Attachment D

Training & Equipment Calibration Records

(8 Pages)

Starett 100' Tape Measure Calibration Record

CENTURY INDUSTRIES **D42**

Calibration Record of Measurement and Test Equipment

Page 1 of 1

Equipment No: S/N 08461846 **Description:** 100 Ft. Tape

Frequency: 5 Years **Location:** Office

Calibrated by: Starrett Company ☐ CPI ☑ Outside Lab **For Certification see File No:**

CALIBRATION INSTRUCTIONS:

Testing is conducted in accordance with ISO 17025, ISO Guide 25, ANSI/NCSL Z540-1 and Mil-STD-45662A and shall be traceable to N.I.S.T.

RESULTS: Acceptable N.I.S.T. Test No. 821/271887

BY: The L.S. Starrett Company

DUE DATE: November 17, 2013

DATE CALIBRATED: November 17, 2008

Starrett®

The L.S. Starrett Company
121 Crescent Street
Athol, MA 01331-1915 USA
Tel.: 978 249-3551
Fax.: 978 249-8495
www.starrett.com

ATTN: QUALITY ASSURANCE
MCMASTER-CARR SUP CO
6100 FULTON IND BLVD
ATLANTA GA 30336-2853

NOVEMBER 17, 2008

STANDARD LETTER of CERTIFICATION

THIS IS TO CERTIFY THAT THE ITEM LISTED BELOW MEETS THE REQUIREMENTS OF ACCURACY OF THE APPLICABLE SPECIFICATION ON DATE OF SHIPMENT.

STANDARDS AND EQUIPMENT USED FOR INSPECTION ARE CERTIFIED ACCURATE WITH REFERENCE TO 68 DEGREES F, TRACEABLE TO MASTER STANDARDS AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, WASHINGTON, D.C. CALIBRATION IS PERFORMED WITH TRANSFER STANDARDS WHICH ARE PROGRESSIVELY MORE ACCURATE IN THE ORDER OF 4: 1.

WE ATTEST THAT OUR MEASURING AND TEST EQUIPMENT, AND CALIBRATIONS PERFORMED ON THE ITEM (S) LISTED BELOW, ARE IN ACCORDANCE WITH ISO 17025, ISO GUIDE 25, ANSI/NCSL Z540-1 AND MIL-STD-45662A.

YOURS VERY TRULY,
THE L. S. STARRETT COMPANY

Candace Sheffield

DEXTER J. CARLSON,
CHIEF INSPECTOR

YOUR ORDER NO.	OUR ORDER NO.	TOOL	SPECIFICATION
QA-87917960	1335247	530-100 TAPE S/N 08461846	GGG-T-106F NIST HANDBOOK #44

N.I. S.T. TEST NO.
821/271887

ACCURACY-WHEN THE TAPE IS SUPPORTED ON A HORIZONTAL SURFACE, AND PULLED WITH A TENSION OF 10 POUNDS AT A TEMPERATURE OF 68 DEGREES FAHRENHEIT, THE OVERALL LENGTH WILL NOT BE IN ERROR BY MORE THAN .100" IN 100' OR LESS.

The estimated uncertainties reflect a Confidence Probability of approximately 95%.

PAGE 1 OF 1 08461846 MCMASTERCARR 1335247 .doc

Calibration Record for Dickson Data Thermometer

CENTURY INDUSTRIES **D42**

Calibration Record of Measurement and Test Equipment

Page 1 of 1

Equipment No: 09057179 **Description:** Dickson Temperature Recorder Model SM320

Frequency: 1 Year **Location:** Office

Calibrated by: Dickson Calibration Services ☐ CPI ☒ Outside Lab **For Certification see File No:**

CALIBRATION INSTRUCTIONS:

Calibrate in accordance with the ISO 17025 and ANSI/NCSL Z540-1 1994

And Traceable to the National Institute of Standards and Technology

RESULTS: Acceptable

BY: Dickson Calibration Services

DUE DATE: February 01, 2010

DATE CALIBRATED: February 01, 2009

Dickson Certificate of Instrument's Initial Calibration

Re-calibration instructions below

Models: SM300/320/325/420/720/725, TM320/325/725, VFC320/325

Calibration Procedure: The customer instrument was compared to the calibration standard. Drifts and faults were determined, and any necessary mechanical or electronic adjustments were taken. The Dickson calibration system conforms to the requirements of ISO 17025 and ANSI/NCSL Z540-1-1994 as appropriate.

Calibration Standards: (The Dickson Calibration Standards are traceable through NIST and are re-certified anually)

- General Eastern Chilled mirrors and RTD (± .4RH, ±.4°F)
- Azonix A1011 PRTD (±.2°F)- Ectron Thermocouple Simulator (± .4°F)

Accuracy Specifications:

- SM300 / SM320 / SM720 internal temperature: ±.8 °F / ± 1.8 °F
- TM320 / TM325 / TM725 temperature accuracy: ±.8°F
- TM320 / TM325 / TM725 RH: ±2%RH from 0 to 60%, ±3% from 60 to 95%
- SM320 / SM325 SM720 / SM725 VFC320/325 external temperature: ±1.8°F (Unit Only)
- SM420 Platinum RTD, ±0.5°F

For Your Next Calibration

This is a precision instrument that requires re-calibration. We recommend every 6-12 months.

Just send this completed form along with your instrument to Dickson, labeling the outside of the box with "CCM"...it's that simple!

A) Purchase Order #: ____________________
Name: ____________________ Phone: ____________________
Model Serial #: ____________________

B) **A 3-pt Deluxe NIST will be performed unless otherwise requested**

- ☐ 1-Point NIST Calibration $156.00
- ☐ 3-Point NIST Calibration $209.00
- ☐ 3-Point A2LA Accredited 3-pt. Calibration $315.00 (includes incoming readings)
- ☐ N995 - User selectable NIST Temperature points $50.00 each (to be selected in addition to one of the above calibration options)

Prices are subject to change

C) Please Return:
- ☐ Ground Freight*
- ☐ 2nd Day Air*
- ☐ Next Day*

***Charges added at factory**

Returned UPS 2nd Day unless otherwise requested

D) Ship to: ____________________

Bill to: ____________________

Let Dickson remind you the next time your unit is due for calibration. Join Calibration Club and receive calibration reminders free on all of instruments, including all non-Dickson brands of instrumentation. Learn more and register on-line at www.dicksonweb.com

Dickson Calibration Services
930 South Westwood Avenue Addison, Illinois 60101
Phone: 630-543-3747 Fax: 630-543-0498
www.dicksondata.com

Calibration Record for PTC Surface Thermometer

CENTURY INDUSTRIES D42

Calibration Record of Measurement and Test Equipment

Page 1 of 1

Equipment No: 05548 **Description:** PTC Instruments Model 330F -100°F to +160°F

Frequency: 3 Months **Location:** Office

Calibrated by: Century Industries ☒ CPI ☐ Outside Lab **For Certification see File No:**

CALIBRATION INSTRUCTIONS:

Surface thermometer shall be place on a flat surface next to the NIST Traceable gauge. The thermometers should be allowed to equalize for a period of not less than 15 minutes at the ambient air temperature. The readings shall be within ± 2°F. A second reading shall also be obtained by placing both units in a cooling chamber, allowing the gauges to equalize for not less than 15 minutes. The reading shall be within ± 2°F. Calibrate in accordance with the ISO 17025 and ANSI/NCSL Z540-1 1994 and Traceable to the National Institute of Standards and Technology.

RESULTS: Acceptable

BY: Century Industries

DUE DATE: October 09, 2009

DATE CALIBRATED: July 09, 2009

Floor Scale

CENTURY INDUSTRIES D42

Calibration Record of Measurement and Test Equipment

Page 1 of 1

Equipment No: 98530806V1812 **Description:** 0-330 Pounds Scale

Frequency: 12 Months **Location:** Office

Calibrated by: Carlton Scale ☐ CPI X☐ Outside Lab For Certification see File No: ______

CALIBRATION INSTRUCTIONS:

1. Using certified check weights verify that readings are within ± 2 pounds of full scale.

RESULTS: Acceptable

BY: Carlton Scale

DUE DATE: February 15, 2010

DATE CALIBRATED: February 15, 2009

Indoctrination or Training Session Outline **D52**

Century Industries

P.O. Box 17084
Bristol, VA 24209
423-646-1864

Page 1 **of** 1

Title **TEST SPECIFICATION & TEST PLAN FOR THE VERSA-PAC SHIPPING CONTIANER** **Type:** ☑ **Indoct.** ☑ **Training** **Recommended Min. Duration:** 40 min.	**Dept** **Testing Assistants** **Outline No** **4F** **Rev.** **0** **APPROVED:** [signature] 2-25-09 **Department Manager** **Date** [signature] 2-25-09 **QA Manager** **Date**

1. **Review duties and responsibilities per:**

   TS-001 Rev. 0 – Versa-Pac Test Specification

   TP-001 Rev. 0 – Versa-Pac Shipping Container Test Plan

Session Record **D50**

Century Industries

P.O. Box 17084
Bristol, VA 24209
423-646-1864

TEST PERSONNEL

Department

Position/Job Classification: **Test Assistant**

Outline Number: **4F** **Date Completed** 2-25-09 **Duration** 1 HR.

Remarks:

Instructor **Date** 2-25-09

The following Personnel have satisfactorily completed the above indoctrination or training outline:

Employee	**Employee**

Appendix 2.12.5

NCT Versa-Pac Test Report for Compression & Penetration
(Consisting of 16 Pages)

Century Industries Box 17084, Bristol, Virginia 24209
Phone: 423-646-1864 E-mail:CenturyIndWMA@aol.com

Test Report

NCT Evaluation Test Series (Compression & Penetration) Of Century Industries' Versa-Pac Shipping Containers

US NRC Docket Number 71-9342

Prepared & Conducted By:
Century Industries
William M. Arnold

Prepared By: ______________________ Date: __________

Table of Contents

1.0 INTRODUCTION

This Report describes the methods and guidelines Century Industries followed for the testing of the Versa-Pac Shipping Container in accordance with the requirements specified in 10 CFR 71. The test program was conducted by Century Industries located in Bristol, Virginia between December 15 & 16. This report includes the objective, procedure, item description, test results, test records and other applicable documents including photographs of the testing.

2.0 OBJECTIVE

The objective of this test series was to conduct the physical performance evaluation tests for Century Industries Versa-Pac Shipping Containers by the designer and manufacturer of the package, in accordance with the normal conditions specified in Title 10 Part 71.71(9) and 71.71(10).

The test items were identified as Versa-Pac shipping container previously tested prototype and subjected to the following performance tests:

1. Initial visual inspection of the outer container surfaces for pre-existing damage from the original HAC test series.

2. Penetration testing in accordance with 10 CFR 71.71(10) and Compression in accordance with 10 CFR 71.71(9).

3. Post Test Visual Inspection of the outer container surfaces.

Following each test the physical condition of the shipping container was inspected and the results recorded.

3.0 RESPONSIBILITIES

Century Industries personnel conducted the test series and were responsible for the base analysis of the test articles, and oversight of the test series

The test series was performed in accordance with the applicable requirements and guidance of Century Industries QA Program QA-1 Revision 1 and 10 CFR 71.

The test manager was William M. Arnold, President of Century Industries.

4.0 TEST ITEM IDENTIFICATION

Century Industries was responsible for the design, fabrication, inspection, and measurements of the previously tested package. 55 Gallon Package - Serial Number 10553. This package was utilized in the 55 gallon test series for shallow angle impacts and penetration test reported in Appendix 2.12.4.

5.0 TEST ITEM DESCRIPTION

The Versa-Pac Shipping Container is designed for the shipment of Type A radioactive and fissile materials in the form U-metal, oxides, fluorides and nitrate for both product and scrap materials. The fissile payload was design for 350 grams at 100% enrichment and a criticality safety index of 1.5.

The Versa-Pac Shipping Container was designed in two basic versions, a UN1A2 -55 gallon and 110 gallon outer drum with a 16 gauge body, bottom and cover, in addition to the standard 12 gauge closure ring with a 5/8" ASTM A307 bolt, the cover is reinforced and secured using the addition of bolts attached to the internal structure of the package as detailed in the design drawings. The internal structure consists of vertical and horizontal stiffeners at specific points around the package. Outer and inner 16 gauge liners, with an insulating ceramic fiber blanket between the liners complete the primary inner structural components. A secondary barrier of insulation consisting of ceramic fiber blanket; surround the inner containment body. The payload gasket is a woven fiberglass yarn in a flexible substrate, coated with high grade silicone rubber. The gasketed payload containment cavity is made of 10 gauge body and bottom with a ¼" thick top flange to which in the initial series of testing, a 3/16" thick top flange was secure using 12 -1/2" bolts. In the second round of testing the 3/16" thick flange was replaced by a ½ " thick flange and secured by the same number of bolts. The payload cavity is attached to the internal structural components by use of a bolted connection through a fiberglass thermal break between the payload cavity and the structure. Closed cell polyurethane foam is utilized to provide insulation and added impact protection, to both the top and bottom of the Versa-Pac. The top insulation plug is encapsulated in sheet metal welded to the outer drum closure lid. Plastic plugs enclosed within the body of the structure provide a path for venting to the external acetate plug on the exterior of the drum. The cavity is designed to be loaded directly or with the use of an insert to reduce the diameter or with up to a 30 gallon standard drum.

The Versa-Pac was designed in accordance with the requirements of 10 CRF 71 [1] and Century Industries – QA-8, Plan for Manufacture of Versa-Pac Shipping Containers [2].

Pre-Test Photographs

Previously Dropped Prototype

6.0 TEST FACILITES & EQUIPMENT

6.1 Release Device

The release device utilized was capable of releasing the package in a manner that provided a smooth clean drop without imparting any twisting or turning of the package. The device has a safe working load limit of 18,000 pounds. The test articles were lifted into place by use of a crane.

6.2 Measurements and Weights

Penetration rod drop heights were determined by use of a pre-measured slide tube set by a 100 foot steel tape measure Serial Number 08461846, calibrated by Starett Company and traceable to NIST.

6.3 Temperature

Surface and air temperatures were obtained using calibrated surface gauge Serial Number 05548 with a range of -100°F to +160°F and Dickson Temperature Recorder Model SM320 and traceable to NIST.

6.4 Puncture Device

The puncture device consists of a 1.25 inch diameter carbon steel round bar, weighing 13.2 pounds.

6.5 Photographic Equipment

Color photographs were taken with a Sony 4.1 Mega pixel digital camera by Century Industries.

7.0 EQUIPMENT AND INSTRUMENT CALIBRATION

All applicable test and measurement equipment was calibrated in accordance with Century Industries Quality Assurance Program. Test and measurement calibration certificates are found in Attachment A. The instrumentation used during testing is listed in Table 1 below.

ITEM	MODEL	S/N	CALIBRATION DUE DATE	COMENTS
16' Tape Measure	N/A	QC-001	May 05, 2010	Used to measure drop height for penetration bar
Dickson Temperature Recorder	SM320	09057179	February 01, 2010	Used to calibrate surface thermometer and record air temperature
PTC Instruments Surface Thermometer	330F	05548	January 09, 2010	Used to measure the temperature of the test articles during the conditioning

Table 1 – Test Instruments

8.0 ACCEPTANCE CRITERIA

The acceptance criteria for this series of testing was (Penetration) retention of the outer closure, no openings, tears or failure that would lead to loss of materials, no open pathway to the insulation materials and (Compression) no buckling of side walls.

9.0 TEST PREPARATION AND RESULTS

9.1 Initial Inspection

On December 15, 2009, the visual inspection of the previously used test item was conducted prior to performing any of the required evaluation tests in order to determine if any unacceptable damage would occur due to the penetration and compression testing.

9.2 Article Temperature

All tests were performed with the test article at ambient temperature of 65°F. Test packages had been stored inside and tests were conducted at that location.

10.0 PENETRATION DROP TEST SEQUENCE

The penetration drop test locations were chosen based upon historical drop testing of similar products and damage results. The test article was utilized in a previous HAC test series. The test article was produced in accordance with the fabrication drawings and QA-8, plan for the Manufacture of Versa-Pac Shipping Containers.

10.1 Penetration Bar Drop – Sidewall Over Vertical Stiffener

The test article was positioned horizontally on a flat 8 inch concrete floor with the penetration bar positioned vertically directly over a vertical inner stiffener thru the outer sidewall of the package. The bar was lifted to a height 40 inches (1 meter) and allowed to be released through a 2 inch PVC guide tube to provide the correct impact on the surface of the test package.

Pre-Drop Surface

Penetration Set-up

10.2 Results

The result of this impact to the sidewall of the test articles resulted in un-measurable damage to the package impact area.

Post Drop Results

10.3 Penetration Bar Drop – Sidewall Between Vertical Stiffeners

The test article was positioned horizontally on a flat 8 inch concrete floor with the penetration bar positioned vertically directly between two vertical inner stiffener thru the outer sidewall of the package. The bar was lifted to a height 40 inches (1 meter) and allowed to be released through a 2 inch PVC guide tube to provide the correct impact on the surface of the test package.

Penetration Set-up

Post Test Results No Damage

10.4 Results

The result of this impact to the sidewall of the test articles resulted in measurable damage to the package impact area with only a slight marring of the package paint.

10.5 Penetration Bar Drop – Top Drum Lid Outer Closure

The test article was positioned vertically on a flat 8 inch concrete floor with the penetration bar positioned vertically directly between on the center of the drum lid of the package. The bar was lifted to a height 40 inches (1 meter) and allowed to be released through a 2 inch PVC guide tube to provide the correct impact on the surface of the test package

Pre-Drop Surface

Penetration Set-up

10.6 Results

The results of this drop produced a slight marring of the drum lid surface.

Post Test Damage - Marring

11.0 Compression Test

The compression test was conducted in accordance with the requirement of 71.71(c)(9). The test article was utilized in a previous HAC & NCT test series. The test article was produced in accordance with the fabrication drawings and QA-8, plan for the Manufacture of Versa-Pac Shipping Containers.

11.1 Compression Loading

The test article was positioned vertically so that the load was directly applied to the top of the package. The test article weighed 624.5 pounds, to meet the requirement of 5 times the weight of the package; a load of 3,200 pounds was loaded on the top surface of the package, for a period of 24 hours.

11.2 Results

No damage or buckling of the package was found upon inspection of the test article.

Stacking Test

Stacking Test

12.0 FINAL CONCLUSIONS OF ALL TEST RESULTS

The results of this test series were found to have little to no affect on the test article and found to be in compliance with the requirements of the 10 CFR 71.71(c)(9) and 71.71(10).

13.0 ATTACHMENTS, REFERENCES & CALIBRATION RECORDS

Attachment A –Calibration Records
Reference 1 – 10 CFR Part 71
Reference 2 – NUREG 6818

Attachment A

Equipment Calibration Records

(5 Pages)

Starett 100' Tape Measure Calibration Record

CENTURY INDUSTRIES **D42**

Calibration Record of Measurement and Test Equipment

Page 1 of 1

Equipment No: S/N 08461846 **Description:** 100 Ft. Tape

Frequency: 5 Years **Location:** Office

Calibrated by: Starrett Company ☐ CPI ☒ Outside Lab **For Certification see File No:** ______

CALIBRATION INSTRUCTIONS:

Testing is conducted in accordance with ISO 17025, ISO Guide 25, ANSI/NCSL Z540-1 and Mil-STD-45662A and shall be traceable to N.I.S.T.

RESULTS: Acceptable N.I.S.T. Test No. 821/271887

BY: The L.S. Starrett Company

DUE DATE: November 17, 2013

DATE CALIBRATED: November 17, 2008

Starrett®

The L.S. Starrett Company
121 Crescent Street
Athol, MA 01331-1915 USA
Tel.: 978 249-3551
Fax.: 978 249-8495
www.starrett.com

ATTN: QUALITY ASSURANCE
MCMASTER-CARR SUP CO
6100 FULTON IND BLVD
ATLANTA GA 30336-2853

NOVEMBER 17, 2008

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YOURS VERY TRULY,
THE L. S. STARRETT COMPANY

DEXTER J. CARLSON,
CHIEF INSPECTOR

YOUR ORDER NO.	OUR ORDER NO.	TOOL	SPECIFICATION
QA-87917960	1335247	530-100 TAPE S/N 08461846	GGG-T-106F NIST HANDBOOK #44

N.I. S.T. TEST NO.
821/271887

ACCURACY-WHEN THE TAPE IS SUPPORTED ON A HORIZONTAL SURFACE, AND PULLED WITH A TENSION OF 10 POUNDS AT A TEMPERATURE OF 68 DEGREES FAHRENHEIT, THE OVERALL LENGTH WILL NOT BE IN ERROR BY MORE THAN .100" IN 100' OR LESS.

The estimated uncertainties reflect a Confidence Probability of approximately 95%.

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CENTURY INDUSTRIES D42

Calibration Record of Measurement and Test Equipment

Page 1 of 1

Equipment No: 09057179 Description: Dickson Temperature Recorder Model SM320

Frequency: 1 Year Location: Office

Calibrated by: Dickson Calibration Services ☐ CPI ☐ Outside Lab For Certification see File No:

CALIBRATION INSTRUCTIONS:

Calibrate in accordance with the ISO 17025 and ANSI/NCSL Z540-1 1994

And Traceable to the National Institute of Standards and Technology

RESULTS: Acceptable

BY: Dickson Calibration Services

DUE DATE: February 01, 2010

DATE CALIBRATED: February 01, 2009

Dickson Certificate of Instrument's Initial Calibration

Re-calibration instructions below

Models: SM300/320/325/420/720/725, TM320/325/725, VFC320/325

Calibration Procedure: The customer instrument was compared to the calibration standard. Drifts and faults were determined, and any necessary mechanical or electronic adjustments were taken. The Dickson calibration system conforms to the requirements of ISO 17025 and ANSI/NCSL Z540-1-1994 as appropriate.

Calibration Standards: (The Dickson Calibration Standards are traceable through NIST and are re-certified anually)

- General Eastern Chilled mirrors and RTD (± .4RH, ±.4°F)
- Azonix A1011 PRTD (±.2°F)- Ectron Thermocouple Simulator (± .4°F)

Accuracy Specifications:

- SM300 / SM320 / SM720 internal temperature: ±.8 °F / ± 1.8 °F
- TM320 / TM325 / TM725 temperature accuracy: ±.8°F
- TM320 / TM325 / TM725 RH: ±2%RH from 0 to 60%, ±3% from 60 to 95%
- SM320 / SM325 SM720 / SM725 VFC320/325 external temperature: ±1.8°F (Unit Only)
- SM420 Platinum RTD, ±0.5°F

For Your Next Calibration

This is a precision instrument that requires re-calibration. We recommend every 6-12 months.

Just send this completed form along with your instrument to Dickson, labeling the outside of the box with "CCM"...it's that simple!

A) Purchase Order #: __________
Name: __________ Phone: __________
Model Serial #: __________

B) **A 3-pt Deluxe NIST will be performed unless otherwise requested**

- ☐ 1-Point NIST Calibration $156.00
- ☐ 3-Point NIST Calibration $209.00
- ☐ 3-Point A2LA Accredited 3-pt. Calibration $315.00 (includes incoming readings)
- ☐ N995 - User selectable NIST Temperature points $50.00 each (to be selected in addition to one of the above calibration options)

Prices are subject to change

C) Please Return:
- ☐ Ground Freight*
- ☐ 2nd Day Air*
- ☐ Next Day*

***Charges added at factory**

Returned UPS 2nd Day unless otherwise requested

D) Ship to: __________

Bill to: __________

Let Dickson remind you the next time your unit is due for calibration. Join Calibration Club and receive calibration reminders free on all of instruments, including all non-Dickson brands of instrumentation. Learn more and register on-line at www.dicksonweb.com

Dickson Calibration Services
930 South Westwood Avenue Addison, Illinois 60101
Phone: 630-543-3747 Fax: 630-543-0498
www.dicksondata.com

CENTURY INDUSTRIES **D42**

Calibration Record of Measurement and Test Equipment

Page 1 of 1

Equipment No: 05548	**Description:** PTC Instruments Model 330F -100°F to +160°F
Frequency: 3 Months	**Location:** Office
Calibrated by: Century Industries	☐ CPI ☐ Outside Lab **For Certification see File No:**

CALIBRATION INSTRUCTIONS:

Surface thermometer shall be place on a flat surface next to the NIST Traceable gauge. The thermometers should be allowed to equalize for a period of not less than 15 minutes at the ambient air temperature. The readings shall be within ± 2°F. A second reading shall also be obtained by placing both units in a cooling chamber, allowing the gauges to equalize for not less than 15 minutes. The reading shall be within ± 2°F. Calibrate in accordance with the ISO 17025 and ANSI/NCSL Z540-1 1994 and Traceable to the National Institute of Standards and Technology.

RESULTS: Acceptable

BY: Century Industries - WMA

DUE DATE: January 09, 2010

DATE CALIBRATED: October 09, 2009

SECTION THREE
THERMAL EVALUATION

Table of Contents

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.

Package contents are typically shipped in an axial array to fill the payload cavity. A fire proof perlite like packing material is used as dunnage to fill the voids between the cans and inner vessel wall. The Versa-Pac design allows for the use of two neoprene pads, a 1/8 inch bottom pad, and a 3/8 inch top pad. The pads serve the purpose of protecting the inner containment shell during repeated use. The use of these pads is optional.

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 normal hot maximum temperature for the payload (contents) is 144°F. During the HAC fire event, the maximum temperature for the payload (contents) occurs 22 minutes into the cool-down sequence, and is 552°F at the top of payload vessel. Additional analyses show that the average wall temperature is 360.4°F, and that the actual contents remains below 300°F during the fire and cool-down period.

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 used in the thermal analyses are provided in Tables 3.5.1-3 through 3.5.1-6. Mechanical material properties including the linear thermal expansion coefficient are provided in Table 2-2. The melting points of typical packing materials are provided in Table 1-4.

A melting point limitation of 600°F is required only for the radioactive contents of the package. The radioactive payload is a stable solid that does not undergo a change of state below 600°F. Given the maximum payload temperatures expected in a hypothetical accident condition (see Section 3.1.3), the radioactive payload will remain in solid form.

The Versa-Pac is not a sealed system; the internal pressure is maintained near atmospheric pressure for all conditions of transport (refer to Sections 4.2 and 4.3). Therefore, payload and materials that degrade or off-gas at temperatures below the HAC average vessel wall temperature of 360.4°F are acceptable for use in the Versa-Pac. The presence of residual moisture in the contents is also allowed.

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

In the case where the Versa-Pac is used for one-way transport and is either buried or destroyed upon reaching its destination, neoprene pads used as packing material within the containment vessel are not required. The Versa-Pac design allows for the use of two neoprene pads, a 1/8 inch bottom pad, and a 3/8 inch top pad. The pads serve the purpose of protecting the inner containment shell during repeated use. The use of these pads is optional. The neoprene material is not included in the thermal model. The flash point available in open literature for neoprene is approximately 500°F. Since the internal temperature of the containment vessel has been shown not to exceed 400°F, the inclusion of neoprene does not increase the thermal load of the package.

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.

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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.

3.3.1 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.

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°F at the top of payload cavity, just below the polyurethane plug, as shown in Figure 3.1. Supplemental thermal analysis of the vessel shows that the average wall temperature is 360.4°F and an analysis of the contents region of the payload vessel shows that the contents remain below 300°F during the fire and cool-down period (see Appendix 3.5.6).

3.4.1 Initial Conditions

The model imposes an initial condition of 100°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°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°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.

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.

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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.

3.4.6 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

3.5.6. Supplemental Thermal Evaluate of Package Contents

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	100°F
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

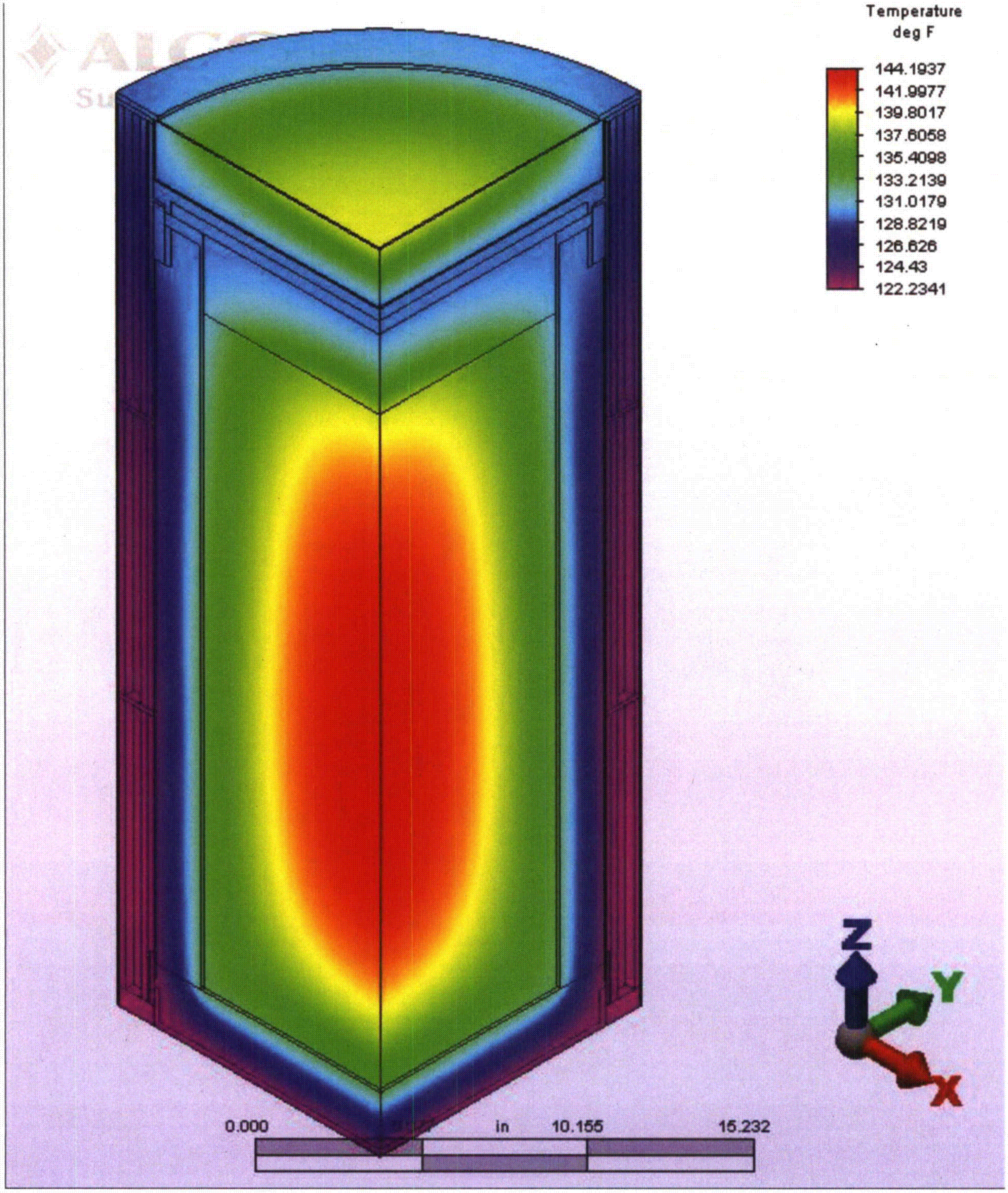


Figure 3-1 Normal Hot Package Peak Temperature Distribution, 55-gallon Versa-Pac

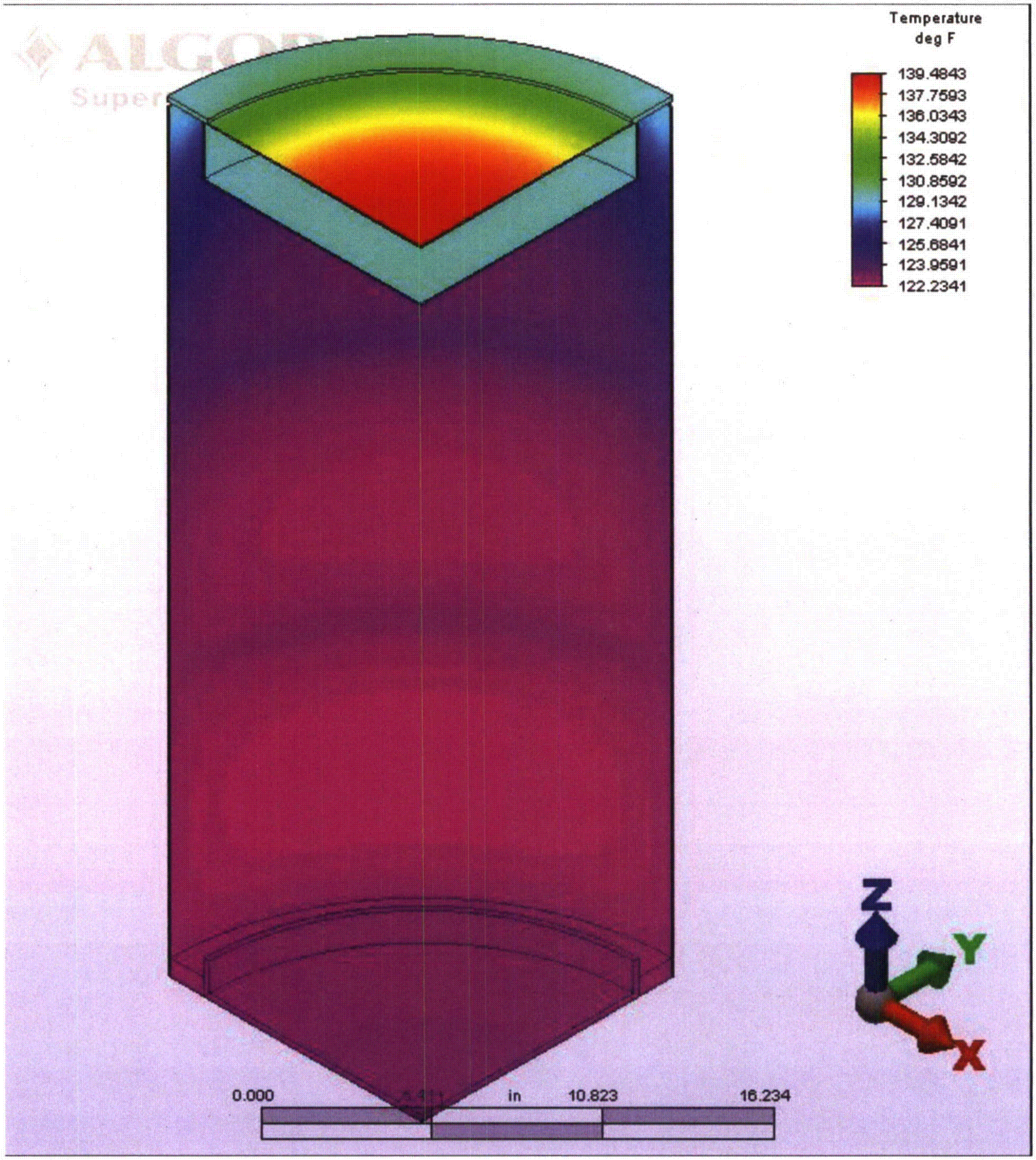


Figure 3-2 Normal Hot Outer Surface Peak Temperature Distribution, 55-gallon Versa-Pac

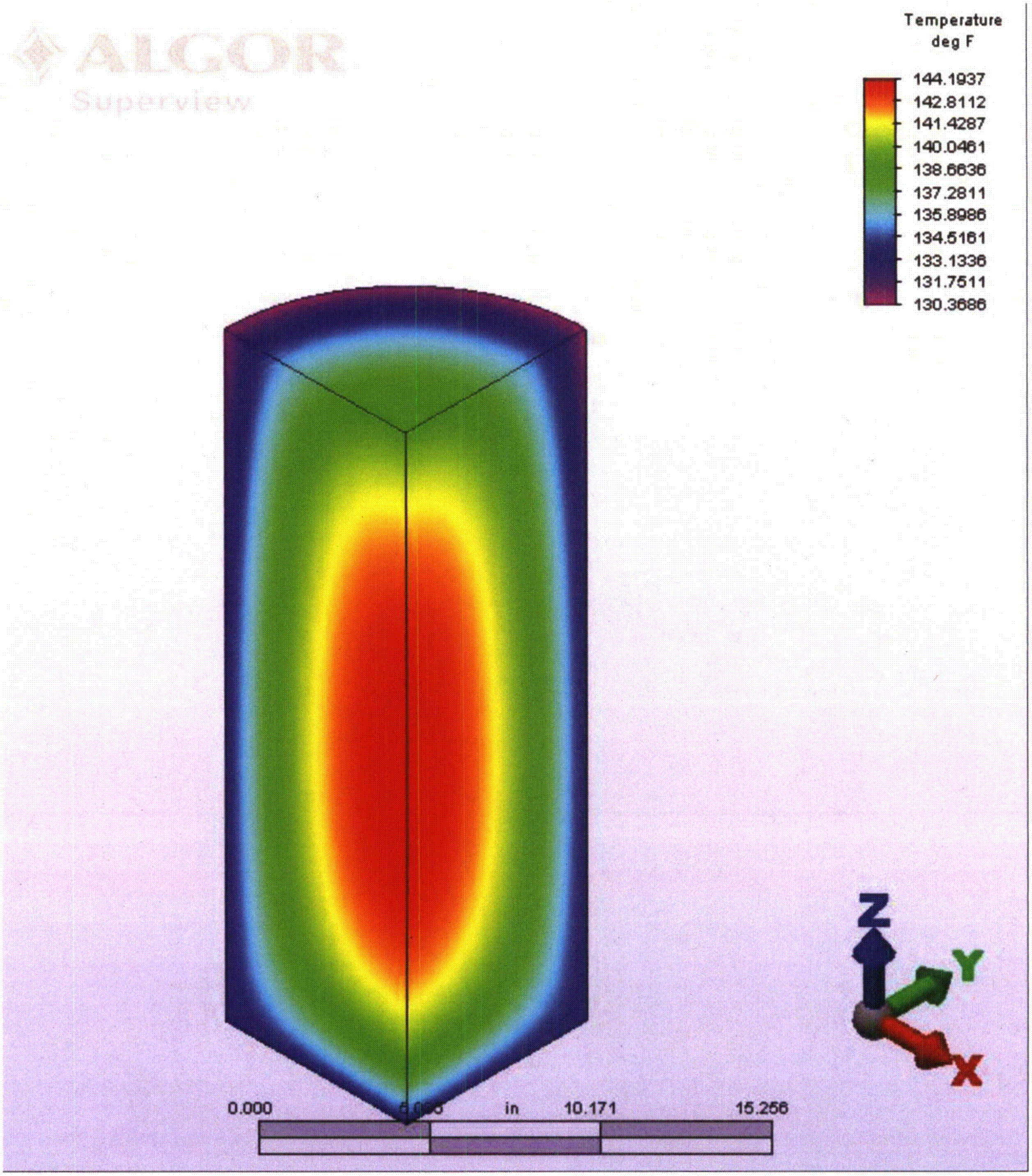


Figure 3-3 Normal Hot Contents Peak Temperature Distribution, 55-gallon Versa-Pac

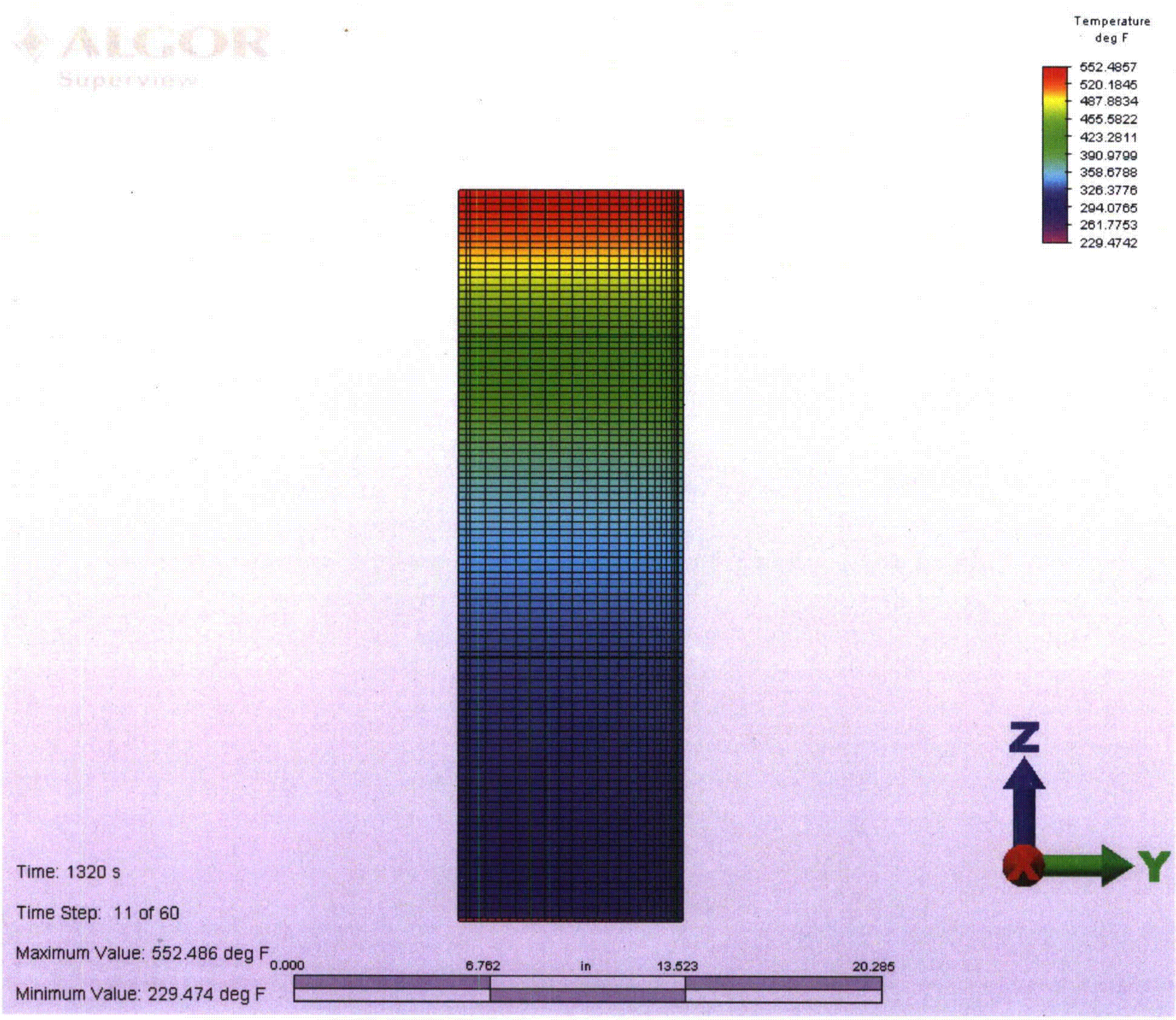


Figure 3-4 Maximum Fire Event Temperature at Cool-down Sequence, 22 minutes after Cessation of Fire, Contents

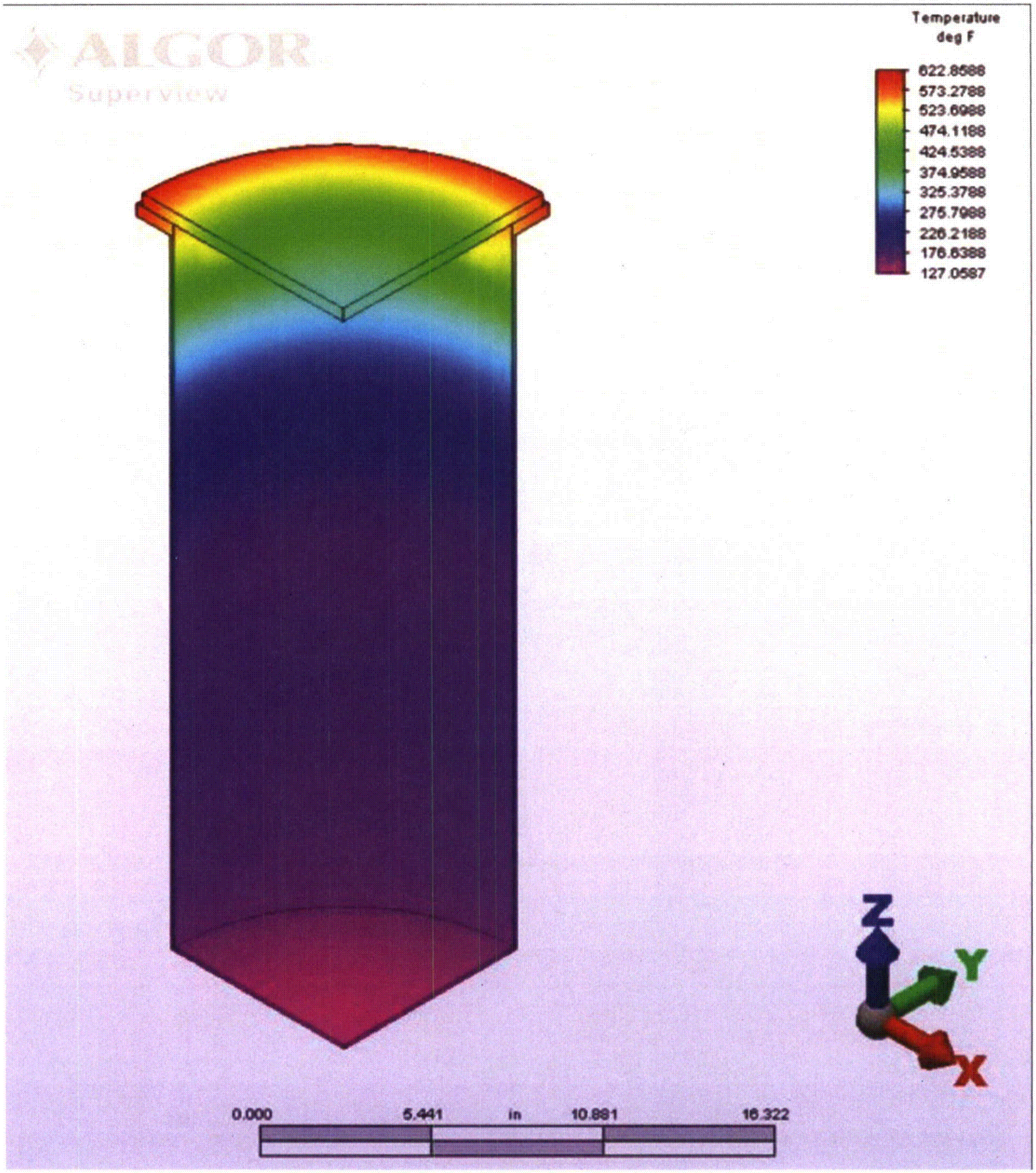


Figure 3-5 Fire Event temperature at 30 minutes, Payload Cavity and Flanges (including polyurethane plug area)

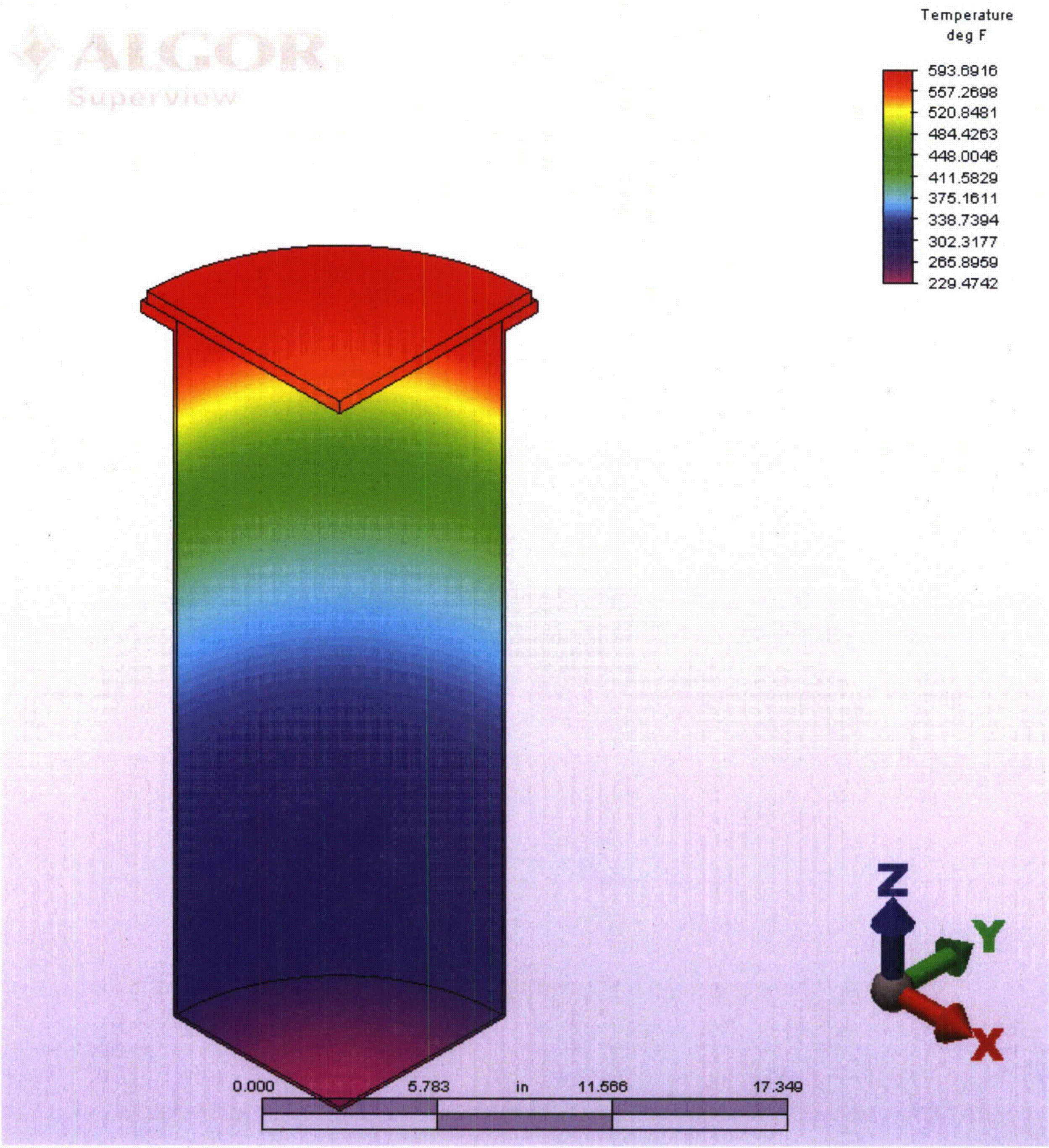


Figure 3-6 Fire Event & Cool-down temperature at 55 total minutes, Payload Cavity and Flanges (including polyurethane plug area)

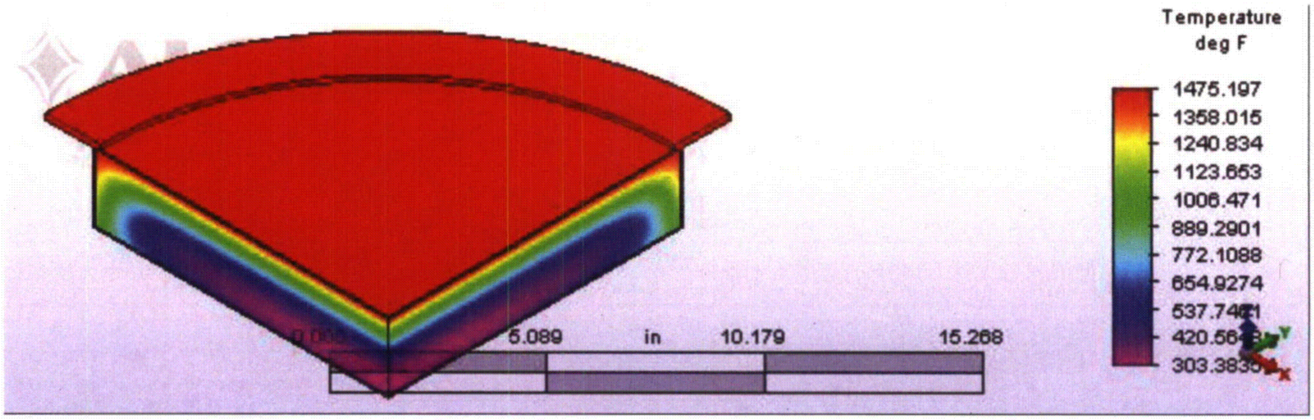


Figure 3-7 Fire Event temperature at 30 minutes, Package Lid

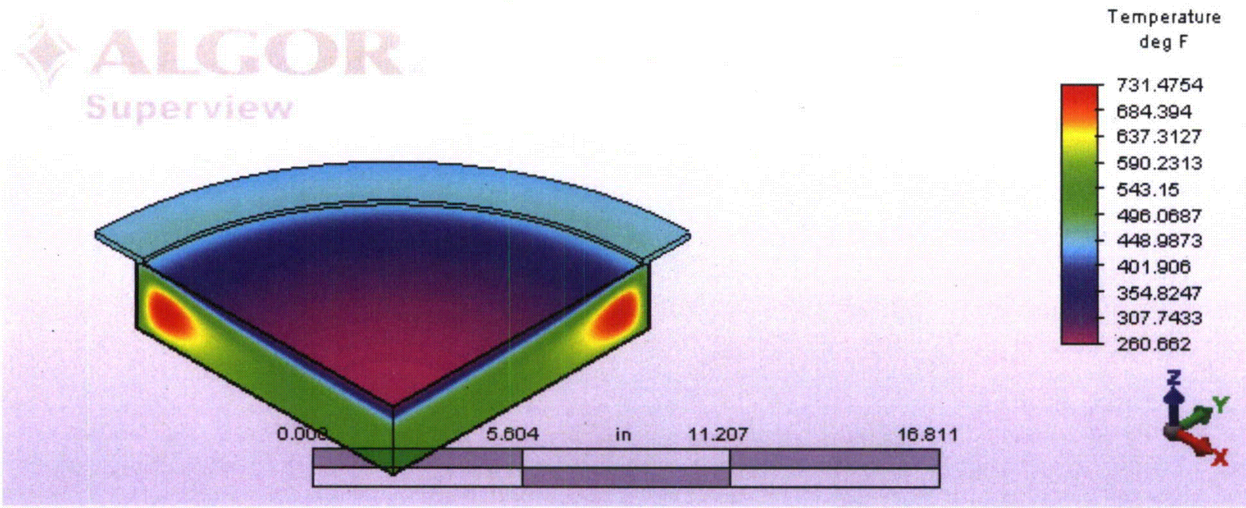


Figure 3-8 Fire Event and Cool-down temperature at 55 total minutes, Package Lid

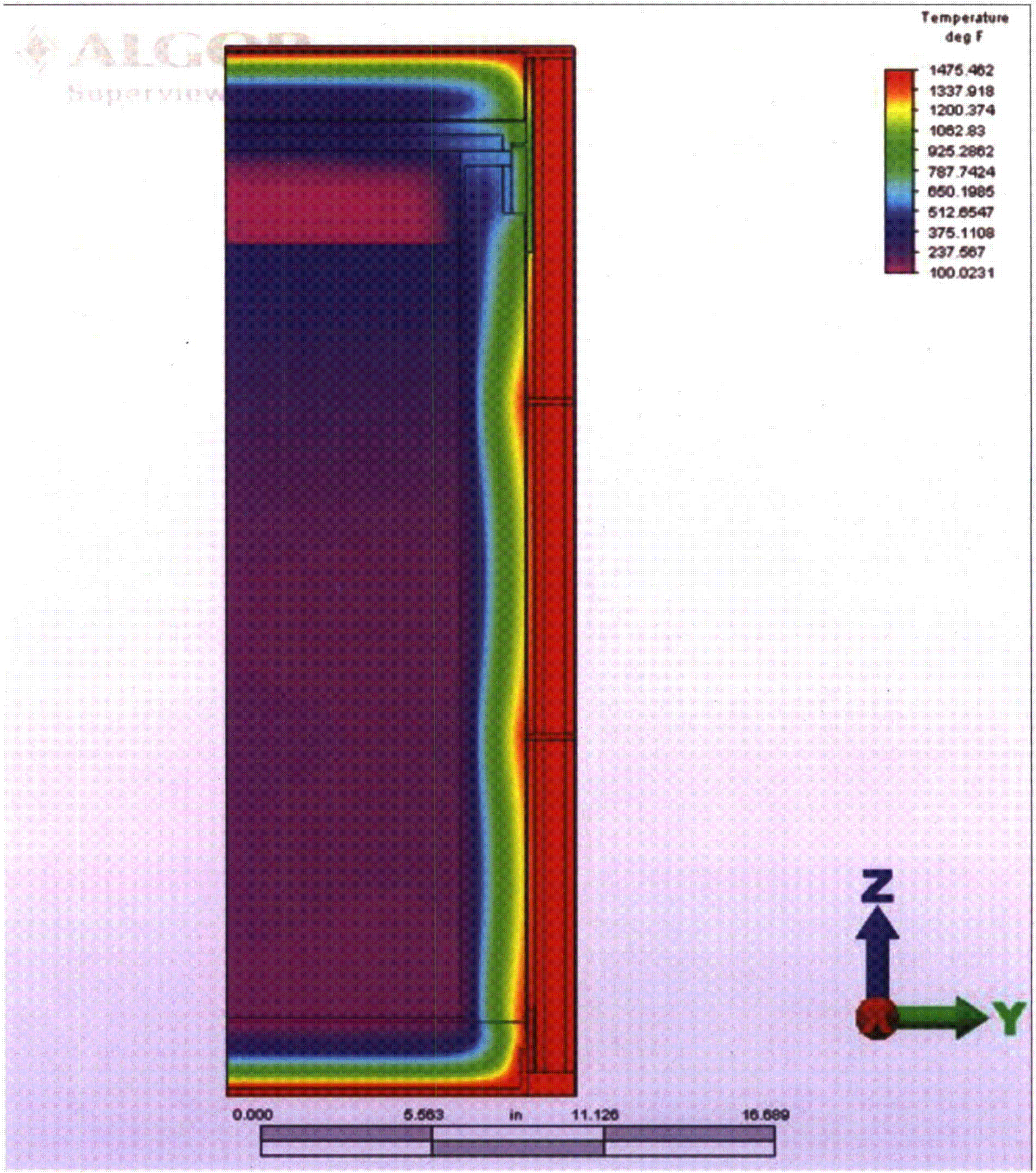


Figure 3-9 Fire Event temperature at 30 minutes, Package side view

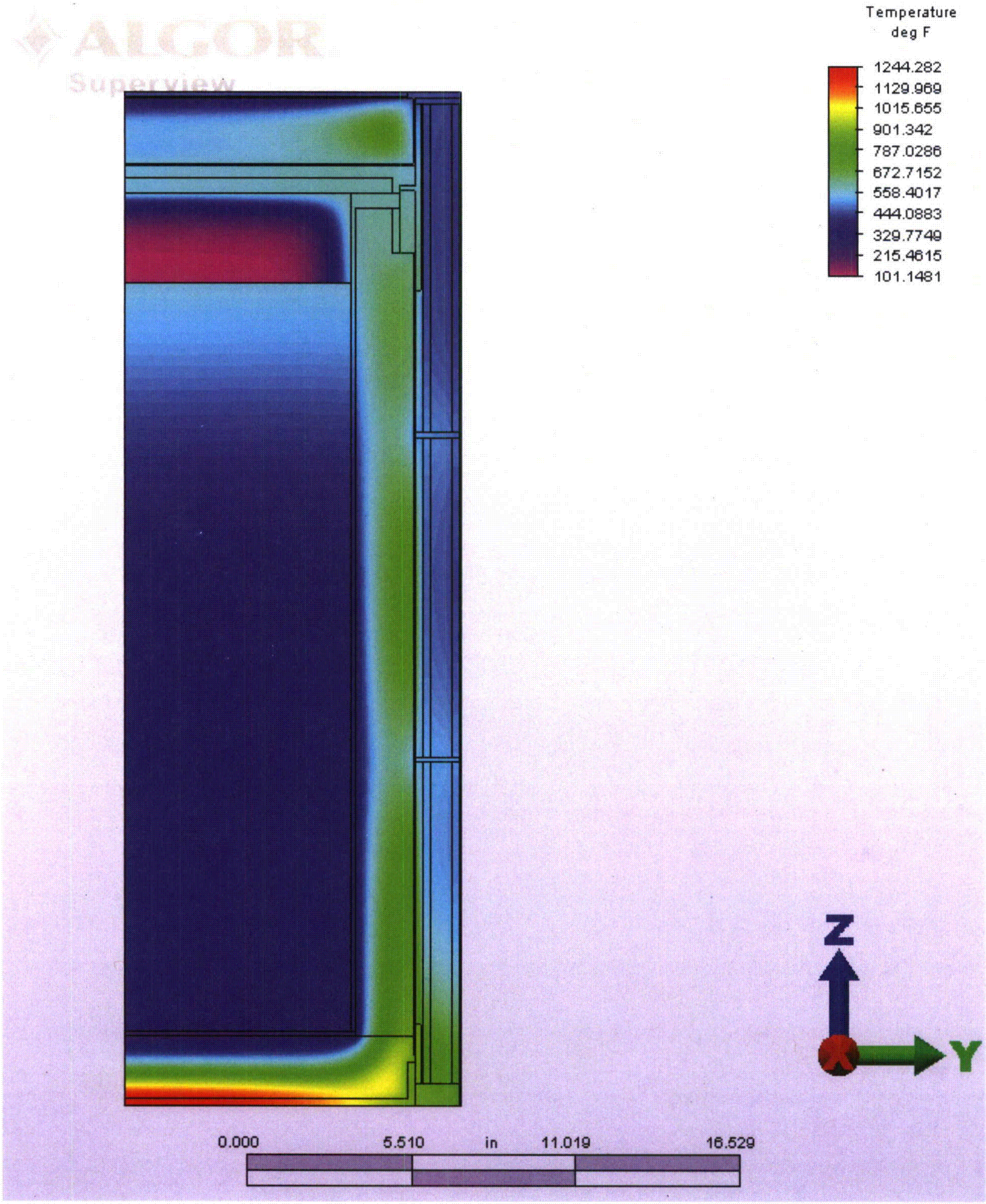


Figure 3-10 Fire Event and Cool-down temperature at 55 total minutes, Package side view

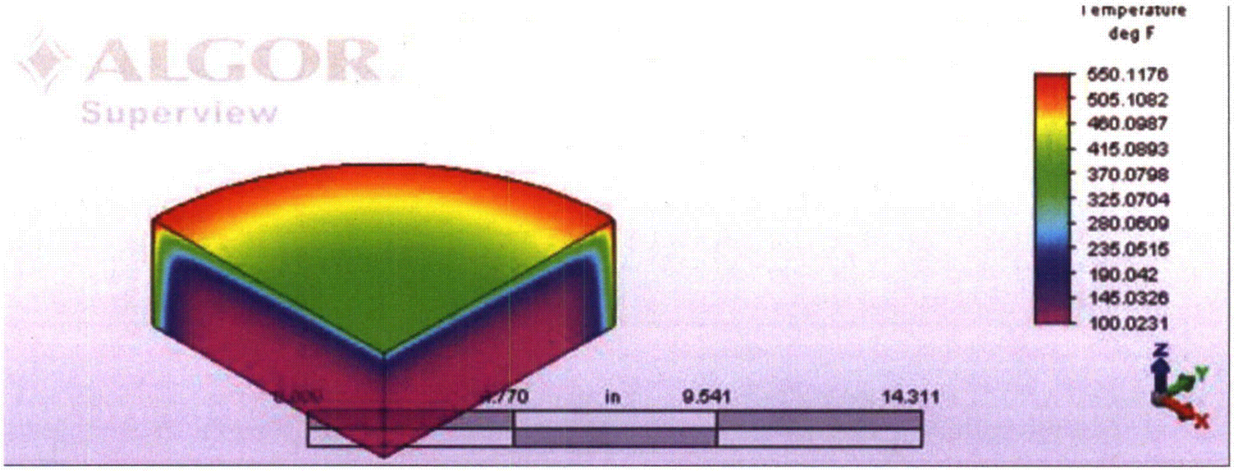


Figure 3-11 Fire Event temperature at 30 minutes, polyurethane plug

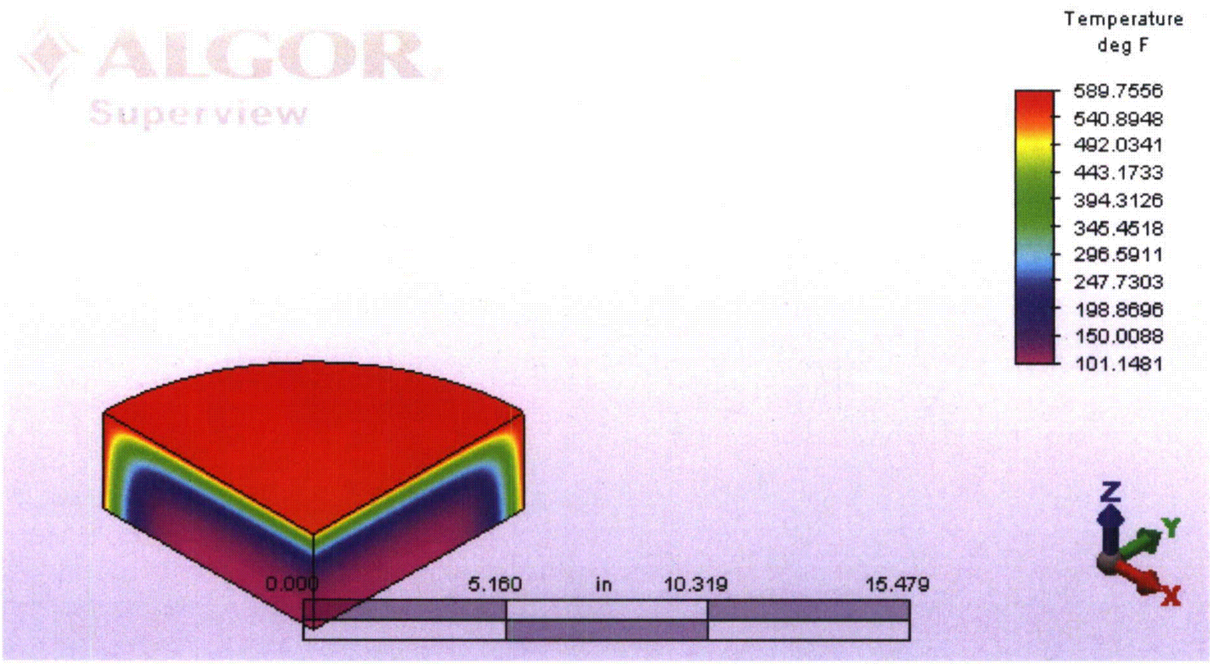


Figure 3-12 Fire Event and Cool-down temperature at 55 total minutes, polyurethane plug

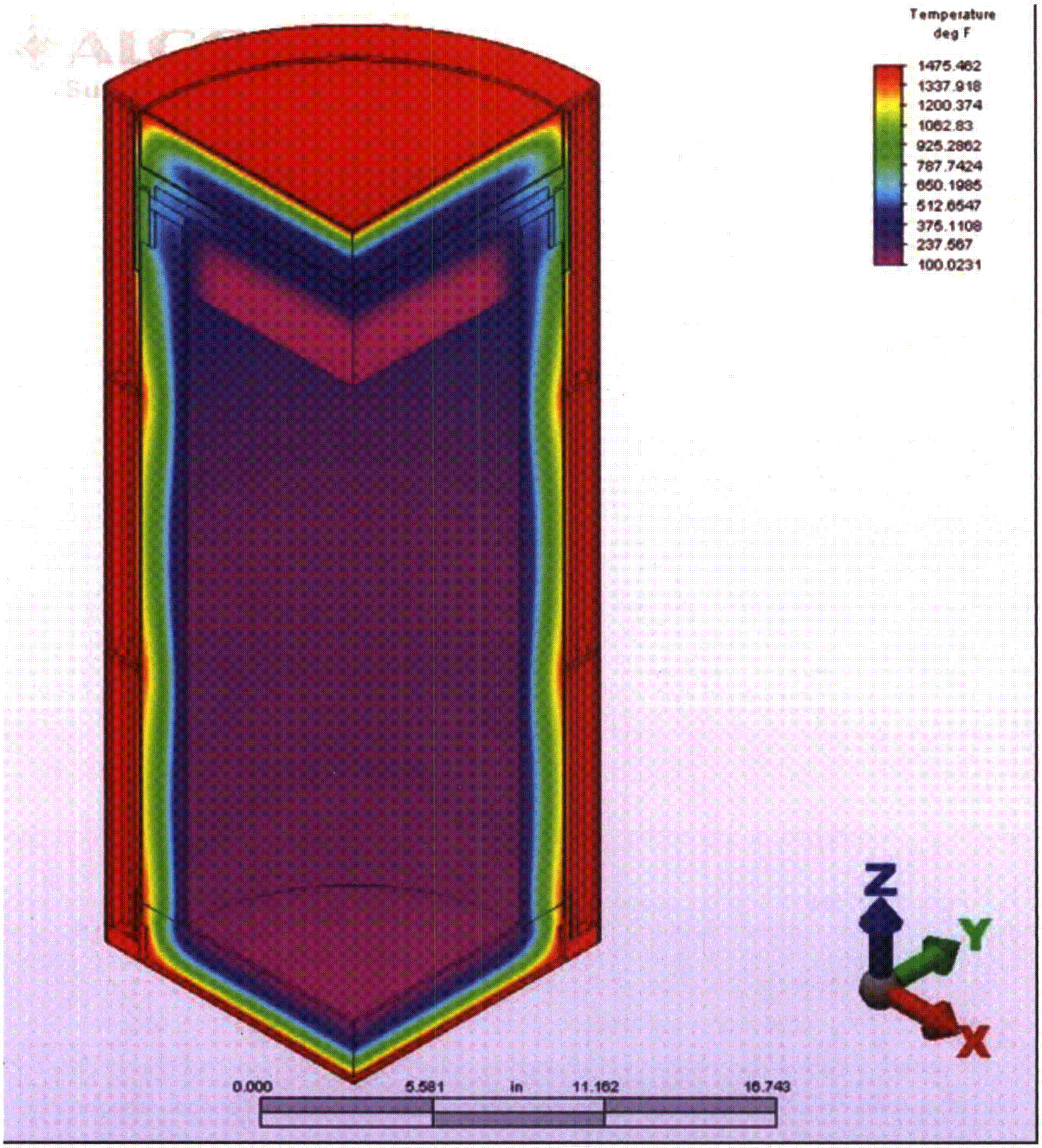


Figure 3-13 Fire Event temperature at 30 minutes, Isometric view of temperature distribution

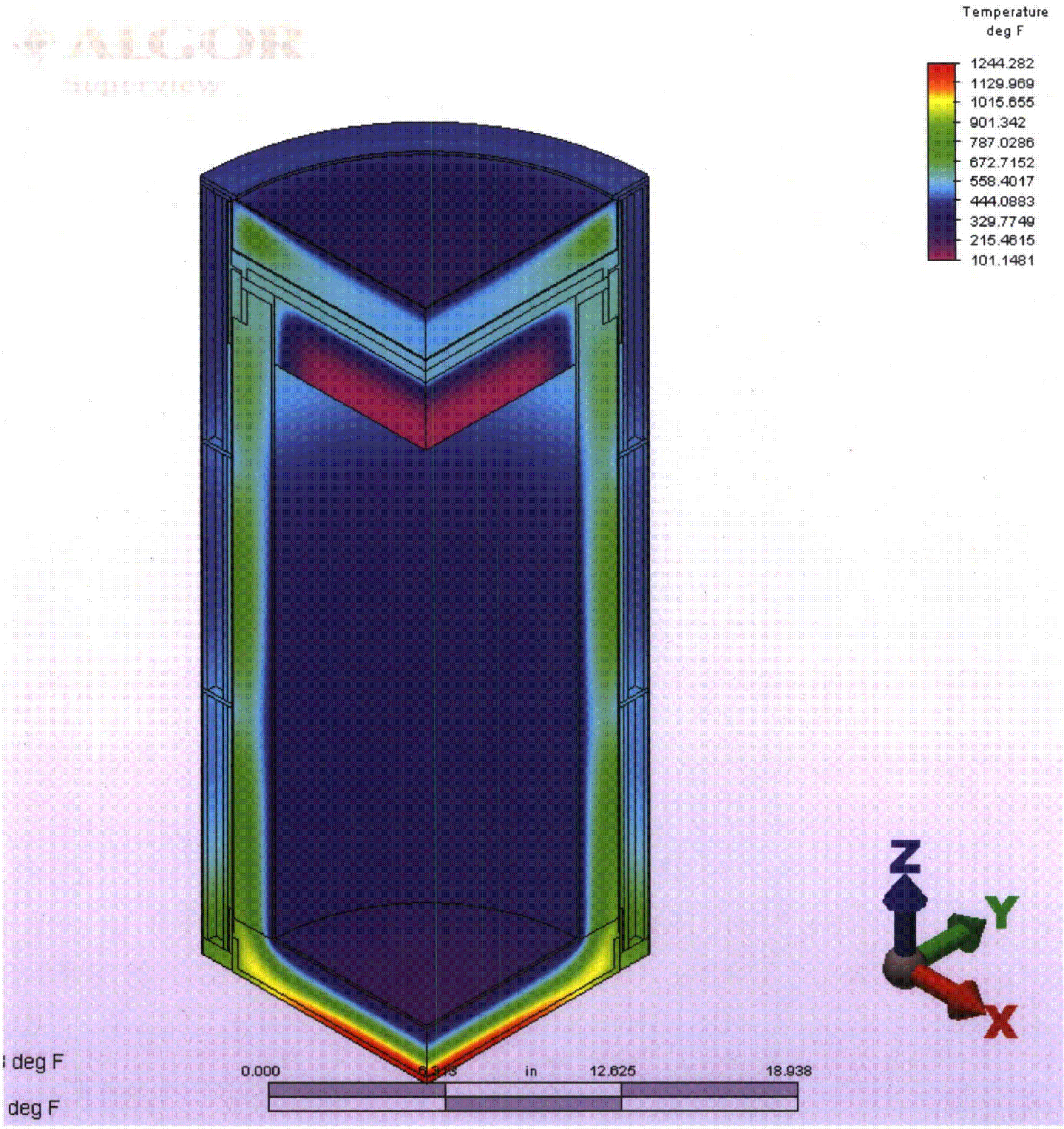


Figure 3-14 Fire Event and Cool-down temperature at 55 total minutes, Isometric view of temperature distribution

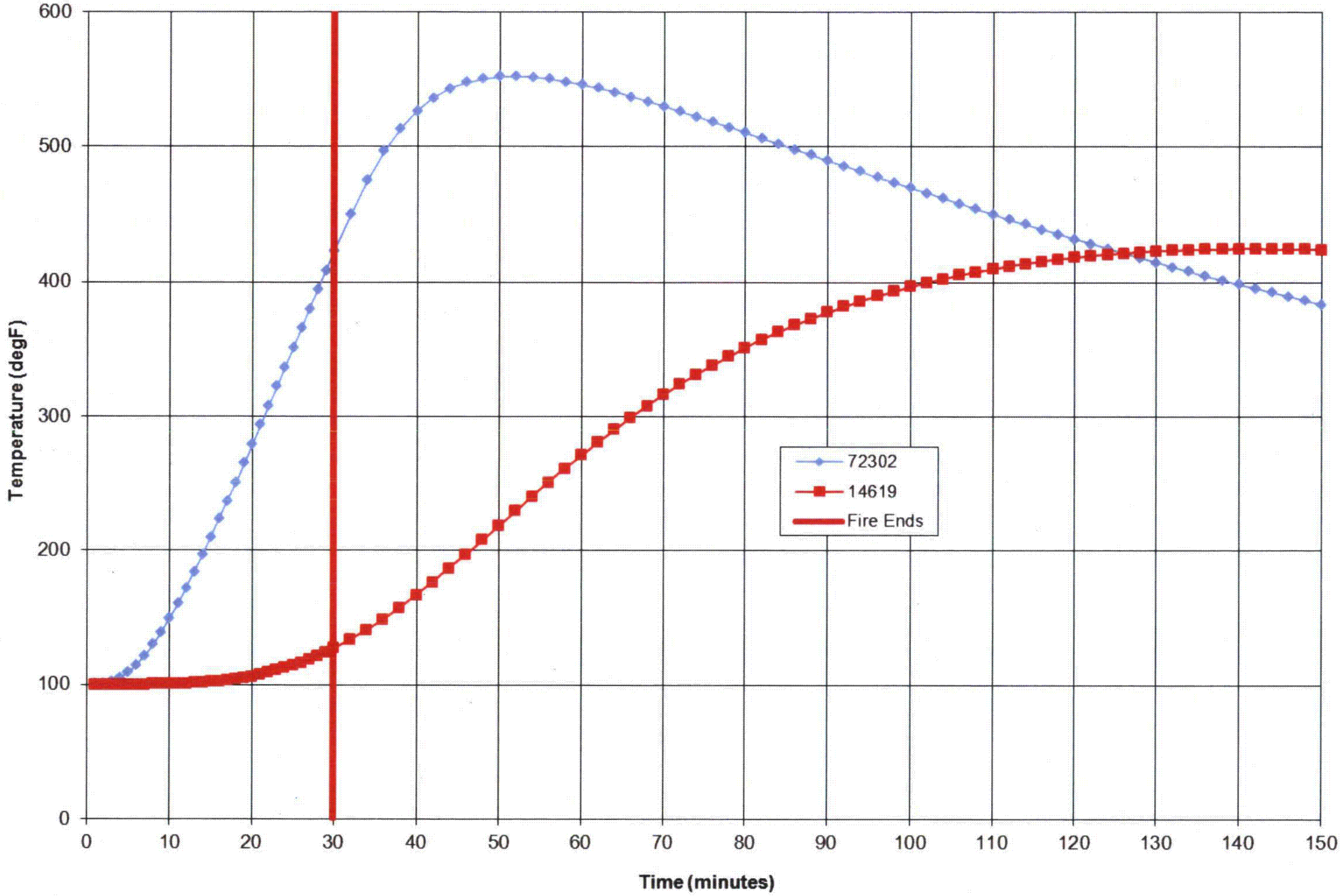


Figure 3-15 Fire Event and Cool-down temperature as a function of Seconds (beginning of cool-down= 0sec) for Payload Cavity Nodes 72302 (at the bottom of the polyurethane insert) and 14619 (at the center of the payload cavity floor part PB)

Appendix 3.5.1 Description of the Thermal Model

In order to evaluate the performance of the Versa-Pac for all conditions of transport, a quarter-symmetric transient finite element analysis (FEA) model was developed using ALGOR Release 18.1. This appendix provides a description of the thermal models.

Both 55-gallon and 110-gallon packages were modeled; the 55-gallon package was found to be bounding in performance and therefore the results for the 110-gallon package are not reported. Also, the package was modeled with and without contents, and the model without contents, even without the decay heat input, was found to be bounding. These results are expected, as can be demonstrated by a simple inspection of the equation of state used in the transient analyses:

$$Q = m\, C_p\, \Delta T$$

Where

Q	is the heat input (fixed by the fire boundary condition),
m	is the mass of the package,
C_p	is the equivalent specific heat of the package, and
ΔT	is the change in temperature of the package.

Since Q is constrained, any increase in m due to the addition or exclusion of contents leads to a lower ΔT. Also, any increase in C_p due to the addition or exclusion of contents leads to a lower ΔT. Thus, exclusion of the contents is expected to produce the highest temperatures on the interior wall of the package. Although Q is slightly higher for the 110-gallon Versa-Pac due to the slightly higher external surface area to which the fire is applied, this is greatly offset by the increased payload capacity and volume of steel and insulation added to the package.

All components were modeled using brick elements. The typical and maximum element side lengths used in the model are 0.25" and 0.79", respectively. With the exception of the air gap between the outer lid and the payload cavity lid, the package is a conduction-only problem. In order to simplify the calculation matrix, the air gap was also reduced to a conduction equivalent condition using the method described in Appendix 3.5.2.

Table 3.5.1.1 provides a comparison of the modeled dimensions versus the nominal package dimensions for the 55-gallon Versa-Pac. Table 3.5.1.2 provides a comparison of the modeled dimensions versus the nominal package dimensions for the 110-gallon Versa-Pac. Table 3.5.1.3 provides the thermal material properties used in the analyses in basic units; Table 3.5.1.4 provides the same information in traditional English units. Table 3.2 lists the conditions analyzed, including the initial conditions and heat loads.

For the fire analysis, the external surface nodes were constrained to a temperature of 1475°F. For both the 55-gallon and 110-gallon versions, the contents was modeled with a decay heat load of 0.022 in-lb_f/s / in^3 and 0.0085 in-lb_f/s / in^3 for the 55-gallon and 110-gallon packages, respectively for a conservative total package heat load of 11.4 W (with the exception of the void case, where the contents is not included in the model). The model was run for 30 time

steps, with each time step 60 seconds long. The convergence tolerance was set to 0.000001 for the non-linear analysis.

For the cooldown sequence, natural convection was applied to the external nodes, assuming an ambient temperature of 100°F. The convection coefficients are applied based on the nodal temperature of the external nodes and are updated at each timestep. The convection coefficients are calculated based on the Rayleigh number and free convection coefficients as presented by Reference 1:

$$Ra_L = [g\,\beta\,(T_s - T_\infty)\,L^3]/\nu\alpha$$

Where:

- Ra_L is the Rayleigh number based on the characteristic plate length,
- g is gravitational acceleration, 9.81 m/s,
- β is the volumetric thermal expansion coefficient for air, evaluated at the average film temperature, $(T_s - T_\infty)/2$, and approximated as $1/T_{\text{film average, absolute}}$,
- T_s is the surface temperature of the heated plate at the node of interest, °C,
- T_∞ is the ambient air temperature, 38°C (100°F),
- L is the characteristic length of the heated plate, 0.8128 m (32"),
- ν is the kinematic viscosity of air evaluated at the average film temperature, $(T_s - T_\infty)/2$, in m^2/s, and
- α is the thermal diffusivity of air evaluated at the average film temperature, $(T_s - T_\infty)/2$, in m^2/s.

Note that for evaluation of the Rayleigh Number the temperatures need not be in absolute units, since the delta is used in the formulation.

The sides of the package are treated as a vertical heated plate:

$$Nu_{L,\,avg} = [0.825 + (0.387\,Ra_L^{1/6})/(1 + (0.492/Pr)^{9/16})^{8/27}]^2$$

Where:

- $Nu_{L,\,avg}$ is the average Nusselt number,
- Ra_L is the Rayleigh number based on the characteristic plate length, and
- Pr is the Prandtl number for air evaluated at the average film temperature, $(T_s - T_\infty)/2$.

Per Reference 1, this correlation is deemed appropriate for vertical cylinders if:

$$D/L \geq 35/Gr^{1/4},$$

Where:

- D is the diameter of the cylinder, 0.57 m (22.5") for the 55-gallon VersaPac,
- L is the height of the cylinder, 0.81 m (32"),
- Gr is the Grashof number and is defined as:

$$Gr = [g\,\beta\,(T_s - T_\infty)\,L^3] / \nu^2$$

For the range of potential package surface temperatures, the correlation is well within the appropriate range for use of the vertical heated plate correlation.

The circular top of the package is treated as a horizontal plate:

$$Nu_{L,avg} = 0.54\ Ra_L^{1/4} \quad (10^4 \leq Ra_L \leq 10^7).$$

Per Reference 1, the characteristic length to be used in the Rayleigh number calculation is defined as:

$$L = A_s / P = 0.14\ m$$

Where:

A_s is the surface area of the plate, $\pi D^2/4$, and

P is the perimeter of the plate, πD.

For the range of potential package surface temperatures and the characteristic length, the correlation is well within the appropriate range for use of the horizontal heated plate correlation.

The natural convection coefficient input to the code is calculated from the Nusselt Number as:

$$h_{avg} = Nu_{L,avg}\ k / L,$$

Where:

h_{avg} is the natural convection coefficient for the horizontal or vertical heated plates,

$Nu_{L,avg}$ is the average Nusselt Number as defined previously, and

k is the thermal conductivity of air evaluated at the average film temperature, $(T_s - T_\infty)/2$.

For purposes of calculating the convection coefficients, 24 discrete package wall temperatures were selected for evaluation, ranging from 39°C to 810°C. Using an ambient air temperature of 100°F (37.8°C), the convection coefficient was calculated in units of W/m^2K and were then converted to the units used in the Algor code (in-lb_f/s-R-in^2). When the nodal temperature falls between the evaluated points, the Algor code linearly interpolates the convection coefficient.

Table 3.5.1.5 summarizes the material properties of air from Reference 1. Table 3.5.1.6 presents the convection coefficient calculations and the coefficients that were input to the code. For both the 55-gallon and 110-gallon versions, the contents was modeled with a decay heat load of 0.022 in-lbf/s / in^3 and 0.0085 in-lbf/s / in^3 for the 55-gallon and 110-gallon packages, respectively for a conservative total package heat load of 11.4 W (with the exception of the void case, where the contents is not modeled). The cooldown sequence utilized the fire sequence nodal temperatures at the end of the 30 minute fire sequence as the initial temperature of the nodes. Insolation was applied to the exterior surface nodes at the rate specified by regulation (see Table 3.2) for 12-hours on and 12-hours off. The model was run for 120 time steps, with each time step 60 seconds long (in order to conserve space, the results were recorded at every third time step only). The convergence tolerance was set to 0.000001 for the non-linear analysis. Since the peak temperatures were reached within the first hour of the cooldown, the results bound the remainder of the cooldown to equilibrium NCT conditions.

The 55-gallon model is illustrated in Figures 3.5.1-1 through 3.5.1-14. The 110-gallon model is illustrated in Figure 3.5.1-15. These same models were used for all NCT and HAC fire and cooldown sequences.

Reference 1: Incropera, Frank P. and David P. DeWitt, *Fundamentals of Heat and Mass Transfer Third Edition, John Wiley & Sons*, New York, 1981, pp. 530-554; A15.

Table 3.5.1- 1 Comparison of Modeled Components versus Nominal Package Components for the 55-gallon Versa-Pac

Model Part #	Drawing component ID	Material of construction	Modeled material (see Table 3.5.1-2)	Component nominal thickness	Modeled component thickness
1	PE & FD	A36	Isotropic steel	1 / 4"	0.250"
2	PF	A36	Isotropic steel	3 / 4"	0.750"
3	FA	A36	Isotropic steel	3/16"	0.188"
4	SA & FA	A1011	Isotropic steel	16 ga.	0.060"
5	FB	A36	Isotropic steel	3/16"	0.188"
9	FC	A1011	Isotropic steel	16 ga.	0.060"
10	PG	A36	Isotropic steel	3/16"	0.188"
11	PB	A1011	Isotropic steel	10 ga.	0.140"
12	PI	A36	Isotropic steel	3/16"	0.188"
13	PA & PH	A1011 & A36	Isotropic steel	10 ga. & 1/4"	0.140" & 0.500"[1]
14	PC, DL, SB, SC	A1011	Isotropic steel	10 ga., 16 ga., 16 ga. & 16 ga.	0.140", 0.060", 0.060" & 0.060"
15	FK	A36	Isotropic steel	¼" x 1½" tall	0.250" x 1.50" tall
16, 17, 18	IA	Alumina silica insulation	Temperature dependent isotropic alumina silica	1.5"	1.25"
19	IB	6pcf polyurethane	6pcf polyurethane	2 1/8"	2.125"
24	IA	Alumina silica insulation	Temperature dependent isotropic alumina silica	2"	1.94"
25	IC	6pcf polyurethane	6pcf polyurethane	2 3/16"	2.188"
26, 27, 28, 29, 30, 31	TB	A500 GR.B	Isotropic steel	1¼" sq x $^{3}/_{16}$" x ~32" tall, volume=25.5 in^3 each	~1.18" sq x 0.2125", ~32" tall, volume = 26.3 in^3 each
62	PolyU insert	10 pcf polyurethane	9.8 pcf polyurethane	3"	3.00"
71	PI	A36	Isotropic steel	3/16"	0.188"
79	IE & IF	Fiberglass	Fiberglass	0.5"	0.500"
96	PD	A36	Isotropic steel	½"	0.500"
104	N/A	N/A	Air	0.5" thick at lid	0.44" thick at lid
115	BB	A36	Isotropic steel	1¼" x 1¼" x 1½"	1.25" x 1.25" x 1.5"
120	N/A	N/A	CONTENTS	15" diameter x 24.06" tall	15.22" diameter x 25.24" tall

[1] Although this component thickness is modeled at twice the actual component thickness, this is considered to be conservative, since it provides an enhanced pathway for heat conduction to the interior of the package.

Table 3.5.1- 2 Comparison of Modeled Components versus Nominal Package Components for the 110-gallon Versa-Pac

Model Part #	Drawing component ID	Material of construction	Modeled material (see Table 3.5.1-2)	Component nominal thickness	Modeled component thickness
1	PE & FD	A36	Isotropic steel	1 / 4"	0.250"
2	PF	A36	Isotropic steel	3 / 4"	0.750"
3	FA	A36	Isotropic steel	3/16"	0.188"
4	SA & FA	A1011	Isotropic steel	16 ga.	0.060"
5	FB	A36	Isotropic steel	3/16"	0.188"
9	FC	A1011	Isotropic steel	16 ga.	0.060"
10	PG	A36	Isotropic steel	3/16"	0.188"
11	PB	A1011	Isotropic steel	10 ga.	0.140"
12	PI	A36	Isotropic steel	3/16"	0.188"
13	PA & PH	A1011 & A36	Isotropic steel	10 ga. & 1/4"	0.140" & 0.500"[2]
14	PC, DL, SB, SC	A1011	Isotropic steel	10 ga., 16 ga., 16 ga. & 16 ga.	0.140", 0.060", 0.060" & 0.060"
15	FK	A36	Isotropic steel	¼" x 1½" tall	0.250" x 1.50" tall
16, 17, 18	IA	Alumina silica insulation	Temperature dependent isotropic alumina silica	1.5"	1.25"
19	IB	6pcf polyurethane	6pcf polyurethane	3 ½"	2.125"
24	IA	Alumina silica insulation	Temperature dependent isotropic alumina silica	2 ½"	1.94"
25	IC	6pcf polyurethane	6pcf polyurethane	3 ¼"	2.188"
26, 27, 28, 29, 30, 31	TB	A500 GR.B	Isotropic steel	1¼" sq x $^3/_{16}$" x ~40 $^3/_4$" tall, volume=32.5 in^3 each	~1.18" sq x 0.2125" x ~40 $^3/_4$" tall, volume = 33.5 in^3 each
62	PolyU insert	10 pcf polyurethane	9.8 pcf polyurethane	3"	3.00"
71	PI	A36	Isotropic steel	3/16"	0.188"
79	IE & IF	Fiberglass	Fiberglass	0.5"	0.500"
96	PD	A36	Isotropic steel	½"	0.500"
104	N/A	N/A	Air	0.5" thick at lid	0.44" thick at lid
115, 116 & 117	BB	A36	Isotropic steel	1¼" x 1¼" x 1½"	1.25" x 1.25" x 1.5"
120	N/A	N/A	CONTENTS	21" diameter x 32.25" tall	NA

[2] Although this component thickness is modeled at twice the actual component thickness, this is considered to be conservative, since it provides an enhanced pathway for heat conduction to the interior of the package.

Table 3.5.1- 3 Thermal Material Properties for the Versa-Pac (Basic Units)

Material	Density (lb$_f$ - s^2/in)/(in^3)	Thermal Conductivity (in-lb$_f$)/(s-in-8F)	Specific Heat (in-lb$_f$)/(lb$_f$ s^2/in)- 8F	Heat Generation Rate (in-lb$_f$)/(s-in^3)	Source
Isotropic steel	7.35E-4	5.84	4.1849E5	N/A	General industry data (matweb, ALGOR material library)
8 pcf Temperature dependent isotropic alumina silica	1.199E-5	8F TC 27 0.007926 500 0.007926 1000 0.016 1500 0.026 1800 0.037 2000 0.048	9.374E5	N/A	Century Industries SOP6.12; general industry data (matweb, Cer-wool, Fiberfrax)
Fiberglass – Extren525 Isophthalic polyester resin	1.606E-4	0.072	1.009E6	N/A	Century Industries SOP6.13, also "Typical Properties – FRP Structural Shapes", Enduro Systems, Inc., www.endurocomposites.com.
Isotropic 6.0 pcf Polyurethane	8.993E-6	3.386E-3	1.273E6	N/A	Century Industries SOP6.11, also General industry data (matweb). Not used in model since alumina silica is bounding
Isotropic 9.8 pcf Polyurethane	1.469E-5	5.026E-3	1.576E6	N/A	Century Industries SOP6.11, also General industry data (matweb). Not used in model since alumina silica is bounding
Air, conduction + radiation	1.087E-7	L=0.44" 8F$_{average}$ TC -40 0.017 22.4 0.017 202.4 0.040 382.4 0.083 562.4 0.147 742.4 0.237 922.4 0.357 1102 0.513 1282 0.709 1462 0.949 1642 1.239	8.671E5	N/A	see Appendix 3.5.2
Contents 1, wood	8.094E-5	0.022	3.358E5	0.022 (55-gal) 0.0085 (110 gal)	General industry data (matweb)
Contents 2, void	N/A	N/A	N/A	N/A	N/A
Contents 3, solid steel	7.35E-4	5.84	4.1849E5	0.022 (55-gal) 0.0085 (110 gal)	General industry data (matweb, ALGOR material library)

Table 3.5.1- 4 Thermal Material Properties for the Versa-Pac (English Units)

Material	Density (lb / ft^3)	Thermal Conductivity (BTU / hr-ft-8F)	Specific Heat (BTU / lb-8F)	Heat Generation Rate (BTU / hr-in^3)	Source
Isotropic steel	2.836E-01	2.251	0.116	N/A	General industry data (matweb, ALGOR material library)
8 pcf Temperature dependent isotropic alumina silica	4.630E-03	8F TC 27 3.083E-03 500 3.083E-03 1000 6.167E-03 1500 1.000E-02 1800 1.425E-02 2000 1.850E-02	0.260	N/A	Century Industries SOP6.12; general industry data (matweb, Cer-wool, Fiberfrax)
Fiberglass – Extren525 Isophthalic polyester resin	6.192E-02	2.775E-02	0.280	N/A	Century Industries SOP6.13, also "Typical Properties – FRP Structural Shapes", Enduro Systems, Inc., www.endurocomposites.com.
Isotropic 6.0 pcf Polyurethane	3.472E-03	1.333E-03	0.353	N/A	Century Industries SOP6.11, also General industry data (matweb). Not used in model since alumina silica is bounding
Isotropic 9.8 pcf Polyurethane	5.671E-03	1.917E-03	0.437	N/A	Century Industries SOP6.11, also General industry data (matweb). Not used in model since alumina silica is bounding
Air, conduction + radiation	4.225E-05	L=0.44" $8F_{average}$ TC -40 6.583E-03 22.4 6.583E-03 202.4 1.542E-02 382.4 3.200E-02 562.4 5.667E-02 742.4 9.133E-02 922.4 1.377E-01 1102 1.978E-01 1282 2.733E-01 1462 3.658E-01 1642 4.777E-01	0.241	N/A	see Appendix 3.5.2
Contents 1, wood	3.125E-02	8.500E-03	0.093	0.008481 (55-gal) 0.003277 (110 gal)	General industry data (matweb)
Contents 2, void	N/A	N/A	N/A	N/A	N/A
Contents 3, solid steel	2.836E-01	2.251	0.116	0.008481 (55-gal) 0.003277 (110 gal)	General industry data (matweb, ALGOR material library)

Table 3.5.1- 5 Material Properties for Air used to evaluate Natural Convection Coefficiencts

All values taken from Reference 1.

Air Temperature (K)	$\nu * 10^6$	$k * 10^3$	$\alpha * 10^6$	Pr
	m^2/s	W/m-K	m^2/s	
300	15.89	26.3	22.5	0.707
350	20.92	30.0	29.9	0.700
400	26.41	33.8	38.3	0.690
450	32.39	37.3	47.2	0.686
500	38.79	40.7	56.7	0.684
550	45.57	43.9	66.7	0.683
600	52.69	46.9	76.9	0.685
650	60.21	49.7	87.3	0.690
700	68.10	52.4	98.0	0.695

Table 3.5.1- 6 Natural Convection Coefficients for the Versa-Pac Cool-down Sequence

Film Temperature (K) (note 2)	Film Temperature (C) (note 2)	Film Temperature (F) (note 2)	v (10^6 m^2/s) (note 1 & 2)	K (10^3 W/m-K) (note 1 & 2)	α (10^6 m^2/s) (note 1 &2)	Pr (note 1 &2)	Nodal Wall temperature (F)	Nodal Wall temperature (C)	Ra vertical	Ra Horizontal	Nu Vertical (note 3)	Nu Horizontal (note 4)	h vertical, (W/m^2-K)	h horizontal, (W/m^2-K)	h vertical ($in-lb_f/s-R-in^2$)	h horizontal ($in-lb_f/s-R-in^2$)
300	27.0	80.6	15.89	26.3	22.5	0.707	61.2	16.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
311	37.9	100.2	16.99	27.1	24.1	0.705	100.4	38.0	9.23E+06	4.71E+04	30.48	7.96	1.02	1.54	3.2245E-03	4.8868E-03
312	38.9	102.0	17.09	27.2	24.3	0.705	104.0	40.0	9.05E+07	4.63E+05	59.23	14.08	1.98	2.73	6.2827E-03	8.6728E-03
317	43.9	111.0	17.59	27.5	25.0	0.705	122.0	50.0	4.62E+08	2.36E+06	96.82	21.17	3.28	4.17	1.0409E-02	1.3212E-02
322	48.9	120.0	18.09	27.9	25.7	0.704	140.0	60.0	7.81E+08	3.99E+06	113.70	24.13	3.91	4.81	1.2388E-02	1.5266E-02
327	53.9	129.0	18.59	28.3	26.5	0.703	158.0	70.0	1.05E+09	5.39E+06	124.70	26.01	4.34	5.26	1.3768E-02	1.6675E-02
332	58.9	138.0	19.10	28.7	27.2	0.703	176.0	80.0	1.29E+09	6.58E+06	132.67	27.35	4.68	5.60	1.4839E-02	1.7763E-02
337	63.9	147.0	19.60	29.0	28.0	0.702	194.0	90.0	1.49E+09	7.61E+06	138.74	28.36	4.96	5.88	1.5718E-02	1.8655E-02
342	68.9	156.0	20.10	29.4	28.7	0.701	212.0	100.0	1.66E+09	8.49E+06	143.49	29.15	5.19	6.12	1.6463E-02	1.9415E-02
350	77.0	170.6	20.92	30.0	29.9	0.700	241.2	116.2	1.89E+09	9.65E+06	149.27	30.09	5.51	6.45	1.7476E-02	2.0455E-02
392	118.9	246.0	25.52	33.2	36.9	0.692	392.0	200.0	2.31E+09	1.18E+07	158.76	31.66 (note 5)	6.48	7.51	2.0559E-02	2.3806E-02
400	127.0	260.6	26.41	33.8	38.3	0.690	421.2	216.2	2.32E+09	1.19E+07	158.92	31.70 (note 5)	6.61	7.65	2.0962E-02	2.4274E-02
442	168.9	336.0	31.42	36.7	45.8	0.687	572.0	300.0	2.17E+09	1.11E+07	155.57	31.18 (note 5)	7.03	8.18	2.2300E-02	2.5947E-02
450	177.0	350.6	32.39	37.3	47.2	0.686	601.2	316.2	2.13E+09	1.09E+07	154.60	31.02 (note 5)	7.09	8.27	2.2504E-02	2.6219E-02
492	218.9	426.0	37.75	40.1	55.2	0.684	752.0	400.0	1.86E+09	9.52E+06	148.19	29.99	7.32	8.60	2.3219E-02	2.7285E-02
500	227.0	440.6	38.79	40.7	56.7	0.684	781.2	416.2	1.81E+09	9.26E+06	146.93	29.79	7.36	8.66	2.3338E-02	2.7472E-02
542	268.9	516.0	44.47	43.4	65.1	0.683	932.0	500.0	1.55E+09	7.93E+06	140.01	28.66	7.47	8.88	2.3703E-02	2.8169E-02
550	277.0	530.6	45.57	43.9	66.7	0.683	961.2	516.2	1.51E+09	7.70E+06	138.73	28.45	7.49	8.92	2.3768E-02	2.8297E-02
592	318.9	606.0	51.53	46.4	75.2	0.685	1112.0	600.0	1.29E+09	6.59E+06	132.25	27.36	7.55	9.07	2.3955E-02	2.8776E-02
600	327.0	620.6	52.69	46.9	76.9	0.685	1141.2	616.2	1.25E+09	6.40E+06	131.08	27.17	7.56	9.10	2.3991E-02	2.8867E-02
642	368.9	696.0	58.99	49.2	85.6	0.689	1292.0	700.0	1.08E+09	5.50E+06	125.15	26.15	7.58	9.20	2.4052E-02	2.9177E-02
650	377.0	710.6	60.21	49.7	87.3	0.690	1321.2	716.2	1.05E+09	5.35E+06	124.08	25.96	7.59	9.22	2.4066E-02	2.9238E-02

Film Temperature (K) (note 2)	Film Temperature (C) (note 2)	Film Temperature (F) (note 2)	v (10^6 m^2/s) (note 1 & 2)	K (10^3 W/m-K) (note 1 & 2)	α (10^6 m^2/s) (note 1 &2)	Pr (note 1 &2)	Nodal Wall temperature (F)	Nodal Wall temperature (C)	Ra vertical	Ra Horizontal	Nu Vertical (note 3)	Nu Horizontal (note 4)	h vertical, (W/m^2-K)	h horizontal, (W/m^2-K)	h vertical (in-lb_f/s-R-in^2)	h horizontal (in-lb_f/s-R-in^2)
692	418.9	786.0	66.82	52.0	96.3	0.694	1472.0	800.0	9.02E+08	4.61E+06	118.65	25.02	7.59	9.29	2.4060E-02	2.9459E-02
697	423.9	795.0	67.61	52.2	97.3	0.695	1490.0	810.0	8.87E+08	4.53E+06	118.04	24.92	7.59	9.30	2.4061E-02	2.9487E-02
700	427.0	800.6	68.10	52.4	98.0	0.695	1501.2	816.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Notes on Table 3.5.1-5:

1. Air material properties are taken from Reference 1 as presented by Table 3.5.1-4. For temperatures between the values provided by the Reference, the material properties are linearly interpolated.
2. The material property values presented are for the air film temperature, which is assumed to be the average of the wall temperature and ambient (1008F≈37.88C≈310.98K).
3. Per Reference 1, the correlation is valid over all ranges of Rayleigh numbers.
4. Per Reference 1, the correlation is valid over a range of Rayleigh numbers from 10^4 to 10^7.
5. Although these Rayleigh numbers are slightly out of range of the correlation, they are conservatively lower than that calculated using the correlation provided by Reference 1 applicable at higher Rayleigh numbers and so is considered acceptable for use.

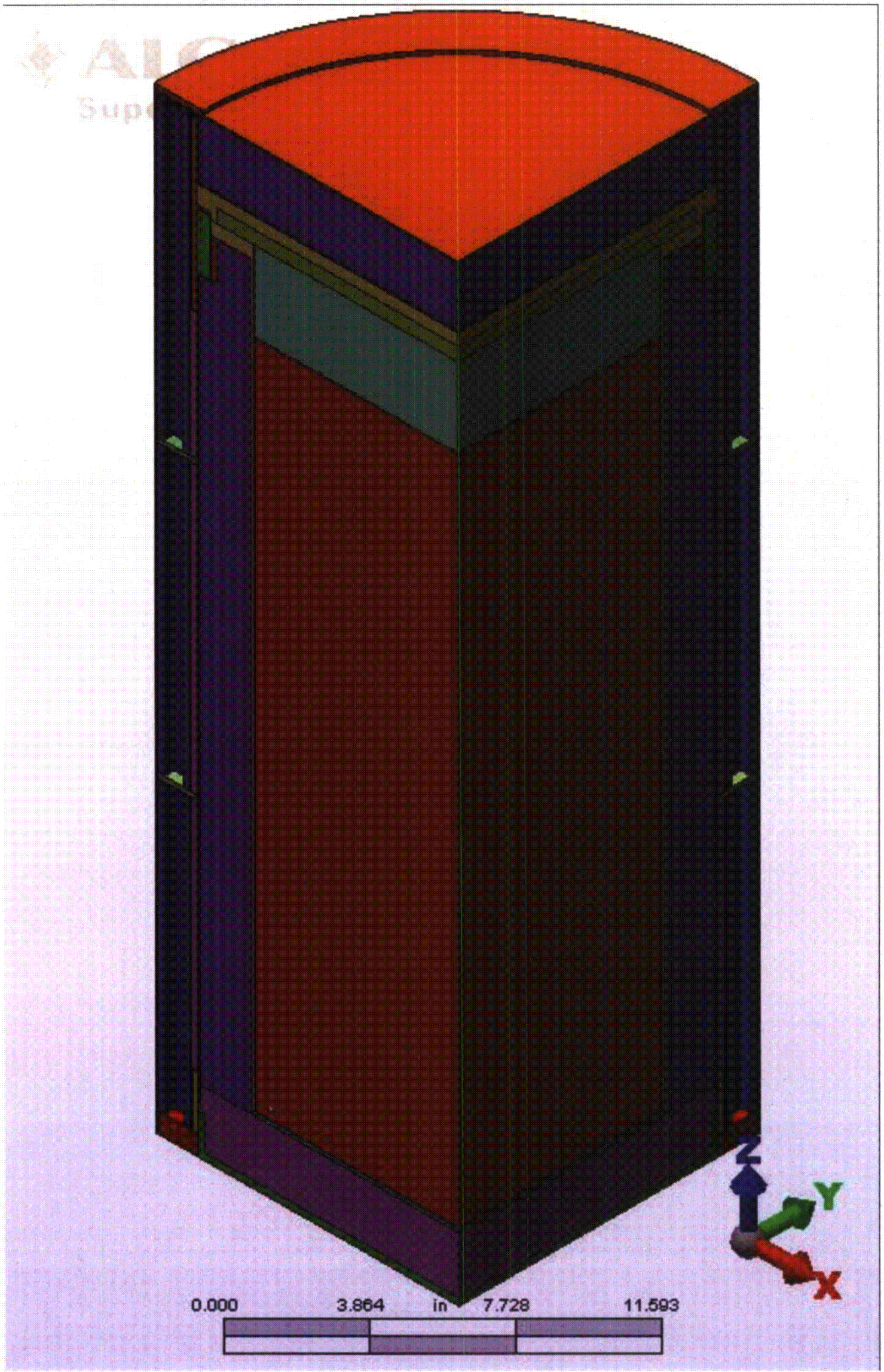


Figure 3.5.1- 1 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, all parts shown

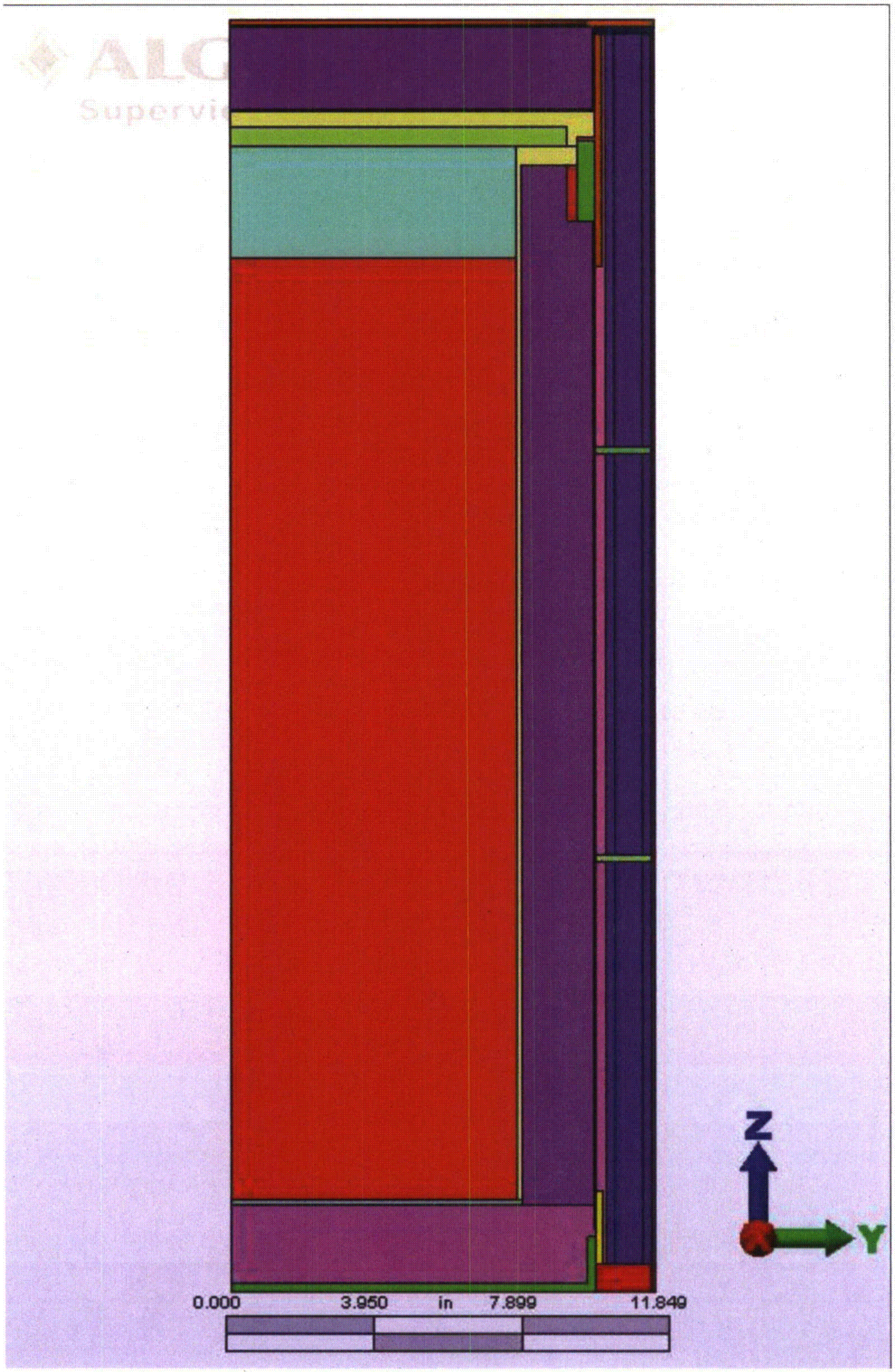


Figure 3.5.1- 2 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, all parts shown, side view

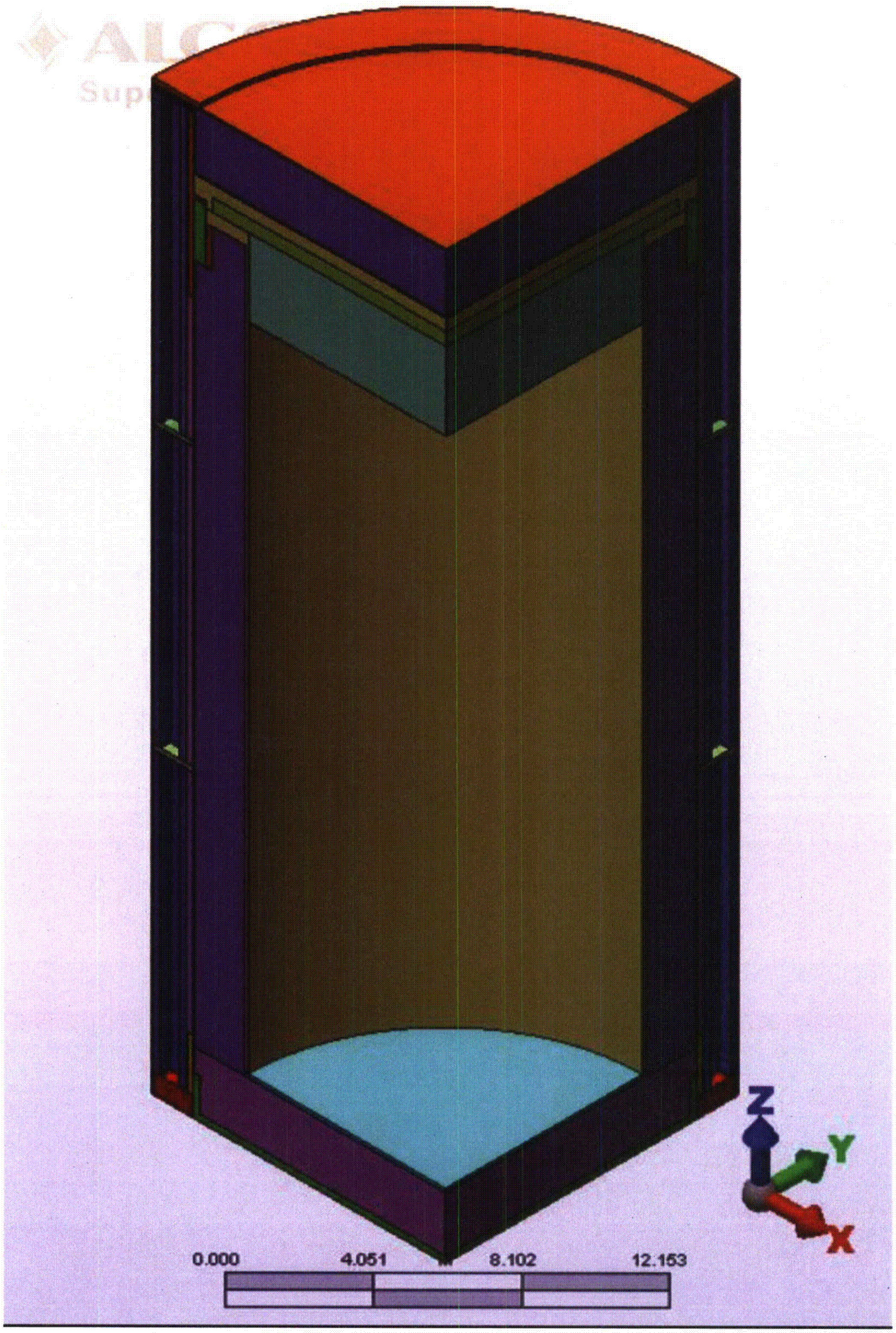


Figure 3.5.1- 3 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, contents not shown

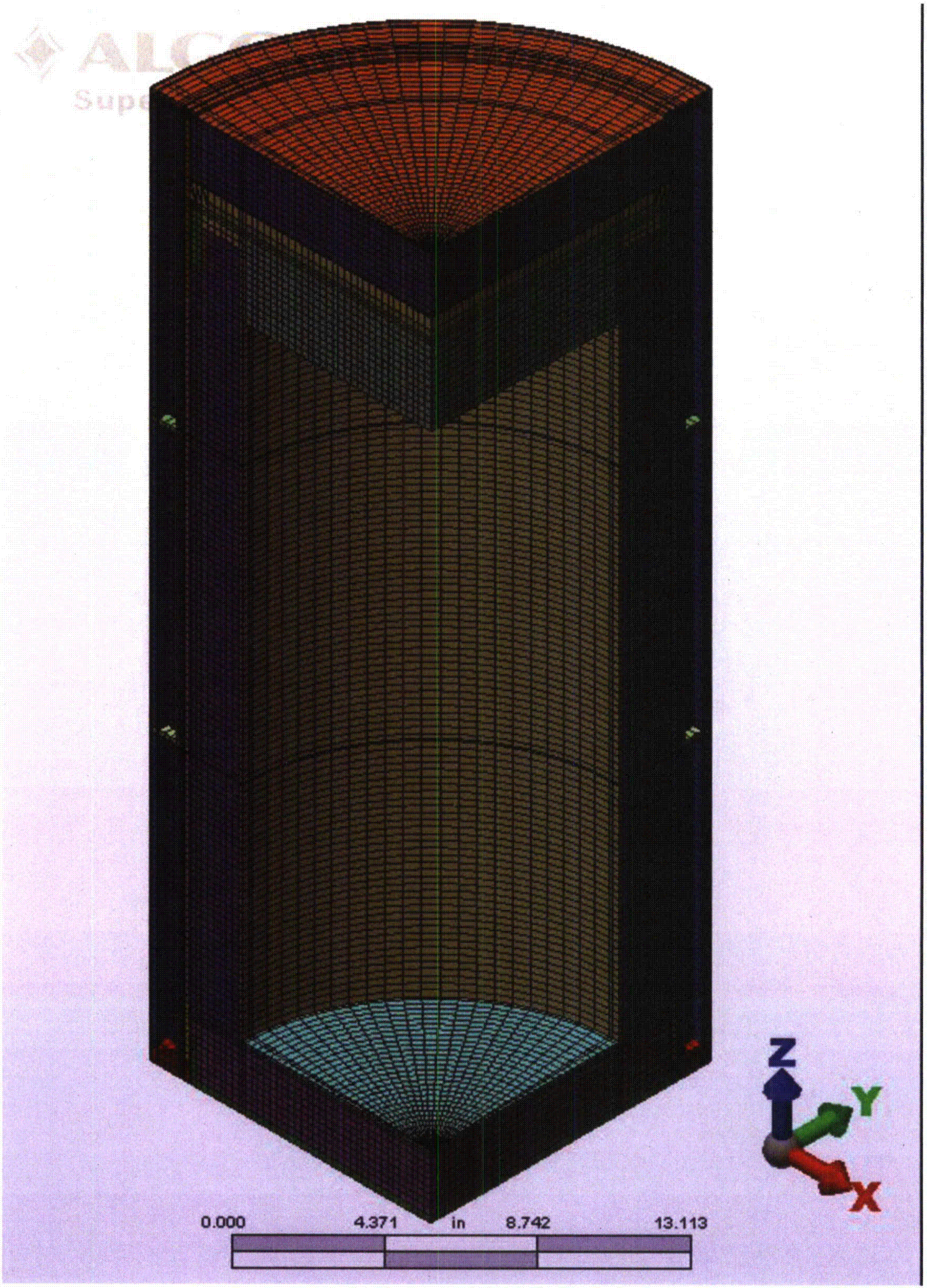


Figure 3.5.1- 4 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, contents not shown, mesh view

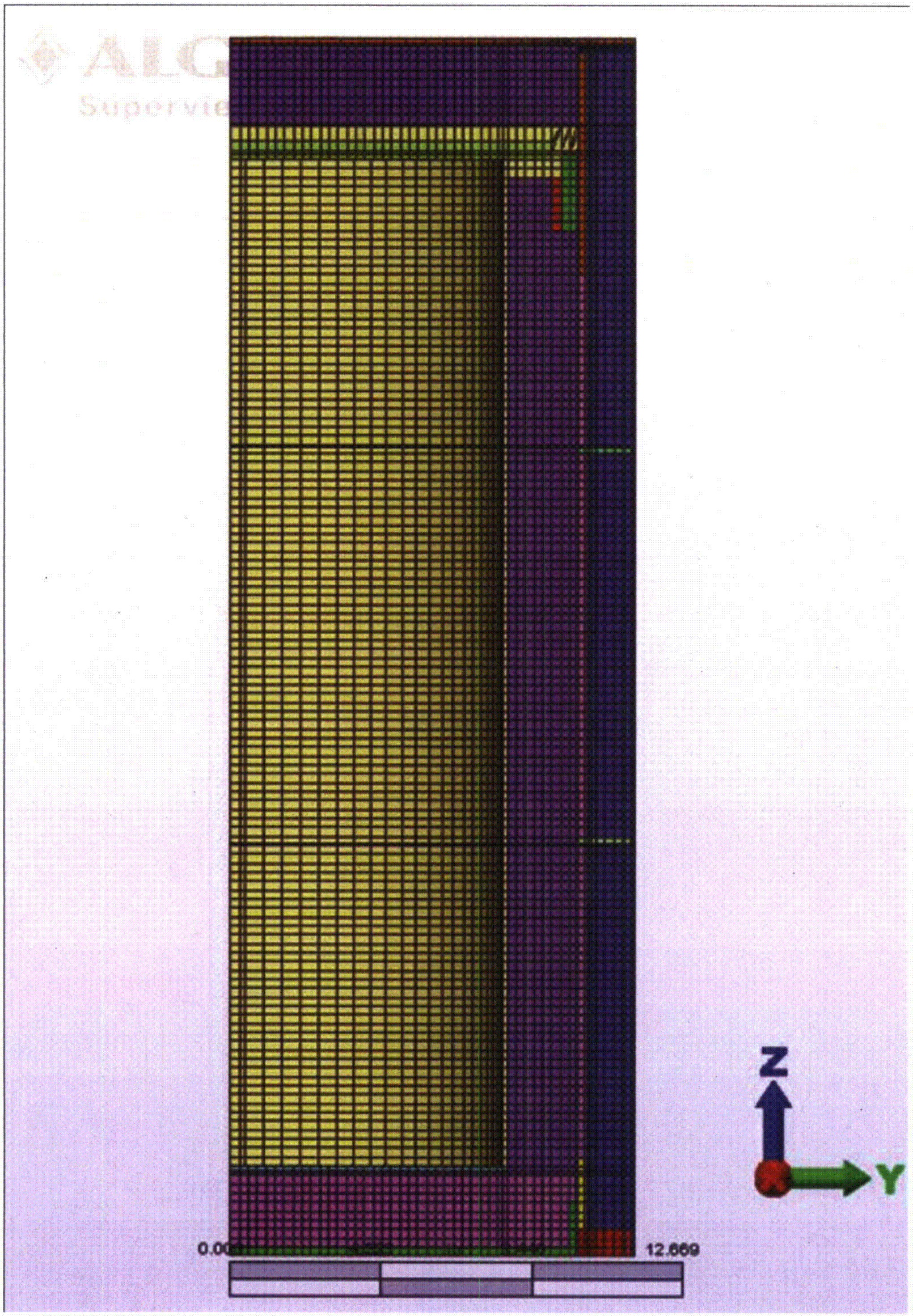


Figure 3.5.1- 5 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, contents not shown, side view with mesh

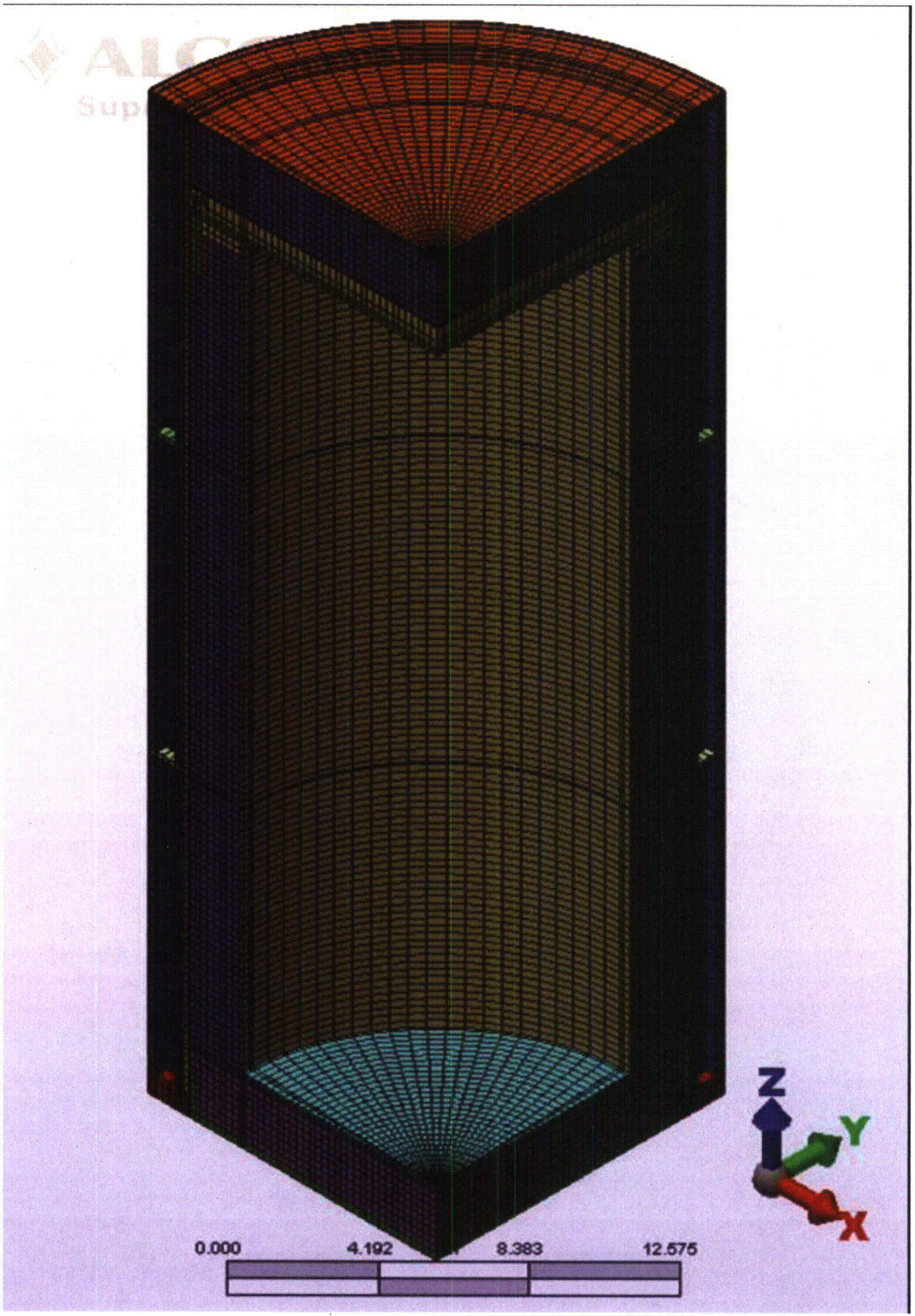


Figure 3.5.1- 6 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, Drum Lid removed (air gap between lids is shown in yellow)

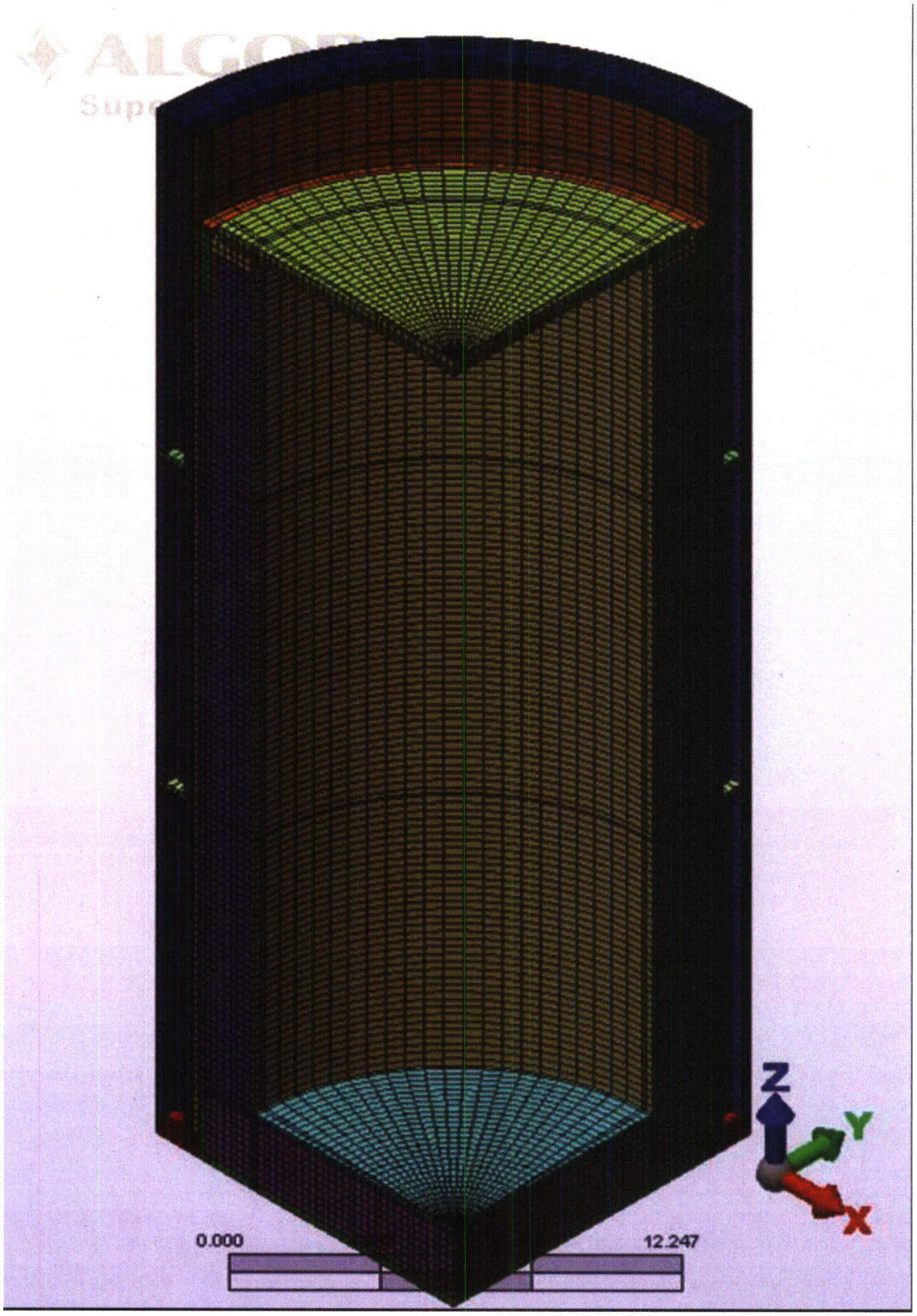


Figure 3.5.1- 7 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac

(drum lid & insulation plug not shown)

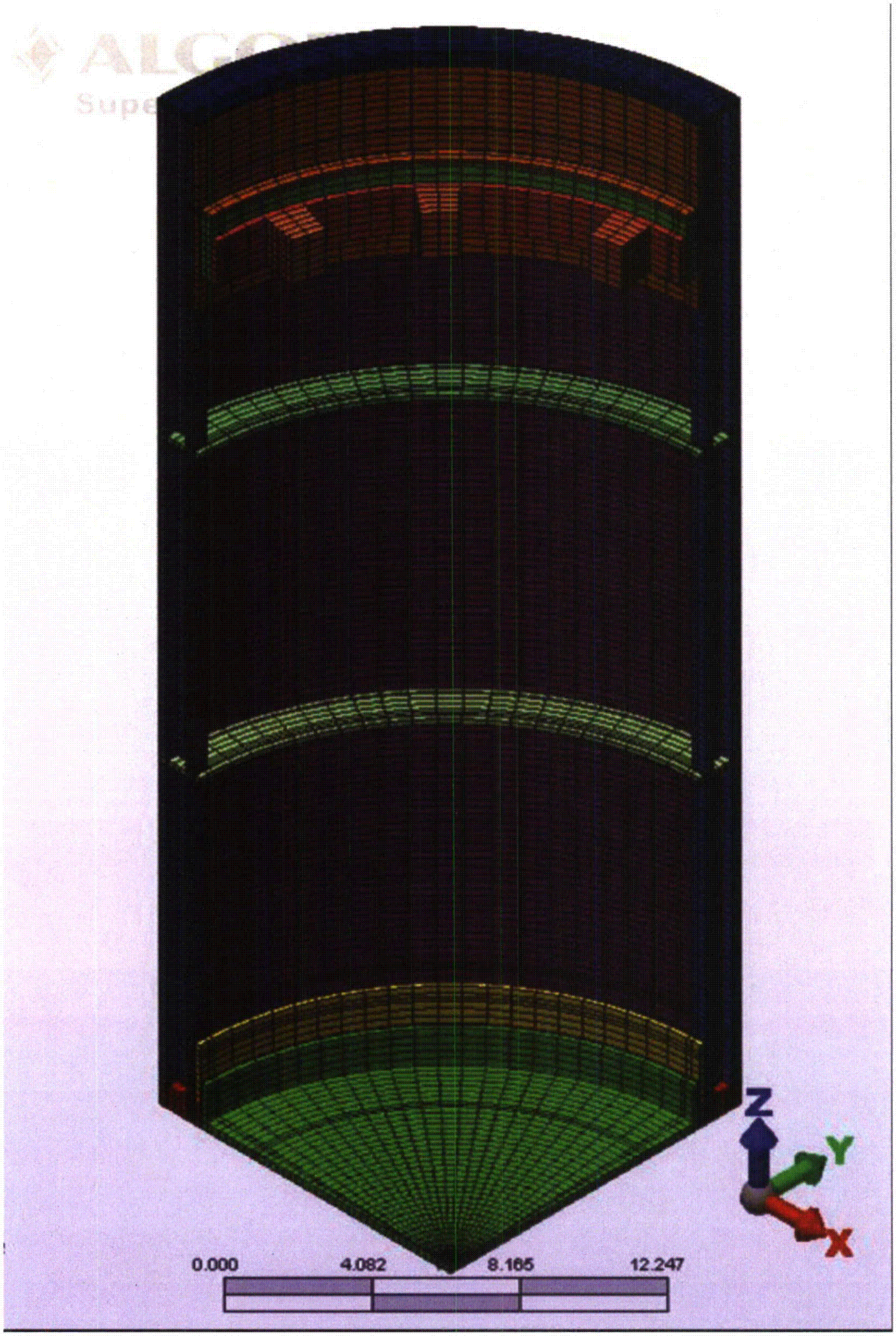


Figure 3.5.1- 8 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, External Metal structure, Fiberglass, & Payload Cavity bolting blocks (payload cavity, drum lid, insulation plug & component SA not shown)

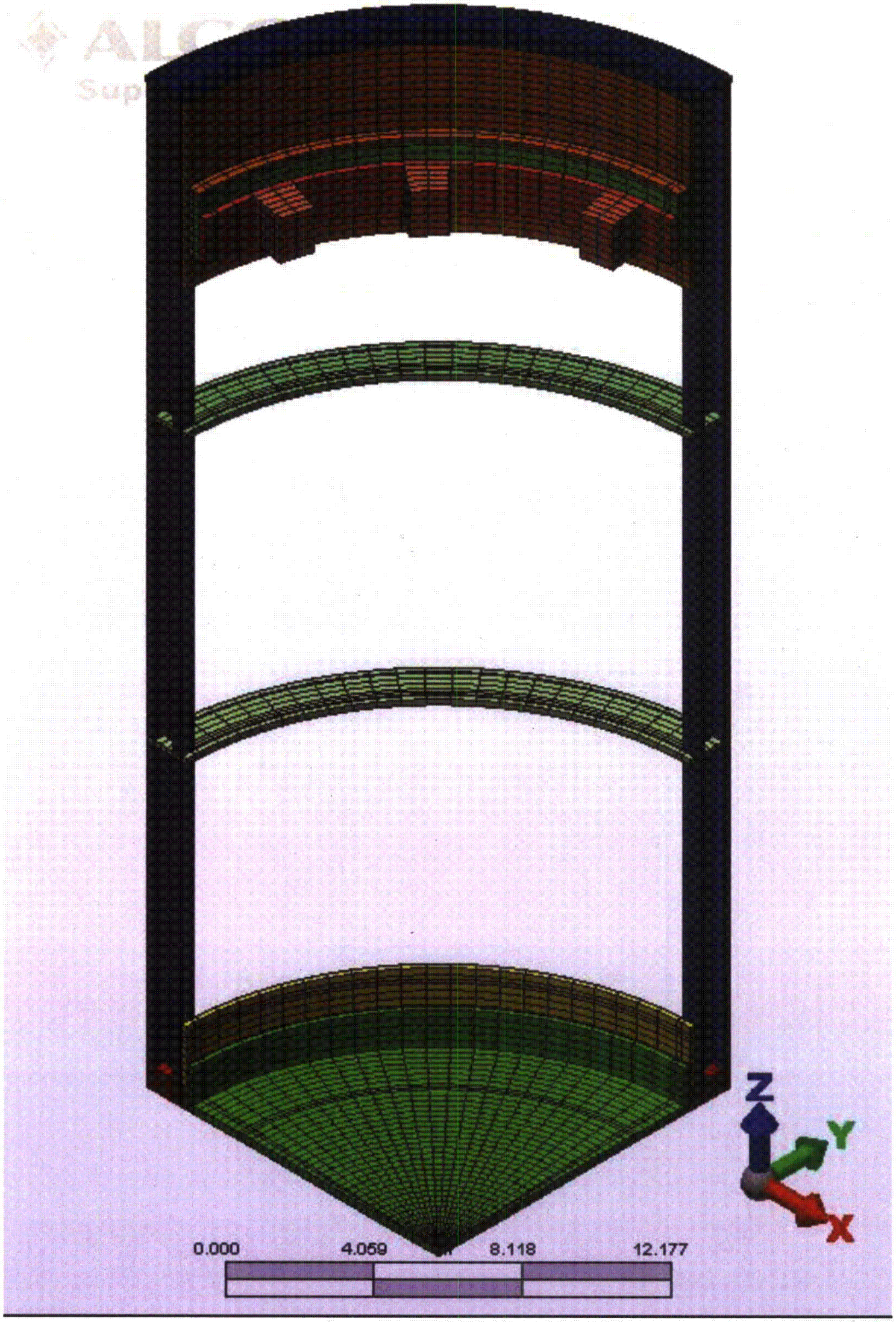


Figure 3.5.1- 9 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, Metal Reinforcing Members

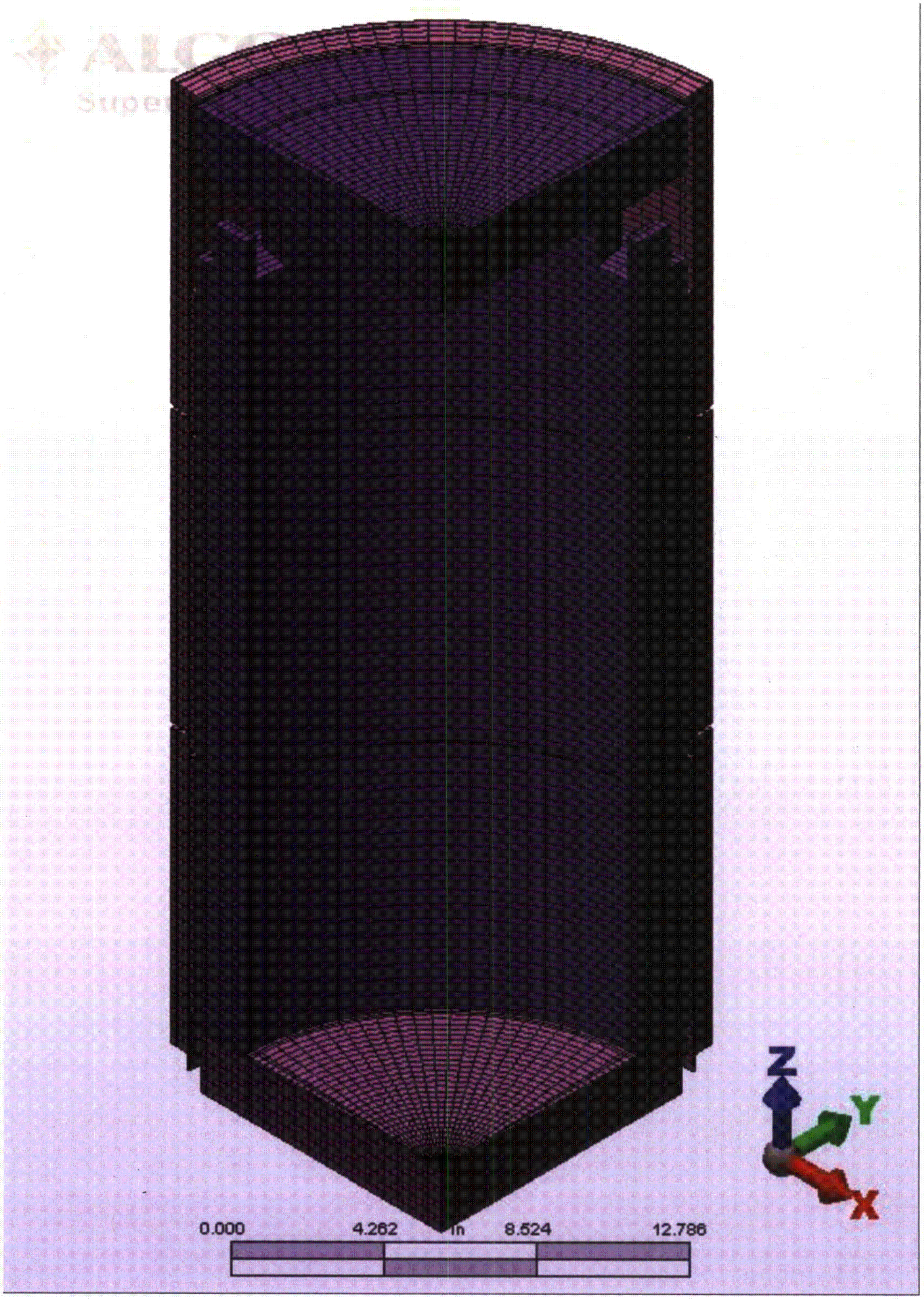


Figure 3.5.1- 10 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, Insulation

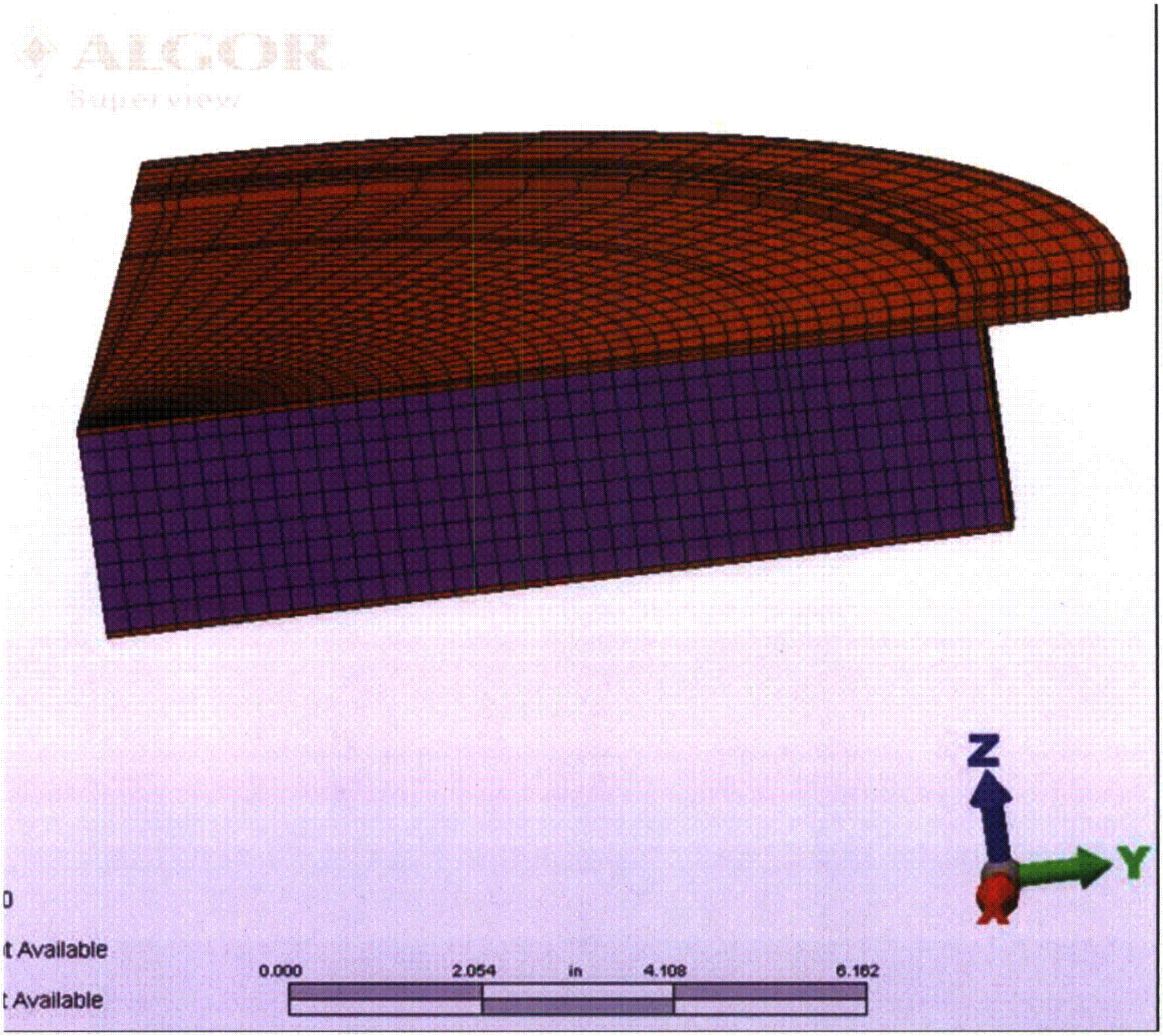


Figure 3.5.1- 11 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, Outer Lid

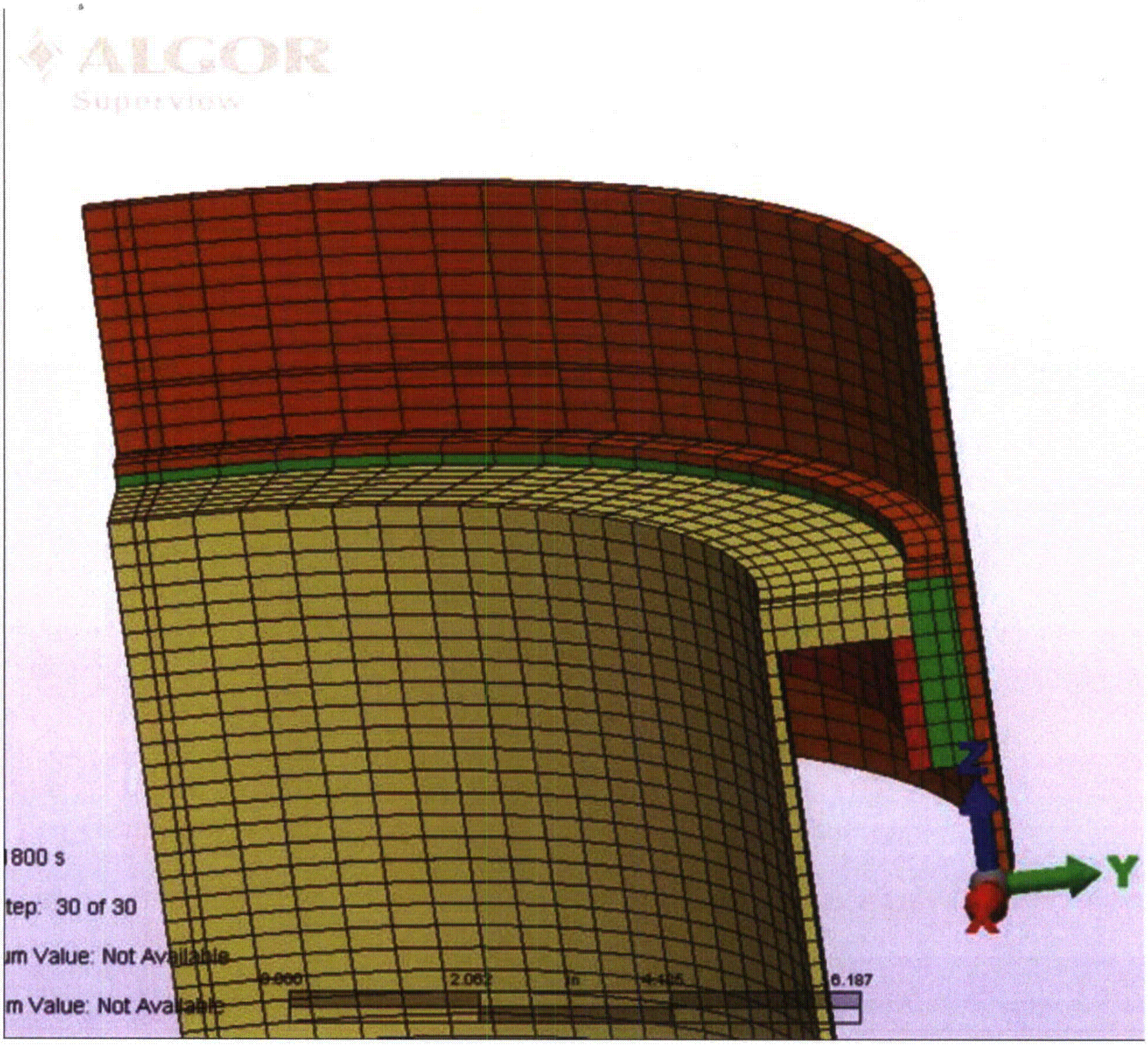


Figure 3.5.1- 12 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, Detail View, Payload Cavity, Fiberglass, and Rivet block (bolting block BB not shown)

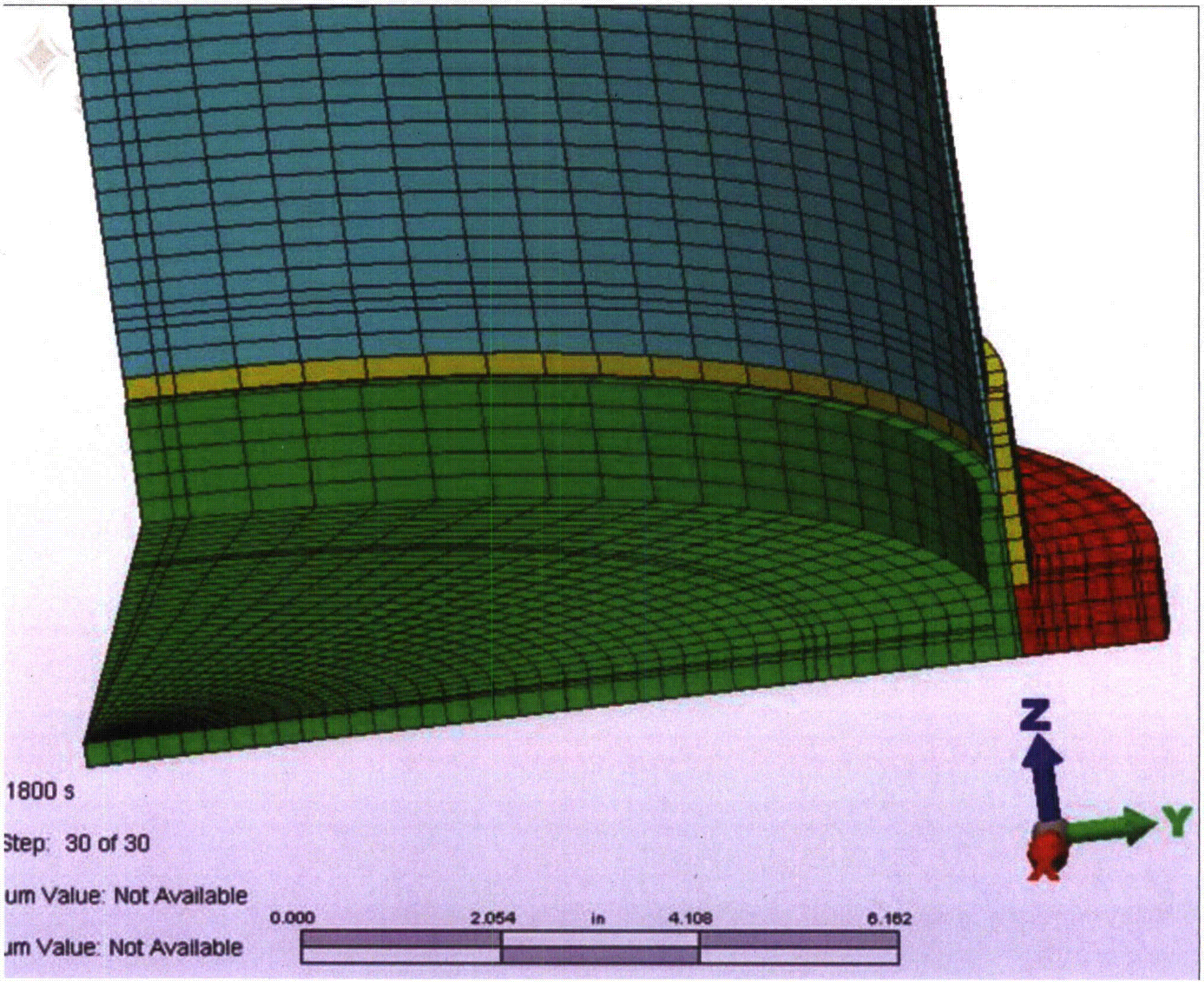


Figure 3.5.1- 13 Quarter-symmetric Thermal Model of the 55-gallon Versa-Pac, Detail View, Lower reinforcing structure

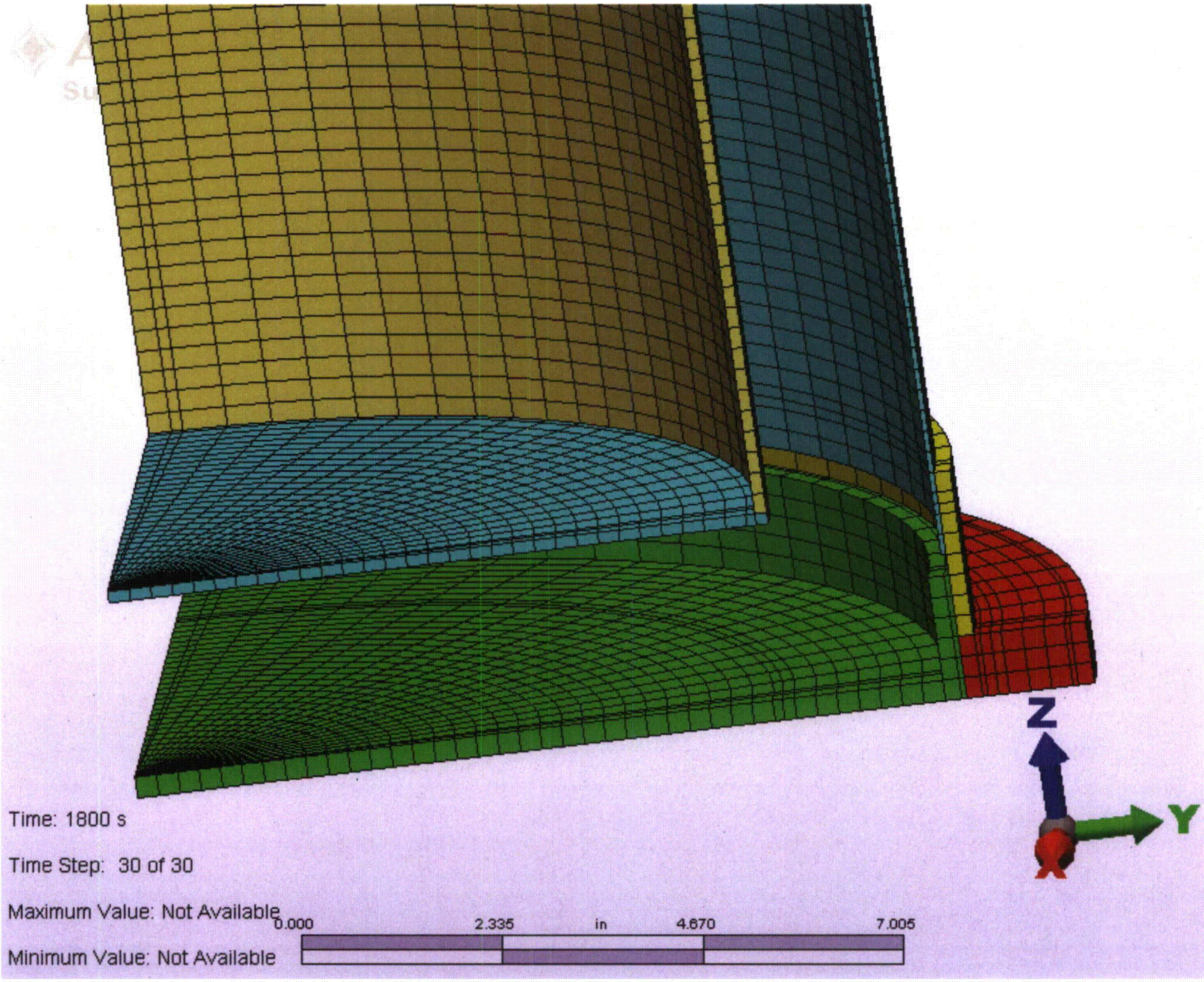


Figure 3.5.1- 14 Quarter-symmetric Thermal Model of 55-gallon Versa-Pac, Detail View, Lower Reinforcing structure with Payload Cavity shown

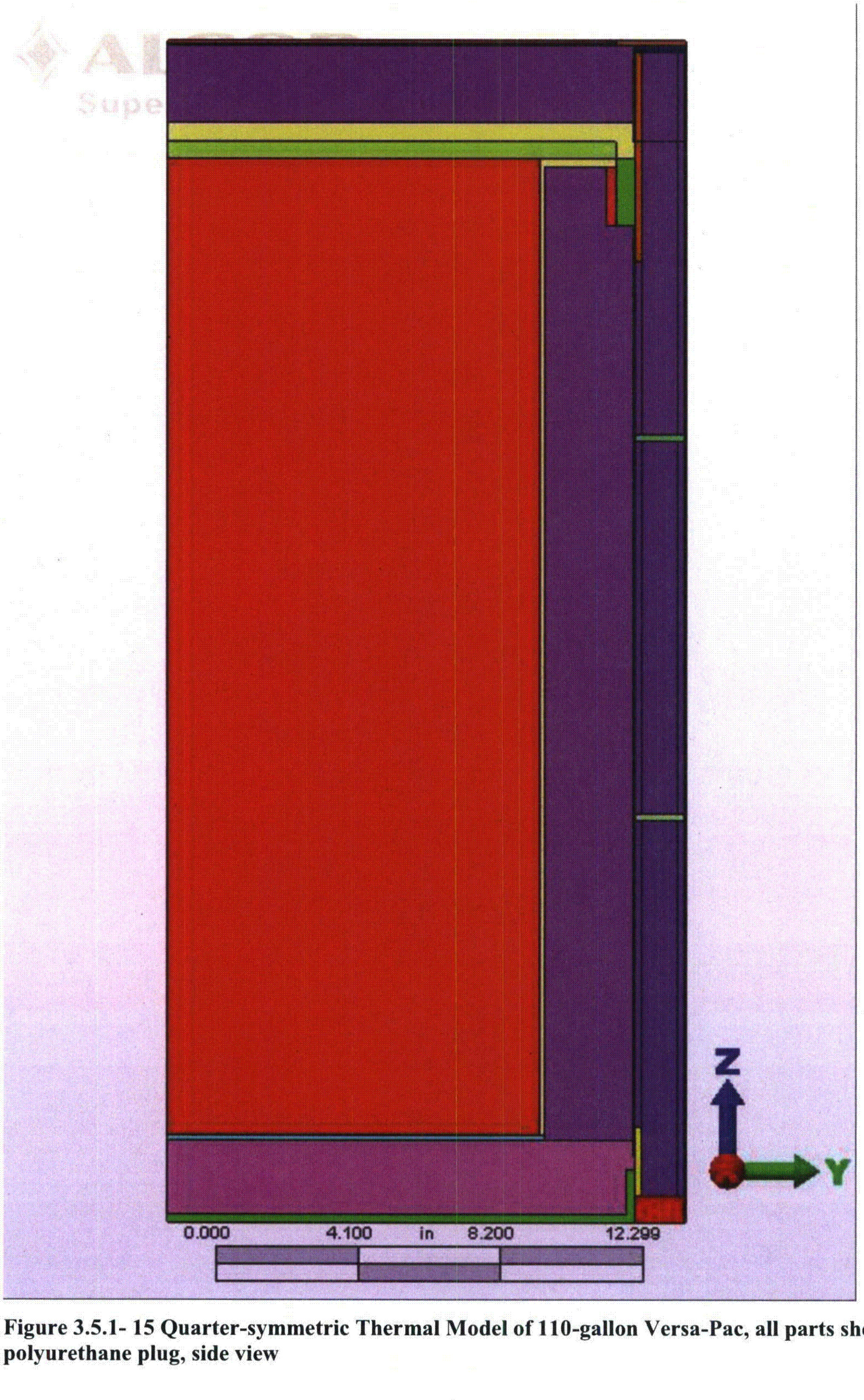


Figure 3.5.1- 15 Quarter-symmetric Thermal Model of 110-gallon Versa-Pac, all parts shown except polyurethane plug, side view

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

In some cases, body-to-body radiation can be emulated using temperature dependent conduction as shown in the figure below:

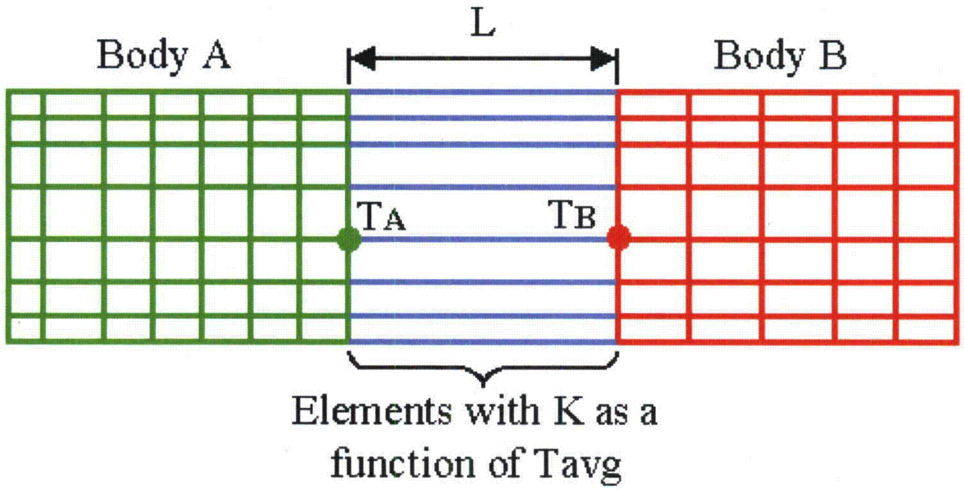


Figure 2: Body to Body Radiation

The requirements for this approximation to be accurate are as follows:

1. The view factor between the bodies must be close to 1.
2. The heat flux out of the system is negligible; that is, there is no radiation to the environment.
3. The surface area of each body is equal.
4. The expected temperatures of the surfaces are approximately known either from hand calculations, experimentation or previous analysis (multiple iterations).

The heat exchanged between two bodies which see each other and nothing else can be written based on the "surface resistance" and "space resistance" of the bodies as

$$q = \frac{A\sigma\left(T_A^4 - T_B^4\right)}{\frac{1-\varepsilon_A}{\varepsilon_A} + \frac{1}{VF_{AB}} + \frac{1-\varepsilon_B}{\varepsilon_B}}$$

Where T_A and T_B are the temperatures of surfaces A and B (in absolute temperatures), ε_A and ε_B are the emissivities of surfaces A and B, and VF_{AB} is the view factor between the two surfaces.

The heat flow due to conduction between the two bodies is

$$q = kA\frac{\Delta T}{L}$$

Since the heat flow due to radiation must equal the heat flow by conduction, equating the above two equations and expanding $T_A^4 - T_B^4$ as follows

$$T_A^4 - T_B^4 = (T_A^2 + T_B^2)(T_A^2 - T_B^2) = (T_A^2 + T_B^2)(T_A + T_B)(T_A - T_B)$$

leads to the solution

$$K = \frac{L\sigma(T_A^2 + T_B^2)(T_A + T_B)}{\frac{1-\varepsilon_A}{\varepsilon_A} + \frac{1}{VF_{AB}} + \frac{1-\varepsilon_B}{\varepsilon_B}}$$

using absolute temperatures.

Letting $T_{average} = (T_A+T_B)/2$, then $T^2_{average}$ is approximately $(T^2_A+T^2_B)/4$.

Using this substitution, and assuming the emissivities are 1 and the view factor is 1, this is further simplified to:

$$K \cong L\sigma(8)(T_{average})^3$$

Since the radiant heat transfer and conduction through the air occur in parallel the conduction coefficient is added to the psuedo radiant coefficient for input into the problem.

One layer of elements is constructed in a new part between the two bodies. The material model is set to orthotropic so that the material properties are temperature dependent. The conductivity is calculated at estimated surface temperatures T_A and T_B (in absolute temperature) using the above equation. The calculated conductivity is entered in the material properties at a temperature of $T_{average}=0.5(T_A+T_B)$. Additional data points are entered by evaluating $T_{average}$ and K at other values of T_A and T_B. A range of temperatures $T_{average}$ is included in the material properties so that the calculated temperature is not outside of the range of material properties.

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

Introduction

The Century Industries Versa-Pac Shipping Container is an evolutionary package design based on the design and testing of the Century Industries Champion Type B package. Due to the similarity in both package designs, tests involving the Century Industries Champion, although not directly applicable, can be used to support the safety basis of the Versa-Pac design as supplemented by further analysis and tests. Tests involving the Champion package that are applicable to the design of the Versa-Pac include drop tests, thermal and immersion tests. The thermal test further indicates the lack of the thermal stresses in the design. The design similarities are further presented with attachment of the test results for the Champion package.

Design Comparison

Both packages share the same basic structural components in that they have an inner and outer liner of sheet metal that is surrounded by vertical and horizontal stiffeners. Both package designs use the same ceramic fiber blanket insulation between the inner and outer liners and also surrounding the radial portion of the containment boundary. Both designs have approximately the same polyurethane foam in their respective bottom and top portions of the container. Both designs are based on an inner structure that slides into an outer drum. Therefore, both package designs should have a similar thermal response including thermal stresses. However, the temperature profiles may be different as further discussed.

The package designs differ in the type of insulation that surrounds the inner containment area. The Champion surrounds the containment area with polyurethane foam that is poured in place while the Versa-Pac utilizes ceramic fiber blanket insulation within the same area.

The Champion utilizes a leak testable inner vessel as the primary containment with a secondary blind cap flange on top of the main sealing flange while the Versa-Pac uses only a ½" blind flange with a high temperature fibrous sleeve at the containment boundary.

Thermal Test

Figure 3.5.3-1 shows the Century Champion Package rigging for the thermal test. Figure 3.5.3-2 displays a typical view of the package during the 30 minute 1475°F thermal test phase. Figure 3.5.3-3 displays the package upon completion of the thermal testing prior to conduct of the immersion test.

Summary of Results

The metallic components of the package, as shown in Figure 3.5.3-3, do not show any signs of failure or fatigue at the conclusion of the thermal test. This demonstrates that thermal stresses induced during thermal testing are low and within the structural capacity of the components. The polyurethane insulation is considered to be a sacrificial component, and in performing its function its structure is broken down by the heat of the fire. However, the polyurethane components (including the internal polyurethane plug utilized in the Versa-Pac) do provide load-carrying capability for the packaging, and the steel components provide the strength and structure required to maintain the packaging intact following the event. The 30 minute thermal test including the post-test natural cool-down did not cause any seam or closure separation in the package. The package structure including outer closure drum does not shown any signs of failure or fatigue. These observations from the testing of the Century Champion are directly applicable to the Versa-Pac design since their outer structures are identical. Therefore, the Versa-Pac design is not anticipated to be subject to deleterious thermal stresses during the required 30 minute thermal test at 1475°F.

Pages 14 and 15 of the Champion Safety Analysis Report are provided as pages 5 and 6 to Appendix 3.5.3. The test results indicate that during a 44-minute fire exposure, the lower portion of the inner vessel attained a maximum temperature of 450°F. Testing of the Versa-Pac would be expected to produce similar results since the structures and thermal insulation are similar to the Champion. The analytical analysis presented in Section 3.0, Thermal Evaluation, indicate a maximum temperature to the contents of 552°F for the Versa-Pac using a 3-inch polyurethane foam plug in the top of the containment vessel. With the plug removed, the analytical results approach 600°F. The analytical results seem reasonable and are generally performed to bound actual thermal tests with sufficient margin to ensure the design meets the requirements. Therefore, the lower temperature experienced in the fire testing of the Champion seems reasonable. In an actual fire test of the Versa-Pac, the maximum temperature at the containment boundary would be expected to be less than 600°F. A lower temperature is anticipated since the Versa-Pac design uses a fiberglass thermal break in the area of the containment boundary closure.

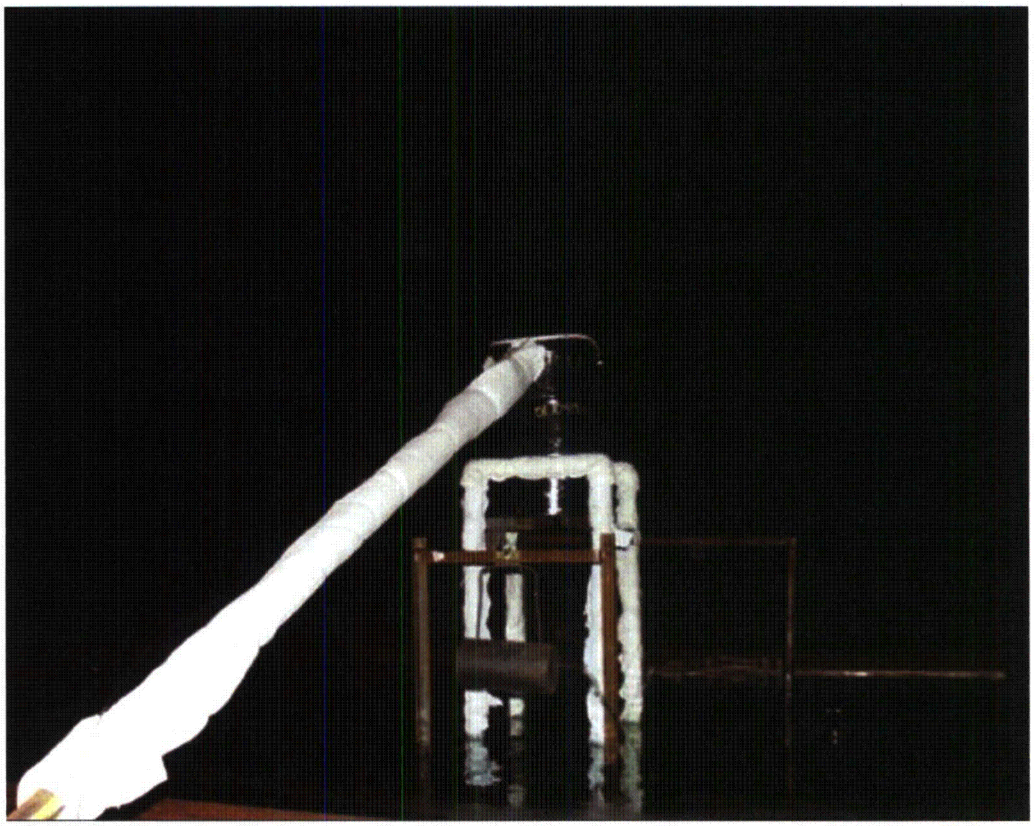


Figure 3.5.3-1 Champion Package on Test Stand – View from Thermocouple Shielding Tube

Figure 3.5.3-2 Champion Package during Thermal Testing Phase

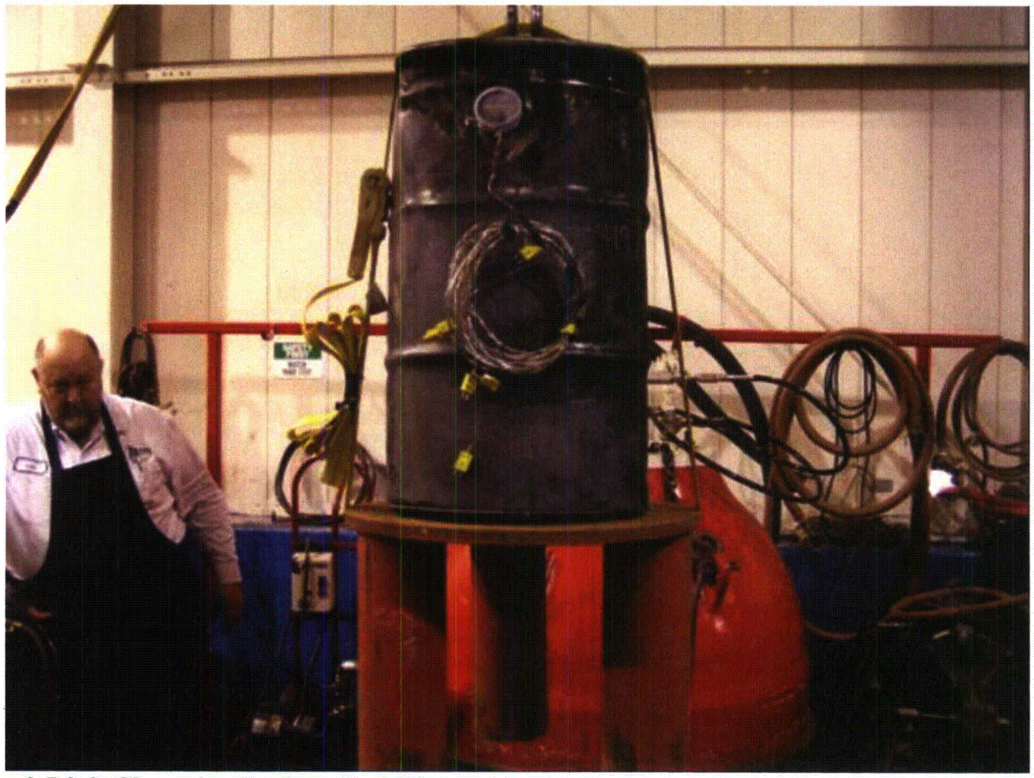


Figure 3.5.3-3 Champion Package Post-Thermal Test

9.2.3.4 Drop Test 4

Figure D-30 shows Drop Test 4 (puncture test, side orientation). Pre-test conditions were:

a) Drop Angle 0° (measured horizontally)

b) Drop Height 40 in. to impact face

The shipping container was released cleanly and impacted the puncture bar in the proper location and orientation. The container remained on its side after impacting the cylindrical puncture bar (see Figure D-32). Deformation data of the exterior was measured and recorded by Fire Technology personnel. Video was taken of the drop event and color photographs showing the extent of damage were taken and are included with this report.

All testing was completed successfully, and all phases of this testing were witnessed by SwRI QA/QC and NSF and Century Industries personnel.

After all drops were completed the CI-1 shipping container was placed in a conditioning chamber overnight and the test article was exposed to warm heat. The test article was exposed to ambient air at a temperature of 140°F ± 10°F for more than 15 hours prior to the fire test.

9.3 Pool Fire Performance Evaluation Test

The CI-1 shipping container was transported to the remote test site in Sabinal, Texas, and the pool fire test described in Title 10 CFR 71.73 (c)(4) was performed on January 28, 2004. Messrs. Mike Arnold and Rick McVey representing Century Industries, Mr. Preston Foster representing BMX Technologies, and Mr. Joseph Pugh representing Nuclear Fuel Services were present to witness the tests. Following initial startup procedures and transfer of 950 gal of diesel fuel to the burn pan, the data acquisition equipment was verified and the fuel was ignited to begin the 30-min pool fire test. Based on visual observation and flame temperatures, it was decided by Century Industries and SwRI to extend the fire exposure due to the lack of complete fire engulfment to the shipping container. An additional 310 gallons of diesel fuel was added for the additional 14 min of burn to compensate for the incomplete engulfment and low flame temperatures. A total of 1260 gallons of diesel fuel was used for the 44 min burn period. A larger pool fire may mitigate these adverse affects. Table 3 lists the significant observations during the pool fire exposure and post-test cool down period.

Following extinguishment, temperature data was recorded during the cool down period. During the cool down, the test article was protected from precipitation and wind effects to eliminate enhanced cooling of the test article.

Table 3. Pool Fire Test Observations.

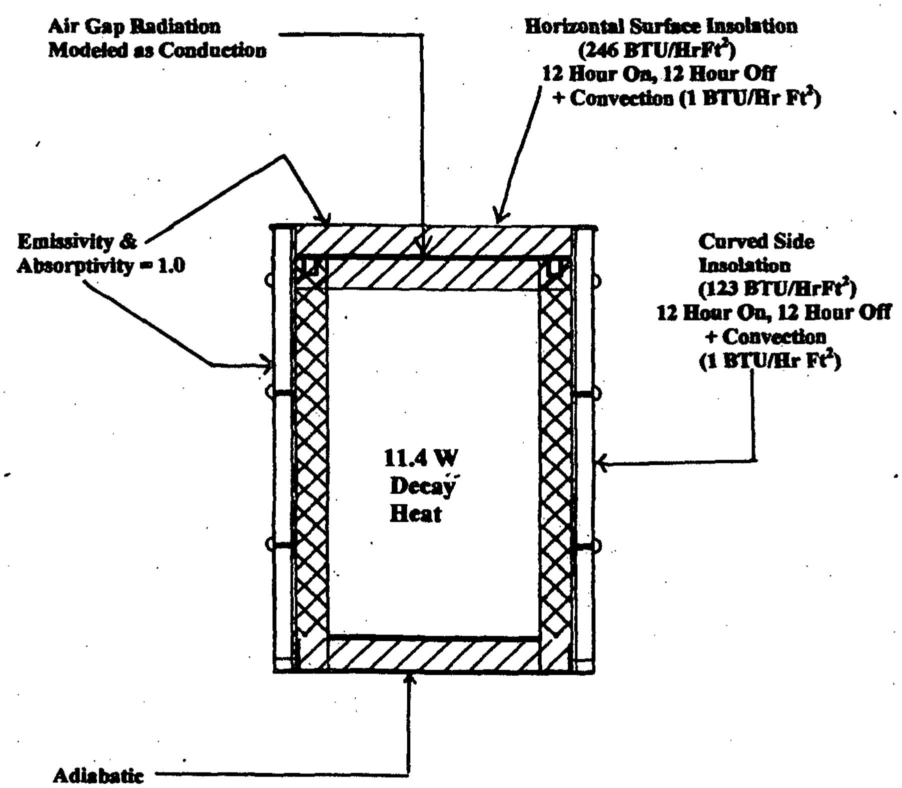
TIME (Min:Sec)	OBSERVATIONS
0:00	Test started. Flames fully developed across pool surface.
1:00	CI-1 shipping container engulfed by flames. Light southeast wind blowing flames northwest. Shipping container mostly engulfed by flames.
17:00	Plug melted and off-gassing from side of container at plug location.
30:00	Decision was made to extend time of exposure.
32:30	Additional 310 gallons of diesel started. Ended with 1260 gallons of diesel fuel.
38:00	Off-gassing burning from crease on bottom of container and off-gassing not burning from plug location.
44:15	Fuel beginning to burn out.
46:30	Residual burning continues on container.
47:00	Off-gassing at TC outlet port and at crease. Both continue to burn.
48:00	No visible flames in pool.
55:00	Temperature monitoring of shipping container continuing (5-10 min stop between burn and cool-down period).

Time-temperature profiles and test condition graphs taken during the pool fire exposure and cool down period are shown in Figures 10 through 15. The average flame temperature recorded by the TCs used to measure the pool fire was 1350°F and the average wind speed during the test was 3.1 mph. During the 44-min fire exposure, TC Nos. 5 and 8 attained maximum temperatures of 450°F and 303°F, respectively. TC Nos. 5 and 8 were located on the lower portion of the inner vessel. As a result of the crush tests, a tear developed at the base of the 55-gal drum. It is SwRI's opinion that the tear provided ventilation, allowing the foam to decompose and burn, causing the elevated temperatures recorded by TC Nos. 5 and 8. Tabular data for the test conditions TC measurements appear in Appendix E.

9.4 Hydrostatic Immersion Test

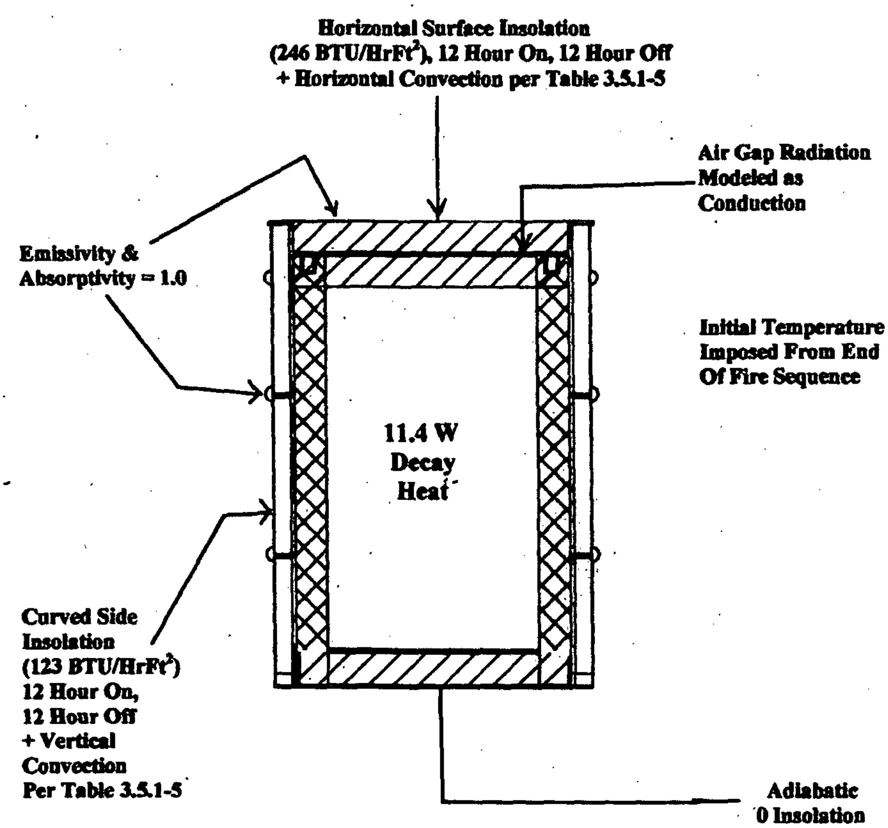
On January 29, 2004, the CI-1 shipping container was transported back to SwRI's main campus facility and delivered to the Test and Evaluation Section of the Department of Structural Engineering. The weight of the container as received from the off-site test facility was 386 lbs. The reduction of weight of 4 lb was due to the consumption of the insulation during the fire exposure.

Appendix 3.5.4



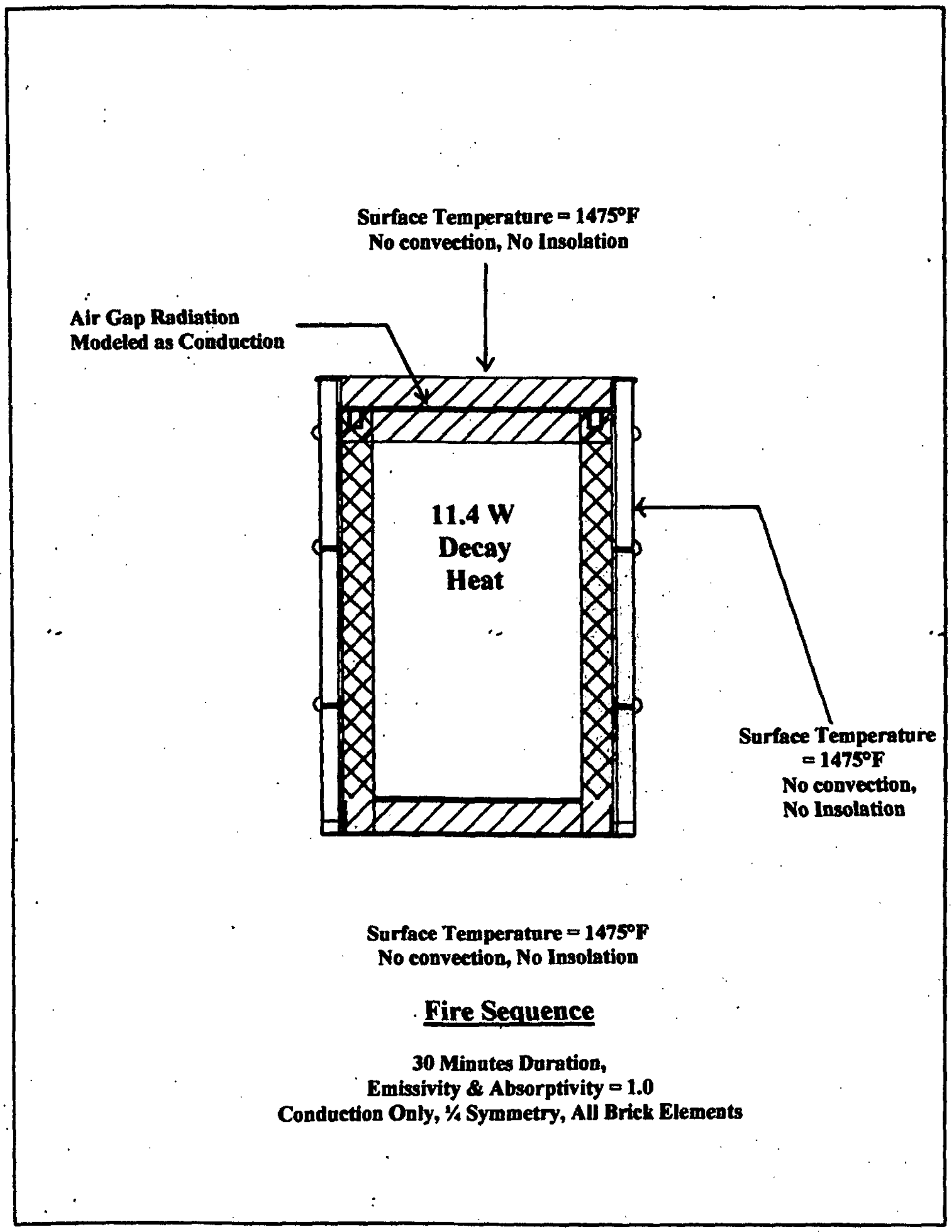
NCT

Package is Modeled Using Conduction Only. ¼ Symmetry, All Brick Elements.
Default Node Temperature = 100°F



Cool-Down Sequence

2 Hour Duration,
Conduction Only,
¼ Symmetry, All Brick Elements



Fire Sequence

30 Minutes Duration,
Emissivity & Absorptivity = 1.0
Conduction Only, ¼ Symmetry, All Brick Elements

Appendix 3.5.5 Thermal Stress Evaluation of the Polyurethane Plug Insert

At the request of USNRC, a thermal stress evaluation was completed for the polyurethane plug (part 62 described in Table 3.5.1-1) that is utilized within the payload cavity. An equivalent part was not utilized in the Champion package fire test (presented as additional performance information, see Appendix 3.5.3); this finite element analysis provides the equivalent data.

ALGOR Release 18.1 was used for the evaluation. The parts, nodes, and elements of the model described in Appendix 3.5.1 and shown in Figures 3.5.1-1 through 3.5.1-15 were used to generate a thermal stress model, and the results from the fire and cooldown model described in Section 3 were imposed on the thermal stress model.

The evaluation utilized static stress conditions with linear material models, and the thermal and mechanical material properties utilized in the model are provided in Tables 3.5.5-1, 3.5.5-2 and 3.5.5-3. The polyurethane compressive modulus varies, depending on the direction of foam rise during its fabrication. Additionally, the compressive modulus is temperature-sensitive. For purposes of bounding the expected performance, the compressive modulus of the polyurethane plug was selected conservatively to produce the highest thermal stress. To confirm the correct selection, a sensitivity case was run.

The evaluation assumes that continuity is maintained at the planes of symmetry of the quarter-model, as shown in Figure 3.5.5-1. Also, a single node at the center of the packaging base (also shown in Figure 3.5.5-1) was constrained against translation in the x-, y- and z-directions.

The temperature condition producing the highest thermal stress in the polyurethane plug is the condition where the steel packaging components are at a low temperature in comparison with the polyurethane plug, since the thermal expansion coefficient of the polyurethane plug is larger than that of the encasing steel components. This maximum thermal differential occurs at 150 minutes (0 minutes is at the start of the fire event) for the VersaPac evaluation. Thus, the thermal stress evaluation was completed utilizing the packaging and contents temperature distribution corresponding to 150 minutes. This distribution is illustrated in Figure 3.5.5-2.

The maximum evaluated stress in the polyurethane plug is 78 psi and is much less than the compressive strength of the material; however, it should be noted that the polyurethane plug is not a structural component of the package, and is considered to be a sacrificial component in the event of a fire.

Table 3.5.5- 1 Material Properties for Versa-Pac Components, excluding Polyurethane Foam

Material	Density (lb / ft^3)	Modulus of Elasticity (psi)	Poison's Ratio	Thermal Expansion Coefficient (in/in/∘F)	Source
Isotropic steel	2.836E-01	2.9E+7	0.29	6.5E-6	ALGOR material library (Mechanics of Materials, 2nd Ed., F.P Beer and E.R. Johnston, Jr.)
8 pcf Temperature dependent isotropic alumina silica	All alumina silica insulation conservatively modeled as 6pcf polyurethane for the thermal stress evaluation (temperatures generated in the fire and cooldown model)				
Fiberglass – Extren525 Isophthalic polyester resin	6.192E-02	8.0E+6	0.3	1.0E-5	Century Industries SOP6.13, also "Typical Properties – FRP Structural Shapes", Enduro Systems, Inc., www.endurocomposites.com
Air	4.225E-05	5000*	0.3*	1E-16*	*Mechanical properties selected such that the air doesn't impose or carry load.
Contents 1, wood	Contents modeled as solid steel to maximize thermal expansion (temperatures generated in the fire and cooldown model)				
Contents 2, void	Contents modeled as solid steel to maximize thermal expansion (temperatures generated in the fire and cooldown model)				
Contents 3, solid steel	2.836E-01	2.9E+7	0.29	6.5E-6	ALGOR material library (Mechanics of Materials, 2nd Ed., F.P Beer and E.R. Johnston, Jr.)

Table 3.5.5- 2 6 pcf Polyurethane Foam Material Properties

Source: General Plastics Manufacturing Company, www.generalplastics.com accessed 1/31/2010. Nominal Physical Property Data for **LAST-A-FOAM® FR-3700 Rigid Foam** at **6** pounds per cubic foot density		
Property	English	Metric
Density (pcf) (kg/m^3)	6	96
Compressive Strength (psi) (kPa) Parallel to Rise		
@ -65° F	243	1675
@ 75° F	154	1063
@ 200° F	102	704
@ 250° F	74	509
Perpendicular to Rise		
@ -65° F	198	1367
@ 75° F	139	955
@ 200° F	82	564
@ 250° F	64	440
Compressive Modulus (psi) (kPa) Parallel to Rise		
@ -65° F	5418*	37357
@ 75° F	4253	29322
@ 200° F	3261	22486
@ 250° F	2383	16428
Perpendicular to Rise		
@ -65° F	4308	29701
@ 75° F	3437	23701
@ 200° F	2465	16998
@ 250° F	2064	14231
Tensile Strength (psi) (kPa)		
Parallel to Rise	182	1252
Perpendicular to Rise	174	1200

Source: General Plastics Manufacturing Company, www.generalplastics.com accessed 1/31/2010. Nominal Physical Property Data for **LAST-A-FOAM® FR-3700 Rigid Foam** at **6** pounds per cubic foot density		
Property	English	Metric
Tensile Modulus (psi) (kPa)		
Parallel to Rise	5947	41008
Perpendicular to Rise	5662	39037
Shear Strength (psi) (kPa)		
Rise Parallel to Specimen Width	116	799
Rise Parallel to Specimen Thick	116	798
CTE: (in/in/°F) (K^-1)	~3.4x10^-5	~6.1x10^-5
Poisson's Ratio	~0.3	~0.3

* Bounding value used in FEA model.
Values used in the model are shown in red

Table 3.5.5- 3 10 pcf Polyurethane Foam Material Properties

Source: General Plastics Manufacturing Company, www.generalplastics.com accessed 1/31/2010.
Nominal Physical Property Data for **LAST-A-FOAM® FR-3700 Rigid Foam** at **10** pounds per cubic foot density

Property	English	Metric
Density (pcf) (kg/m^3)	10	160
Compressive Strength (psi) (kPa) Parallel to Rise		
@ -65° F	552	3809
@ 75° F	350	2415
@ 200° F	215	1485
@ 250° F	143	988
Perpendicular to Rise		
@ -65° F	527	3630
@ 75° F	325	2238
@ 200° F	209	1440
@ 250° F	146	1008
Compressive Modulus (psi) (kPa) Parallel to Rise		
@ -65° F	11306*	77955
@ 75° F	10156	70028
@ 200° F	7250	49986
@ 250° F	5797	39969
Perpendicular to Rise		
@ -65° F	10958	75557
@ 75° F	8759	60390
@ 200° F	6365	43888
@ 250° F	5797	39969
Tensile Strength (psi) (kPa)		
Parallel to Rise	319	2202
Perpendicular to Rise	313	2155

Source: General Plastics Manufacturing Company, www.generalplastics.com accessed 1/31/2010. Nominal Physical Property Data for **LAST-A-FOAM® FR-3700 Rigid Foam** at **10** pounds per cubic foot density		
Property	English	Metric
Tensile Modulus (psi) (kPa)		
Parallel to Rise	11855	81742
Perpendicular to Rise	12489	86111
Shear Strength (psi) (kPa)		
Rise Parallel to Specimen Width	249	1719
Rise Parallel to Specimen Thick	242	1670
CTE: (in/in/°F) (K^-1)	~3.4x10^-5	~6.1x10^-5
Poisson's Ratio	~0.3	~0.3

*** Bounding value used in FEA model.**

Values used in the model are shown in red

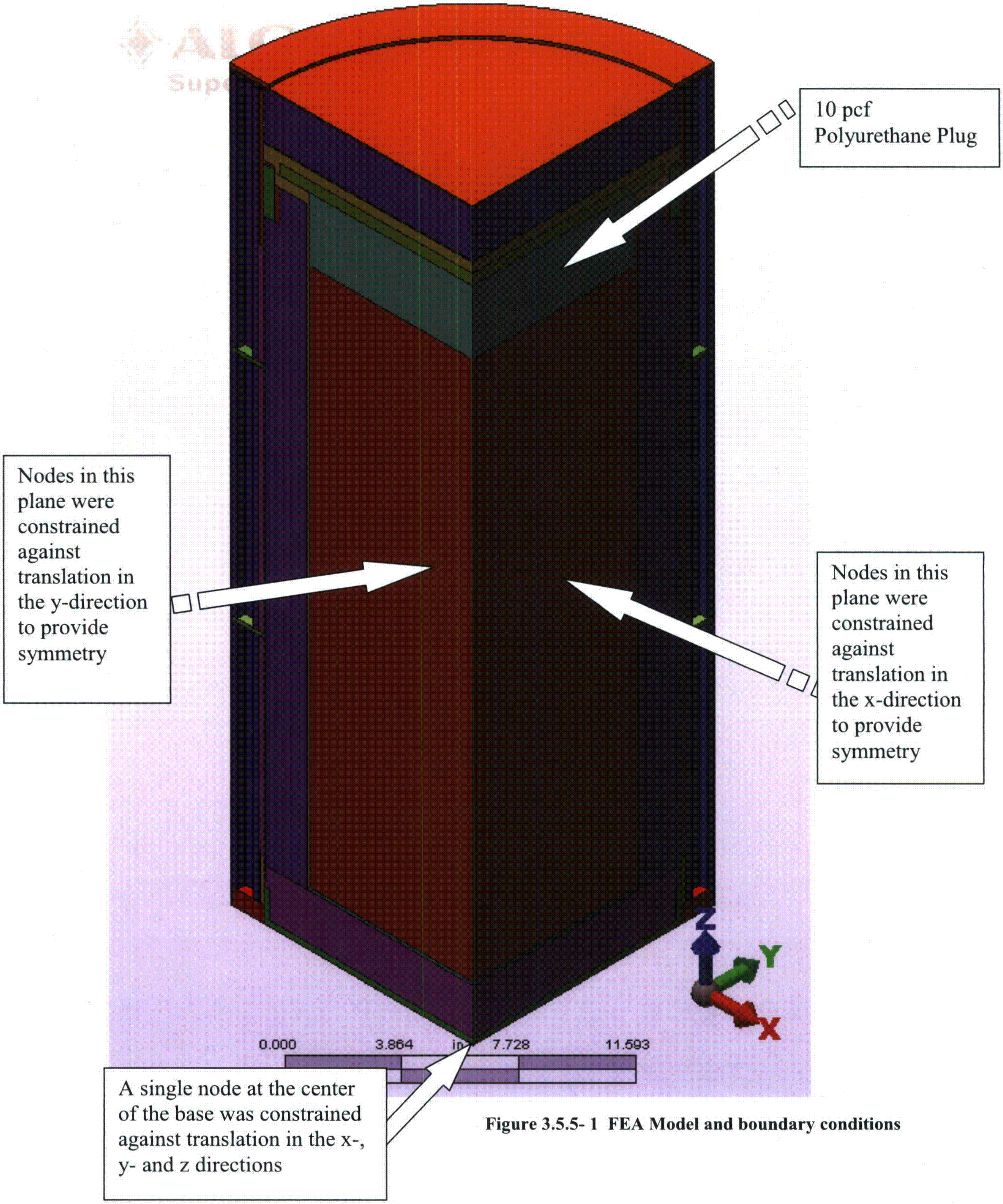


Figure 3.5.5- 1 FEA Model and boundary conditions

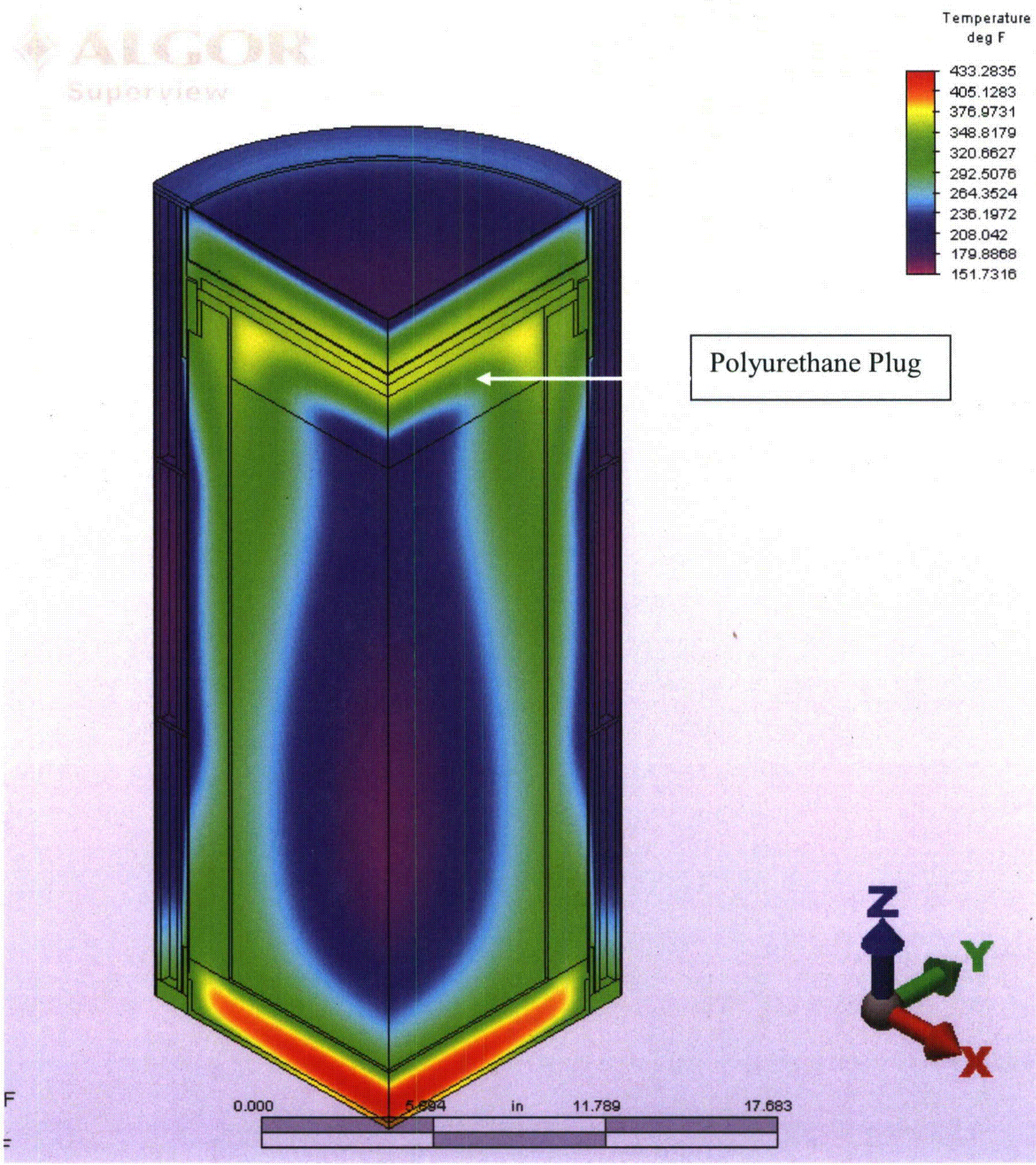


Figure 3.5.5- 2 Imposed Temperature Distribution

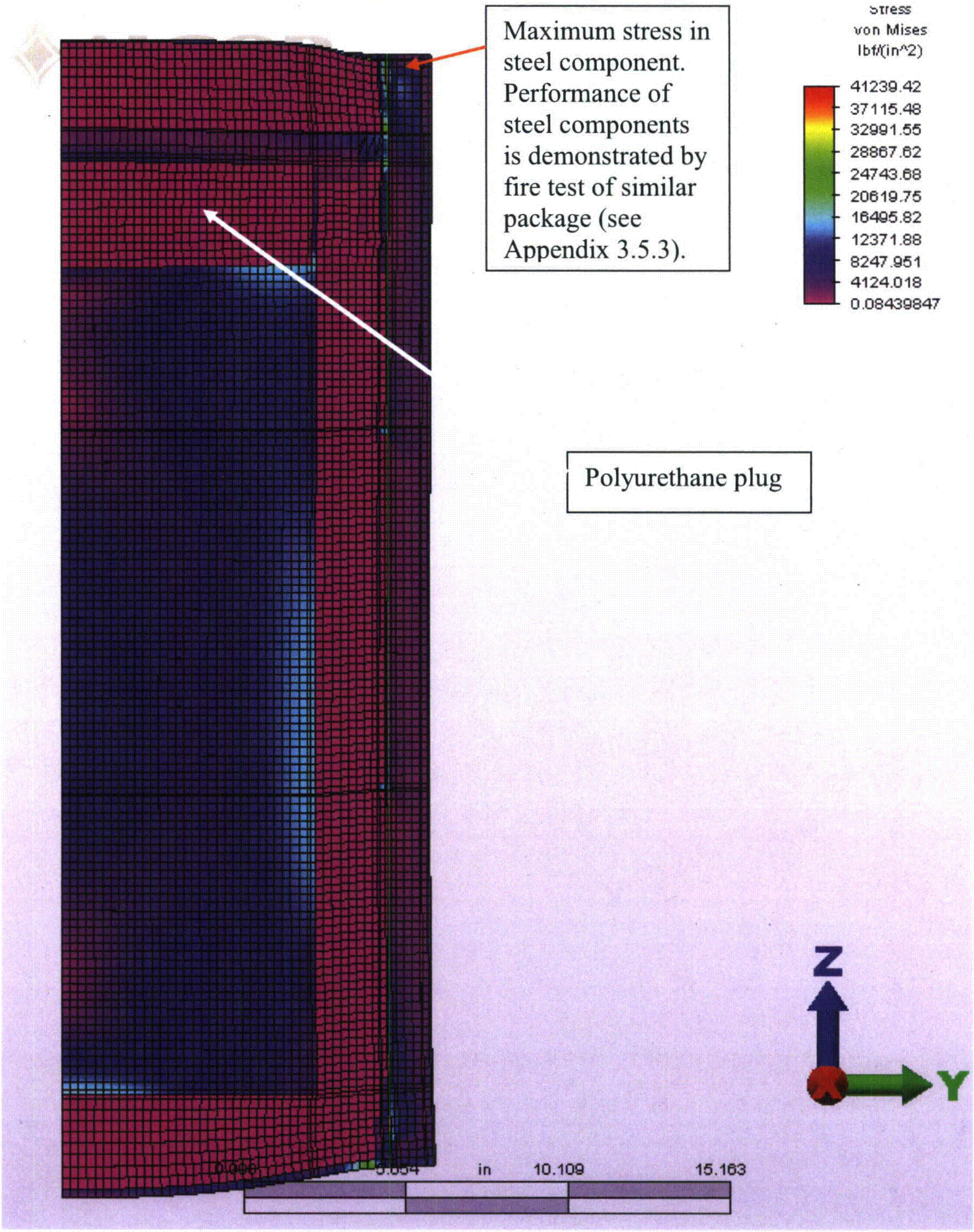


Figure 3.5.5- 3 Side View of Thermal Expansion at 150 minutes, Von Mises Stress Distribution Shown

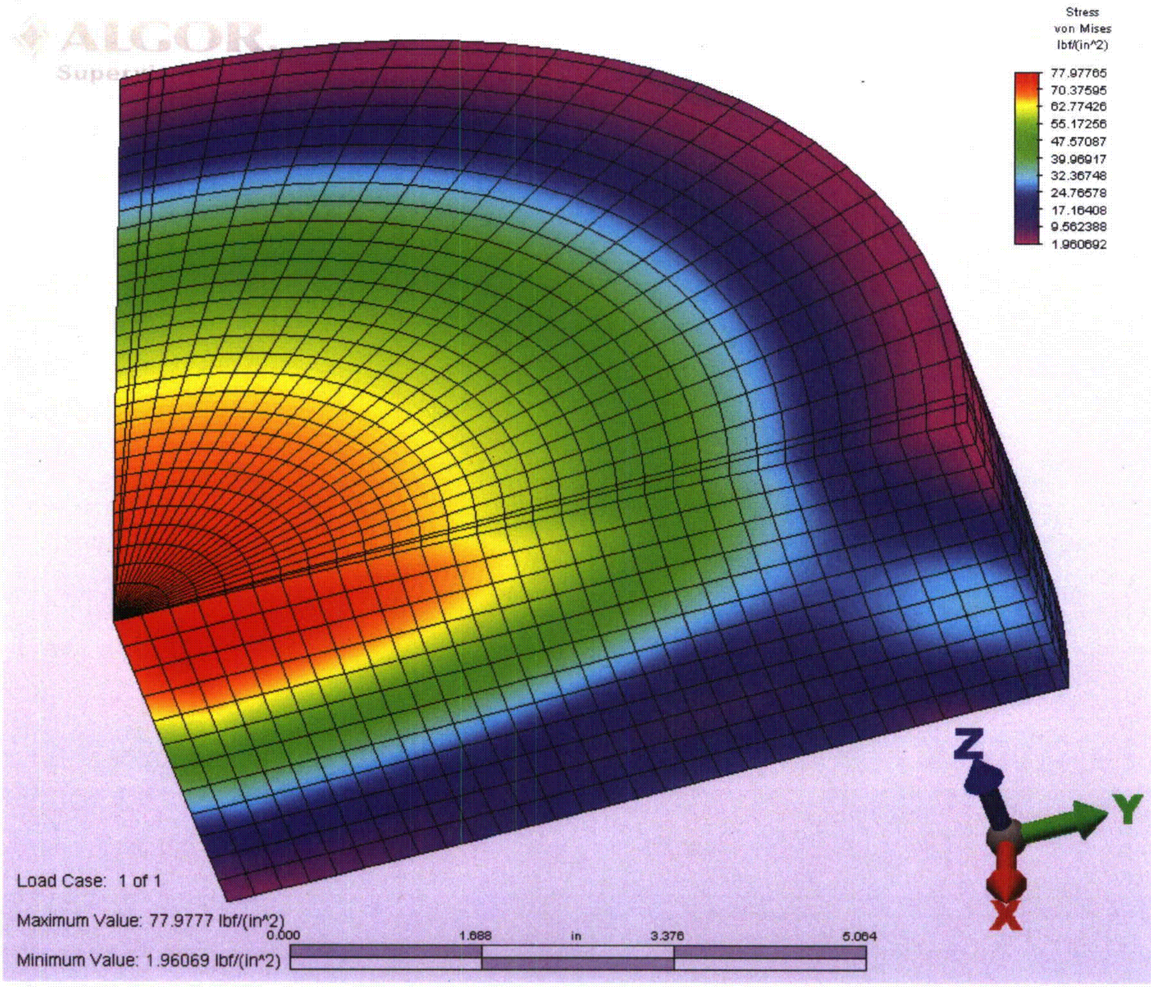


Figure 3.5.5- 4 Thermal Stress on the Polyurethane Plug (Von Mises) at 150 minutes

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Appendix 3.5.6 Supplemental Thermal Evaluation of Package Contents

As previously stated, 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. Evaluation of the payload vessel wall temperatures extracted from the fire analysis results show that the average temperature of the vessel wall is 360.4°F[1]. However, the actual temperature of the contents will be significantly less due the insulating value of the air within the cavity volume and dunnage materials that is not assumed in the thermal analysis. Fire testing of a similar package also provides supporting evidence for this assumption (see Appendix 3.5.3).

As stated in the Century Industries CI-1 package fire test report, the metallic components of the package "showed no signs of failure or fatigue" at the conclusion of the thermal test. This demonstrated acceptability of the drum design to withstand the fire and post-test cool-down induced thermal stresses. Because the Versa-Pac package is allowed to vent to the atmosphere, pressure stresses are not a concern.

Examination of the CI-1 contents following the test series shows that the O-ring gaskets were unaffected by the fire event (Figure 3.5.6-1). This provides further evidence that the contents remained below 400°F since the gasket material is rated to 400°F (Silicone Rubber AMS 3304-F).

A simplified transient thermal conduction analysis using ANSYS[2] is performed assuming paint can sized steel cylinder surrounded by perlite. The model is shown in Figure 3.5.6-2. Physical properties used in the analysis are presented in Table 3.5.6-1. The inner steel cylinder is modelled with a diameter of 6.5 inches. The perlite layer surrounding the steel cylinder has a diameter of 15 inches. The total length of the model is 24 inches with the end perfectly insulated. To simulate the fire event, an initial temperature of 100°F is applied to the outer surface and an internal heat generate of 20 W/m^3 applied uniformly to the steel cylinder. At 30 minutes, the peak fire temperature of 552°F is applied to the outer surface of the model. The analysis is allowed to run for an additional 80 minutes to bound the cool-down phase of the fire. The result of the analysis suggests that the internal temperature of the contents remains below 300°F during the fire and cool-down period. Figure 3.5.6-2 shows the analysis results. The inner cylinder surface temperature reaches a maximum temperature of 125.44°F.

Based upon the thermal averaging of the containment vessel temperatures, test results from similar packages and simplified thermal conduction analysis, the contents of the Versa-Pac payload vessel will not cause chemical or galvanic reactions with either the contents or packaging materials. As a result, no adverse reactions are predicted during NCT and HAC.

[1] Averaging analysis report

[2] ANSYS Version 13.0, SAS IP, Inc., 2010.

Table 3.5.6-1 Applied Heat Loads, Heat Transfer Coefficients and Initial Conditions

Material	Density (Kg/m³)	Thermal Conductivity (W/m•K)	Specific Heat (J/kg•K)	Heat Generation Rate (W/m³)	Reference
Structural Steel	7850	60.5	434	20	ANSYS Material Library
Perlite	32	0.1	387	N/A	The Engineer ToolBox[3]

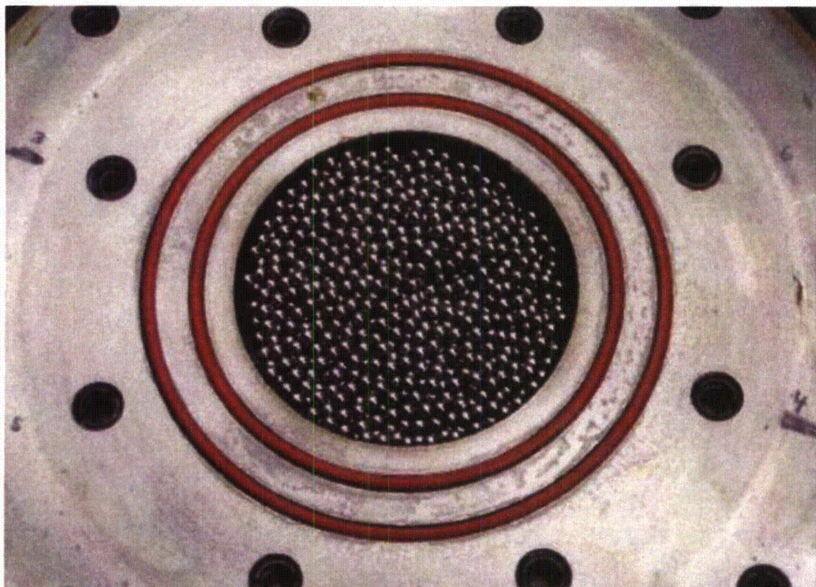

Figure 3.5.6-1 CI-1 Inner Vessel and Gasket Post Fire Test

[3] http://www.engineeringtoolbox.com/perlite-insulation-k-values-d_1173.html

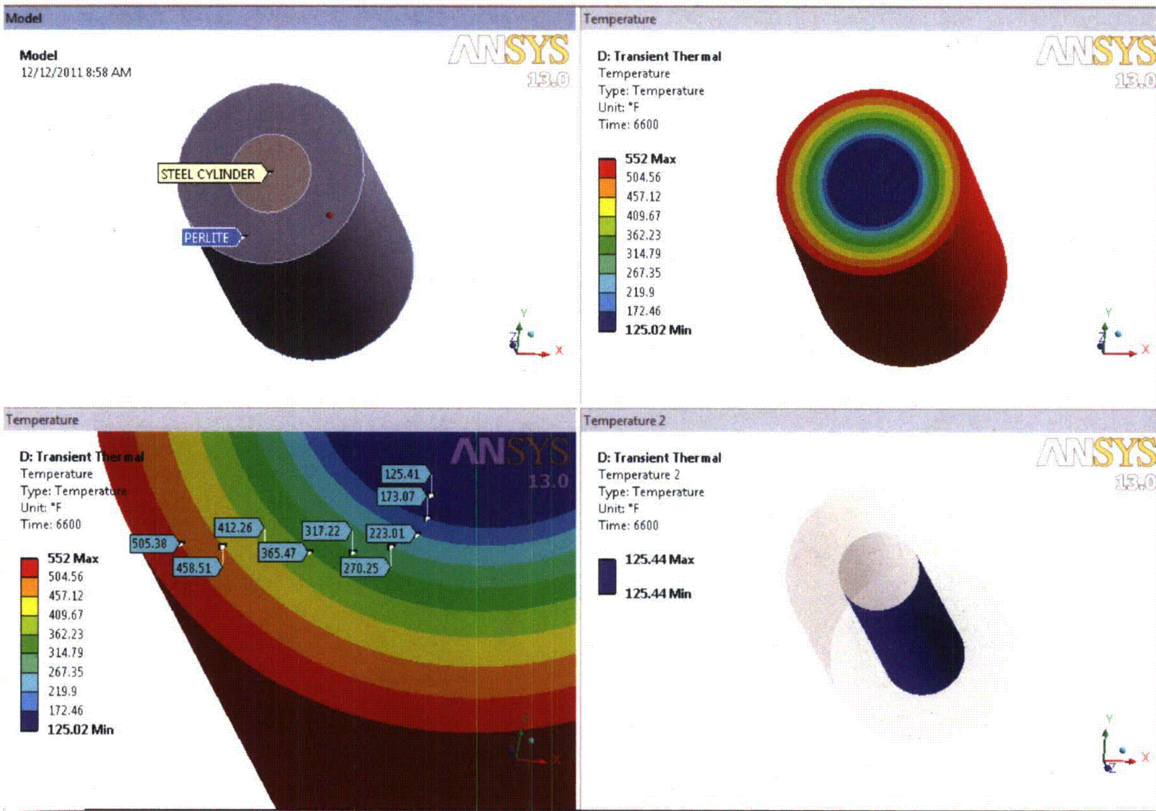

Figure 3.5.6-2 Results of ANSYS Analysis of Payload Vessel Contents Region

SECTION FOUR

CONTAINMENT

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4 CONTAINMENT

4.1 Description of the Containment System

The containment boundary of the package is defined as the payload vessel with its associated welds, payload vessel high temperature heat resistant fiberglass sleeve gasket, payload vessel blind flange, and reinforcing ring.

The payload vessel is comprised of a 10-gauge carbon steel sheet for the body and bottom. The upper end of the vessel is fitted with a ¼" inner carbon steel flange ring with a $^1/_2$" thick carbon steel blind flange. The vessel has three circumferential welds (two at the flange, one at the base) and one longitudinal weld. A $^1/_8$" high temperature resistant silicone coated fiberglass gasket is used between the steel flange ring and blind flange. The payload vessel blind flange is secured to the flange with twelve ½" bolts. There are no penetrations, valves or venting devices used within the containment boundary.

A specified torque is applied to the closure bolts and tightened as part of the closure steps defined within Section 7.1.3 to assure positive closure of the containment boundary, and given the mode of the closure, it cannot be opened unintentionally. The use of lock washers assures that the closure bolts are not loosed due to vibration during shipment. A location for installation of a tamper-indicating device is provided at the drum closure.

4.2 Containment under Normal Conditions of Transport

The Versa-Pac Shipping Container is classified as a Type A Fissile package. Performance tests consistent with the requirements of 10CFR71.71 and 10CFR71.73 have demonstrated that the Versa-Pac effectively prevents loss or dispersal of the radioactive contents under the postulated conditions of transport. Additionally, the tests have demonstrated that there is no substantial reduction in the effectiveness of the packaging during normal conditions of transport; thus, there is no significant increase in external surface radiation levels resulting from the postulated conditions of transport. Section 2.0 provides a description of the tests performed and analyses completed. Section 6.0 demonstrates that the package remains subcritical under normal and hypothetical accident conditions.

Since the package is not a sealed system, the internal pressure is maintained near atmospheric pressure for all conditions of transport. Any packing materials or residual moisture in the payload vessel that may off-gas are allowed to freely vent from the package. (Note that the normal hot maximum temperature for the payload (contents), reported in Section 3.1.3, is 144 ^{o}F.)

4.3 Containment Requirements for Hypothetical Accident Conditions

As discussed in Section 4.2 and Section 2.0, performance tests consistent with the requirements of 10CFR71.71 and 10CFR71.73 have demonstrated that the Versa-Pac effectively prevents loss or dispersal of the radioactive contents under the postulated conditions of transport. Section 6.0 demonstrates that the package remains subcritical under normal and hypothetical accident conditions.

Since the package is not a sealed system, the internal pressure of the package is maintained near atmospheric pressure for all conditions of transport. During the fire event, some water moisture within the payload will be converted to steam. Any pressure build up will be relieved through the package closure.

4.4 Leakage Rate Tests for Type B Packages

This section is not applicable.

4.5 List of Appendices

This section is not applicable.

SECTION FIVE

SHIELDING EVALUATION

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5 SHIELDING EVALUATION

Gamma and neutron shielding are not required for the materials transported in the Century Versa-Pac Shipping Container. However, it is the responsibility of the shipper to assure compliance with 10 CFR 71.47 regarding radiation standards for each individual shipment.

6 Criticality Evaluation

The Century Versa-Pac Shipping Container is described in Section 1.2, *Package Description*. The package exists in two distinct but similar versions consisting of outer 55-gallon and 110-gallon drums.

The 55-gallon drum version of the Versa-Pac Shipping Container consists of a 16 gauge body, bottom and cover. The drum uses a 12 gauge bolted closure ring, standard carbon steel lugs, 5/8" diameter, ASTM A307 bolts and nuts, and a closed-cell EPDM gasket. The overall outer dimensions of the 55 gallon package are 23-1/16" OD x 34-3/4" in height to the top of the drum bolt ring. The drum cover is reinforced by an eighth-inch thick 22-3/8" OD x 18-3/8" ID plate, and four ½" bolts are provided to lend additional strength to the drum closure ring.

The 110-gallon version utilizes a 16 gauge body, bottom and cover. The drum uses a 12 gauge bolted closure ring, standard carbon steel lugs, 5/8" diameter ASTM A307 bolts and nuts, and a closed-cell EPDM gasket. The overall outer dimensions for the 110 gallon package are 30-7/16" OD x 42-3/4" in height to the top of the druim bolt ring. The drum cover is reinforced by an eighth-inch thick 29-3/4" OD x 27-1/4" ID plate and eight ½" bolts are provided to lend additional strength to the drum closure ring.

Both drums are further strengthened with vertical stiffeners fabricated from 1-1/4" carbon steel square tubing, two inner liners of rolled 16 gauge carbon steel insulated by ceramic fiber blanket encase the vertical tubing, and a ¼" carbon steel reinforcing plate on the bottom. Reinforcing angles and solid bars within the liners provides additional strength.

The package's interior is completely insulated with layered ceramic fiber blanket around the containment area with rigid polyurethane foam disks on the top and bottom. The ceramic fiber blanket and polyurethane foam provide shock and thermal protection to the containment area.

The containment and exterior structure including their respective closures provide two barriers to prevent the payload dispersion and water inleakage. An illustration of the packaging is provided in Figure 1-1.

The criticality analysis demonstrates that the payload material may be pre-packaged in hydrogenous or non-hydrogenous containers within the payload vessel. Hydrogenous pre-packaging materials consist of polyethylene, polypropylene, or PVC. PTFE or Teflon® pre-packaging material are also allowed. Metallic pre-packaging materials consisting of aluminum, stainless and carbon steel are further allowed provided their total weight is controlled to within the payload allotment of the package. In addition only materials listed in Table 1-4 are presently qualified for use within the Versa-Pac shipping container; all other materials must meet the 600°F minimum auto-ignition temperature describe in Section 1.2.2. The user is required to establish that the auto-ignition temperature is a minimum of 600°F using an established method, such as the method prescribed by ASTM D883 (Test Method for Reaction Threshold Temperature of

Liquid and Solid Materials).

A summary of the results for the most reactive HAC cofiguration for the criticality evaluation is provided in Table 6-1. The most reactive HAC configuration was determined to consist of an arrangement of in-homogeneous spheres placed within the containment area of the package to achieve maximum interaction from contiguous packages in a triangular array.

6.1 Description of Criticality Design

6.1.1 Design Features

The Century Versa-Pac Shipping Container does not use any neutron moderators or absorbers, however minimum thicknesses of continuous sheet and plate carbon steel (e.g., containment liner, inner/outer liner, drum lid, body and bottom, including top and bottom reinforcing plates) are modeled in the analysis. Descrete carbon steel consisting of the vertical stiffeners, flanges, angles, and bars are not modeled. Also not modeled are the flange ring interfaces with the flange which are model assuming a continuous thickness of the flange material.

Criticality control of the Century Versa-Pac Shipping Container relies on control of the payload vessel diameter, the vessel-to-vessel spacing provided by the drum, and number of packagings that may be shipped together. Additionally, each payload is subject to a mass limit of 350 gram U-235. The U-235 mass limit is an absolute value which is typically defined as a nominal measured value with a measurement uncertainty at a 95% confidence level.

Further, the payload does not rely on moderation-control. Moderation in the payload vessel is evaluated using optimum polyethylene. The moderator is evaluated by varying the corresponding volume fractions. Polyethylene is further evaluated at an increased density. A polyethylene density of 0.98 g/cc conservatively bounds the use of pre-packaging materials containing carbon (including graphite and paraffin) and hydrogen. Basically, the higher density polyethylene bounds other moderating materials with a Hydrogen density less than or equal to 0.141 g/cc.[1]

Thus, the physical packaging design features that are important to criticality safety are the payload vessel diameter, the drum outer diameter, and the payload vessel body, body welds, blind flange and seals. Administrative control of the payload mass and shipment array must also be implemented.

6.1.2 Summary Table of Criticality Evaluation

Table 6-1 provides a summary of the results of the criticality evaluation of the Century Versa-Pac Shipping Container for the most reactive configuration. The 350 gram U-235 fissile mass modeled as a lumped 12.0-cm radius sphere leads to the most reactive configuration. A detailed description of the analytical models and methodology is provided in Section 6.3. All results are less than the conservative administrative Upper Subcritical Limit of 0.95 minus the code bias and bias uncertainty[2].

As indicated in Section 6.3, a single model is conservatively constructed to

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[1] Refer to Table 6-3 for a comparison of the moderating materials considered in this analysis.

[2] The k_{eff} used in all cases represents the KENO k_{eff} plus two sigma (sigma was typically on the order of 0.002). Discussion on the code bias and bias uncertainty is provided in Section 6.5.

represent the Normal Condition of Transport (NCT) and Hypothetical Accident Condition (HAC) package configurations for both the 55-gallon and 110-gallon package versions. As further indicated in Section 2.12.3, the tested 110-gallon package version sustained little damage from both the NCT and HAC testing suggesting small differences in the final evaluated package array sizes. Section 2.0 also indicates that prototype testing of both package designs shows that more damage resulted to the 110-gallon package version due to the heavier weight and greater distance between vertical stiffeners. Therefore, the criticality analysis model is conservatively constructed based on the 55-gallon package dimensions, due to the potential for higher package and fissile mass densities, with the conservative application of actual damage sustained during testing of the 110-gallon package version. This model conservatively bounds the HAC testing and is very conservative with respect to the NCT configuration for both package versions.

6.1.3 Criticality Safety Index (CSI)

The Criticality Safety Index (CSI) is 1.0. Arrays of at least 272 packages are evaluated for the Normal and Hypothetical Accident Conditions. Thus, N is $272/5 \approx 55$ or $272/2 = 136$, and the minimum CSI is $50/55 \approx 0.91$, which is rounded upto 1.0. The corresponding maximum number of packages to be transported non-exclusive use based on a CSI of 1.0 is 50.

6.2 Fissile Material Contents

All materials shall be in solid form with no freestanding liquids; density is not limited. These materials quantities may not exceed 350 grams U-235 in any non-pyrophoric form, enriched up to 100 Wt%. Materials that may be shipped in the Versa-Pac include uranium oxides (U_yO_x), uranium metal (U-metal), uranyl nitrate crystals (UNX), and other uranium compounds (e.g., Uranyl Fluorides and Uranyl Carbonates) enriched up to 100 Wt% U-235. The uranium compounds may also contain carbon or graphite (e.g., UC, U_2C_3, and UC_2). UNX may be in the form of uranyl nitrate hexahydrate, trihydrate or dihydrate, and may contain any amount of moisture; however, the UNX must be in solid form with no freestanding liquid. The payload may be in homogeneous (powder or crystalline) or non-homogeneous (pelleted or lumped) form. Table 1-5 identifies the limits for U-324 and U-236 as applied to the Versa-Pac Shipping Container. The A_2 values are used as stated in 10 CFR 71 and are applied to the package since the payload is limited to normal form material.

The package is evaluated assuming optimum moderation using a bounding high-density polyethylene plastic (Density = 0.98 g/cc) and supports packaging applications containing both carbon (graphite) and hydrogen based materials. Non-fissile chemical impurities do not increase the reactivity of the system; therefore, they may be present in any quantity. The payload may be enriched in U-235 to 100 Wt%.

The payload material may be pre-packaged in hydrogenous or non-hydrogenous containers within the payload vessel. Hydrogenous pre-packaging materials may include polyethylene, polypropylene, and PVC. PTFE or Teflon pre-packaging material are also

allowed. Metallic pre-packaging materials such as aluminum, stainless and carbon steel are further allowed provided their total weight is controlled to within the payload allotment of the package. In addition only materials listed in Table 1-4 are presently qualified for use within the Versa-Pac shipping container; all other materials must meet the 600°F minimum auto-ignition temperature describe in Section 1.2.2. The user is required to establish that the auto-ignition temperature is a minimum of 600°F using an established method, such as the method prescribed by ASTM D883 (Test Method for Reaction Threshold Temperature of Liquid and Solid Materials).

No materials, excluding the minimum steel wall thickness of the package, are used as neutron absorbers or moderators.

6.3 General Considerations

6.3.1 Model Configuration

Figure 6-1 provides a representation of the unit model used in the criticality analysis. The modeled dimensions represent a damaged 55-gallon package. The packaging consists of a cylindrical carbon steel shell surrounded by insulation, an inner/outer steel liner, and an outer carbon steel shell. The steel payload vessel, flange, and blind flange are modeled as carbon steel with reduced minimum dimensions. The drum, inner and outer liners, and upper and lower drum plates are also modeled as carbon steel with reduced minimum dimensions. An enrichment of 100 Wt% U-235 is used to evaluate all cases.

The constructed model evaluated in the criticality analysis, as also discussed in Section 6.1.2, conservatively represents the HAC package configuration (damaged package configuration) for the 55-gallon package design. The model is constructed considering worst case damage to both the 55-gallon and 110-gallon package designs. Due to the smaller package envelope of the 55-galon package design the package is inherently more reactive when compared to the 110-gallon package design. The modeled reduction in package dimensions leads to significant more interaction between packages and results in a lower CSI. The reduced dimensions of the modeled 55-gallon package (damaged package configuration) design results in a more reactive package array when compared to undamaged 55-gallon and 110-gallon designs. Therefore, the conservatively modeled HAC package configuration for the 55-gallon package design bounds the NCT (undamaged package configurations) for both the 55-gallon and 110-gallon packages and further bounds the HAC (damaged package configuration) for the 110-gallon package design. Further evaluation of the HAC (damaged package configuration) modeled array size to the more restrictive NCT criteria (5N) the resulting CSI (1.0) conservatively bounds the NCT criteria (5N) and HAC criteria (2N) for evaluation of package arrays using the single model.

With construction of a NCT model (undamaged package design) based on the 55-gallon design, the evaluated array size would be increased due to additional spacing afforded between fissile material in adjacent packages. This would further lead to a reduced CSI. Thus, a smaller package design, considering worst case damage of the two

designs, to the most restrictive CSI criteria can conservatively represent the Versa-Pac 55-gallon and 110-gallon packages.

6.3.1.1 Model Conservatisms

Table 6-2 summarizes the dimensional changes to the test packages indicated as Test Articles with Serial Numbers 10550, 10551, and 10553. The pre and post test measured results for each package is provided in Section 2.12.3, *Century Industries Performance Test Report for the Versa-Pac*. The worst case dimensional reductions from these tests, as summarized in Table 6-2, are + 1/8" increase in the inner containment diameter, - 5/16" reduction in the outer drum diameter, and -1/4" reducion in the outer drum height (including lid). Note that the measured dimensions provided in Section 2.12.3 do not include the outer drum lid. Also, the outer drum diameter reduction only occurs on one side of the drum mostly due to compression of the area between drum stiffeners at the impact location of the test plate.

The overall outer dimensions of the 55 gallon package are 23" OD x 34-1/2" in height. Neglicting the drum stiffeners and bolt ring reduces the outer diameter to 22-1/2". For the bounding HAC/NCT model, the 55-gallon drum is further modeled with a reduced outer diameter of 1.313" which significantly bounds the maximum reduced dimension resulting from the tests of 0.313" (5/16"). The reduced outer diameter further bounds and still provides margin for the 1/8" increase in the inner containment diameter. The 55-gallon drum is further modeled with a reduced outer height of 0.875" which bounds the maximum reduced dimension resulting from the tests of 0.250" (1/4"). The containment area is further modeled at both nominal and with increased dimensions of 1/8" for the diameter and 1/16" for the height[3]. The nominal dimensions being 15" inner diameter with a height of 27 1/16". The overall outer dimensions of the 55 gallon package model are then 21.1875" OD x 33.625" in height. The drum and payload vessel walls, upper and lower plates are modeled at their minimum thickness as indicated in Table 6-3.

The four vertical members (square tubing), reinforcing angles, and bottom plate ring constructed from carbon steel have been conservatively neglected resulting in modeling less than 50% of the package carbon steel. All insulation products are conservatively modeled as optimum interspersed water moderation.

Packages and arrays of packages were also modeled with full density water boundary reflection.

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[3] Additional performance testing of the 55-gallon package version as documented in Section 2.12.4, indicates that the payload diameter is decreased by $^1/_{16}$". This decrease in diameter will have a net increase, although insignificant, on the k_{eff} for the homogeneous criticality model as discussed in Section 6.6.2.1. The reduced diameter has no impact on the in-homogeneous model k_{eff} since the reduction does not limit placement of the fissile lump. Also, additional array configurations are evaluated in Section 6.6.2.2.8 for the in-homogeneous models that demonstrate that the array k_{eff} is reduced as the fissile lump is moved inward.

6.3.2 Material Properties

Table 6-3 provides the materials and key dimensions used to evaluate the Century Versa-Pac Shipping Container. The density for each material used in the models is provided in Table 6-4. The default atomic number densities from the SCALE library were used for all materials and mixtures.

6.3.3 Computer Codes and Cross Section Libraries

The SCALE 4.4a code with the 44-Group Standard Cross Section Library was used to evaluate k_{eff} of the Century Versa-Pac Shipping Container under all conditions of transport. The code sequence BOMANI, NITAWL, and KENO VI (CSAS6) was used in all analyses.

The verification cases CSAS6 and KENOVI, as provided with the code for verification purposes, were executed prior to commencement of calculations and then upon completion of the final calculations. Other than time and date differences no additional differences were noted in a comparison of the different verification runs.

6.3.4 Demonstration of Maximum Reactivity

6.3.4.1 Fuel Density and Distribution

The fissile payload consisting of a maximum of 350 grams U-235 was modeled in all cases as U-Metal at an enrichment of 100 Wt%. This bounds other uranium compounds including oxides, fluorides, and nitrates. Moderation by both carbon and hydrogen, as discussed in Section 6.3.4.3, further bounds the presence of uranium containing carbon or graphite.

A fissile payload consisting of 350 grams U-235 was initially modeled as a function of the drum fill percentage ranging from 5% to 100% of the drum fill volume. The payload was also modeled as both spherical and cylindrical lumped configurations. The diameters of the spheres and cylinders were further varied to determine the effect on the fissile mass density. Also, the cylindrical heights were further varied to determine the effect on fissile mass density and interaction. The sensivity of k_{eff} with the fissile mass was further investigated at 375 and 400 grams U-235.

Polyethylene was modeled filling the voids of the fissile material with reductions in its volume fraction to consider partial moderation. The inner payload cavity, insulated package regions and exterior regions of the package were further evaluated with moderation ranging from partial to full water densities.

6.3.4.2 Heterogeneous Effects

All of the analyses of the Century Versa-Pac Shipping Container were completed using a homogeneous source material at an enrichment of 100 Wt%. The heterogenic effect noted with enriched Uranium is caused by the presence of U-238, which is not present in the model configurations. Therefore, the modeled homogeneous souce material is representative of and bounding of the proposed payload.

The material was modeled as descrete lumps as both spheres and cylinders to study in-homogeneous distribution effects of the fissile mass. The height-to-diameter ratio of the modeled cylinder was also varied. Spheres are typically more reactive than cylinders while cylinders are more interactive. The modeled conditions of the package will dictate the more reactive geometry. For instance, the modeled package carbon steel will have a more significant effect on the cylindrical geometry due to the higher degree of interaction between neibhoring cylinders. Both geometrical configurations are specifically evaluated in the criticality analysis.

6.3.4.3 Internal Moderation

6.3.4.3.1 Poly-Moderation

The fissile uranium mass was modeled with polyethylene (CH_2) moderation to bound a full range of packaging materials. The polyethylene was initially modeled at a density of 0.92 g/cc which results in a hydrogen density of 0.132 g/cc. This bounds water moderation (density of about 0.998 g/cc) with a corresponding hydrogen density of 0.112 g/cc. To bound other compounds containing more carbon and hydrogen, the polyethylene compound density is increased to 0.98 g/cc which increases the hydrogen density to 0.141 g/cc. At this increased density, the polyethylene moderation would bound paraffin ($C_{25}H_{52}$) at a density of 0.90 g/cc. Paraffin has a hydrogen density of 0.134 g/cc. Optimum poly-moderation with an increased poly-density is therefore demonstrated for the package.

With evaluation of partial poly-moderation of the fissile contents a full range of moderation is considered for the package. Since water-moderation is bounded by poly-moderation, any amount of water- or poly-moderation may be present in the package, and pre-packaging materials having a hydrogen density less than or equal to that of high density polyethylene (0.141 g/cc) do not need to be controlled for criticality purposes. Materials with a hydrogen density greater than 0.141 g/cc are not allowed.

6.3.4.3.2 Carbon-Moderation

The fissile uranium mass was modeled with polyethylene (CH_2) moderation to bound a full range of packaging materials. The polyethylene was modeled at a density of 0.98 g/cc which results in an evaluated carbon density of 0.840 g/cc.

In all instances, the carbon-moderated cases are bounded by the poly-moderated cases. For the unlimited moderation case, there is no limit imposed on pre-packaging material or carbon-containing pre-packaging materials, as the carbon-moderation case is bounded by the increased density poly-moderation case.

6.3.4.4 Interspersed Moderation

A full range of interspersed moderator (water) densities from 0.0001 to 1.00 g/cc were evaluated to determine the optimum interspersed moderator density for the packaging. Interspersed water moderation was evaluated for the thermal blanket and foam regions of the package. Water moderation was also considered in the package area

that contains the vertical carbon steel stiffeners (e.g., square tubing and support angles) and further above the payload within the containment boundary. Also, interspersed water moderation was considered between packages. Due to the higher k_{eff} results for the in-homogeneous modeled configurations, additional region dependent cases are analyzed individually for the payload, payload containment insulation, inner/outer liners, top/bottom insulation, and the package exterior.

The analysis results, as further presented, show that increasing the interspersed moderation from 0.0001 g/cc in all moderator regions causes an increase in the single package multiplication factor and further causes a reduction in the multiplication factor for arrays of packages.

6.3.4.5 Package Array Configurations

Several different shipment package array configurations were evaluated to determine the most reactive arrangement. The package was evaluated using both square-pitched close-packed arrays and triangular-pitched close-packed arrays. The triangular-pitched arrays provide slightly more interaction between packages and yield the higher system k_{eff}.

The homogeneously distributed fissile mass systems, as indicated in Section 6.3.4.1, only considered the triangular-pitch close-packaged array. Square-pitched close-packed array calculations were not performed with the homogeneously distributed fissile mass since the k_{eff} results for these calculations were low and the results were significantly lower than the lumped fissile mass sytems.

However, the lumped fissile mass systems, as indicated in Section 6.3.4.2, considered both square-pitched close-packed arrays and triangular-pitched close-packed arrays. These calculations further considered the fissile mass as both spheres and cylinders. Both spheres and cylinders were considered in the array calculations due to the lower than expected differences noted in the k_{eff} results.

6.4 Single Package Evaluation

6.4.1 Configuration

The single package evaluation considered both the distributed fissile mass and a lumped fissile mass. The package geometry was considered in the distributed fissile mass calculations for the single package. Variations in the fissile mass moderator density and interspersed moderation were also considered in these calculations. A single model was constructed as previously indicated based on the HAC test results which is further bounding of the NCT configuration.

A lumped fissile mass is further evaluated without considering the package geometry since the mass could be essentially fully reflected with flooding of the package. Only variations in the fissile mass poly-moderator density were considered in these calculations since the lumped fissile mass is modeled with full boundary water reflection.

The HAC model would in general have the higher k_{eff} results when compared to a similar NCT model due to the reduced exterior package dimensions resulting from the required performance testing. However, the lumped spherical fissile mass with full boundary reflection bounds both NCT and HAC models in all cases since it is independent of the package modeled geometry. Therefore, the single package safety can be assessed with the use of a single very conservative model.

6.4.2 Results

The single package results are summarized in Table 6-5. All results are less than the conservative administrative Upper Subcritical Limit of 0.95 minus any code bias and uncertainty. Table 6-5 provides a summary of the multiplication factors for all calculations for the single package configurations. Figures 6-2 through 6-5 graphically display the results of the calculations.

The fully poly-moderated and reflected lumped spherical fissile mass provides the most reactive arrangement, Figure 6-5. However, the single package with distributed fissile mass is most reactive when the drum is filled to about 20%, Figures 6-2 and 6-4. Increasing the interspersed water moderation (within the package) density to about 1.0 g/cc maximizes the k_{eff} result (Figure 6-4) while reducing the poly-moderator density decreases the k_{eff} result (Figure 6-3).

Due to their simplicity, single package input cases are not provided in Section 6.9. However input cases can be constructed using the provided array input cases with modification of the array boundaries.

6.5 Evaluation of Package Arrays Under Normal Conditions of Transport

6.5.1 Configuration

The Normal Transport condition postulates a group of 5N Century Versa-Pac Shipping Containers (5(50)=250), optimized as discussed in Section 6.3.4. Close full water reflection is applied at the array boundary. Table 6-1 summarizes the evaluated fuel loadings and conditions for the Hypothetical Accident Conditions. Tables 6-6 through 6-9 provide summaries of the multiplication factors for all calculations for the Hypothetical Accident Condition package configuration including sensitivity studies.

A single model was constructed as previously indicated based on the HAC test results which is further bounding of the NCT configuration. The HAC model would in general have higher k_{eff} results when compared to a similar NCT model due to the more extensive damage resulting from testing. Therefore, the package array safety can be assessed with the use of a single very conservative model.

The package array evaluation considered both the distributed fissile mass and a lumped fissile mass. The package geometry was considered in the distributed fissile mass calculations for the package array evaluation. Variations in the fissile mass moderator density and interspersed moderation were also considered in these

calculations.

6.5.2 Results

As discussed in Section 6.5.1, the package array safety can be assessed with the use of a single very conservative (HAC) model.The results of these bounding HAC calculations are further detailed in Section 6.6.2.

6.6 Evaluation of Package Arrays Under Hypothetical Accident Conditions

6.6.1 Configuration

Regulation requires that a minimum of 2N damaged packages (2(125)=250), arranged in the most reactive array, be evaluated for Hypothetical Accident Conditions (HAC). However, since a single model is used for both NCT and HAC, the more limiting NCT 5N criterion is used in the determination of the appropriate CSI. Additionally, the evaluation includes optimum interspersed moderation, optimum fissile mass moderation, and close full reflection by water at the boundaries. Also, the fissile payload contents are arranged within the package in support of the most reactive array determination.

The package bottom offers the lowest amount of carbon steel interms of amount and thicknesses and further provides the shortest distance to the boundary of the package. Therefore, the most reactive package orientation occurs when the fissile mass is oriented at the base of the package with the bottom package further inverted and the top package stacked in its normal orientation. This places the lumped fissile mass within two contiguous packages in their closest proximity. The packages are then evaluated in both square and triangular configurations with the lumped fissile mass further oriented to achieve maximum interaction between contiguous drums. Large package arrays are then constructed with duplication of the inverted and normal package arrangement. Figures 6-16 and 6-17 illustrate the package arrangement with lumped fissile mass for the triangular and square configurations, respectively. By comparison of both Figures 6-16 and 6-17 it is evident that more packages can be placed within a triangular array. Figure 6-18 illustrates the original stacked package configuration, hereafter refered to as the MOD0 array, with inverted bottom package and normally positioned top package and further shows the duplicated stack in a 4-high package array.

Figures 6-19, 6-20, and 6-21 illustrate additional array configurations (X-Z view) used in the criticality analysis. The MOD1 array as shown in Figure 6-19 is similar to the MOD0 array however only a central cluster is modeled with the remaining lumped spherical masses moved to the opposite extents of the package. The MOD2 array as shown in Figure 6-20 is similary to the MOD1 array however all lumped spherical masses are moved to the opposite extents of the package thereby eliminating the central cluster. The MOD3 array is similar to MOD1 however the spherical masses are centered on the package bottom thereby eliminating the triangular cluster of spheres. A fourth configuration MOD4 is shown in Figure 6-22. MOD4 is similar to MOD0 and MOD1

however the central clustered is moved to the lower region of the package array.

The results of the drop tests reported in Section 2 were used as a basis for determining the structural damage to the package under HAC. The overall OD and height of the package are modeled at 21.1875" and 33.625", respectively, per the configuration, conservatisms and approximations discussed in Section 6.3. This reduction in package diameter conservatively encompasses the damage resulting from both the side and top impact tests (see Section 2).

The density for each material used in the models is provided in Table 6-4. The default atomic number densities from the SCALE library were used for all materials and mixtures. Specific package orientations are further discussed.

6.6.1.1 Homogeneous Model

Two homogeneous model configuarations are investigated. The first model is similar to the single package array model but imployes specular reflection in a triangular array to produce an infinite array of packages. For the second model, the 350 gram U-235 fissile mass is evenly distributed in the base of the package with two packages oriented with one inverted such that the fissile mass within the two stacked drums are in a closer proximity. A finite model is constructed of this double stacked arrangement with specular boundary reflection applied to generate an infinite 3D array of packages. The packages are modeled in both a square and triangular configuration. The effect of interspersed moderation and variations in the fissile mass moderation density are further investigated.

The calculation results are significantly lower than that for the in-homogeneous models as further discussed in Section 6.6.1.2. The results are further presented in Section 6.6.2.

6.6.1.2 In-Homogeneous Model

Similar to the homogeneous model discussed in Section 6.6.1.1, the 350 gram U-235 fissile mass is lumped in the base of the containment region of the package with two packages oriented with one inverted such that the fissile mass within the two stacked packages are in close proximity. A finite model is constructed of this double stacked arrangement with placement of additional packages (drums) in a similar arrangement with their lumped fissile mass further placed in a similar fashion. A finite array of packages are then configured with explicitly modeled full water boundary reflection. The packages are modeled in both a square and triangular configuration with the lumped fissile masses further oriented in their respective packages to optimize interaction between the lumped masses of adjacent packages. The effect of interspersed moderation and variations in the fissile mass poly-moderation density are further investigated.

Figures 6-16 and 6-17 display the modeled drum arrays in both the triangular and square lattice, respectively. Figure 6-18 further shows the X-Z view of the model which in this case shows the sphere placement. A cylinder, with an H/D of 1.0, would occupy the same region as the sphere allowing easy conversion of the model from either sphere

to cylinder and visa-versa. The package model places the fissile lump in the bottom of the package since the package bottom recognizies the shortest distance to a neibhoring lump in an adjacent package. The bottom portion of the package also has the least amount of carbon steel as the bottom plate is ¼" and the top containment closure is ½". The bottom package is then inverted, with the lump further in the bottom, with a normally oriented package above also with the fissile lump positioned in the base of the package containment region.

The calculated results for the lumped spherical and cylindrical results are anticipated to be very close. Additional sensitivity studies will be performed for the most reactive lumped configuration within the Century Versa-Pac Shipping Containers. Further sensitivity calculations consider different cross section libraries, an increased fissile mass, further reductions in the minimum modeled carbon steel thicknesses, an increased poly-moderation density, and lumped spherical mass placement within the package.

The results are further discussed in Section 6.6.2.

6.6.2 Results

The maximum $k_{eff} + 2\sigma$ evaluated for an array of 272 packages for HAC is less than 0.94. This result is based on a fissile mass of 350 grams U-235 with poly-moderation at an increased density of 0.98 g/cc, which corresponds to a Hydrogen density of 0.141 g/cc. The arrangement models about 50% of the carbon steel of the package with those selected components modeled at their minimum values based on standard manufacturing tolerances.

The maximum result occurs with a finite arrangement of Century Versa-Pac Shipping Containers oriented in a triangular configuration with the fissile mass modeled as spheres and further oriented within the package to achieve optimum interaction. A fully poly-moderated sphere of 12.0-cm diameter produces the maximum k_{eff} result for the evaluated package array. The MOD0 and MOD1 configurations for the lumped spherical mass appear to interchangeably produce the higher k_{eff} results as dependent on the number of stacked packages. Sensitivity calculations as discussed in Section 6.6.1.2 are further provided.

Table 6-1 summarizes the evaluated fuel loadings and conditions for the most reactive Hypothetical Accident Condition model. However, Tables 6-6 through 6-9 provide summaries of the multiplication factors for all calculations for the Hypothetical Accident Condition package configuration.

6.6.2.1 Homogeneous Model

The infinite array calculations for the model discussed in Section 6.6.1.1 produced a maximum $k_{eff} + 2\sigma$ of 0.7175 with a 10% volume fill level for a homogeneously distributed 350 gram U-235 mass. Little difference is observed between packages modeled in a triangular and square lattice but the triangular lattice does yield the higher k_{eff} by a difference of 0.0016. Reductions in the poly-moderation density cause the k_{eff} to

be reduced. Likewise, increasing the interspersed water moderation also causes the keff to be reduced. Table 6-6 provides a summary of the multiplication factors for all calculations for the homogeneous model Hypothetical Accident Condition package configuration.

Figure 6-6 displays the results of the homogeneously distributed fissile mass calculations for the inverted bottom/top package model in both triangular and square configurations as a function of the package fill percentage. Packages with a 10% fill volume appear to produce the higher k_{eff} results for this modeled configuration. Although not shown the the figure, the normally oriented packages have lower k_{eff} results and appear to have a maximum value also corresponding to a 10% fill volume. The results of both modeled configurations appear to be consistent.

Figure 6-7 displays the calculation results for conditions with reduced poly-moderation. The array k_{eff} is reduced with reduced poly-moderation density. The array k_{eff} is also reduced with increased interspersed moderation.

The maximum $k_{eff} + 2\sigma$ for this modeled configuration is 0.7175 and results in an EALF of 3.46E-02 eV. Due to the low k_{eff} results further sensitivity studies are not performed for the homogeneous model.

A reduction in the modeled diameter of the package slightly increases k_{eff} for the homogeneously modeled system. Table 6-6 summarizes the result for the homogeneous case in which the package radius is reduced from 19.2088-cm to 19.05-cm. A reduction in the radius of 0.1588-cm (~$^{1}/_{16}$") results in an increase in k_{eff} for the homogeneous case of 0.0129, however the maximum k_{eff} for the homogeneous model of 0.7304 is significantly low such that additional reductions in the diameter will not challenge the USL. Thus, with a further reduction in the diameter of ~$^{1}/_{16}$" the k_{eff} for the homogeneously modeled system is not expected to exceed a k_{eff} of 0.75.[4]

Two input cases are provided in Section 6.9. Case Versa_HAC_INFH_10_A represents an infinite (INF) array of packages with their fissile mass content occupying the bottom 10 volume percent of the inner package (containment). The package is modeled in a hexagonal (H) lattice arrangement with full fissile mass poly-moderation (A). Case Versa_HAC_INFH2_10_A represents an infinite (INF) array of packages with their fissile mass content occupying the bottom 10 volume percent of the inner package (containment). The packages are stacked in an array with the bottom package being inverted to achieve maximum interaction with a top package in its normal orientation. The package is modeled in a hexagonal (H) lattice arrangement as the second evaluated model (2) with full fissile mass poly-moderation (A). The results of these cases are presented in Table 6-6. These input cases can be modified to produce other input cases as referenced in Table 6-6.

[4] Section 2.12.4 indicates that the inner diameter of a VP-55 package was slightly reduced by $^{1}/_{16}$" after the 30-ft slap-down test.

6.6.2.2 In-Homogeneous Model

Both spheres and cylinders are evaluated in the lumped fissile mass model for the Century Versa-Pac Shipping Containers. Sphere and cylinder diameters ranging from 8-cm to 14-cm are modeled with cylinders further modeled by varying their height-to-diameter H/D ratios. Since the fissile mass is fixed at 350 grams U-235, cylinders modeled with a high H/D ratio will have a lower U-235 density when compared to cylinders with a lower H/D ratio. Thus, as the cylinder height is increased to further increase interaction between cylinders in adjacent packages the single unit reactivity is reduced with the reduction in the fissile mass density. The drums are arranged in both a triangular and square lattice. Calculations are initially performed with expansion of a 2x2x2 drum array to a final array size of 10x10x8. Drum arrays are initially modeled consisting of 8, 64, 144, 216, 384, 512, and 800 packages in the MODO sphere placement configuration.

The 12.0-cm diameter sphere consistently produces the higher k_{eff} results in both triangular and square arrays with the triangular arrays consistently producing the highest result. The results of the lumped spherical mass calculations indicate that the triangular configuration is more reactive than the square arrays with an optimum sphere diameter of 12.0-cm. The triangular array is more reactive with increased sphere diameters of 14.0-cm, however reducing the sphere diameter to 10.0-cm causes the square array to become slightly more reactive. The lumped cylindrical fissile mass calculations are further described below. The cylindrical mass calculations will only consider arrangement in a triangular configuration since these arrays produced the higher k_{eff} results in the spherical model calculations.

The 10.0-cm and 12.0-cm diameter cylinders consistently produce the higher k_{eff} results. The 10.0-cm diameter cylinder produces a maximum value at an H/D of 1.0 while the 12.0-cm diameter cylinder produces a maximum value at an H/D of 0.80 with the k_{eff} results differing by only 0.0005. The results of the lumped spherical mass calculations for the 12.0-cm diameter sphere produce higher k_{eff} results with a k_{eff} difference of about 0.02. Therefore, sensitivity studies as indicated in Section 6.6.1.2 will be performed with the lumped spherical mass model.

The results of these cases are summarized in Table 6-7. Table 6-8 summarizes the results of increased poly-moderation density studies. Table 6-9 provides the sensitivity studies for the lumped spherical mass models as indicated in the preceding paragraph.

A reduction in the modeled diameter of the package will have little or no effect on the more reactive in-homogeneous (lumped fissile mass) modeled system since the reduced diameter does not otherwise limit placement of the modeled spherical mass.[5]

Two input cases are provided in Section 6.9. Case Versa_HAC_FINS_12S_A7

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[5] Section 2.12.4 indicates that the inner diameter of a VP-55 package was slightly reduced by $^{1}/_{16}$" after the 30-ft slap-down test.

and Versa_HAC_FINH_12S_A7 represent finite (FIN) arrays of packages in square (S) and hexagonal lattices (H). The fissile mass is modeled as a 12-cm radius sphere in both cases (12S) with full fissile mass poly-moderation (A). The modeled array size is 800 packages (7) in an 10x10x8 array. Corresponding cases A1 through A6, as indicated in Table 6-7, can be reproduced with modification of the array parameters. Likewise, the cylindrical fissile mass models can be duplicated by changing the modeled sphere to a cylinder with further indication of the cylindrical height.

6.6.2.2.1 Expanded Array Analysis

The lumped 12.0-cm diameter spherical mass is used in an expanded array interaction analysis with sphere placement as shown in Figure 6-18 for the MOD0 configuration. Poly-moderation with a density of 0.92 g/cc is used in this analysis. The purpose of the analysis being to evaluate arrays of at least 400 packages starting with a single layer (Z=1) and continuing to a multiple stacked layer (Z=10). The object being to stack 400 packages in layers until the USL is exceeded and then reduce the number of packages in each layer and proceed with additional stacking. Stacked layers with a Z>10 were not modeled due to the decreased k_{eff} trend with the same package array size as the Z is increased from 8 to 10.

The calculation results are combined with the initial package array calculations as show in Figure 6-14. The initial results are indicated by "Trend 1" while the latter results are shown as "Trend 2". The results of these calculations indicate that package arrays consisting of 400, each containing a lumped fissile mass, has a $k_{eff} + 2\sigma$ of 0.94.

The results of these cases are further summarized in Table 6-8. A single input case is provided in Section 6.9. Case Versa_HAC_FINH_12S_10x064, representing an 8x8x10 package array. The nomenclature is similar to that described for other array input cases, however the 10x064 designation represents a modeled array with 10 packages stacked in the Z direction with a single layer of 64 packages modeled in the X-Y direction (an 8x8 array). Other cases, as indicated in Table 6-8, can be reproduced with modification of the array parameters. Likewise, the cylindrical fissile mass models can be duplicated by changing the modeled sphere to a cylinder with further indication of the cylindrical height.

6.6.2.2.2 Increased Poly-Moderation Density

The calculations performed in Section 6.6.2.2.1 were duplicated with an increased poly-moderation density from 0.92 to 0.98 g/cc. The results, shown in Figures 6-14 and 6-15, indicate that an increase in the poly-moderation density causes a reduction in the drum array size from 400 to 300 while maintaining a $k_{eff} + 2\sigma$ of 0.94.

Increasing the evaluated poly-moderation density to 0.98 g/cc bounds other carbon-hydrogen based moderators (paraffin) with sufficient margin. The k_{eff} for cases with paraffin moderation are greater than cases with poly-moderation at a density of 0.92 g/cc however these same cases are all lower than cases with an increased poly-

moderation density of 0.98 g/cc. Therefore, poly-moderation with a density of 0.98 g/cc is bounding for this analysis.[6]

Replacing the poly-moderation with graphite causes the array k_{eff}'s to decrease significantly. A single calculation for an 10x10x8 package array with the 12.0-cm diameter lumped 350 gram U-235 fissile mass moderated with graphite reported a k_{eff} of 0.1554. Therefore, the package array reactivity is dictated exclusively by the presence of hydrogen based moderation. This allows Uranium-Carbon/Graphite compounds such as UC, U_2C_3, and UC_2 in the context of "other uranium compounds" , as proposed in Section 6.2, since they are bound by the analysis of Uranium Metal. Also, the other uranium compounds, including UC, U_2C_3, and UC_2 may also be mixed with carbon or graphite, as both moderator materials are bound by the modeled hydrogen (high density polyethylene) moderation.

The results of these cases are summarized in Table 6-8. The single calculation with only graphite moderation is provided in Table 6-9. The input cases provided in Section 6.9 can be modified to duplicate the cases described in this section by changing the poly-moderation density from 0.92 to 0.98 and by further substitution of the poly-moderation input with graphite or paraffin at their respective material densities.

6.6.2.2.3 Interspersed Moderation

The initial array calculation model involving 800 drums with a 12.0-cm diameter sphere with an interspersed moderation volume fraction (VF) of 0.0001 were duplicated with the interspersed moderation values of 0.001, 0.01, 0.1, 0.5, and 1.0. The results, provided in Table 6-9, show that increasing the interspersed moderation consistently within all regions causes the array k_{eff} to be reduced. With full interspersed moderation the k_{eff} result approaches the value of a single fully reflected sphere.

Input cases can be duplicated by changing mixture 5 in the provided input cases to the desired value.

Additional interspersed moderation calculations as a function of each modeled package region are documented in Section 6.6.2.2.9.

6.6.2.2.4 Fissile Moderation Density

The initial array calculation model involving 800 drums with a fully poly-moderated (VF=1.0) 12.0-cm diameter sphere with an interspersed moderation volume fraction (VF) of 0.0001 were duplicated with reduced poly-moderation values (VF) of 0.90, 0.80, 0.70, 0.60, and 0.50. The results, provided in Table 6-9, show that decreasing the poly-moderation volume fraction causes the array k_{eff} to be reduced.

Input cases can be duplicated by changing the poly-moderation in mixture 1 in the provided input cases to the desired value.

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[6] The Hydrogen density associated with high density polyethylene (HDPE) is 0.141 g/cc. Moderators with a Hydrogen density exceeding 0.141 g/cc are expected to produce higher k_{eff} results.

6.6.2.2.5 Carbon Steel Reduction

The drum arrays initially modeled consisting of 8, 64, 144, 216, 384, 512, and 800 packages, as presented in Section 6.6.2.2, were duplicated by changing the Material and Volume Fraction for Carbon Steel to Water with a Volume Fraction of 0.0001. The results, provided in Table 6-9, show that eliminating the minimum modeled carbon steel causes the array k_{eff} to be increased. By comparison, the analysis involving the minimum modeled carbon steel thicknesses supported an array size of 400 drums.

A reduction of the minimum fabricated carbon steel thicknesses to values below the manufacturing tolerances causes a significant impact on the results. The original analysis essentially considered approximately 50% of the carbon steel of the package. Eliminating the minimum carbon steel in the modeled configuration decreases the array size from 400 to about 216. Further reductions may be necessary when considering a cylindrical lumped fissile mass. Therefore, the minimum modeled carbon steel thicknesses are not only required for structural integrity but also needed to ensure that the USL is not exceeded.

Input cases can be duplicated by changing the volume fraction of mixture 3 in the provided input cases to 0.50.

6.6.2.2.6 Cross Section and Neutron Histories

The initial array calculation model involving 800 drums is executed again by changing the modeled cross sections from the 44-Group Standard Cross Section Library to the 238 group. The case is executed with 600 generations and 1000 neutrons per group (600,000 neutron histories). The results differ by 0.0001 with the 44-Group generating the larger value.

To determine the sensitivity to the magnitude of the neutron histories the case is again executed with the 238-group cross sections with 600 generations and the neutrons per group increased from 1000 to 2000 (1,200,000 neutron histories). Although the $k_{eff} + 2\sigma$ for the case increases by 0.0017 the result is within 2σ of the original result. For comparison, the case using the 44-group cross sections is executed with 600 generations and 2000 neutrons per group. The raw k_{eff} for this case increases by 0.0010 however with reduction in the uncertainty the final $k_{eff} + 2\sigma$ result remains the same.

The use of differenct cross sections and increasing the neutron histories did not change the final result. Therefore, the cases used in the original analysis are sufficient and properly converged. There is also no observed benefit with migration of a larger group cross section library as the 44-group produces consistent results. The results are further summarized in Table 6-9.

Input cases can be duplicated by changing the cross section input, neutron generations and neutrons per group to their desired values.

6.6.2.2.7 Increased Fissile Mass

The drum arrays initially modeled consisting of 8, 64, 144, 216, 384, 512, and 800 packages, as presented in Section 6.6.2.2, were each duplicated by increasing the fissile

mass from 350 grams U-235 to 375 and 400 grams U-235. The results, provided in Table 6-9, show that increasing the fissile mass by 25 grams requires that the drum array size be reduced. The 350 gram U-235 model, as originally evaluated, could potentially support a 550 package array and remain below a $k_{eff} + 2\sigma$ of 0.94. The 375 and 400 gram U-235 models require that the array, using the original array models, be reduced to 350 and 275 packages to remain below a $k_{eff} + 2\sigma$ of 0.94, respectively.

Increasing the fissile mass above 350 grams U-235 requires additional sensitivity analysis as it is quite possible that a larger or smaller fissile lump could become more reactive than the 12.0-cm diameter sphere as modeled in the above cases. Therefore, a fissile mass content no greater than 350 grams U-235 is recommended for the Century Versa-Pac Shipping Containers.

Input cases can be duplicated from those provided in Section 6.9 by changing the fissile constituent volume fraction of mixture 1 to correspond to the increased fissile mass.

6.6.2.2.8 Lumped Spherical Mass Placement Sensitivity

The array configuration illustrated in Figure 6-18 (MOD0) was anticipated to produce the higher k_{eff} results for the lumped spherical mass calculations due to the modeled cluster configuration of fissile mass within the array. The results of the original MOD0 calculations indicate that the USL is less than 0.94 for package arrays of 300 within high density poly-moderation. To demonstrate that the MOD0 array is more, or less, reactive, four additional array configurations are chosen as further illustrated in Figures 6-19, 6-20, 6-21, 6-22 for array configurations defined as MOD1, MOD2, MOD3, and MOD4, respectively. For reference, the results of additional calculations for the MOD0 configuration for arrays of 300 packages are shown in Table 6-10.

The MOD1 array is identical to the MOD0 array for stacked package heights ranging from 1 to 3. The arrays are further similar inthat the MOD1 array has a central clustered sphere array however the remaining spheres are positioned in the opposite ends of the packages. The MOD1 configuration places more spheres in the vicinity of the array full water boundary reflection. The results of the MOD1 calculations with high density poly-moderation are shown in Table 6-10. The MOD0 and MOD1 results interchange as to the higher k_{eff} results however the majority of the results with the exception of two are not stastically different. When compared to the MOD0 array, the MOD1 array produced stastically different and higher k_{eff} results for package array heights of 4 and 6 on the order of 4σ. The maximum observed k_{eff} differences for these package array heights were 0.0071 and 0.0072, respectively. The modeled package arrays for the 4 and 6 high stacks were 308 and 312, respectively. Since the USL of 0.94 is also exceeded for these two calculations, the maximum modeled array size for the 4 and 6 high package stacks are reduced to 272 and 288 packages, respectively. For the reduced package array size (272) the k_{eff} is less than the USL of 0.94.

The MOD2 array is similar to the MOD1 array however the central cluster of spheres as modeled in the MOD1 array are further positioned in the opposite ends of the packages. The MOD2 array eliminates the central cluster of spheres with sphere

migration more toward the array bondary reflection. These calculations demonstrate which is more important, the clustering of the spheres or the presence of full water boundary reflection. The results of the MOD2 calculations with high density poly-moderation are shown in Table 6-10. In all cases, the MOD2 results are significant lower that the MOD0 and MOD1 results. All results are within the USL of 0.94 for package arrays of 300.

The MOD3 array is similar to the MOD1 array however the spheres are centered about the package base as opposed to being clustered. The results of the MOD3 calculations with high density poly-moderation are shown in Table 6-10. In all cases, the MOD3 results are significant lower that the MOD1 results. Centralization of the main cluster within the package array appears to produce the most reactive case by comparison of the MOD1 and MOD3 case results.

The maximum k_{eff} interchanges in comparison of MOD1 and MOD0 results. The MOD1 array is more reactive for the package heights of 4, 6, 7 and 8 with MOD0 being more reactive with package heights of 5 and 9 through 12. However, only the results for package heights of 10 and 12 are stastically different. All results are within the USL of 0.94 for package arrays of 272.

A final sensitivity series of calculations are performed using a variation of the MOD1 configuration with the central cluster of spheres being moved to the bottom of the array. These calculations for the MOD4 array are only performed for the configurations with package heights of 4 and 6. The MOD4 configuration is shown in Figure 6-22. The results are shown in Table 6-10. For the modeled cases, the MOD1 configuration yields the higher k_{eff} results. The MOD4 results are not stastically different from the original MOD0 calculations for the same package stack heights. All results are within the USL of 0.94 for package arrays of 300 in the MOD4 configuration.

Table 6-11 summarizes the results of the sphere sensitivity studies with the maximum k_{eff} result high-lighted for each configuration. The calculations demonstrate that arrays of 272 packages is within the USL of 0.94.

6.6.2.2.9 Interspersed Moderation with Modeled Package Region

The input cases for the MOD1 array are modified to allow different moderator volume fractions to be specified for five different package regions, including the payload region (Mixture 5), payload insulation region (Mixture 6), inner/outer liners (Mixture 8), top/bottom insulation regions (Mixture 7), and the exterior region between packages (Mixture 9). The MOD1 calculations presented in Section 6.6.2.2.9 are duplicated with modified input cases with the volume fractions of each designated moderator region of 0.001, 0.01, 0.1, 0.5 and 1.0. The results of these calculations are presented in Table 6-12. The calculations indicated that the MOD1 configurations with moderator volume fractions of 0.0001, 0.001, and 0.01 produce the higher k_{eff} results. All results are with the USL of 0.94.

It is noted that, since the k_{eff} has been shown to increase with region varied moderator volume fractions that, the larger 300-400 package arrays of the MOD0

configuration (Section 6.6.2.2.4) could have potentially exceeded the USL had the moderating regions been modeled separately. Modeling the MOD0 configuration in a similar fashion is expected to produce similar results. However, necessary reductions in the modeled array size due to the more reactive MOD1 array would also result in lower k_{eff} results for the MOD0 array configuration. To confirm this, the arrays with package heights ranging from 1 through 5 are executed using the same modeled configuration as presented above with the MOD0 array configuration. The MOD0 configuration with package heights of 4 and 5 were less reactive than the MOD1 array for the same package height. For package heights ranging from 1 to 3 the array configurations for MOD0 and MOD1 are identical. The results are also presented in Table 6-12. The calculations indicated that the MOD0 configurations with moderator volume fractions of 0.0001, 0.001, and 0.01 also produce the higher k_{eff} results similar to the MOD1 configuration with the exception of the single package height model which has a maximum k_{eff} with full moderation within the payload (Region 5). All results are within the USL of 0.94.

It is further noted that the majority of results are statistically indeterminate such that a correlation of the modeled array (MOD0 and MOD1) to the modeled interspersed moderation with the k_{eff} result is difficult to produce. In many cases, the next highest k_{eff} result is within 0.0001 of the maximum result. A summary (essentially of Tables 6-11 and 6-12) of the maximum k_{eff} results is provided in Table 6-1.

An input case of the revised base model is provided in Section 6.9.

6.7 Fissile Material Packages for Air Transport

The Century Versa-Pac Shipping Container is not authorized for air transport.

6.8 Benchmark Evaluations

6.8.1 Benchmark Experiments and Applicability

Reference 6-1 documents 161 critical experiments modeled using the SCALE 4.4a code (KENO VI) with the 44 Group Standard Cross Section Library. Uranium compounds used in the experiments include uranyl nitrate, uranium fluoride, uranium dioxide, uranium-aluminum alloys, and uranium metal. Moderators included water, alcohol, nitric acid, hydrofluoric acid, beryllium, aluminum and silicon oxides, water, D_2O, iron, tungsten, plastics and graphite. Reflectors included aluminum, steel, concrete, water, D_2O, titanium, tungsten, lead, iron, and graphite. Enrichments ranged from 62.4 to 97.68 wt% U-235. The H/X ratio ranged from 0 to 1,837. ALCF (eV) ranged from 3.0E-02 to 9.14E+05. The fuel density ranged from 0.014 to 18.6 gU-235/cc.

The HEU experiments were selected and categorized into four distinct groups. These groupings consisted of:

Group 1: All experiments (161) used in this validation,

Group 2: Experiments (81) with ALCF $\leq 10^{-2}$ eV, data sets 1-82, and

Group 3: Experiments (56) with ALCF $> 10^{-2}$ eV and $\leq 10^{5}$ eV, data sets 83-138,

and

Group 4: Experiments (24) with ALCF > 10^5 eV, data sets 139-162.

The cases evaluated for the Century Versa-Pac Shipping Container include uranium metal, water, graphite, steel, and plastic moderation/reflection. The Century Versa-Pac Shipping Container cases were evaluated at an enrichment of 100 wt% ^{235}U, and the H/X ratio ranged from 0 to 1,011. The ALCF for the Century Versa-Pac Shipping Container cases ranged from 3.00E-02 to 9.90E-02. The fuel density ranged from 0.00160 to 0.020 gU-235/cc. Although the evaluated higher enrichment falls very slightly outside the validated range, the benchmark results for Group 2 and Group 3 are directly applicable to the Century Versa-Pac Shipping Container cases.

6.8.2 Bias Determination

Details of the benchmark calculations are provided in Reference 6-1. In order to validate the SCALE 4.4a code for use with high-enriched uranium systems, it is necessary to determine if KENO predicts the multiplication factor in an accurate and precise manner throughout the range of fission energies of interest. To evaluate the accuracy of the code, the mean of each Group of experiments was compared to the mean of the experimental results. A t-test was performed for each Group to determine whether or not the average result of a KENO calculation (the mean calculated k_{eff} for each Group) is statistically the same as the experimental result (unity). Passing the t-test affirms that the KENO code predicts multiplication factors accurately for the Group being tested, without bias. Failure of the t-test indicates that the mean KENO k_{eff} is statistically different from the experimental mean, and that a bias exists in the data. Groups that failed the t-test were further evaluated for bias and uncertainty, and these parameters applied to provide an upper limit subcritical multiplication factor for the Group.

Each Group of KENO-calculated k_{eff}s are also graphed against key system parameters (Energy of the Average Lethargy Causing Fission (ALCF), Hydrogen-to-Fissile Atom Ratio ($H/^{235}U$), enrichment, and fissile material density (g ^{235}U/cc)) to identify trends within the data that may indicate inaccurate cross-sections or instabilities in the code. The normality of residuals is also tested using the Anderson-Darling method. The null hypothesis of a normality test is that there is no significant departure from normality. When the probability level, ρ is greater than 0.05, it fails to reject the null hypothesis and thus the assumption holds. Histogram, skewness and kurtosis plots are also provided for each group.

Jaech's[7] method for bias determination is applied, and the upper subcritical limit is calculated based upon NUREG/CR-6361.[8]

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[7] Jaech, J., *Statistical Methods in Nuclear Material Control,* Exxon Nuclear Company, Richland, WA (1973).

[8] *Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages*, NUREG/CR-6361 (ORNL/TM-13211), (March 1997).

6.8.3 Benchmark Results

For the groups of interest for the Century Versa-Pac Shipping Container, the bounding combined bias and bias uncertainty was reported as 0.0026 (Group 3). Thus, including a conservative 5% administrative margin, the applicable upper subcritical limit for the Century Versa-Pac Shipping Container is 0.9466 for the calculated $k_{eff} + 2\sigma$. For conservatism, a USL of 0.94 is further adopted.

6.9 List of Appendices

6.9.1 References

[6-1] Montgomery, Richard D. Validation of SCALE-PC for High Enriched Uranium (HEU) Systems, MTS423, Rev. 1, 5/30/09.

6.9.2 Selected SCALE 4.4a Input Cases

6.9.3 Reference [6-1]