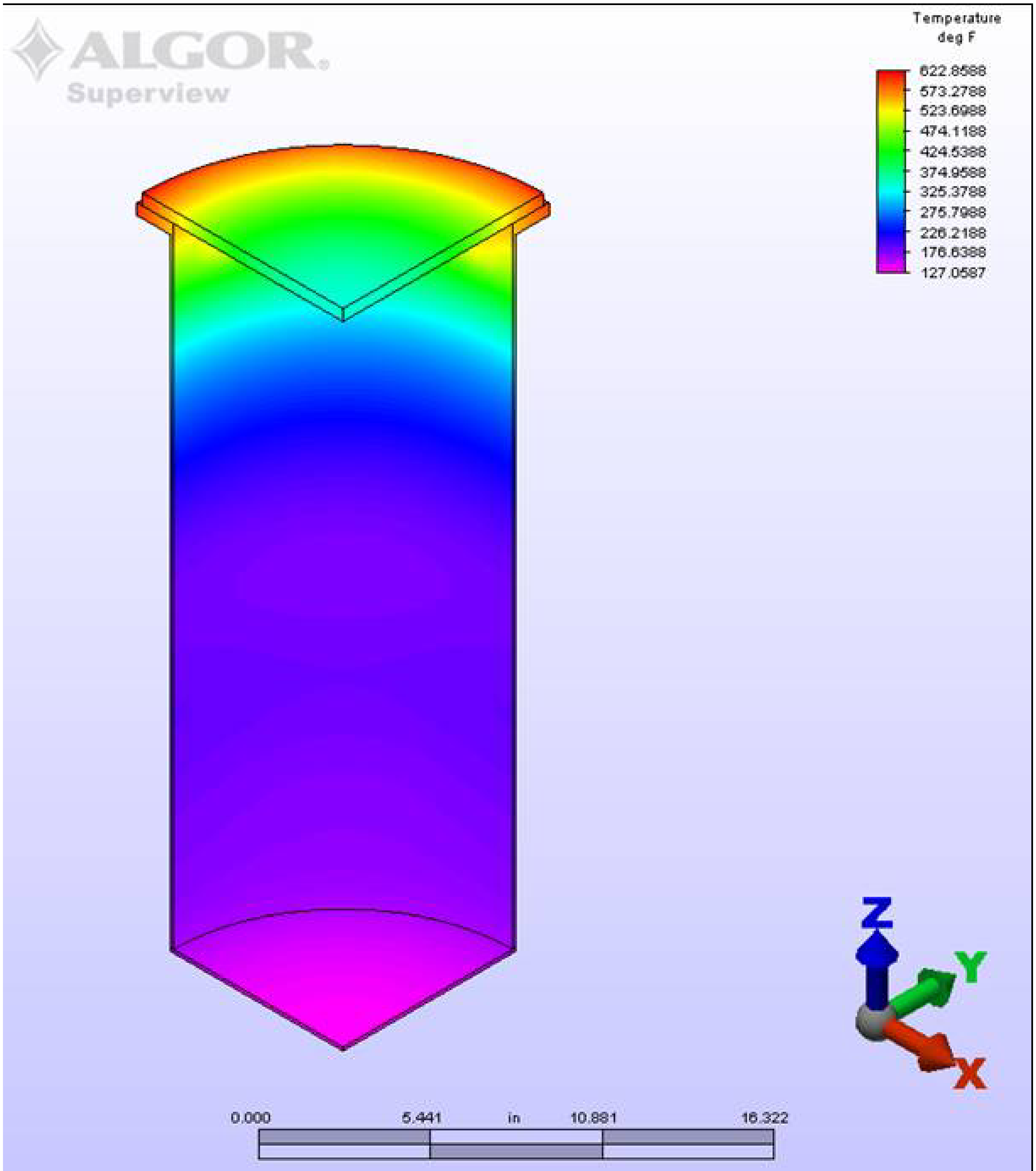

Figure 3-5 Fire Event temperature at 30 minutes, Payload Cavity and Flanges (including polyurethane plug area)

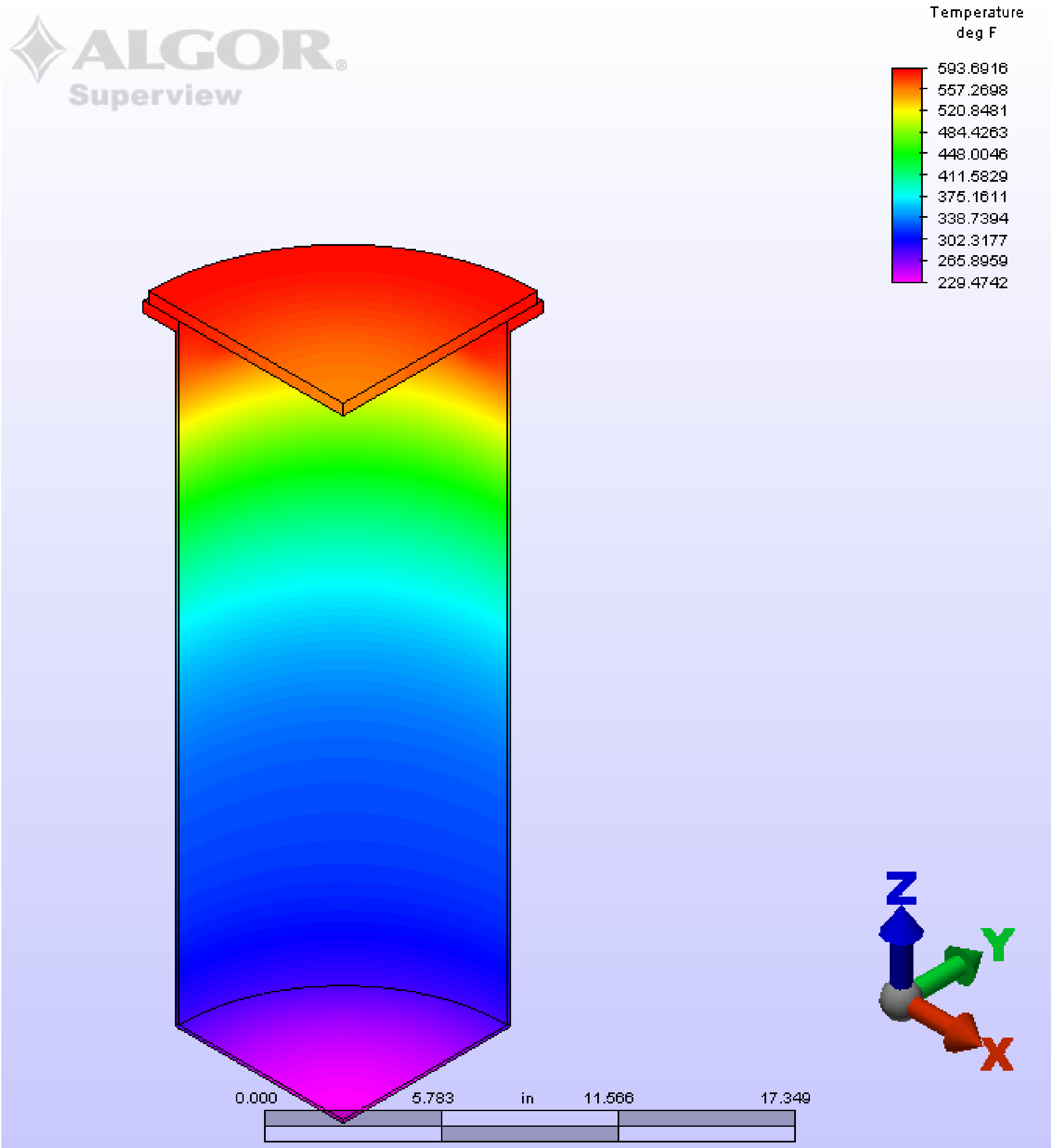

Figure 3-6 Fire Event & Cool-down temperature at 55 total minutes, Payload Cavity and Flanges (including polyurethane plug area)

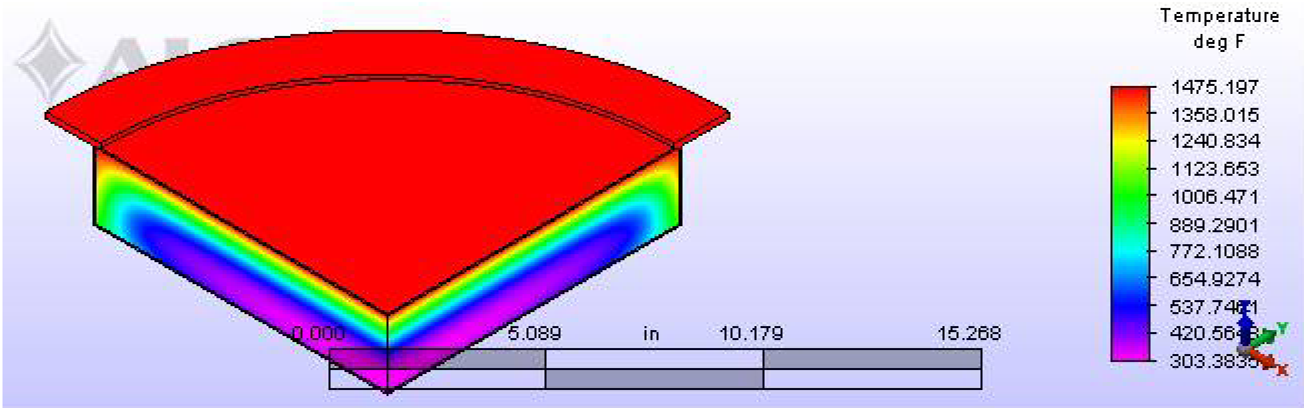

Figure 3-7 Fire Event temperature at 30 minutes, Package Lid

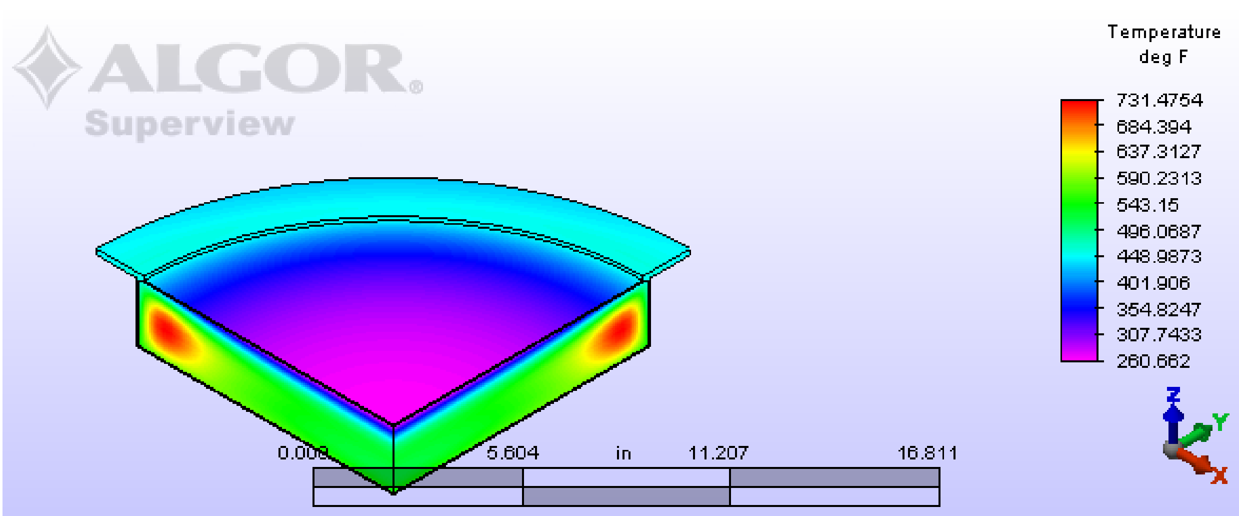

Figure 3-8 Fire Event and Cool-down temperature at 55 total minutes, Package Lid

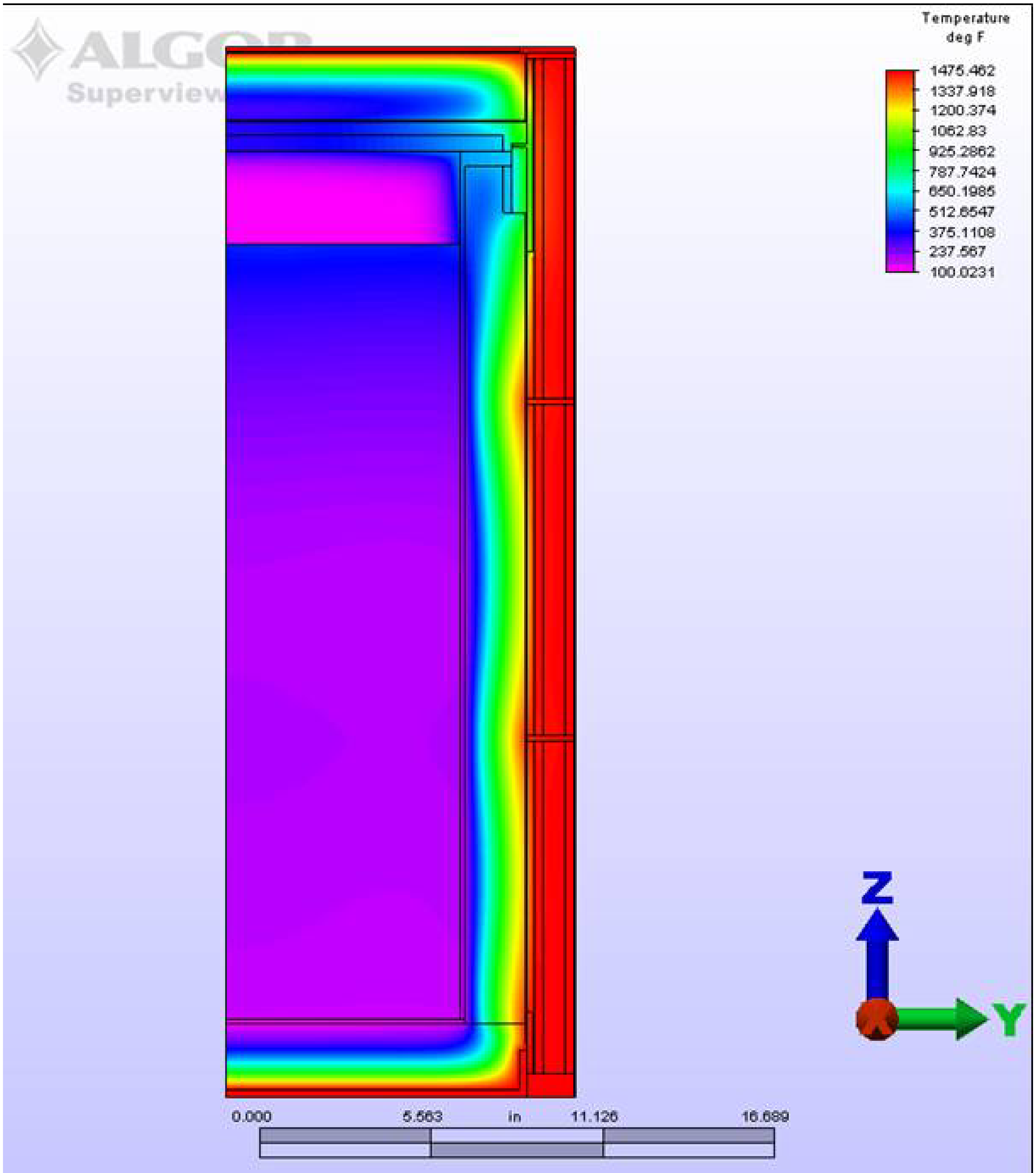

Figure 3-9 Fire Event temperature at 30 minutes, Package side view

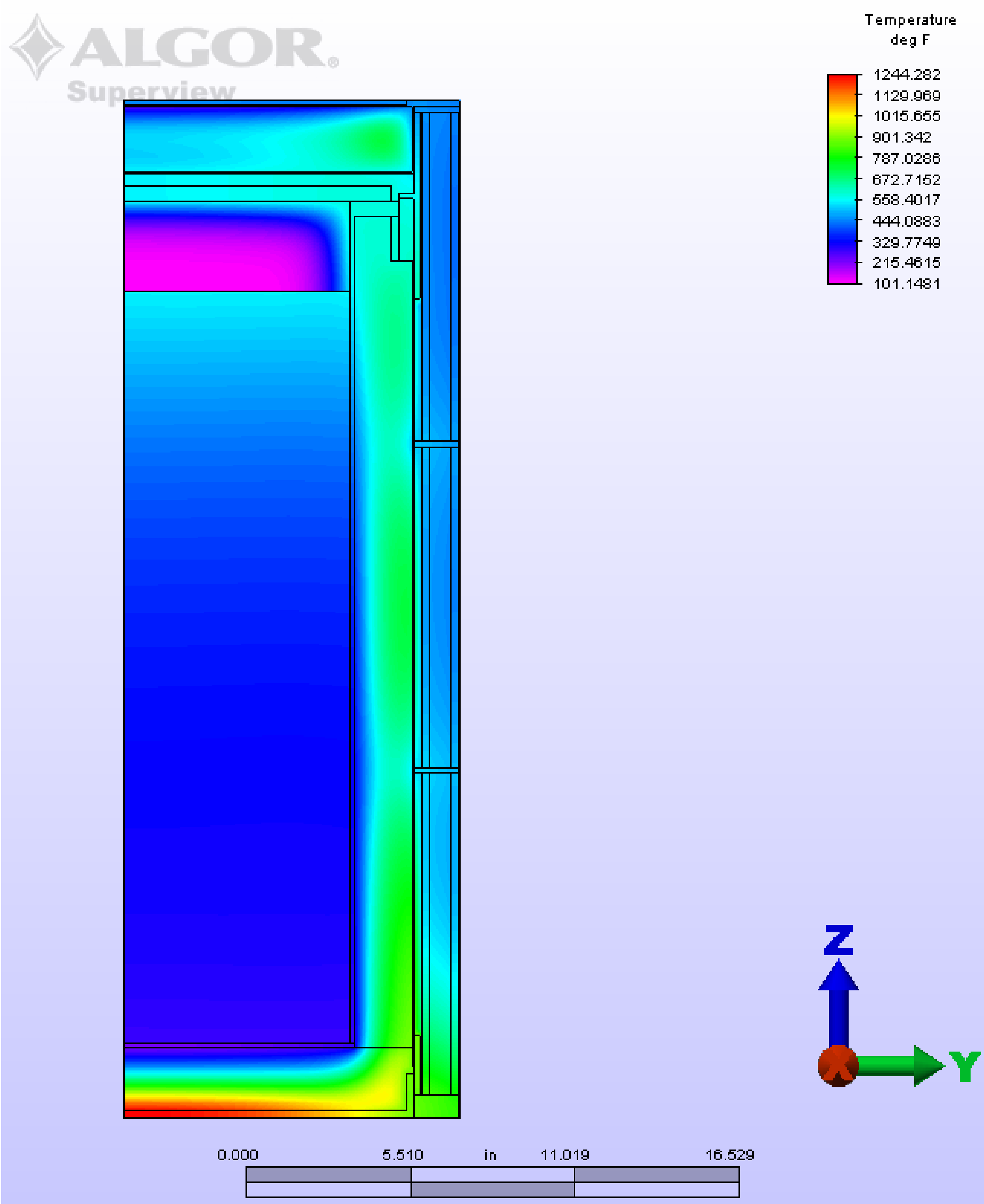

Figure 3-10 Fire Event and Cool-down temperature at 55 total minutes, Package side view

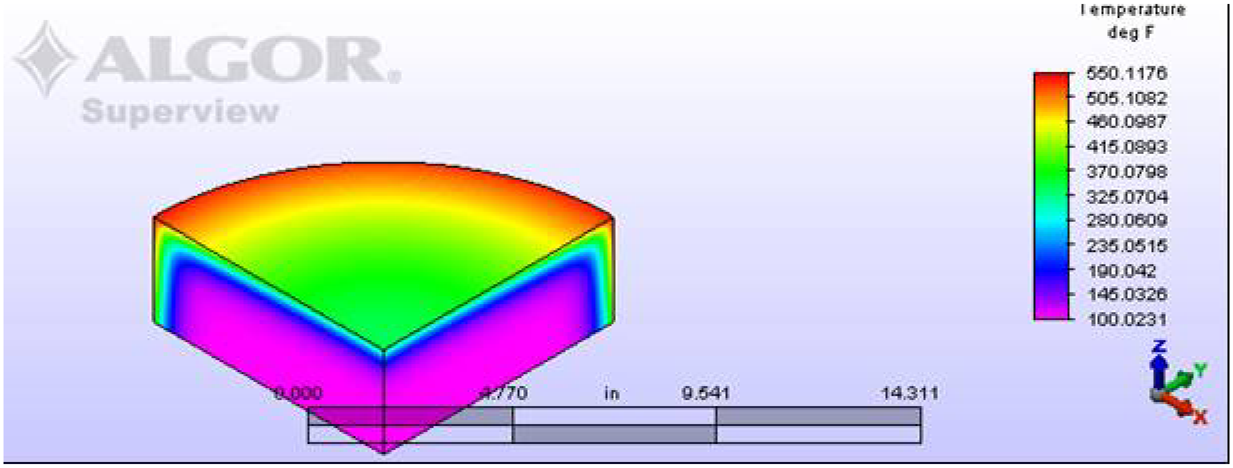

Figure 3-11 Fire Event temperature at 30 minutes, polyurethane plug

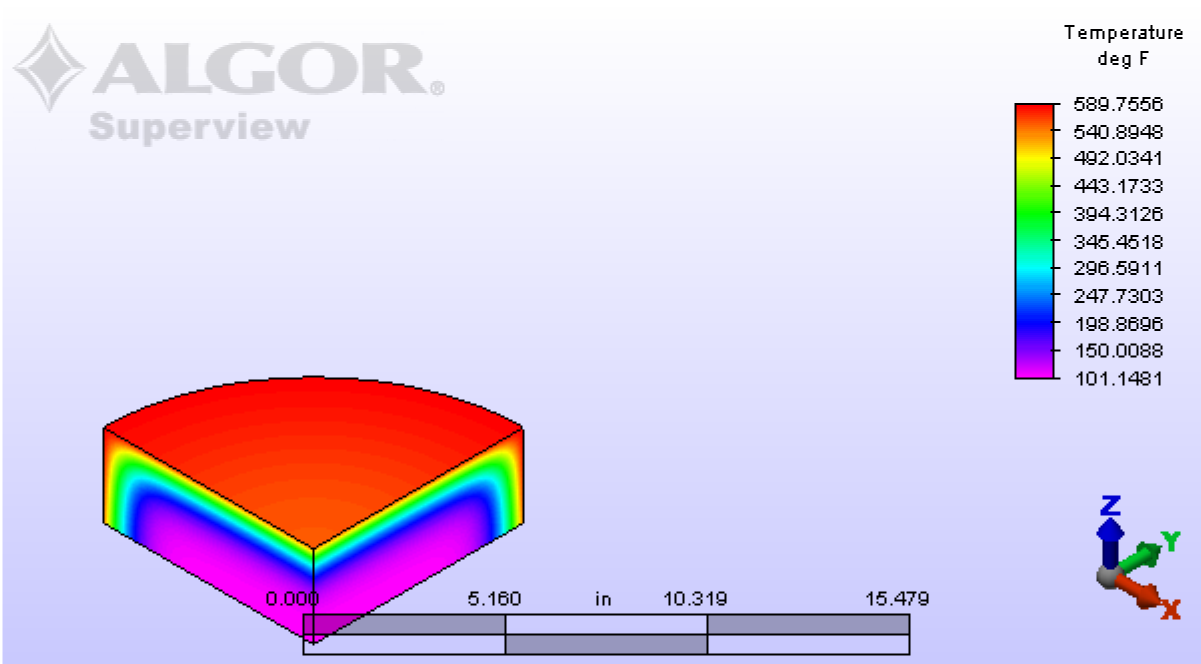

Figure 3-12 Fire Event and Cool-down temperature at 55 total minutes, polyurethane plug

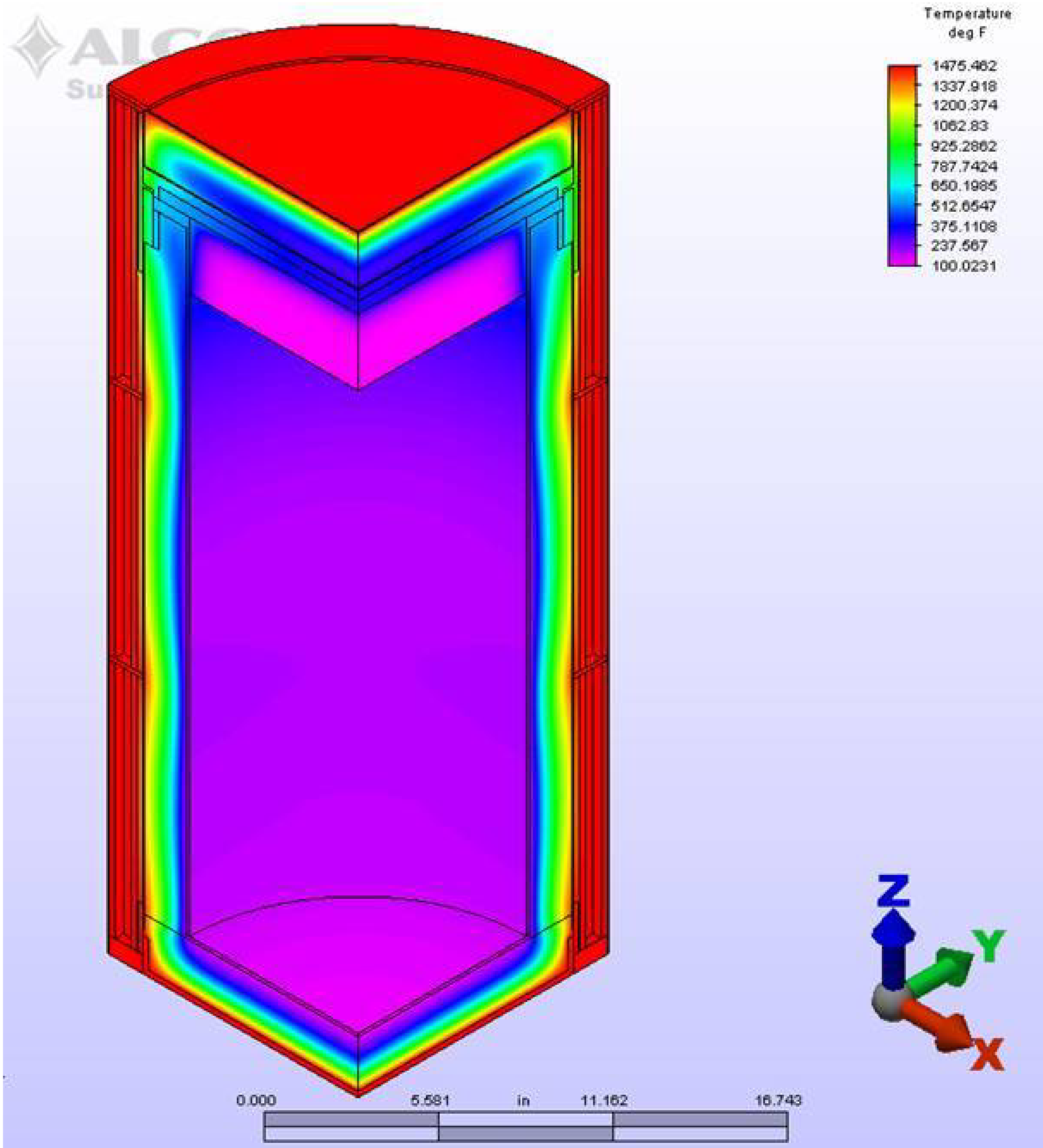

Figure 3-13 Fire Event temperature at 30 minutes, Isometric view of temperature distribution

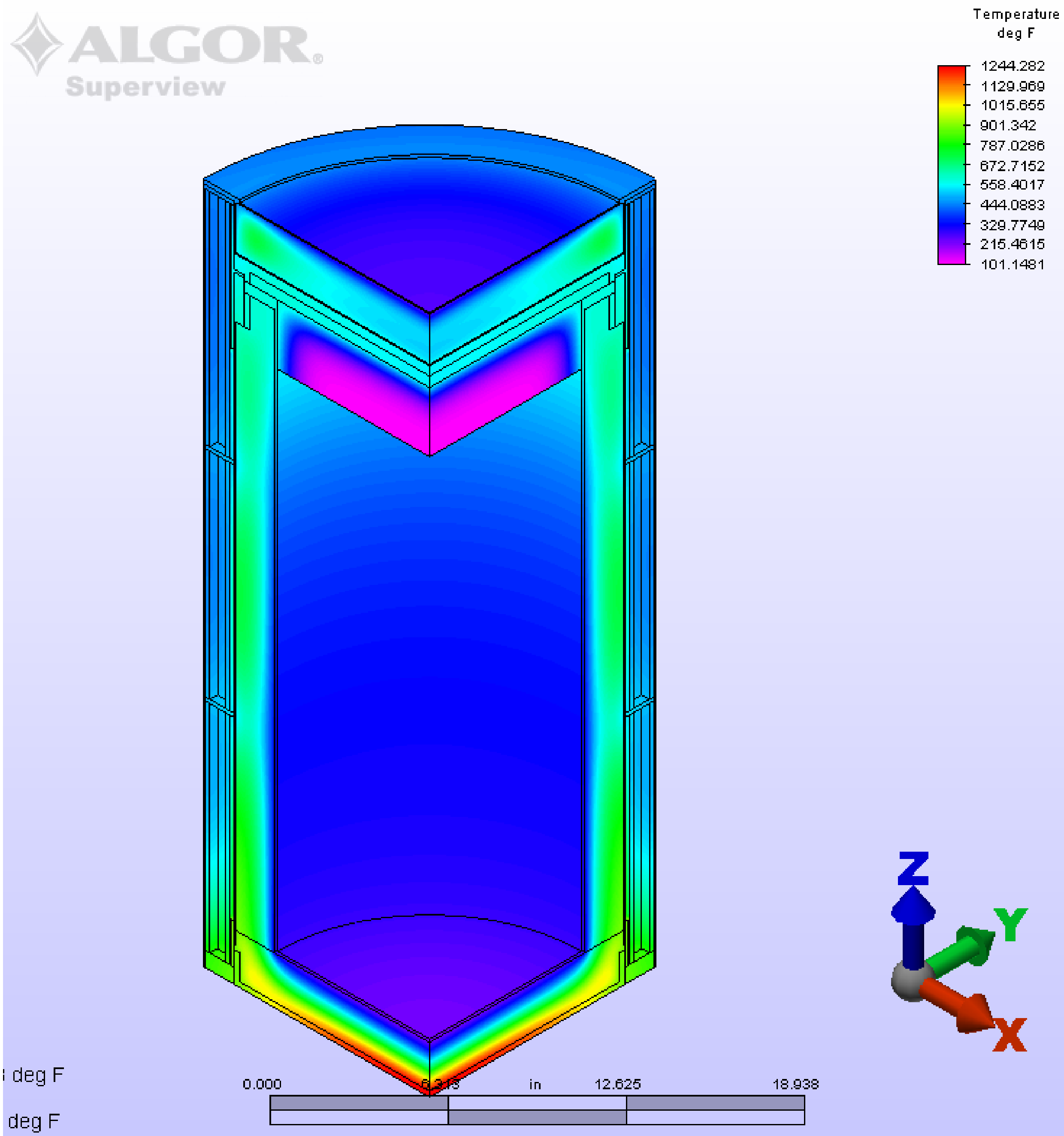

Figure 3-14 Fire Event and Cool-down temperature at 55 total minutes, Isometric view of temperature distribution

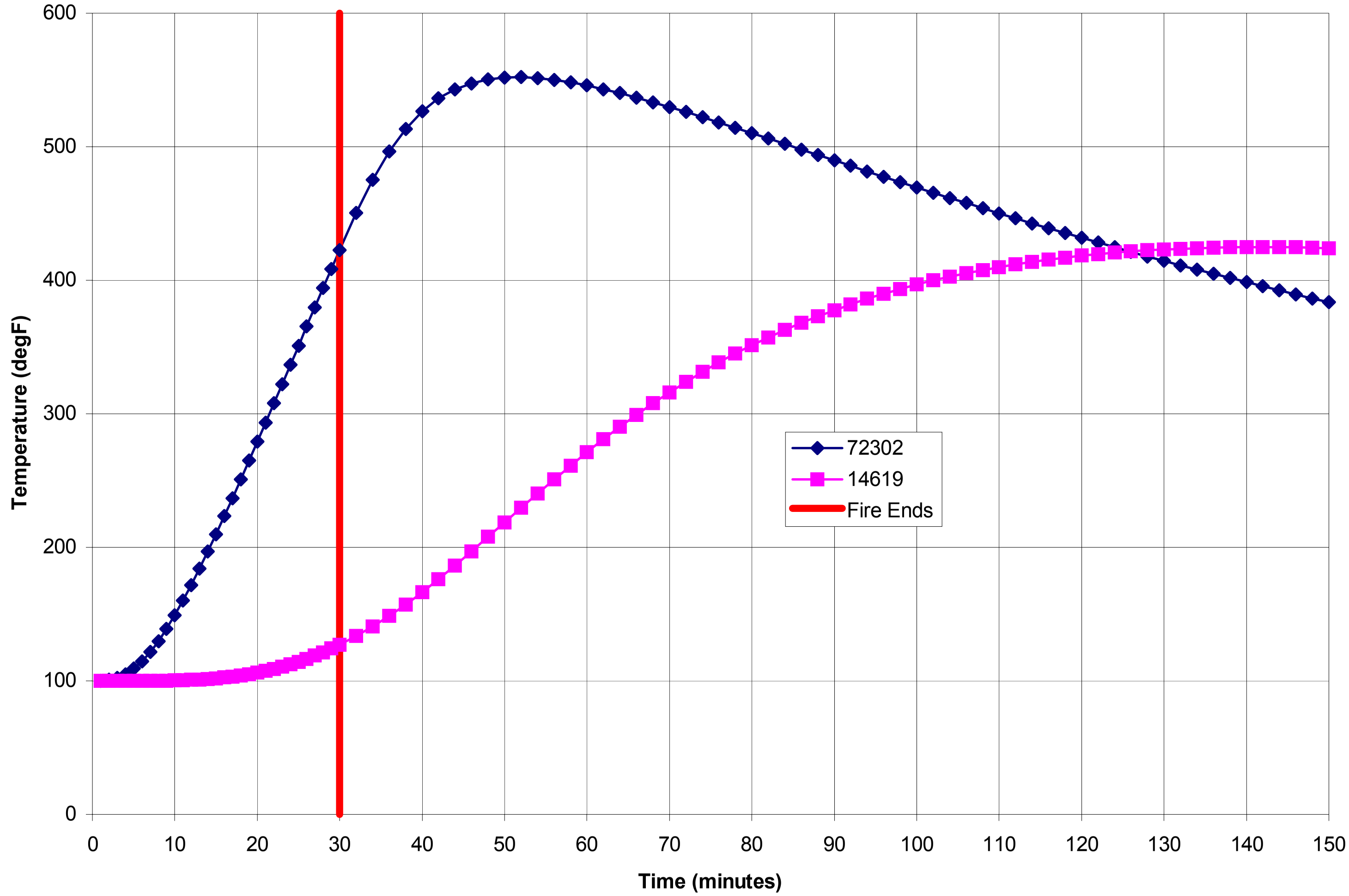

Figure 3-15 Fire Event and Cool-down temperature as a function of Seconds (beginning of cool-down= 0sec) for Payload Cavity Nodes 72302 (at the bottom of the polyurethane insert) and 14619 (at the center of the payload cavity floor part PB)