5.2 Post-test Leak Tests

After the CVs were removed from TU-1 through TU-5, two different leak tests were performed on each CV:

- an operational leak test of the CV O-rings,
- a full containment boundary leak test with helium

5.2.1 Post-test Operational Leak Test

The O-rings of the CV were leak tested using a CALT5 leak tester. Additional details regarding the CALT5 leak tests can be found in Section 2.4. The sensitivity of the leak check was 5×10^{-5} cc/sec. Using the algorithm referenced in Section 2.4, all of the test units had leak rates less than 1×10^{-4} ref-cc/sec (Table 5.1).

Table 5.1 Post-test leak rate for the test unit CV lids

Drum ID	TU-1	TU-2	TU-3	TU-4	TU-5
Lid Leak Rate, ref-cc/sec	4.1432E-5	3.2361E-5	2.5899E-5	2.4773E-5	2.3829E-5

5.2.2 Post-test Helium Leak Test

The main body of the each CV was leak checked to a sensitivity of 1×10^{-7} cc/sec using the Varian Model 959 helium leak test system and was performed to the TTG Procedure TTG-PRF-02, Rev. 0, dated 1-30-04. Each CV was prepared for the test by drilling a hole in the CV lid and tapping for a ¼-inch NPT tapered pipe thread. A K-flange adapter was screwed into the hole with fast setting epoxy on the threads to seal them. After the epoxy hardened, the mass spectrometer helium leak tester was connected to the adapter. The vacuum pump was then engaged and the volume of the CV was evacuated to < 100 milliTorr. The CV was enclosed in a plastic bag and evacuated with a shop vacuum to reduce the ambient air in the bag. A constant flow of helium gas was introduced into the bag to ensure that the CV would remain bathed in helium during the test. The helium atmosphere was maintained for at least 20 minutes. Figure 5.11 shows one of the test units being subjected to the full containment boundary leak test. Complete data from these tests are given on Appendices H – L. Photos of the various leak tests are shown in Appendices A – E.

Figure 5.11 TU-4 undergoing the containment boundary helium leak test

TU-1 was tested twice. The first test indicated no helium detected at all. It was discovered that the test port plug had not been removed; thus the helium was not against the inner O-ring. The plug was removed and the CV evacuated and leak tested again. The second test indicated no leaks, just typical diffusion through the polymer O-ring. See Figure 5.12 for details of the leak rate curve.

TU-2 remained at 0.0E-9 cc/sec for most of the 20 minute test period but displayed an unusual pulsing. Because of these unusual readings it was re-tested 3 days later. Due to the unusual pulsing of the leak-rate reading the data was taken differently during the second test. The start time, amplitude, and duration of the pulses were recorded rather than the leak-rate readings at regular time intervals. The second test showed pulsing that initiated at roughly 1-minute intervals and had a duration 10 s, 10s, 13, 15, 15, 20, 21.5, 23, 24.3, and 30 seconds respectively. The leak rate pulses ranged from less than 1E-8 to 1.4E-6. The readings between pulses were <1E-9. See Figure 5.13 for details of the leak rate curve. The peak amplitude changed after adding helium in a manner expected for diffusion through the O-rings rather than a rise immediately following the addition of helium that would indicate a leak to the outside of the CV. This indicated that there were no leaks.

TU-3 was leak tested and there were no indicated leaks, just typical diffusion through the polymer O-ring. See Figure 5.14 for details of the leak rate curve.

TU-4 was leak tested and there were no indicated leaks, just typical diffusion through the polymer O-ring. See Figure 5.15 for details of the leak rate curve.

TU-5 was tested 4 times because of unusual pulsing of the leak rate reading. During the first test it was discovered that the brass plug had not been removed. The plug was removed and the test restarted. The first test showed a typical diffusion curve with 5 short duration pulses occurring during the test. These pulses occurred between the readings taken every 2 minutes. See Figure 5.16.

TU-5 had three product cans as the surrogate payload. As the CV was evacuated, the lids of the can popped loose allowing the air inside to escape. It was speculated that the lids remained against the sealing surface and allowed the remaining air in the cans to slowly and intermittently leak out thus giving an indicated leak rate on the leak detector. TU-5 was tested a second time with similar results. The pulses in the leak rate reading occurred even when there was no helium being added to the bag. This indicated that the 'leak' was internally from the cans rather than from the containment boundary. The third test was an attempt to test the inner O-ring. The intent was to connect the leak tester to the leak test port and add helium to the inside of the CV through the hole drilled for the first leak test. This attempt was aborted because a tight seal between the leak tester adapter and the leak test port could not be made. The fourth test, setup as in the normal manner, was allowed to pump down over the weekend. This test showed a typical diffusion curve with only three unusual pulses. The peak amplitude changed after adding helium in a manner expected for diffusion through the O-rings rather than a rise immediately following the addition of helium that would indicate a leak to the outside of the CV. The CV is considered to be leak tight. The fourth test is charted in Figure 5.17.

Although some units had unusual spikes in the leak rate readings, all five test units show leak rate curves typical of diffusion through the O-rings and did not show a typical sustained jump in the leak rate readings. Therefore, all of these test units are considered to be leak-tight.

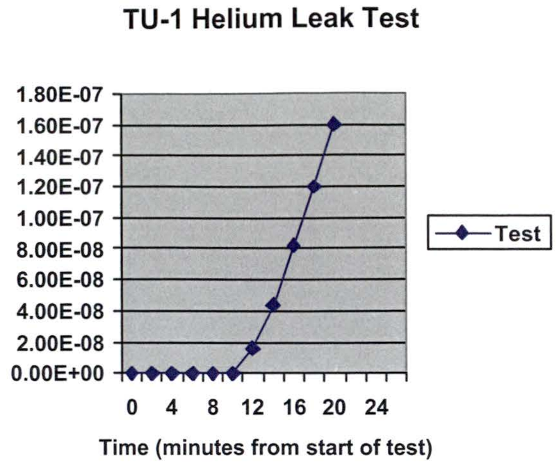

Figure 5.12 TU-1 helium leak (in cc/sec) rate for full boundary leak check

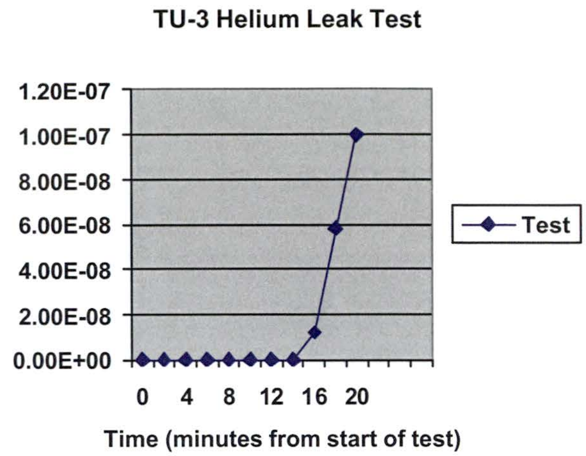

Figure 5.14 TU-3 helium leak rate (in cc/sec) for full boundary leak check

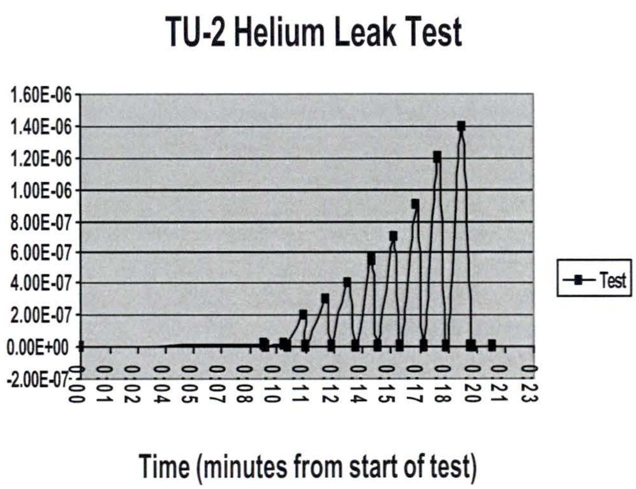

Figure 5.13 TU-2 helium leak rate (in cc/sec) for full boundary leak check

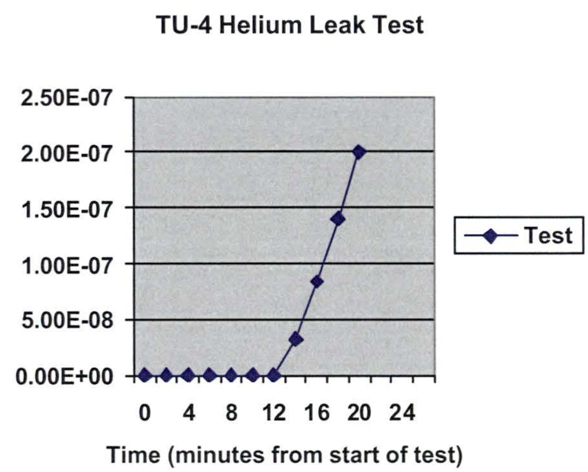

Figure 5.15 TU-4 helium leak rate (in cc/sec) for full boundary leak check

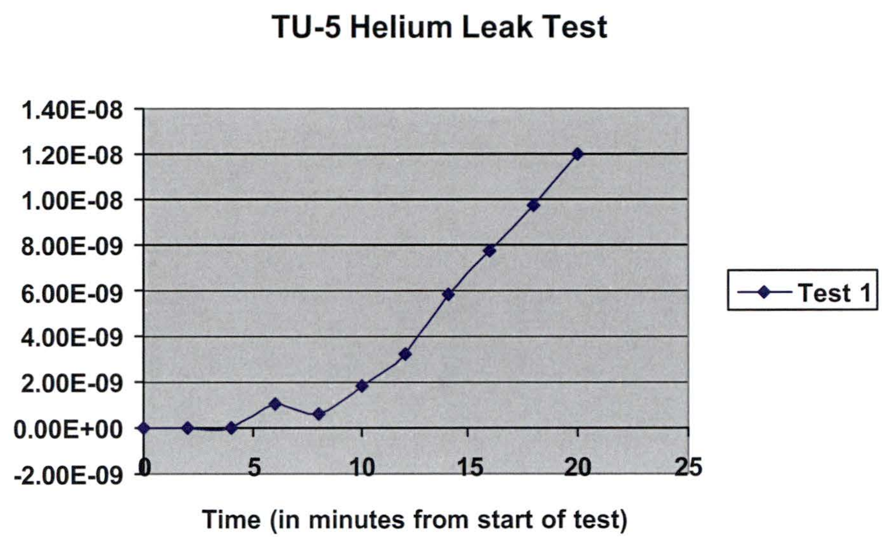

Figure 5.16 Test #1 - TU-5 helium leak rate (in cc/sec) for full boundary leak check

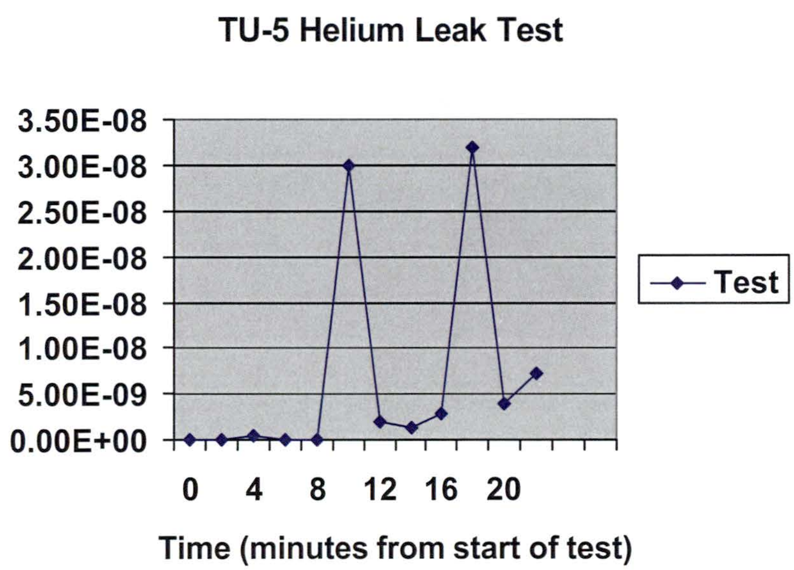

Figure 5.17 Test # 4 - TU-5 helium leak rate (in cc/sec) for full boundary leak check

5.3 0.9-m (3 ft) Immersion Test

After the operational leak tests were performed, the test units were subjected to the required 0.9 m (3 ft) water immersion test. The CVs from TU-1 through TU-5 were immersed under a head of water of at least 0.9 m (3 ft) for over 8 hours. Figure 5.18 shows three of the units undergoing testing and a tape measure being used to assure that the water depth was greater than 0.9 m.

Once the immersion tests had been completed, the CVs were opened to remove the contents, gather available data and look for signs of water in-leakage. No water in-leakage was detected in any of the units.

Figure 5.18 TU-1, -2, and -5 inside immersion tank

5.4 15-m (50 ft) Immersion Test on TU-6

10 CFR 71 requires that a "separate undamaged specimen must be subjected to a water pressure equivalent to immersion under a head of water of at least 15 m (50 ft)." The CV from TU-6 was used as the undamaged specimen. This CV was tested in the Y-12 Immersion Test Tank. The test tank is a vertical axis cylinder about 30 inches in diameter and 6 ft in height with a lid on the top secured by bolts.

Because this test was conducted at the hydro-testing facility in the secure area of Y-12, no photographs could be taken. The tank was filled with water and TU-6 was placed in it so that it sat upright on the bottom of the tank. The lid was then installed onto the tank. The tank was pressurized to 21.7 psig [the equivalent of 15.26 m (50.05 ft.) of water] and held at that pressure for 8 hours. At the end of the test run, TU-6 was removed from the tank and allowed to drip dry. Data forms from this test can be found in Appendix M.

The CV was opened and inspected for water in-leakage and physical damage to the test unit. There was no sign of water in-leakage or physical damage. Some small drops of water were noticed on the outside of the O-rings when the top of the CV was removed. Water on the outside of the O-ring is a normal occurrence.

5.5 CV Disassembly Observations

Once the top plug was removed from the units, the CVs were easily removed from the drums. During the disassembly of the CVs the torque required to remove the lid was measured and recorded. (The nuts of the lid were initially torqued to 115 ± 5 ft-lbs.) Table 5.2 shows the torque required to loosen the CV lid nut. The surrogate payloads of TU-1, TU-2, TU-3, and TU-4 had rust on their surface, which is likely a result of oils and moisture transferred from fingerprints during handling. Often the cable lanyards of the lower two sections of the surrogate load were flattened because the cable had been squeezed between the test weights and the CV wall. The Borobond4 spacers functioned well and withstood the tests with little visible damage, whereas the silicone vibration absorbing pad on the top of each surrogate test weight often showed signs of shredding if not outright disintegration. Because the temperature labels can be blemished by impact or abrasion, some of the labels inside the units were unreadable.

Table 5.2 CV Lid removal torque

	TU-1	TU-2	TU-3	TU-4	TU-5	TU-6
Torque (ft-lbs)	105	45	60	30	60	100

More specific details of the disassembly of the test units are presented below, and temperatures of the temperature-indicating labels attached to both the inside and outside of the units can be found in Section 5.6.

Inside the CV of TU-1, the spacer cushion on the top surrogate load had partially disintegrated (see Figure 5.19) because of the pounding it experienced, and the temperature labels attached just below the flange were scraped and marred due to movement of the surrogate load. The lifting cables attached to the loads were flattened, and the loads had rust spots that were believed to have been caused by handprints from assembling the CV and the leak check procedure pulling moisture from the Borobond4 spacers. (See Figure 5.20.) The spacer cushions on the lower two surrogate load units survived the testing intact. The protective silicone cushion placed on the CV floor was in very good condition, remaining partially stuck to the bottom of the CV after the surrogate load was removed.

The surrogate payloads of TU-2 were also easily removed from the CV and showed nothing remarkable. The Borobond4 spacers were in excellent condition with the upper one being dented only slightly. The cable lanyards attached to the load showed some damage. Referring to Figure 5.21, the cable attached to the load to the left actually broke, and the cable of the next load showed damage. None of the cables of the other test units broke.

The surrogate payloads of TU-3 displayed more rust than most of the other units. Also, the silicone pads on top of the metallic payloads were beginning to unravel and fray. In Figure 5.22, note particularly how the cushion of the top load (further left in the picture) had stripped. On the other hand, the Borobond4 spacers were in excellent condition. Figure 5.23 is an illustration of how the temperature labels were abraded and marred by the movement of the load inside the CV.

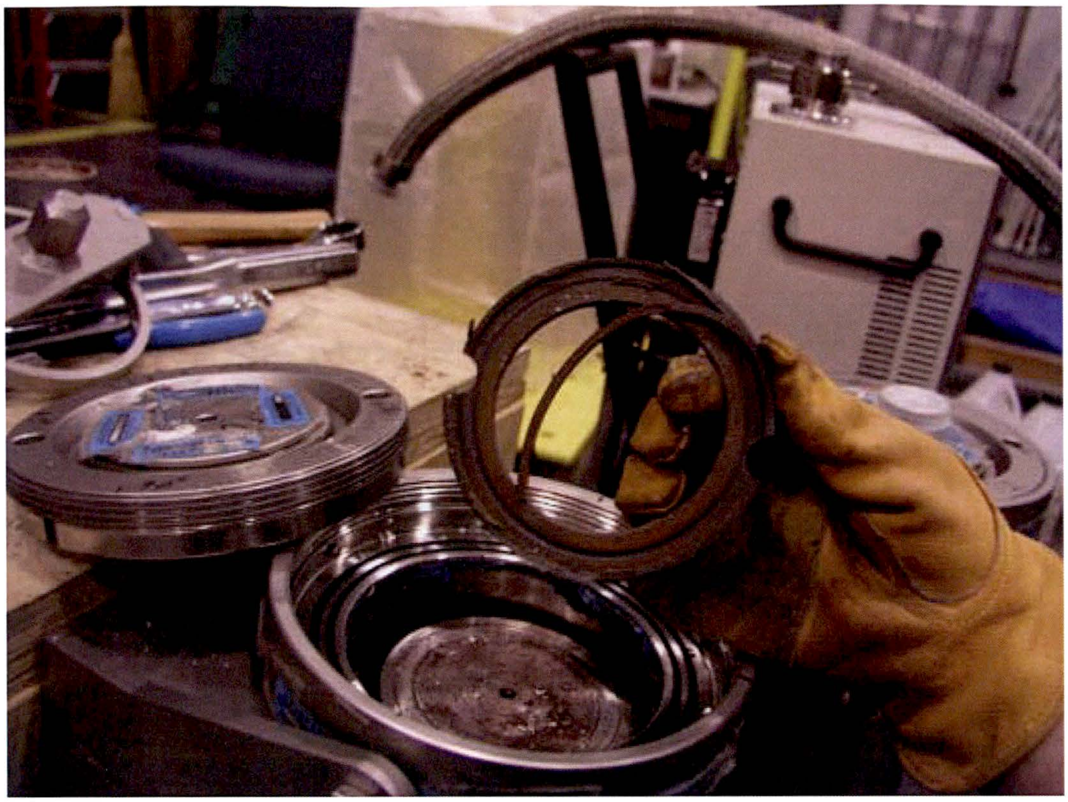

Figure 5.19 Disintegration of spacer cushion of surrogate load

Figure 5.20 TU-1 surrogate load showing rust

Figure 5.21 Broken cable lanyard of TU-2

Figure 5.22 Surrogate payloads of TU-3

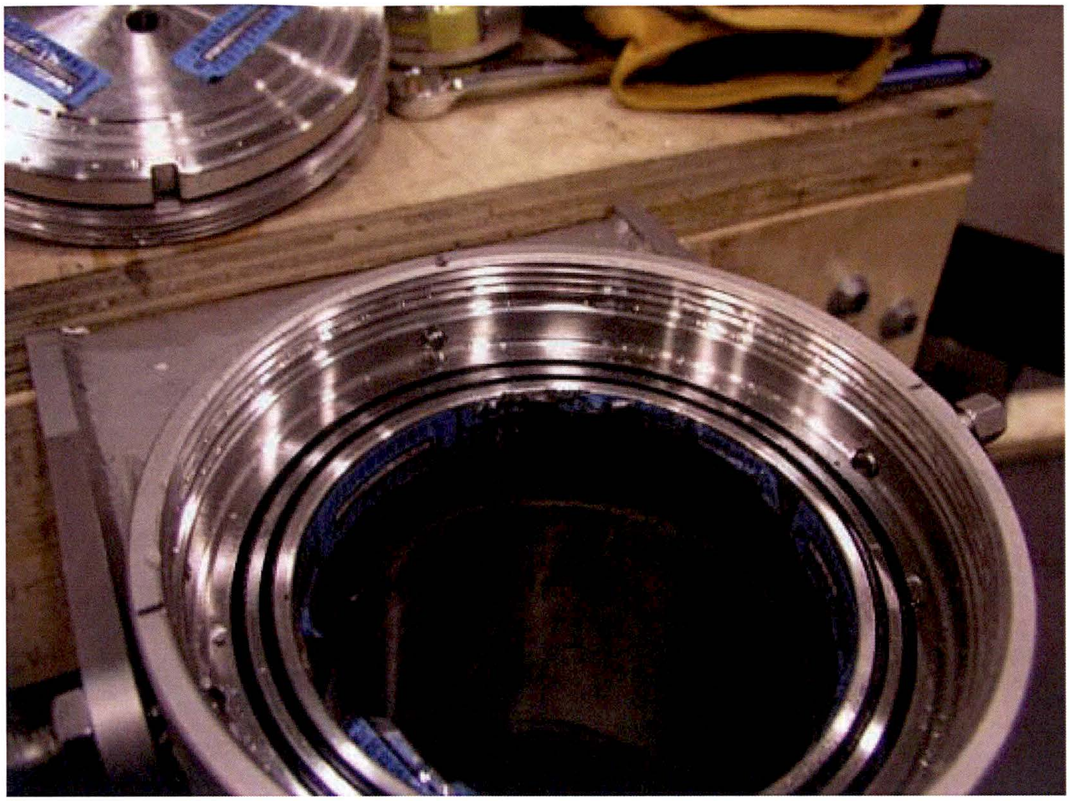

Figure 5.23 Blemishing of temperature labels on flange of CV

TU-4 was disassembled with no difficulties. Some temperature-indicating labels around the flange of TU-4 were blemished by the movement of the surrogate load. In this case, though, the bottom half of the horizontally-placed labels appeared to be more chewed up than blackened. As usual, the silicone pad of the top load showed damage. An oddity that was not seen in any of the other test units was that the lower containment vessel's silicone cushion, which was designed to absorb vibration and shock, expanded around the outside of the CV vessel and worked its way upward. Figure 5.24 shows the silicone cushion wrapped around the body of the CV and another undamaged silicone cushion being displayed for comparison. It is believed that the silicone cushion became "impaled" on the CV during the vibration test, though it may have occurred during either the top-down drop test or top crush test.

TU-5 had lightweight surrogate payloads. The placement of empty cans into the unit to simulate a lightweight load had an unexpected effect. A vacuum was placed on the unit to conduct the post-helium leak test. Later when the vacuum in the CV was being vented, after the initial helium leak check, the lids of the cans were apparently re-sealed and hence collapsed by atmospheric pressure. Figure 5.25 shows how the surrogate payloads were crushed by the pressure of the atmosphere after the cans retained a vacuum. The silicone cushioning was in good condition.

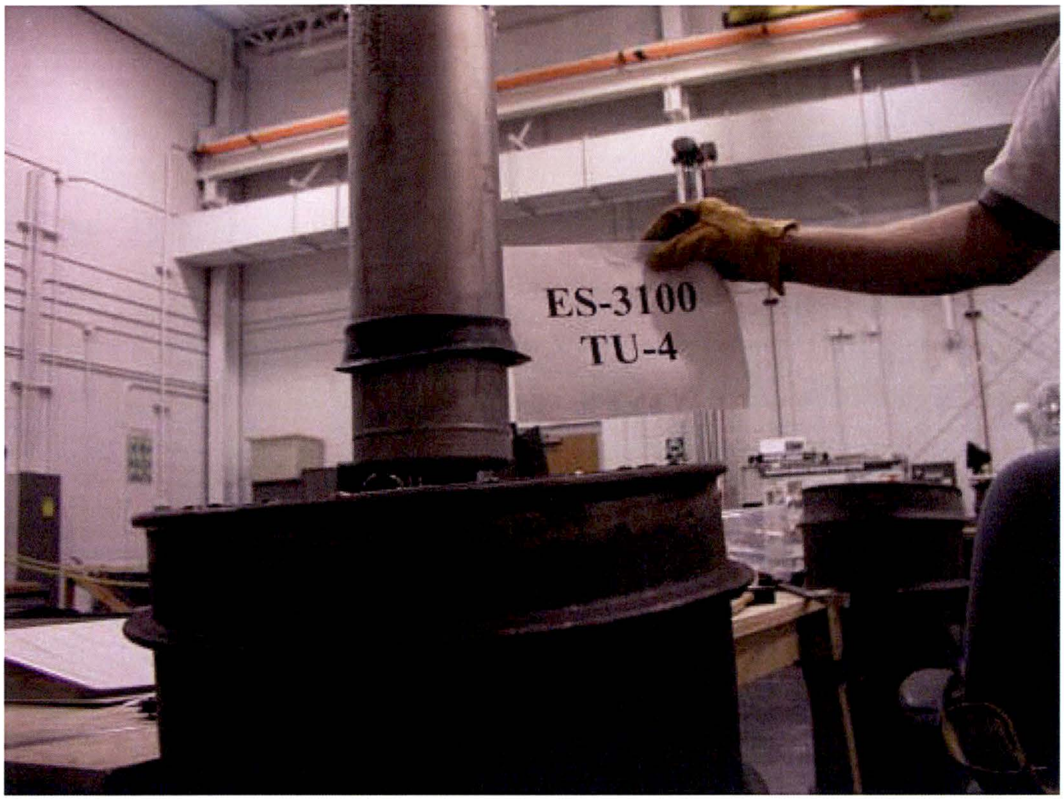

Figure 5.24 Silicone cushion skirting TU-4

Figure 5.25 Crushed surrogate payloads due to vacuum during helium leak test

5.6 Temperature-indicating Label Results

Each test unit had 48 temperature-indicating label locations installed during the assembly of the test unit. Upon disassembly the temperature-indicating labels were read and the highest indicated temperatures recorded. The locations of the temperature labels are shown in Figure 5.26 through Figure 5.31. When applying the temperature labels to the CV lids the B range labels (171°F-261°F) were mistakenly used in place of the 125°F-300°F label specified in the Test Plan.

In general, none of the labels were burned and the temperatures of the CV flanges were less than 300°F. The labels on the top of the CV and on the Borobond4 step of the outer drum of TU-4 were almost completely black. These temperature labels are impact sensitive as well as temperature sensitive. These labels on TU-4 were directly impacted since this unit was subjected to multiple axial impacts. As noted on the data form, the labels on the top of the Borobond4 liner are inconsistent and are likely blacked-out from the impact of the CV rather than temperature. The same is true for the CV top of TU-4 where the CV impacted the top plug. Impact damage is probable because some temperature-indicating spots show part of the spot black while part is still white. Also several labels were lost due to physical damage especially the ones on the inside of the CV flange. The readings of the temperature labels for each test unit are presented in Table 5.3 through Table 5.7.

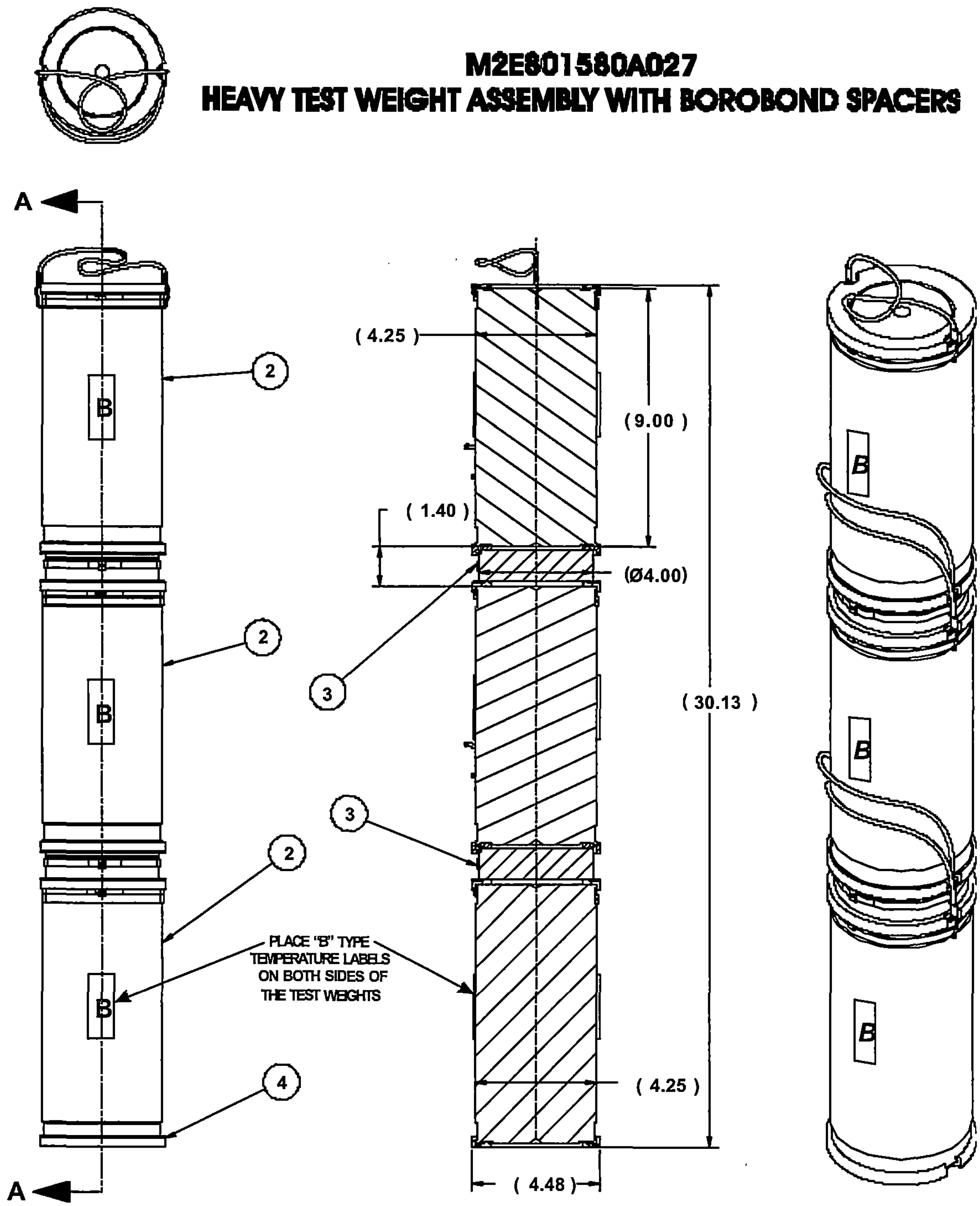

Figure 5.26 Surrogate payload temperature label locations (TU-1, TU-2, TU-3, and TU-4)

M2E801580A029; LIGHT TEST WEIGHT ASSEMBLY (BALLAST FILLED)

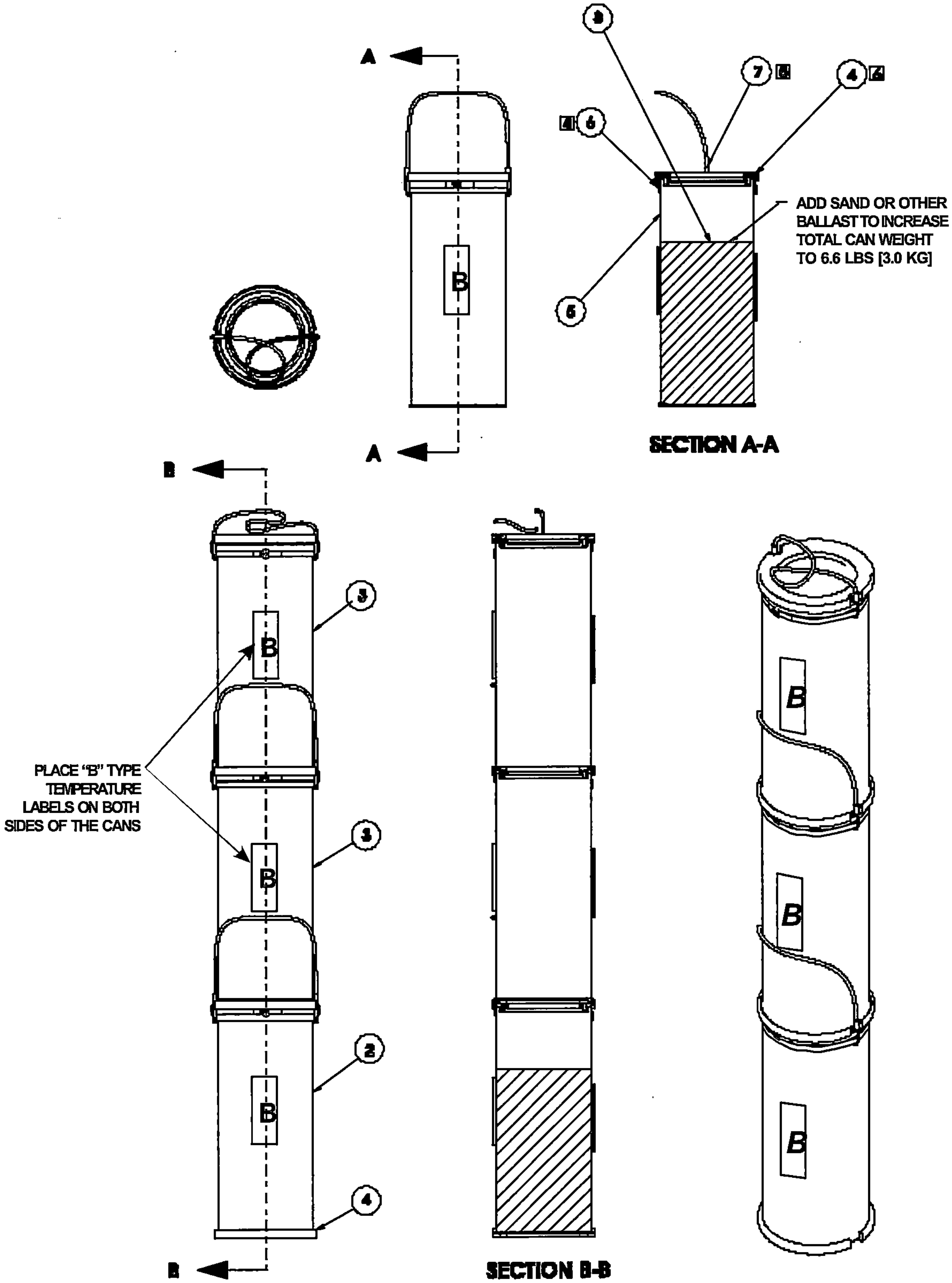

Figure 5.27 Light-weight test assembly temperature-indicating label locations

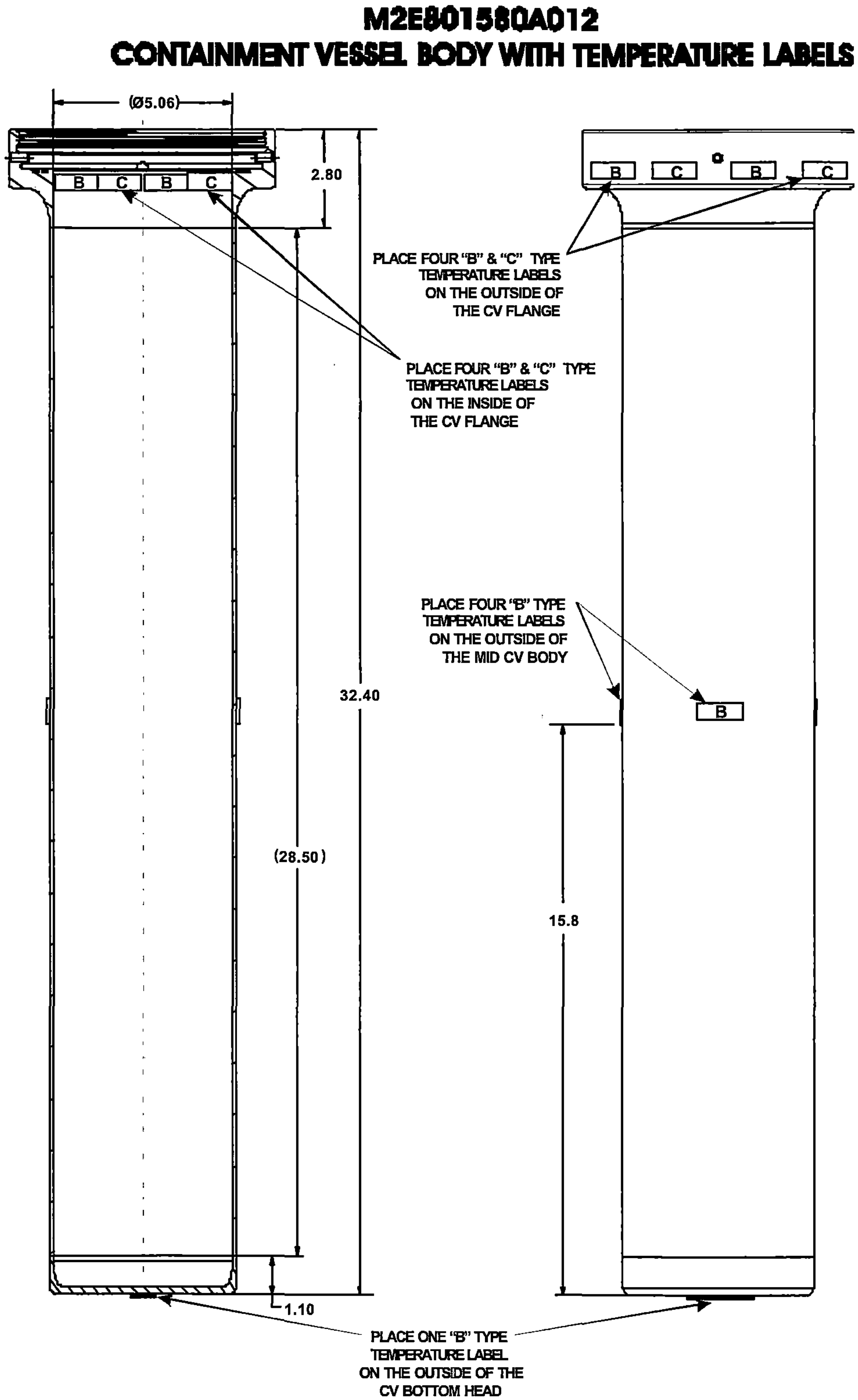

Figure 5.28 CV body temperature-indicating label locations

M2E801580A014
CONTAINMENT VESSEL LID ASSEMBLY

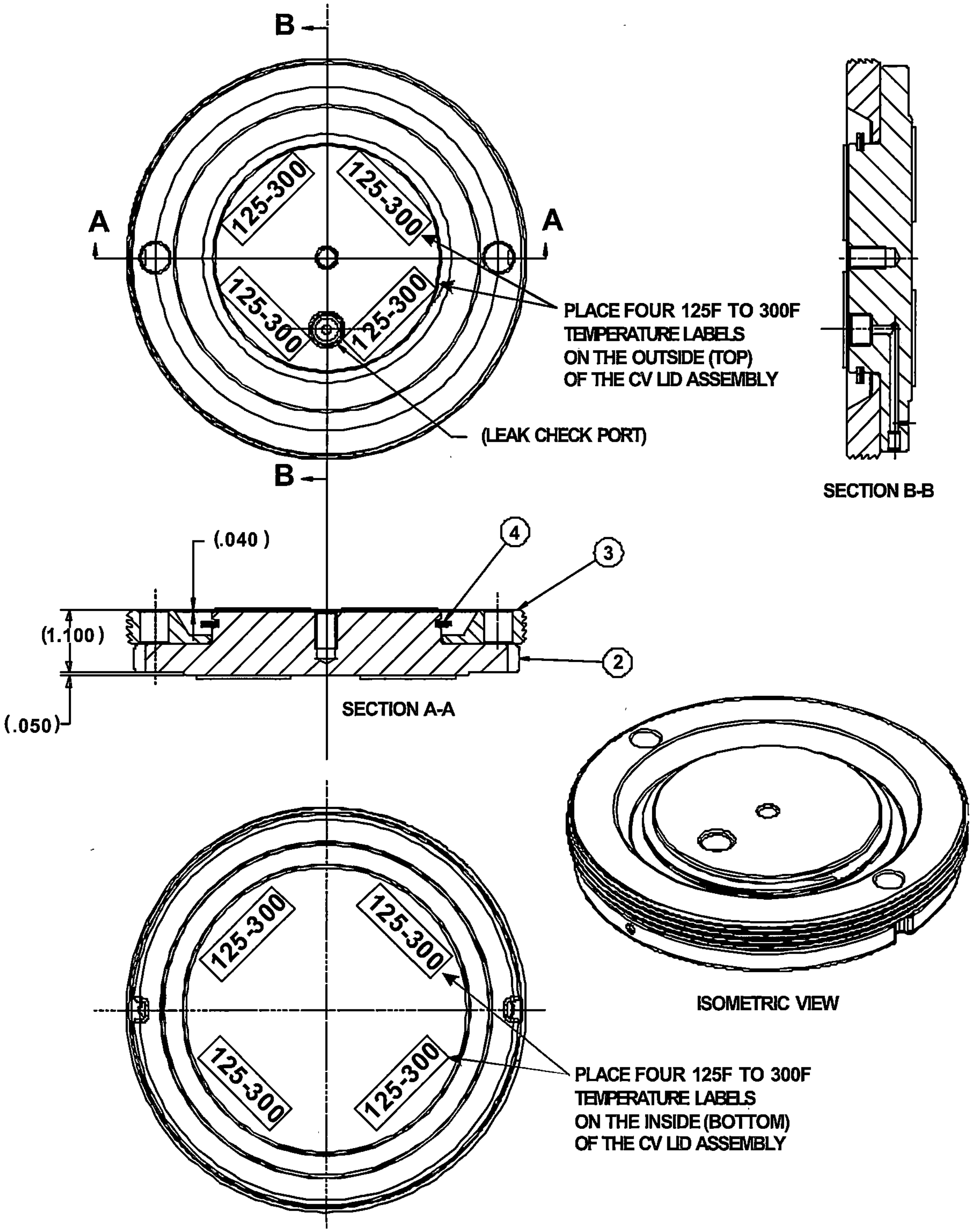

Figure 5.29 CV lid temperature-indicating label locations

(Note: B range labels were mistakenly used on the CV lid instead of the 125-300°F range labels.)

M2E801580A002, BODY WELDMENT

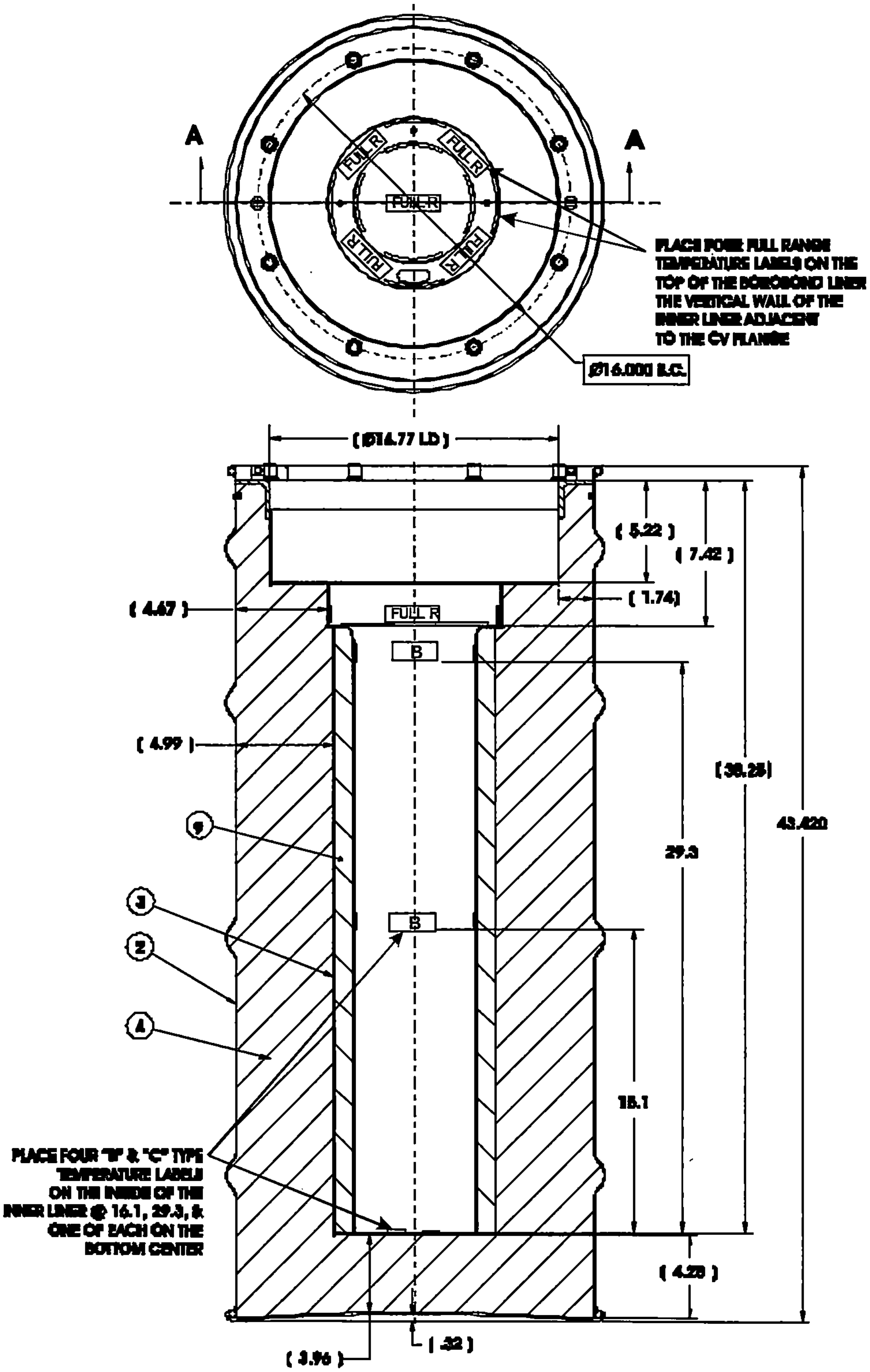

Figure 5.30 Inner liner temperature label indicating locations

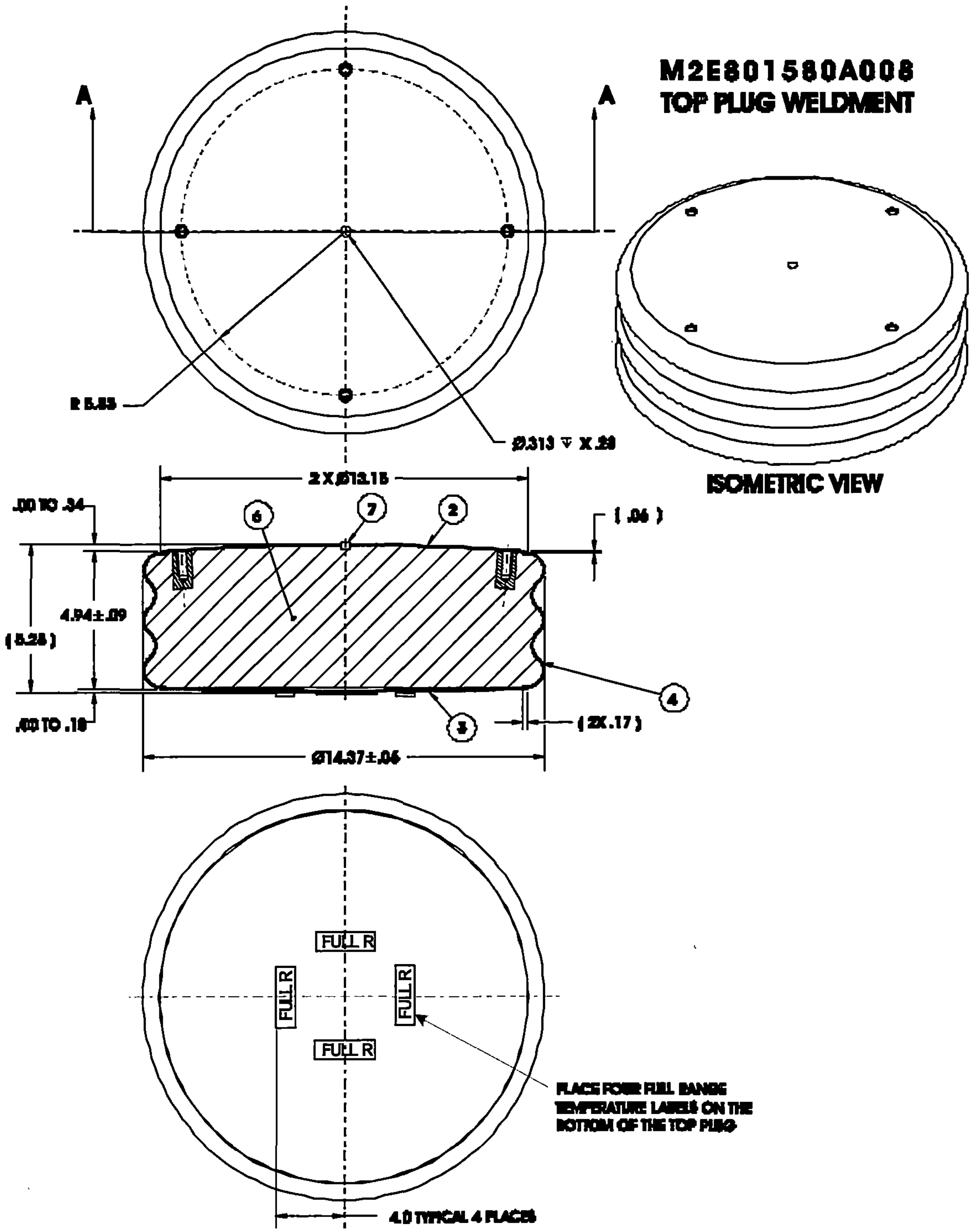

Figure 5.31 Top Plug temperature-indicating label locations

Table 5.3 Temperature-indicating Labels reading for TU-1

TEMPERATURE INDICATOR NUMBER LOCATION CHART												
ON THE SURROGATE PAYLOAD												
Location	**0°**						**180°**					
Side Top	1	B 180	°F				4	B 180	°F			
Side Middle	2	B 171	°F				5	B 171	°F			
Side Bottom	3	B 171	°F				6	B 171	°F			
ON THE CV												
Location	**0°**			**90°**			**180°**			**270°**		
CV Lid Top (outside)	7	B 230	°F	8	B 241	°F	9	B 241	°F	10	B 230	°F
CV Lid Bottom (inside)	11	B 210	°F	12	B 210	°F	13	B 210	°F	14	B 219	°F
Flange (outside)	15	B 230 C ----	°F	16	B 230 C ----	°F	17	B 241 C ----	°F	18	B 230 C ----	°F
Flange (inside)	19	B-Destroyed C- Destroyed	°F	20	B 210 C-Damaged	°F	21	B 210 C ----	°F	22	B 219 C ----	°F
Body Mid Height (outside)	23	B 210	°F	24	B 171	°F	25	B 171	°F	26	B 180	°F
CV Base (outside)	27	B 210	°F	Note: Temp label centered on bottom								
ON THE INNER LINER AND TOP PLUG												
Location	**0°**			**90°**			**180°**			**270°**		
Top Plug Bottom	28	300	°F	29	300	°F	30	300	°F	31	300	°F
Flange Step Wall	32	275	°F	33	200	°F	34	250	°F	35	275	°F
BoroBond4 Step	36	225	°F	37	200	°F	38	225	°F	39	225	°F
CV Body Wall High	40	B 210	°F	41	C ----	°F	42	B 210	°F	43	C ----	°F
CV Body Wall Middle	44	B 210	°F	45	C ----	°F	46	B 190	°F	47	C ----	°F
Liner Bottom	48	B 219	°F	Note: Temp label centered on bottom								

Note: B and C indicate range type of label.

Note: ---- indicates no spots were blacked-out.

Table 5.4 Temperature-indicating Labels reading for TU-2

TEMPERATURE INDICATOR NUMBER LOCATION CHART												
ON THE SURROGATE PAYLOAD												
Location	**0°**						**180°**					
Side Top	1	B 171	°F				4	B 171	°F			
Side Middle	2	B 171	°F				5	B 171	°F			
Side Bottom	3	B 171	°F				6	B 171	°F			
ON THE CV												
Location	**0°**			**90°**			**180°**			**270°**		
CV Lid Top (outside)	7	B 230	°F	8	B 230	°F	9	B 230	°F	10	B 230	°F
CV Lid Bottom (inside)	11	B 190	°F	12	B 219	°F	13	B 210	°F	14	B 219	°F
Flange (outside)	15	B 210 C ----	°F	16	B 230 C ----	°F	17	B 230 C ----	°F	18	B 230 C ----	°F
Flange (inside)	19	B-Destroyed C- Destroyed	°F	20	B 210 C ----	°F	21	B-Destroyed C- Destroyed	°F	22	B-Destroyed C- Destroyed	°F
Body Mid Height (outside)	23	B 180	°F	24	B 180	°F	25	B 190	°F	26	B 180	°F
CV Base (outside)	27	B 210	°F	Note: Temp label centered on bottom								
ON THE INNER LINER AND TOP PLUG												
Location	**0°**			**90°**			**180°**			**270°**		
Top Plug Bottom	28	325	°F	29	325	°F	30	300	°F	31	300	°F
Flange Step Wall	32	Destroyed	°F	33	250	°F	34	325	°F	35	275	°F
BoroBond4 Step	36	225	°F	37	225	°F	38	275	°F	39	225	°F
CV Body Wall High	40	B 210	°F	41	C ----	°F	42	B 210	°F	43	C ---	°F
CV Body Wall Middle	44	B 171	°F	45	C ----	°F	46	B 199	°F	47	C ----	°F
Liner Bottom	48	B 210	°F	Note: Temp label centered on bottom								

Note: B and C indicate range type of label.

Note: ---- indicates no spots were blacked-out.

Table 5.5 Temperature-indicating Labels reading for TU-3

TEMPERATURE INDICATOR NUMBER LOCATION CHART												
ON THE SURROGATE PAYLOAD												
Location	**0°**						**180°**					
Side Top	1	B 171				°F	4	B 171				°F
Side Middle	2	B 171				°F	5	B 171				°F
Side Bottom	3	B 171				°F	6	B 171				°F
ON THE CV												
Location	**0°**			**90°**			**180°**			**270°**		
CV Lid Top (outside)	7	B 230	°F	8	B 230	°F	9	B 241	°F	10	B 241	°F
CV Lid Bottom (inside)	11	B 230	°F	12	B 230	°F	13	B 230	°F	14	B 230	°F
Flange (outside)	15	B 230 C ----	°F	16	B 230 C ----	°F	17	B 230 C ----	°F	18	B 230 C ----	°F
Flange (inside)	19	B 210 C ----	°F	20	B-Destroyed C- Destroyed	°F	21	B 230 C ----	°F	22	B-Destroyed C- Destroyed	°F
Body Mid Height (outside)	23	B 210	°F	24	B 180	°F	25	B 180	°F	26	B 171	°F
CV Base (outside)	27	B 190	°F	Note: Temp label centered on bottom								
ON THE INNER LINER AND TOP PLUG												
Location	**0°**			**90°**			**180°**			**270°**		
Top Plug Bottom	28	275	°F	29	300	°F	30	350	°F	31	300	°F
Flange Step Wall	32	225	°F	33	275	°F	34	275	°F	35	275	°F
BoroBond4 Step	36	200	°F	37	225	°F	38	225	°F	39	225	°F
CV Body Wall High	40	B 210	°F	41	C ----	°F	42	B 210	°F	43	C ----	°F
CV Body Wall Middle	44	B 241	°F	45	C ----	°F	46	B 199	°F	47	C ----	°F
Liner Bottom	48	B 210	°F	Note: Temp label centered on bottom								

Note: B and C indicate range type of label.
Note: ---- indicates no spots were blacked-out.

Table 5.6 Temperature-indicating Labels reading for TU-4

TEMPERATURE INDICATOR NUMBER LOCATION CHART												
ON THE SURROGATE PAYLOAD												
Location	**0°**						**180°**					
Side Top	1	B 171	°F				4	B 171	°F			
Side Middle	2	B 171	°F				5	B 171	°F			
Side Bottom	3	B 171	°F				6	B 171	°F			
ON THE CV												
Location	**0°**			**90°**			**180°**			**270°**		
CV Lid Top (outside)	7	B 261	°F	8	B 261	°F	9	B 261	°F	10	B 261	°F
CV Lid Bottom (inside)	11	B 230	°F	12	B 230	°F	13	B 230	°F	14	B 230	°F
Flange (outside)	15	B 241 C ----	°F	16	B 241 C ----	°F	17	B 241 C ----	°F	18	B 241 C ----	°F
Flange (inside)	19	B 219 C ----	°F	20	B-Destroyed C- Destroyed	°F	21	B-Destroyed C- Destroyed	°F	22	B 219 C ----	°F
Body Mid Height (outside)	23	B 180	°F	24	B 180	°F	25	B 180	°F	26	B 180	°F
CV Base (outside)	27	B 230	°F	Note: Temp label centered on bottom								
ON THE INNER LINER AND TOP PLUG												
Location	**0°**			**90°**			**180°**			**270°**		
Top Plug Bottom	28	350	°F	29	350	°F	30	350	°F	31	350	°F
Flange Step Wall	32	275	°F	33	275	°F	34	275	°F	35	275	°F
BoroBond4 Step	36	350	°F	37	350	°F	38	300	°F	39	350	°F
CV Body Wall High	40	B 210	°F	41	C ----	°F	42	B 210	°F	43	C ----	°F
CV Body Wall Middle	44	B 190	°F	45	C ----	°F	46	B 199	°F	47	C ----	°F
Liner Bottom	48	B 261	°F	Note: Temp label centered on bottom								

Note: B and C indicate range type of label.

Note: ---- indicates no spots were blacked-out.

Table 5.7 Temperature-indicating Labels reading for TU-5

TEMPERATURE INDICATOR NUMBER LOCATION CHART												
ON THE SURROGATE PAYLOAD												
Location	**0°**						**180°**					
Side Top	1	B 210				°F	4	B 210				°F
Side Middle	2	B 199				°F	5	B 199				°F
Side Bottom	3	B 190				°F	6	B 190				°F
ON THE CV												
Location	**0°**			**90°**			**180°**			**270°**		
CV Lid Top (outside)	7	B 250	°F	8	B 261	°F	9	B 261	°F	10	B 250	°F
CV Lid Bottom (inside)	11	B 241	°F	12	B 241	°F	13	B 241	°F	14	B 241	°F
Flange (outside)	15	B 250 C ----	°F	16	B 241 C ----	°F	17	B 250 C ----	°F	18	B 241 C ----	°F
Flange (inside)	19	B 230 C ----	°F	20	B 241 C ----	°F	21	B 241 C ----	°F	22	B 230 C ----	°F
Body Mid Height (outside)	23	B 199	°F	24	B 199	°F	25	B 199	°F	26	B 199	°F
CV Base (outside)	27	B 210	°F	Note: Temp label centered on bottom								
ON THE INNER LINER AND TOP PLUG												
Location	**0°**			**90°**			**180°**			**270°**		
Top Plug Bottom	28	325	°F	29	300	°F	30	325	°F	31	350	°F
Flange Step Wall	32	250	°F	33	250	°F	34	275	°F	35	275	°F
BoroBond4 Step	36	225	°F	37	225	°F	38	250	°F	39	250	°F
CV Body Wall High	40	B 210	°F	41	C ----	°F	42	B 219	°F	43	C ----	°F
CV Body Wall Middle	44	B 210	°F	45	C ----	°F	46	B 210	°F	47	C ----	°F
Liner Bottom	48	B 230	°F	Note: Temp label centered on bottom								

Note: B and C indicate range type of label.

Note: ---- indicates no spots were blacked-out.

Appendix 2.10.8

THE ES-3100 TEST REPORT; VOL. 3, APPENDIX K - TU-4 DATA SHEETS

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Appendix K –
TU-4 Data Sheets

TEST FORM 1 - COMPONENT WEIGHTS

Test Plan ES-3100

Test Unit 4

PRE-DROP TEST WEIGHTS			POST THERMAL TEST WEIGHTS		
PART NAME	**WEIGHT**	**UNITS**	**PART NAME**	**WEIGHT**	**UNITS**
CV (lid assem. & body)	32	*lbs.*			*lbs.*
CV surrogate payload,	110	*lbs.*			*lbs.*
CV assembly	143	*lbs.*	CV assembly	143	*lbs.*
Drum Silicone inserts	1	*lbs.*	Drum Silicone inserts	2	*lbs.*
Drum Top Plug	19	*lbs.*	Drum Top Plug	18	*lbs.*
Drum Body Assy	282	*lbs.*	Drum Body Assy	281	*lbs.*
Test package Assy	445	*lbs.*	Test package Assy	444	*lbs.*

)UIPMENT

Scale: X-502322 Expiration Date: 10-28-04

Accuracy: ± 1 lb

Comments: Drum plug was weighed twice to verify its lighter weight (2 lbs less than other units')

I certify that the above tasks have been performed and that the observations and comments are correct.

Leonard Dickerson — Testing Technician — Date 5-19-04 — [signature] — Witness — Date 5-19-04

*All photographs/movies will be uniquely identified with test unit, date and time to ensure that the proper sequence can be reconstructed

TEST FORM 2 - ASSEMBLY OF THE CV

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	CV test unit serial number: ES-3100 04/04-09
✓	All containment vessel (CV) components have been visually inspected to ensure they are present and in good condition.
✓	Temperature indicators have been affixed to the surface of the CV and on Surrogate payload as indicated on Figure 5.1 through Figure 5.6.
✓	None of the temperature indicators indicate exposure to a temperature in the measured range.
✓	The container and lid have been clearly marked as "TU- 4".
✓	The CV O-rings and sealing surfaces have been inspected for defects and found acceptable.
✓	Clean all surfaces with isopropyl alcohol and air dry.
N/A	The CV O-rings have been lubricated and installed. Use new O-rings.
✓	The surrogate payload # N/A, weighing 110 pounds was aligned and installed in the CV.
✓	The nut ring has been lubricated with Krytox grease per Y-12 Drawing M2E801580A011.
✓	The lid has been installed on the container and the previously applied markings align. This lid has had a torque of 115±5 ft-lb applied. Ambient temperature at closure is 21 °C (72 °F).
	Torque wrench # 2020040628A2 Calibration Expiration Date 5/14/05
✓	Mark the top of the CV lid with 0°, 90°, 180° and 270° locations with a permanent marker. 0° is on the centerline of the leak test port and the axis of the package
✓	The CV assembly has been weighed and the weight has been recorded on TEST FORM 1.
✓	The CV assembly has been leak tested with the CALT5 per the Manufacturer's Instructions Manual.
✓	Install modified VCO plug (Y-12 will supply) in leak test port and hex plug in lifting ring hole. * [initials]
✓	Photographs of the assembly have been taken*.

Comments: * approved the hex plug to be left out

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-19-04	[signature: Leonard Dickerson]	5-19-04
Testing Technician	Date	Witness	Date

*All photographs/movies will be uniquely identified with test unit, date and time to ensure that the proper sequence can be reconstructed

TEST FORM 3 - ASSEMBLY OF TEST PACKAGE

Test Plan ES-3100

Test Unit 4

VERIFIED	TASK
✓	Verify operational leak test is complete and form completed and modified VCO plug is installed.
✓	The exterior of the drum has been clearly marked "TU-4".
✓	Record the drum serial number: ES-3100 04/04-09
✓	The center-of-gravity markings have been applied to the drum.
✓	Mark the 0°, 90°, 180°, 270° locations on the Drum Lid, Top Plug, and the inner and outside walls of the drum with a permanent marker. The 0° location is the vertical, outside-wall seam of the drum.
✓	The silicone CV Bottom Pad has been installed at the bottom of the inner liner.
✓	The silicone Plug Pad has been installed on the horizontal portion of the top plug step of the inner liner.
✓	The CV assembly has been loaded into the drum with the 0° rotated and aligned with the 0° location on the drum.
✓	The silicone CV Flange Pad has been installed over the CV lid.
✓	The Drum Top Plug was weighed and the weight has been recorded on TEST FORM 1
✓	The Drum Top Plug has been loaded into the drum with the 0° rotated and aligned with the 0° location on the drum.
✓	The Drum Lid has been installed with the 0° mark aligned with the 0° mark on the drum.
✓	The drum lid washers are placed over the lugs and the drum lid nuts were initially installed and a torque of 30 ± 1 ft.-lb applied. The nuts were then tightened a second time with a torque of 30 ± 1 ft-lbs again applied No torque sequence is required to be followed. Torque wrench # 4010282626 Calibration Expiration Date 10-27-04
✓	The test package assembly has been weighed and the weight recorded on TEST FORM
✓	Photographs of the assembly have been taken*.

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

Leonard Dickerson	5-19-04	[signature]	5-19-04
Testing Technician	Date	Witness	Date

*All photographs/movies will be uniquely identified with test unit, date and time to ensure that the proper sequence can be reconstructed

Procedure Checklist

Test Plan: ORNL/TTG-NTRC-011 ES-3100

Test Unit: TU-4

VERIFIED	TASK
✓	Have a photographer's clapboard with package name and test unit number.
✓	A photograph of the leak tester connections has been taken.
✓	Both CALT5 Leak Tester and CVs have been in the same ambient conditions for 24 hours.
✓	Determine the interstitial volume of the test unit. Print out results.
✓	Determine the length of test from CALT5 Instruction Manual Table according to volume and accuracy needed.
✓	Program the info into the CALT5 tester.
✓	Run the CALT5 leak test. Print out results.
✓	Enter the data from CALT5 printout onto Data Sheet.
✓	Calculate the leak rate and enter on Data Sheet.

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature] Testing Technician — Date 5/19/04

[signature] — Date 5-19-04

5. Data Sheet

Test Plan: ORNL/NTRC-011 ES-3100

Test Unit: 4

VERIFIED	TASK	
✓	Assembly Leak Test	Post Testing Leak Test
✓		
✓	A leak test in accordance with the CALT5 Manufacturer's Instructions Manual was performed on the CV assembly. Both CALT5 Leak Tester and CVs have been in the same ambient conditions for 24 hours.	

Leak Tester Cert. # M287134 Expiration Date: 3/3/2005

✓ Ambient temperature: 21 °C (___ °F)

Measuring device TTG Fluke

Attach CALT5 Printout Here

$$Lr = \frac{3.84\ cm3 * 4.96667}{9\ min}\left(\frac{\frac{1969.06\ mBar}{1013.25\ mBar/atm}}{(21\ °C + 273)°K} - \frac{\frac{1964.89\ mBar}{1013.25\ mBar/atm}}{(21\ °C + 273)°K}\right) ref-cc/\sec$$

$$Lr = \frac{3.84\ cm3 * 4.96667}{9\ min}\left(\frac{atm}{294\ °K} - \frac{atm}{294\ °K}\right) ref-cc/\sec$$

$$Lr = 2.1191 * 1.38982\times10^{-5} = 2.96638\times10^{-5}\ ref-cc/\sec$$

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5/19/04	[signature]	5-19-04
Testing Technician	Date	Checked by	Date

System Date WED 19 MAY 2004 00:51:29
CALT No: 0052 Transducer No: 835279
Days since last calibration: 8

ORNL
CALT5 – Version U1.43

MEASURE VOLUME

Reference Volume: 2 cc
Reference Volume No: ISN026
Test Reference No: TTGPRF01
Design/Serial Nos: ES-3100/TU-4
Number of Readings: 2
Comment: cv lid

Atmos	Pressure mbar Start	Final	Volume (cc)
977.74	1915.88	1588.91	3.84
977.96	1981.90	1632.77	3.84

Average Volume: 3.84 cc

Sig: [signature] Date: 5/19/04
(Tested by)

Sig: [signature] Date: 5-19-04
(Supervisor)

System Date WED 19 MAY 2004 00:56:18
CALT No: 0052 Transducer No: 835279
Days since last calibration: 8

ORNL
CALT5 – Version U1.43

Pressure Drop
** LEAKAGE TEST **

Test Reference No: TTGPRF01
Design/Serial Nos: ES-3100/TU-4
Comment: cv lid
Interspace Volume: 3.84 cc
Settling Time: 3 mins
Test Duration: 9 mins
Temperature: 21°C
Temperature ratio: 1.014

Sig: ____
(Tested by)

Sig: ____ Date: 5-19-04
(Supervisor)

System Date WED 19 MAY 2004 00:56:18
CALT No: 0052 Transducer No: 835279
Days since last calibration: 8

ORNL
CALT5 – Version U1.43

Pressure Drop
** LEAKAGE TEST **

Test Reference No: TTGPRF01
Design/Serial Nos: ES-3100/TU-4
Comment: cv lid
Interspace Volume: 3.84 cc
Settling Time: 3 mins
Test Duration: 9 mins
Temperature: 21°C
Temperature ratio: 1.014
μ ratio: 0.991
Pass Rate (SLR): 1.0E-04 bar cc/sec
Allowable δP : -40 mbar

**** RESULTS ****

	Pressure mbar	Date/Time
Atmos:	977.85	
Start:	1969.06	19 MAY 2004 01:01:46
Final:	1964.89	19 MAY 2004 01:10:45

Leakage Rate: 1.0E-05 bar cc/sec

PASS

Standard conditions:
Temperature: 25°C
Up stream pressure: 1013 mbar
Down stream pressure: 0 mbar

Sig: ____ Date: 5/19/04
(Tested by)

Sig: ____ Date: 5-19-04

5. Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Water Spray apparatus has been assembled (§4.2).
✓	Photographer's clapboard with package name and test unit number recorded (§4.2).
✓	Test Unit placed properly in the water spray zone and spray function verified (§4.3).
✓	Photograph of the test arrangement taken, documenting test unit identification (§4.3).
✓	Place the rain gauge upright on the ground adjacent to the test specimen (§4.4).
✓	Water spray has been started is spraying on the top and 4 sides, with a minimum rate of 2 in/hr (5 cm/hr) (§4.5). 9:10 a.m. — 1 p.m.
✓	Water spray has been stopped after 1 hour, ✓ rain gauge reading has been recorded ✓ and any damage noted (§4.5).
✓	Photographs of the resulting damage (if any) were taken (§4.5).

Comments. rain gage used to measure flowrate; four readings of 10 to 15 min duration were taken from different sides to give an average 15 in/h (nominally 0.16 in/min)

I certify that the above tasks have been performed and that the observations and comments are correct.

Leonard Dickerson	5-20-04	[signature]	5-20-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Start Date and Time of Water Spray Test: 5-20-04 9:10 a.m. (§4.5)
✓	End Date and Time of Water Spray Test: 5-20-04 13:00 (§4.6)
✓	Rain Gauge Reading: 15 in/h (§4.6)
✓	Ambient temperature: °C (69.4 °F) Measuring device: Fluke 52 K/J Thermometer

Testing Damage Observations: ______

Comments: after test, unit was lowered to its side and inverted by crane to drain water

I certify that the above tasks have been performed and that the observations and comments are correct.

Leonard Dickerson	5-20-04	[signature]	5-20-04
Testing Technician	Date	Checked by	Date

5. Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Water Spray Test (TTG-PRF-05) has been completed within 2 hours before Drop Test. (§4.3)
✓	Have a photographer's clapboard with package name and test unit number. (§4.4)
✓	Attitude of the rigged and raised test unit is set. (§4.5)
✓	Photograph of the rigging arrangements has been taken. (§4.5)
✓	Photograph of the measured drop angle has been taken. (§4.5)
✓	The test unit has been raised designated drop height. (§4.6)
✓	Photograph of the height measurement has been taken. (§4.6)
✓	Video camera(s) are setup and running to take video of the drop. (§4.7)
✓	The release mechanism has been plugged into power outlet. (§4.7)
✓	Countdown, Release the test unit, unplug release mechanism. (§4.7)
✓	Videos camera stopped. (§4.8)
✓	Photographs of the resulting damage were taken. (§4.9)
✓	Ambient temperature recorded. (§4.10)
✓	Date and time of test recorded. (§4.10)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-20-04	[signature] Leonard Dickerson	5-20-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Water Spray Test (TTG-PRF-05) Time completed: 13:00. (§4.3)
✓	Intended attitude and angle of the test unit 0. Tolerance ± 2. (§4.2)
✓	Attitude Description: Head down (§4.2)
✓	Measured attitude and angle of the test unit 0.1 degrees. (§4.2)
✓	Level number 311-024-501 Calibration Exp. Date 6-04 (§4.2)
✓	Height above the drop pad 4 ft Measuring device TTG Rod (§4.6)
✓	Date and Time of Drop Test: 14:10 (§4.10)
✓	Ambient temperature: 22.4°C (72.4°F) Measuring device Fluke 52 (§4.10)

Testing Damage Observations:

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-20-04	Leonard Dickerson	5-20-04
Testing Technician	Date	Checked by	Date

TEST FORM 1 – **Post 1.2m (4 ft) FREE FALL DROP TEST**

Test Plan - ES-3100

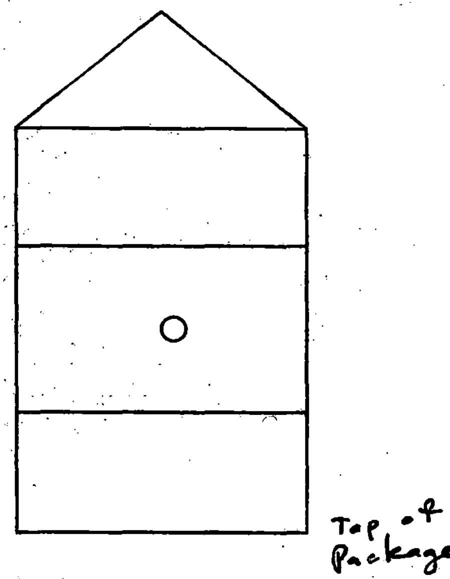
DAMAGE MEASUREMENTS

Test Unit TU 4

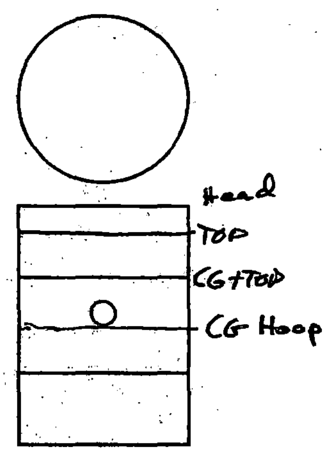
Height	0	90	180	270
Pre	43 1/2	43 1/2	43 5/8	43 5/8
Post	43 1/2	43 1/2	43 1/2	43 1/2

DIAMETER	0 to 180		90 to 270	
	Pre	Post	Pre	Post
Top Chime	19 1/4	19 1/4	19 3/8	19 3/8
Top Hoop	19 1/4	19 1/4	19 1/4	19 1/4
CG Hoop	19 1/8	19 1/8	19 1/4	19 1/4
Bottom Hoop	19 1/8	19 1/8	19 1/4	19 1/4
Bottom Chime	19 3/8	19 3/8	19 1/4	19 1/4
CG+Top Hoop	19 1/4	19 1/4	19 1/4	19 1/4

Sketch Drop Setup Here



Sketch Package Damage Here



Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[illegible] — Testing Technician | 5-20-04 — Date | Leonard [illegible] — Verified By | 5-20-04 — Date

5. Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Water Spray Test (TIN-03) has been completed within 2 hours before Drop Test. (§4.2)
✓	Have a photographer's clapboard with package name and test unit number. (§4.3)
✓	Penetration Bar Serial Number: NTRC - 001
✓	The package has been placed on the drop pad and blocked to keep from moving during test. (§4.4)
✓	The penetration bar has been suspended above and aligned to the target point on the package. (§4.5)
✓	Photograph of the target alignment has been taken. (§4.5)
✓	The penetration bar has been raised to the specified drop height above the target point. (§4.5)
✓	Photograph of the height measurement has been taken. (§4.5)
✓	Video camera(s) are setup and running to take video of the drop. (§4.6)
✓	The release mechanism has been plugged into power outlet. (§4.6)
✓	Countdown; release the test unit; unplug release mechanism. (§4.6)
✓	The penetration bar has impacted the package at the target point. (§4.6)
✓	Videos camera stopped. (§4.7)
✓	Date and Time of test recorded. (§4.8)
✓	Ambient temperature recorded. (§4.9)
✓	Photographs of the resulting damage were taken. (§4.10)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-20-04	Leonard Dickerson	5-20-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Water Spray Test (TTG-PRF-05) Time completed: 13:00 (§4.2)
✓	Description of the target point: 7½ from top on 0° line (§4.5)
✓	Height above the package: 1 m Measuring device: 1m Stick (§4.5)
✓	Date and Time of Penetration Test: 14:30 (§4.8)
✓	Ambient temperature: 21.6°C (___°F) Measuring device TTG Fluke (§4.9)

Testing Damage Observations:

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-20-04	Leonard Dickerson	5-20-04
Testing Technician	Date	Checked by	Date

5. Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Determine load to be applied. (§4)
✓	Water Spray Test (TTG-PRF-05) completed within 2 hours prior to Compression Test. (§4.3)
✓	Excess water from the Water Spray Test permitted to drain from test specimen. (§4.3)
✓	Photographer's clapboard with package name and test unit number prepared. (§4.4)
✓	Package placed in the center of the compression tester base and upper platen lowered onto package top. Alternatively, package placed on sturdy horizontal surface for stacking test, and initial dead weight placed on top. (§4.5)
✓	Photograph of the test specimen test setup taken. (§4.6)
✓	Record height measurement of the package prior to loading. (§4.6)
✓	Photograph of the height measurement taken. (§4.6)
	Program the compression tester to apply the required force and duration per Procedure TTG-PRF-17 and start the test. Alternatively, stack the remaining required dead weight onto the package top, completing the stack. (§4.7)
✓	Compression tester has successfully completed per program. Alternatively, carefully remove the dead weight from the test specimen. (§4.8)
✓	Record final height measurement of the test specimen (post-test). (§4.8)
✓	Photograph of the post test height measurement taken. (§4.8)
✓	Photographs of any other resulting damage taken. (§4.9)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature] Testing Technician — 5-21-04 Date

[signature] — 5/21/04 Date

6. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED | TASK

✓ Calculate and record the greater of 5 times the weight of the package OR 1.9 psi times the projected vertical area of the package. (§4)

5 × 450 = 2,250 lbs => 2,300 lbs applied

1.9 psi × projected vertical area N/A = ______ lbs.

✓ Load to be applied to package 2,300 lbs. (§4)

✓ Water Spray Test (TIN-03) Time completed: 1 P.M. (§4.3)

✓ Height Measurements: 0°: 43.5 in; 90°: 43.5 in; 270°: 43 5/8; 43 5/8 (§4.6)

✓ Start Date and Time: May 20, 2004; 2:55 p.m. (§4.7)

✓ Finish Date and Time: 5-21-04, 18:00 (§4.8)

Height Measurements: 0° → 43.5, 90° → 43.5, 180° → 43 5/8, 270° 43 5/8 (§4.8)

✓ Ambient temperature: 21.4 °C (70.6 °F) Measuring device: Fluke 52 (§4.9)

Testing Damage Observations: No observable damage

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature] 5-21-04 [signature] 5/21/04

Testing Technician | Date | Checked by | Date

Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Prepare photographer's clapboard with package name and test unit number (§4.2).
✓	Package has been placed in the center of the vibration table (§4.3).
✓	Package has been secured to the vibration table, if required (§4.3).
✓	Photograph of the package in place has been taken (§4.4).
✓	Vibration table controller has been programmed for applied vibration and duration per Procedure TTG-PRF-16, using specifications outlined in the Test Plan (§4.5).
✓	Vibration test initiated per program (§4.6).
✓	Record vibration test information on Data Sheet (§4.7).
✓	Vibration test successfully completed per program, results printed (§4.8).
✓	Test specimen removed from vibration table and examined for damage (§4.9).
✓	Photographs of any observed damage completed, and recorded on Data Sheet (§4.9).

Comments: No observable damage externally. Not disassembled

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-28-04	Leonard Dickerson	6-2-04
Testing Technician	Date	Checked by	Date

Data Sheet

Test Plan: ES-3100

Test Unit: TU-4

VERIFIED	TASK
✓	Ambient temperature: 20.6°C (____°F) (§4.6)
✓	Start Date and Time: 5-22-04 08:15 (§4.6)
N/A	The DOT Bounce test has been performed for one hour. (§4.8)
OR	
✓	The random vibration test has been performed for 4 hour(s). (§4.8) The PSD for this test was as follows:
✓	End Date and Time: 5-22-04 | 12:20 (§4.8)
	Vibration controller test printout attached: Y/N (§4.8)

Testing Damage Observations: None not disassembled

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-28-04	Leonard Dickerson	6-2-04
Testing Technician	Date	Checked by	Date

5. Procedure Checklist

Test Plan: ORNL-NTRL-011 Test Unit: 4

VERIFIED	TASK
✓	Have a photographer's clapboard with package name and test unit number. (§4.3)
✓	The ambient temperature has been recorded. (§4.4)
✓	Attitude of the rigged test unit is set. (§4.5)
✓	Photograph of the rigging arrangements has been taken. (§4.5)
✓	Photograph of the measured drop angle has been taken. (§4.5)
✓	The test unit has been raised to the designated drop height. (§4.7)
✓	Photograph of the height measurement has been taken. (§4.7)
✓	Video camera(s) are setup and running to take video of the drop. (§4.8)
✓	The release mechanism has been plugged into power outlet. (§4.8)
✓	Countdown, Release the test unit, unplug release mechanism. (§4.8)
✓	Videos camera stopped. (§4.9)
✓	Date and time of test were recorded. (§4.10)
✓	Photographs of the resulting damage were taken. (§4.11)
✓	Remove plumbob from Test piece
✓	Hold release mechanism in hand and ensure it is in hand until after drop is completed.

wLF 5/25/04

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-25-04	Leonard Dickerson	5-25-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ORNL/NTRC-011

Test Unit: 4

VERIFIED	TASK
✓	Intended attitude of the test unit 0° Tolerance ± 2 (§4.2)
✓	Measured attitude of the test unit 0.2° degrees. (§4.5)
✓	Level number 311-006-501 Calibration Exp. Date 6/04 (§4.5)
✓	Height above the drop pad 9m Measuring device TTG string (§4.7)
✓	Date and Time of Drop Test: 5/25/04 11:54 (§4.10)
✓	Ambient temperature: 27.3 °C (____°F) Measuring device TTG Fluke (§4.4)

Testing Damage Observations: ____________________

Comments. ____________________

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-25-04	Leonard Dickerson	5-25-04
Testing Technician	Date	Checked by	Date

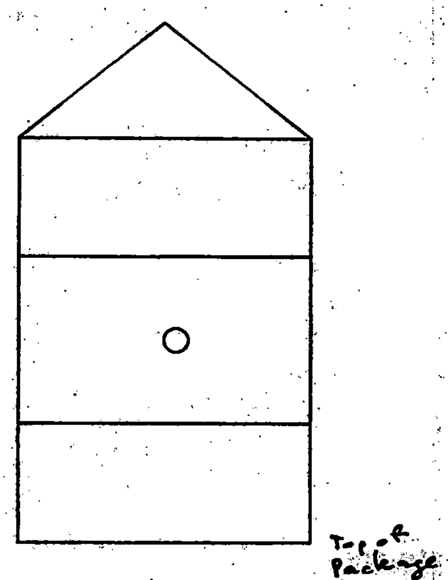
TEST FORM 2 – **Post 9m (30 ft) FREE FALL DROP TEST** Test Plan - ES-3100

DAMAGE MEASUREMENTS ES 3100 Test Unit 4

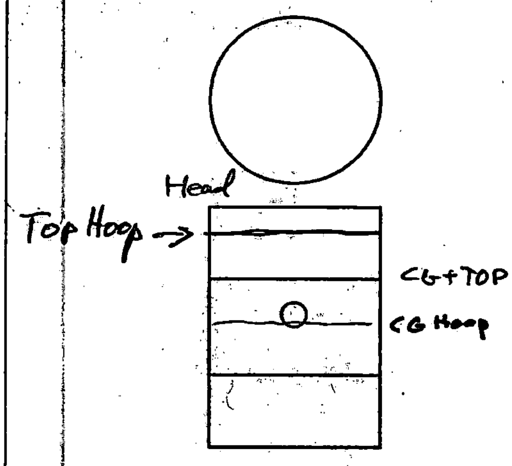
Height	0	90	180	270
Pre	43 1/2	43 1/2	43 1/2	43 1/2
Post	43	43 1/8	42 7/8	42 5/8

DIAMETER	0 to 180		90 to 270	
	Pre	Post	Pre	Post
Top Chime	19 1/4	19 1/4	19 3/8	19 3/8
Top Hoop	19 1/4	19 1/8	19 1/4	19 7/8
CG Hoop	19 1/8	19 1/8	19 1/4	19 1/4
Bottom Hoop	19 1/8	19 1/4	19 1/4	19 1/4
Bottom Chime	19 3/8	19 1/4	19 1/4	19 1/4
CG+Top Hoop	19 1/4	19 13/16	19 1/4	19 3/8

Sketch Drop Setup Here



Sketch Package Damage Here



Comments: No Flats noted.

Concavity on bottom evenly distributed from edge, maximum depth is 3/8 inch.

Top Hoop narrowed – no value recorded.

I certify that the above tasks have been performed and that the observations and comments are correct.

Leonard Dickerson 5-25-04 [signature] 5-25-04

Testing Technician Date Verified By Date

5. Procedure Checklist

Test Plan: ES-3100 Test Unit: 4

VERIFIED	TASK
✓	Have a photographer's clapboard with package name and test unit number. (§4.3)
✓	The ambient temperature has been recorded. (§4.4)
✓	Attitude of the test unit is set. (§4.5)
✓	Photograph of the attitude has been taken. (§4.5)
N/A	Photograph of the measured angle has been taken. (§4.5)
✓	The crush plate has been raised to the designated drop height and located over the target point. (§4.7)
✓	Photograph of the set position has been taken. (§4.7)
✓	Video camera(s) are setup and running to take video of the drop. (§4.8)
✓	The release mechanism has been plugged into power outlet. (§4.8)
✓	Countdown, Release the crush plate, unplug release mechanism. (§4.8)
✓	Videos camera stopped. (§4.9)
✓	Date and time of test recorded. (§4.10)
✓	Photographs of the resulting damage were taken. (§4.11)
✓	Remove plumbob from ~~test piece~~ crush plate.
✓	Hold release mechanism in hand and ensure it is in hand until after drop is completed

— wff 5/25/04

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-25-04	Leonard Dickerson	5-25-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Intended attitude of the test unit ~~[illegible]~~ Vert. Tolerance ± ____ (§4.5)
N/A	Measured attitude of the test unit ____ degrees. (§4.5)
N/A	Level number ____ Calibration Exp. Date ____ (§4.5)
✓	Height above the target: 30 feet Measuring device TTG String (§4.7)
✓	Date and Time of Crush Test: 5/25/04 2:18p (§4.10)
✓	Ambient temperature: 29.8 °C (____ °F) Measuring device TTG Fluke (§4.11)

Testing Damage Observations: ____

Comments: ____

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-25-04	Lenard Dickerson	5-25-04
Testing Technician	Date	Checked by	Date

TEST FORM 3 – Post 9m (30 ft) DYNAMIC CRUSH TEST

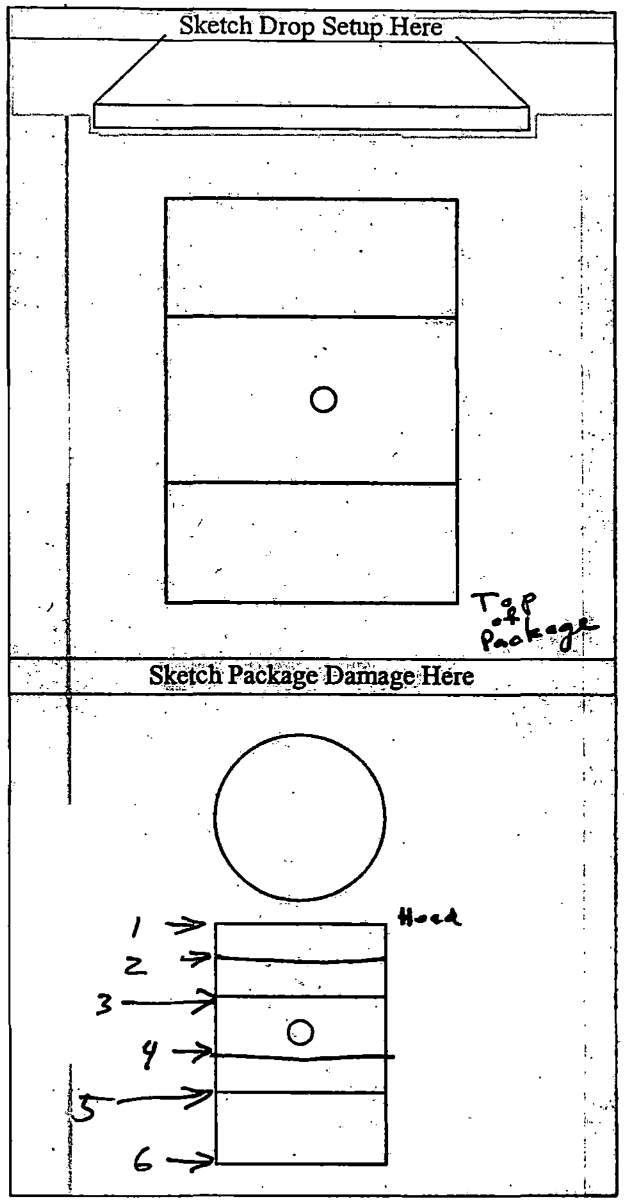
Test Plan - ES-3100

DAMAGE MEASUREMENTS

Test Unit 4

Height	0	90	180	270
Pre	43	43 1/8	42 7/8	42 5/8
Post	39 3/8	40 7/8	40 5/8	39 3/4

	DIAMETER	0 to 180		90 to 270	
		Pre	Post	Pre	Post
1	~~Top Chime~~	19 1/4	19 1/4	19 3/4	19 3/8
2	~~Top Hoop~~	19 1/8	20	19 7/8	20 1/8
3	~~CG~~	19 15/16	20	19 7/8	20 1/16
4	~~Bottom Hoop~~	19 1/8	19 7/16	19 3/4	19 1/2
5	~~Bottom Chime~~	19 1/4	19 15/16	19 1/4	20
6		19 1/4	19 1/4	19 1/4	19 1/4



Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-26-04	Leonard Dickerson	5-26-04
Testing Technician	Date	Verified By	Date

5. Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Have a photographer's clapboard with package name and test unit number. (§4.3)
✓	Attitude of the rigged test unit is set. (§4.4)
✓	Photograph of the rigging arrangements has been taken. (§4.4)
✓	Photograph of the measured drop angle has been taken. (§4.4)
✓	The test unit has been raised to the designated drop height. (§4.5)
✓	Photograph of the height measurement has been taken. (§4.5)
✓	Video camera(s) are setup and running to take video of the drop. (§4.6)
✓	The release mechanism has been plugged into power outlet. (§4.6)
✓	Countdown, Release the test unit, unplug release mechanism. (§4.6)
✓	Videos camera stopped. (§4.7)
✓	The ambient temperature has been recorded. (§4.8)
✓	Date and time of test recorded. (§4.9)
✓	Photographs of the resulting damage were taken. (§4.10)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	5-27-04	Leonard Dickerson	5-27-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100 Test Unit: 4

VERIFIED	TASK
✓	Intended attitude of the test unit 90°. Vertical head down Tolerance ± 2 (§4.4)
✓	Measured attitude of the test unit 89.7 degrees. (§4.4)
✓	Level number 381-006-501 Calibration Exp. Date 6-04 (§4.4)
✓	Height above the punch 1 m Measuring device TTG 1m Rod (§4.5)
✓	Date and Time of Drop Test: 5-27-04 1315 (§4.8)
✓	Ambient temperature: 22 °C (71.4°F) Measuring device TTG Fluke (§4.9)

Testing Damage Observations: __________

Comments: Package stood on punch after impact.

I certify that the above tasks have been performed and that the observations and comments are correct.

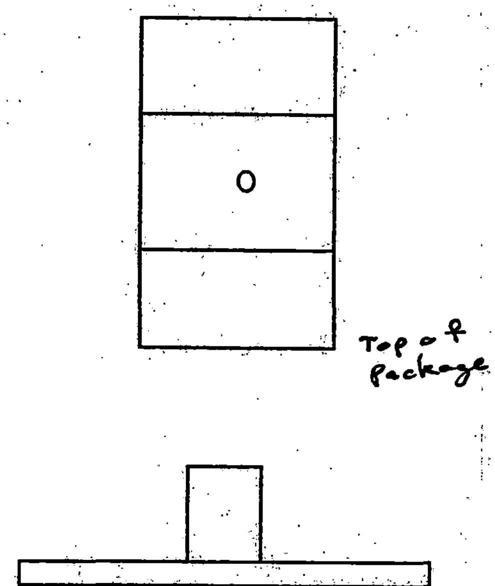
[signature]	5-27-04	Leonard Dickerson	5-27-04
Technician	Date	Checked by	Date

TEST FORM 4 – **Post 1 m (40 in) PUNCTURE DROP TEST** **Test Plan - ES-3100**

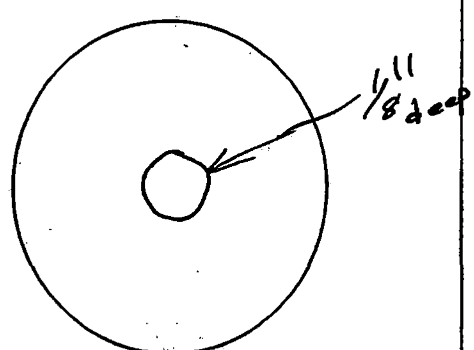
DAMAGE MEASUREMENTS

Test Unit 4

Sketch Drop Setup Here



Sketch Package Damage Here



Comments: Slight indent ≈ 1/8" deep

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	6-2-04	[signature]	6/2/04
Testing Technician	Date	Verified By	Date

5. Procedure Checklist

Test Plan: ES-3100 ORNL/NTRC-011

Test Unit: TU-4

VERIFIED	TASK
✓	All thermocouples channels on the data acquisition system have been tested. (§4.2a)
✓	All thermocouples have been installed in the furnace, connected to Data Acquisition System (DAS), labeled and tested. (§4.3c)
✓	The test unit has been preheated to over 38 °C (100 °F). (§4.2b)
✓	Furnace has reached the minimum soak point temperature of 800 °C (1475 °F), and has soaked at this temperature for a minimum of 24 hours. (§4.3c)
✓	The thermal data acquisition system is set to read every 30 seconds or less. (§4.3c) 15 s
✓	All thermocouples have been installed on the exterior of drum, in accordance with the Test Plan, attached to DAS , labeled and tested. (§4.2c)
✓	Photographs and/or video of the test setup have been taken. (§4.3c)
✓	The unit has been placed in the furnace, on the support stand, with the 0° point down or as specified in the test plan. (§4.4c)
✓	The 30 minute timed test begins when 5 out of 6 test unit thermocouples and 15 of 18 furnace thermocouples reached the test temperature of 800 °C (1475 °F), as specified in this procedure. (§4.4d)
✓	Immediately following the timed test (minimum of 30 minutes at 800 °C) the test unit was taken out of the furnace and allowed to cool naturally. (§4.4e)
✓	Notes regarding smoke and/or flames emanating from the test specimen are recorded. (§4.4e)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	6/16/04	Leonard Dickerson	6-16-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100 ORNL/NTRC-011

Test Unit: TU-4

VERIFIED TASK

✓ The test unit has been preheated to over 38 °C (100 °F).
Measuring device: TTG DATA Acq. Calibration expiration date: n/a (§4.2b)

✓ The furnace has reached the minimum soak point temperature of 800 °C (1475 °F), and has soaked at this temperature for a minimum of 8 hours. The furnace set point temperature has been adjusted to ______ °C (1600 °F) at least ~~one hour~~ 45 min prior to each test (§4.3c) MK CHB

Date: 6/16 Time: 8:55 am/pm

✓ The test unit has been placed in the furnace, on the support stand, at: (§4.4c)

Time: 9:53 am/pm Open furnace door time: 50 seconds

✓ The 30 minute timed test began when 5 out of 6 test unit thermocouples and 15 of 18 furnace thermocouples reached the test temperature of 800 °C (1475 °F): (§4.4d)

Time: 10:02 am/pm

✓ The test unit was removed from the furnace and allowed to cool naturally. (§4.4e)

Time: 10:32 am/pm Ambient Temperature ______ °C (95 °F)

✓ The unit stopped outgassing (flames) at ______; outgassing/burnout elapsed time was ______ minutes. (§4.4e)

Testing Damage Observations: Flaming from TID when removed. Flaming ceased in less than 1 minute. Smoking continued. Outgassing (smoking) stopped at 10:44 (12 min after run).

Comments:

I certify that the above [tasks were perf]ormed and that the observations and comments are correct.

[signature]	6/16/04	Leonard Dickerson	6/16/04
Testing Technician	Date	Checked by	Date

Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Have a photographer's clapboard with package name and test unit number.
✓	A photograph of the leak tester connections has been taken.
✓	Both CALT5 Leak Tester and CVs have been in the same ambient conditions for 24 hours.
✓	Determine the interstitial volume of the test unit. Print out results.
✓	Determine the length of test from CALT5 Instruction Manual Table according to volume and accuracy needed.
✓	Program the info into the CALT5 tester.
✓	Run the CALT5 leak test. Print out results.
✓	Enter the data from CALT5 printout onto Data Sheet.
✓	Calculate the leak rate and enter on Data Sheet.

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	6-30-04	Leonard Dickerson	6-30-04
Testing Technician	Date	Checked by	Date

5. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED TASK

✓ Assembly Leak Test Post Testing Leak Test X

✓ Length of test from CALT5 Instruction Manual Table according to volume and accuracy needed. Test Time: 9 min.

✓ A leak test in accordance with the CALT5 Manufacturer's Instructions Manual was performed on the CV assembly. Both CALT5 Leak Tester and CVs have been in the same ambient conditions for 24 hours.

Leak Tester Cert. # M287137 Expiration Date: 3/3/05

✓ Ambient temperature: 21.1 °C (°F)

Measuring device TTG Fluke

Attach CALT5 Printout Here

$$Lr = \frac{3.772\ cm3 * 4.96667}{9\ min}\left(\frac{\frac{2131.16\ mBar}{1013.25\ mBar/atm}}{(21.1\ °C+273)°K} - \frac{\frac{2127.63\ mBar}{1013.25\ mBar/atm}}{(21.1\ °C+273)°K}\right) ref-cc/\sec$$

$$Lr = \frac{3.772\ cm3 * 4.96667}{9\ min}\left(\frac{2.1033\ atm}{294.1\ °K} - \frac{2.0998\ atm}{294.1\ °K}\right) ref-cc/\sec$$

$$Lr = 2.0816 * .00001190 = 2.4773 \times 10^{-5}\ ref-cc/\sec$$

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature] Testing Technician — Date 6-30-04

Leonard Dickerson Checked by — Date 6-30-04

System Date WED 30 JUN 2004 04:29:44
CALT No: 0052 Transducer No: 835279
Days since last calibration: 50

ORNL
CALT5 - Version U1.43

MEASURE VOLUME

Reference Volume: 2 cc
Reference Volume No: ISN026
Test Reference No: TTGPRF01
Design/Serial Nos: ES-3100/TU-4
Number of Readings: 2
Comment: cv lid

Atmos	Pressure mbar Start	Pressure mbar Final	Volume (cc)
977.00	2107.94	1709.49	3.76
976.57	2121.53	1719.55	3.78

Average Volume: 3.772 cc

Sig: [signature] Date: 6-30-04
(Tested by)

Sig: [signature] Date: 6-30-04
(Supervisor)

System Date WED 30 JUN 2004 04:34:23
CALT No: 0052 Transducer No: 835279
Days since last calibration: 50

ORNL
CALT5 - Version U1.43

Pressure Drop
** LEAKAGE TEST **

Test Reference No: TTGPRF01
Design/Serial Nos: ES-3100/TU-4
Comment: cv lid
Interspace Volume: 3.772 cc
Settling Time: 3 mins
Test Duration: 9 mins
Temperature: 21.1°C
Temperature ratio: 1.013
μ ratio: 0.992
Pass Rate (SLR): 1.0E-04 bar cc/sec
Allowable δP : -50 mbar

*** RESULTS ***

	Pressure mbar	Date/Time
Atmos:	976.46	
Start:	2131.16	30 JUN 2004 04:38:38
Final:	2127.63	30 JUN 2004 04:47:38

Leakage Rate: 7.1E-06 bar cc/sec

PASS

Standard conditions:
Temperature: 25°C
Up stream pressure: 1013 mbar
Down stream pressure: 0 mbar

Sig: [signature] Date: 6-30-04
(Tested by)

Sig: [signature] Date: 6-30-04
(Supervisor)

5. Procedure Checklist

a. Prepare Test Unit

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Area around where the package will be penetrated cleared of any tape, paint, loose labels, etc. (§4a.1)
✓	¼ in NPT threaded hole drilled and tapped. (§4a.2)
✓	Test weight bag penetrated (if necessary). (§4a.3)
✓	Threaded hole and surrounding surface cleaned with a wiping cloth or tissue soaked in isopropyl alcohol or a wet Vacu-Solve swab. (§4a.4)
✓	Solvent has evaporated. (§4a.5)
✓	Epoxy mixed and applied to the thread of a ¼ in NPT to K-Flange adaptor taking care to not obstruct the hole in the adaptor with epoxy. (§4a.6)
✓	Adapter threaded into the ¼ in NPT hole in the package ensuring that there is a continuous filet of epoxy between the adaptor stem and the surface of the Test Unit (if necessary, add epoxy to create a filet). (§4a.7)
✓	Epoxy has hardened at least 4 hours. (§4a.8)
✓	Mixing tools properly disposed of. (§4a.9)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	7-21-04	Leonard Dickerson	7-30-04
Testing Technician	Date	Checked by	Date

b. Check List for Test Unit Pump-out

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Test unit placed on a plastic bag that is large enough to envelop the test unit. (§4b.1)
✓	Varian 959 Turbo Leak Detector positioned so that it can be attached to the test unit without further movement. (§4b.2)
✓	Varian 959 Turbo Leak Detector started. (CAUTION: Once the leak detector is started DO NOT move the leak detector until it is fully shutdown and the internal turbo-pump has come to a complete stop. Movement of the leak detector with a spinning turbo-pump will damage or destroy the pump.) (§4b.3)
✓	Varian 959 Turbo Leak Detector calibrated and zeroed per the calibration procedure provided in the leak detector manual. (§4b.4)
✓	Calibration leak rate, serial number, and calibration expiration date recorded. (§4b.5)
✓	Leak detector attached to the test unit. (§4b.6)
✓	Test unit pump-out initiated (record date and time). (§4b.7)
N/A	¼ in. flexible plastic tubing used for vent attached hear the bottom of the test unit. (§4b.8)
✓	¼ in. flexible plastic tubing used for He fill attached at the top of the test unit. (§4b.9)
✓	Test unit enveloped in the plastic bag and bag secured with a reasonably tight seal. Note: Do not envelop the K-Flange adaptor or the point where the adaptor enters the test unit. (§4b.10)
✓	Slit for evacuating bag cut into bag. (§4b.11)
✓	He regulator attached to the He cylinder and the ¼ in. plastic tubing that is attached to the top of the test unit. (§4b.12)
✓	Picture taken of test unit connected to leak check system, including photo clapboard. (§4b.13)

Comments

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	7-23-04	[signature]	7-30-04
Testing Technician	Date	Checked by	Date

c. Check List for Leak Check of Test Unit

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Vacuum in test unit less than 100 milliTorr (preferably less than 50 milliTorr). Record date and time. (§4c.1)
✓	Leak detector range switch set to the 10^{-9} position. (§4c.2)
✓	Plastic bag surrounding test unit evacuated using shop-vac. (§4c.3)
✓	Inflate bag with He. Record the time (hour:minute:second ± 5 sec) and leak rate reading from the leak detector display. (§4c.4)
✓	He leak rate recorded every 2 minutes (±5 sec) and the time that the range switch is changed to the next higher decade (e.g. from 10^{-9} to the 10^{-8} range). (§4c.5)
✓	Final reading taken at 20 minutes (± 5 sec) elapsed time and He supply turned off. (§4c.7)
✓	Leak detector placed in Vent mode. (§4c.8)
✓	Plastic bag and tubes removed from the test unit. (§4c.9)
✓	Leak Detector detached from test unit. (§4c.10)
✓	Close out test unit data sheet with signatures and date. (§4c.11)
NA	IF another test unit is to be leak checked THEN bring the next test unit into position for checking. (CAUTION: Once the leak detector is started DO NOT move the leak detector until it is fully shutdown and the internal turbo-pump has come to a complete stop. Movement of the leak detector with a spinning turbo-pump will damage or destroy the pump.) (§4c.12)
✓	IF this is the last test unit THEN completely shutdown the leak detector. Allow all components to come to a full stop prior to moving the leak detector. (§4c.13)

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	7-23-04	Leonard Dickerson	7-30-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	He calibration leak identification: Leak rate He cc/sec 7.2 *10 - 8 (§4b.5) Calibration expiration date mm 8 /dd 29 /yyyy 2004
✓	Test unit pump-out started Date and time mm 7 /dd 21 /yyyy 2004 hh 16 :mm 35 (§4b.7)
✓	Test unit vacuum at or below 100 milliTorr. Pressure in milliTorr 60 (§4c.4) Date and time mm 7 /dd 23 /yyyy 2004 hh 11 :mm 04
✓	He Leak Rate Table (§4c.4 - 6)

Clock Time hr:min:sec	He Leak Rate
11:04	0×10^{-9}
11:06	0×10^{-9}
11:08	0×10^{-9}
11:10	0×10^{-9}
11:12	0×10^{-9}
11:14	0×10^{-9}
11:16	0×10^{-9}
11:18	3.2×10^{-8}
11:20	8.4×10^{-8}
11:22	1.4×10^{-7}
11:24	2.0×10^{-7}

✓ Ambient temperature during test: 21.8°C Measuring device TTG Fluke (§4c.7)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	7-23-04	Leonard Dickerson	7-30-04
Testing Technician	Date	Checked by	Date

TEST FORM 4 - POST-THERMAL TESTING INSPECTION

Test Plan ES-3100

Test Unit 4

VERIFIED	TASK
✓	Following the thermal test and after cooling, the test package was weighed, and the weight recorded on TEST FORM 1 .
✓	The drum, lid, nuts, and studs have been visually examined to determine the extent of the testing damage. Observations:______
✓	The camera(s) are set up to take photographs* and/or videotape of the damage due to testing.
✓	The drum lid has been removed and the condition of the exposed parts have been visually examined for damage and the condition has been recorded. Observations:______
✓	The Top Plug Assembly has been removed and visually inspected to determine the extent of impact and thermal damage. Record the exposed temperature indicator blackout reading on TEST FORM 5 . Observations:______
✓	The CV assembly has been removed and visually examined for damage. Record the exposed temperature indicator blackout readings on TEST FORM 5 . Observations:______
✓	The CV assembly has been weighed and the weight recorded on TEST FORM 1
✓	Use TTG-PRF-01 for the CV post-test operational leak check, TTG-PRF-02 for the full containment boundary leak check and TTG-PRF-14 for the 3 ft. immersion test.
✓	Disassemble the CV. Record torque value needed to loosen CV lid. 30 ft-lb.
✓	Read the temperature indicators from the surrogate payload. Record the temperature indicators' blackout readings on TEST FORM 5 .
✓	All loose parts will be placed in separate polyethylene bags, marked with test unit identification, tape closed, and prepared for storage with the test package.
✓	Mark and reassemble the test package to the extent possible for shipment.
✓	*Photographs and/or video of the damage resulting from the testing have been taken.

Comments: Borobond cans intact

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature] Testing Technician — 7-27-04 Date — Leonard Dickerson Witness — 7-30-04 Date

5. Procedure Checklist

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Have a photographer's clapboard with package name and test unit number. (§4.2)
✓	The test unit has been lowered to the bottom of the tank in designated orientation. (§4.5)
✓	The depth to the highest point of the test unit has been measured and is at least 0.9m (3 ft.). (§4.5)
✓	Photograph of the depth measurement has been taken. (§4.5)
✓	Start date and time has been noted. (§4.6)
✓	Test time has expired. (§4.7)
✓	Test unit has been removed from the tank. (§4.7)
✓	End date and time has been noted. (§4.7)
✓	Open the test unit and record breaking torque values during removal, if required. (§4.8)
✓	Inspect for water in-leakage or structural damage. (§4.8)
✓	Photographs of any resulting damage or lack thereof were taken. (§4.8)

Comments:

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	7-26-04	Leonard Dickerson	7-30-04
Testing Technician	Date	Checked by	Date

6. Data Sheet

Test Plan: ES-3100

Test Unit: 4

VERIFIED	TASK
✓	Intended attitude of the test unit in tank (e.g. on side) on side (§4.3)
✓	Depth of water above the test unit 39" Measuring device Tape Measure (§4.5)
✓	Start Date and Time of Immersion Test: 7-26-04 10:40 (§4.6)
✓	Water temperature: 22.1°C (°F) Measuring device TTG Fluke (§4.6)
✓	End Date and Time of Immersion Test: 7-27-04 08:30 (§4.7)
✓	Water temperature: 21.1°C (69.8°F) Measuring device TTG Fluke (§4.7)
✓	Detected in-leakage of water: (YES/NO) [NO circled] (§4.7)
✓	Detected structural damage: (YES/NO) [NO circled] (§4.7)

Testing Damage Observations: ______

Comments: ______

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	7-26-04	Leonard Dickerson	7-26/30-04
Testing Technician	Date	Checked by	Date

TEST FORM 5 - TEMPERATURE INDICATOR READINGS

Test Plan ES-3100

Test Unit 4

A visual inspection of each temperature indicator on the package consisting of those indicators inside the CV, outside the CV, and on the drum liner will be made. The values of the blackouts that occurred will be recorded below.

RECORD BLACKOUT TEMPERATURES AT THESE LOCATIONS:

TEMPERATURE INDICATOR NUMBER LOCATION CHART

ON THE SURROGATE PAYLOAD

Location	0°	180°
Side Top	1 B 171 °F	2 B 171 °F
Side Middle	3 B 171 °F	4 B 171 °F
Side Bottom	5 B 171 °F	6 B 171 °F

ON THE CV

Location	0°	90°	180°	270°
CV Lid Top (outside)	7 B 261 °F	8 B 261 °F	9 B 261 °F	10 B 261 °F
CV Lid Bottom (inside)	11 B 230 °F	12 B 230 °F	13 B 230 °F	14 B 230 °F
Flange (outside)	15 B 241 °F	16 B 241 °F	17 B 241 °F	18 B 241 °F
Flange (inside)	19 B 219 °F	20 B Destroyed °F	21 B Destroyed °F	22 B 219 °F
Body Mid Height (outside)	23 B 180 °F	24 B 180 °F	25 B 180 °F	26 B 180 °F
CV Base (outside)	27 B 230 °F	Note: Temp label centered on bottom		

ON THE INNER LINER AND TOP PLUG

Location	0°	90°	180°	270°
Top Plug Bottom	28 350 °F	29 350 °F	30 350 °F	31 350 °F
Flange Step Wall	32 275 °F	33 275 °F	34 275 °F	35 275 °F
BoroBond4 Step	36 350 °F	37 350 °F	38 300 °F	39 350 °F
CV Body Wall High	40 B 210 °F	41 C — °F	42 B 210 °F	43 C — °F
CV Body Wall Middle	44 B 190 °F	45 C — °F	46 B 199 °F	47 C — °F
Liner Bottom	48 B 261 °F	Note: Temp label centered on bottom Impact damage on Liner Bottom Label		

Comments: Borobond4 Step temperature are higher than Flange Step wall, these labels may be blacked from impact damage. Labels on CV lid maxed out - inconsistent - may be black from impact damage.

I certify that the above tasks have been performed and that the observations and comments are correct.

[signature]	7-27-04	Leonard Dickerson	7-30-04
Testing Technician	Date	Witness	Date

*All photographs/movies will be uniquely identified with test unit, date and time to ensure that the proper sequence can be reconstructed

ORNL/NTRC-011 - May 17, 2004

Appendix 2.10.9

PACKAGING MATERIALS OUTGASSING STUDY FINAL REPORT

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UCN-13672 (11-03)

Y/DZ-2720

Packaging Materials Outgassing Study
Final Report

R. A. Smith
Compatibility and Surveillance
Technology Development

Issue Date: September 26, 2006

Prepared by the
Y-12 National Security Complex
Oak Ridge, TN 37831
Managed by
BWXT Y-12, L.L.C.
for the
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under contract DE-AC05-00OR22800

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Y/DZ-2720

PACKAGING MATERIALS OUTGASSING STUDY FINAL REPORT

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Technology Development
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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

PE	polyethylene
PTFE	polytetrafluoroethylene
HAC	Hypothetical Accident Conditions
HDPE	high-density polyethylene
NCS	Normal Condition for Storage
PU	polyurethane
DSC	differential scanning calorimetry
TGA	thermogravimetric analysis
ppm	parts per million
STP	standard temperature and pressure
NRC	Nuclear Regulatory Commission

ABSTRACT

An outgassing study was conducted on two polyurethane packaging foams, two polymer bottles (polytetrafluoroethylene and polyethylene), and two polymer lids. The purpose was to measure the volume of gases that diffuse from these packaging materials at a maximum of 400°F when stored in ambient air within sealed containers. A specific heating profile was used to measure the offgassing quantities in a set of accelerated aging tests. This set of experiments was designed to duplicate an earlier study conducted in 1991. Thermogravimetric analysis and differential scanning calorimetry tests were conducted to obtain basic information about the polyurethane foams. The polyurethane foams demonstrated the largest degree of outgassing per mass; specifically, the white foam outgassed 50% less than the red foam. The polytetrafluoroethylene and polyethylene materials provided relatively small amounts of outgassing. The polyethylene materials appeared to react further upon cooling, leading to negative outgassing values due to consumption of gas in the container.

INTRODUCTION

Various materials are required for safely packaging items for transport or storage. Polymeric foams are a common means of protecting items from impact damage. The use of the foams in this study has the added requirement of minimal outgassing such that the closed container is not breeched if exposed to fire. The experiments completed here provide measurements of the gases per polymer mass that would be released at elevated temperatures. It is assumed that the major constituent of such gases is water, as polymers have a tendency to adsorb water, particularly if a filler is compounded into the polymeric matrix. Fillers, processing aids, colorants, stabilizers, and other additives are typically added to polymers for mechanical property enhancement (Fried). Little information is available about the composition of the materials in this study.

Another packaging application for polymers includes plastic bottles, used to contain liquids and solid powders. The current study measures outgassing from a Teflon (polytetrafluoroethylene or PTFE) and a polyethylene (PE) bottle, as well as their respective lids. The latter are unknown polymer types, although one is assumed to be high-density polyethylene by its manufacturer's stamp. Table 1 lists some characteristic average values for the polymer resins under study. The polyurethane (PU) foam, also listed in this table, has a significantly low moisture absorption level due to its probable closed cell configuration (MatWeb). PU resin properties vary widely according to the formulation and processing.

Table 1. Characteristic values for polymer resins and PU foam in this study (Fried, Gibson, and MatWeb

Polymer	T_g (°C)	T_m (°C)	Density (g/cm^3)	Water absorption (%)
Polytetrafluoroethylene	−73 (−99°F)	327 (621°F)	2.1	0.01
Polyethylene	−120 (−184°F)	98–135 (208–275°F)	1.0	0.03
Polyurethane	−70 (−94°F)	177 (350°F)	1.2	1.0–38.0
Polyurethane foam	−70 (−94°F)	177 (350°F)	0.45	1.0–5.0

The objective of this project is to heat plastic materials in ramped stages up to 400°F (204°C) and measure outgassing quantities within sealed containers. The goal is to reproduce test results from similar tests done in 1991, as reported in a letter authored by earlier researchers (Tinnel). Data from that document were used in safety documentation submitted in 1991 as characterization for the scenarios called Hypothetical Accident Conditions (HAC) and Normal Condition for Storage (NCS). Starting with the assumption that an item being shipped is contained in a polyethylene bag, it is then cushioned in PU foam. The foam is sealed in a can that is insulated by a lightweight concrete. The concrete is packaged in an outer steel drum that is vented. According to standards set forth by the U. S. Nuclear Regulatory Commission,

- In the HAC scenario, the drum is assumed to burn in a fire for 30 min, and the foam reaches a 300°F (149°C) temperature.
- In the NCS situation, a drum is assumed to sit out in the sun for several days and nights, which means that it is subject to continual temperature excursions between cool and 180°F (82°C).

In both cases, the PU foam will outgas over a short or long time, and it is required not to exceed a pressure that will damage the shipping container and cause the container to be breeched. It is assumed that moisture is the major offgassed constituent from this polymer structure, which only degrades beyond temperatures higher than 250°C (Hobbs).

PU foams are typically formulated from a polyol and an isocyanate component, adding a gas or blowing agent to one of these components to achieve the cellular structure. As stated earlier, additional constituents may be among the starting materials, as required in various applications. The original PU foam is a reddish-orange polyurethane formulated from Dow Chemicals components and was used for shipping protection until Dow decided to no longer manufacture this material. A white PU foam is now being considered to replace the earlier type and has components produced by BJB Enterprises, Inc. Both PU foams are tough and rigid and feature a nonporous skin where the foam apparently contacted the mold walls. There was random variability between the ratio of foam to skin in the specimens cut initially; smaller samples tended to have a larger fraction of skin. Care was taken to cut specimens from the mass of the foam, as the skin can demonstrate different properties; these foams are essentially composite materials (Broos). The density of the red foam specimens ranged from 0.45 to 0.50 g/cm^3 in the experiments discussed here. The density of the white foam material ranged from 0.27 to 0.49 g/cm^3. The polyethylene bottle is an opaque white material and has a density typically similar to water (1.0 g/cm^3). Teflon material typically has a density of 2.1 g/cm^3; this bottle has a smooth waxy texture.

Preliminary examination of the two foams was done using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) in order to characterize some thermal properties. Figures 2 through 5 present the data. Figures 6 through 13 provide the outgassing data in this study. Figures 14, 15, and 16 comprise the basic molecular structures of these polymers.

DIFFERENTIAL SCANNING CALORIMETRY

DSC is an analytical method that measures the quantity of heat flow required to maintain a reference and sample at a particular temperature. The specific heat of the sample is then determined over a temperature range, giving information about phase transitions, kinetic processes, and other thermal attributes (Kämpf). The PU foams undergo some type of transition, cell softening or a glass transition, near 200°F (93°C); however, the presence of additives such as flame retardants, catalysts, or antioxidants could also have an effect on the DSC output. The red foams and white foams begin melting at 480°F and 560°F, respectively (250°C and 293°C).

THERMOGRAVIMETRIC ANALYSIS

TGA was run on each polymer, and weight loss was tracked as a function of temperature. The structure of PUs typically begins degradation between 250 and 350°C (480–660°F). The red PU demonstrates three regions of decomposition at 480°F, 553°F, and 696°F. The white PU only gives evidence of two decomposition processes, at 562°F and 689°F. The 550–560°F temperature is where polymer bridges begin to break and re-form into a secondary polymer structure; over 600°F, the secondary polymer structure breaks down as well. In the case of the red PU, the early decomposition is possibly loss of some additive. In both cases, the initial 1–2% weight loss corresponds well with the loss of moisture.

OUTGASSING STUDIES

During the outgassing study, samples of polymeric packaging materials were placed in vacuum-sealed stainless steel containers (retorts). Each retort was then attached to a capacitance manometer or "baratron" for direct measurement of the internal container pressure as the temperature was increased. This method allows tracking of the volatiles emitted from the materials, which are thought to mainly comprise moisture but also decomposition products at sufficiently high temperatures. While absorbed moisture is not immediately apparent under ambient conditions, the water contained in packaging is available to diffuse out over long time frames, such as years. Controlled heating provides a method to ascertain the maximum amount of outgassing from a material mass. This study provides information about the outgassing of volatiles in the situation combining elevated temperatures with the presence of air.

After the polymer specimens were loaded into retorts, the open or "free" volume within the containers was calculated. This study was initiated in the presence of atmospheric moisture and air pressure with a single absolute pressure gauge established to monitor the pressure as the temperature was ramped to a 204°C (400°F) maximum. Outgassing pressures are the sum of those gases emitted from the polymer specimen and retort, in addition to the air trapped inside the retort. The pressure gauge used has a maximum measurement range of 10,000 torr and was located outside the oven. The actual measurement volume included the retort headspace and the 24-in. flexible stainless steel hose used to connect the sample retort in the oven to the measurement device. An additional 1000-torr baratron was used as a reference to provide a measurement of the ambient pressure in the laboratory.

EXPERIMENTAL

Materials

The Packaging Engineering group provided the following test items for this study:

1. orange/dark red polyurethane foam in blocks (111.58 g)—this material had been formulated using components from Dow Chemical;
2. off-white polyurethane foam in blocks (168.8 g)—this material was formulated with components known as BJB280;
3. a clear/translucent Teflon (polytetrafluoroethylene) bottle capped with a white plastic lid labeled "Nalgene," possibly made of high-density polyethylene; and
4. an opaque polyethylene bottle capped with a black plastic lid, probably polyethylene.

Samples of random sizes and weights were cut using a blade or large scissors. Care was taken to exclude the skin from the foam materials being tested. Specimens were cut and weighed immediately before being sealed into a vacuum container. The total weight of pieces placed into a particular container was recorded in grams.

Equipment and Procedure

Standard vacuum hardware was used to seal randomly sized specimens of each material (weighing from 8 to 12 g) in air after these were weighed on a calibrated scale. (For the two PU foams, the experiment had been repeated with smaller masses.) Additionally a "blank" container was tested over the temperature range. This blank served to provide a baseline outgassing level for the container. The oven was programmed to heat to specific temperature plateaus and hold for a specified time period

before ramping linearly to the next temperature. The temperature profile, named "Profile 5," is described in Table 2. Despite the programming of the oven to cool to 50°F, its minimum temperature after heating was about 110°F; to cool the oven to room temperature the oven door was opened, which allowed free circulation of air into the heating zone.

Table 2. Heating and cooling profile (Profile 5) for outgassing tests

Temperature setting		Duration of ramp or hold
77–150°F	25–65°C	1-h ramp
150°F	65°C	2-h hold
150–200°F	65–93°C	1-h ramp
200°F	93°C	2-h hold
200–250°F	93–121°C	1-h ramp
250°F	121°C	2-h hold
250–300°F	121–149°C	1-h ramp
300°F	149°C	4-h hold
300–350°F	149–177°C	1-h ramp
350°F	177°C	4-h hold
350–400°F	177–204°C	1-h ramp
400°F	204°C	4-h hold
400–111°F	204–44°C	2-h ramp
111°F	44°C	Lower oven limit
77°F	25°C	Oven opened to lab

It should be noted that during the test period the test laboratory experienced continual temperature swings between 56 and 80°F (13–27°C). This range is typical for this laboratory and can cause random noise in the data under collection. For example, according to its specifications, the Despatch oven control stability is ±0.5°C per 5°C change in ambient temperature. The signal conditioner and display have linearity and accuracies in the parts per million (ppm) range per degree °C, but the combination of these small variations provides a visible noise level at extremely small outgassing levels.

The containers were constructed of stainless steel and bolted with the use of a copper gasket between 2.75-in. conflat flanges (Fig. 1). The assembly was completed with ¼-in. VCR® fittings and Swagelok or Nupro valves, using silver-plated nickel gaskets to seal interfaces.

Fig. 1. Stainless steel vacuum container or *retort*.

Pressure measurements were conducted using an MKS Instruments Type 690A14TRB 10,000-torr baratron providing output to an MKS 670 signal conditioner electronics unit. The baratron had an accuracy of 0.12% of reading and operates with a 59–104°F (15–40°C) ambient temperature span. The signal outputs were processed using a program called "Generic Application for Reading Pressure Gages for Import into Excel," and data were collected using LabView software on a laboratory computer. Data were downloaded from this computer for storage and analysis on an office personal computer.

The heating procedure displayed in Table 2 was conducted in a Despatch LAC 1-67-6 programmable laboratory oven that uses a Protocol Plus microprocessor control. A thermocouple was used to separately track and write the oven temperature to the aforementioned LabView program.

Experimental Steps

- Clean stainless steel retorts using isopropanol and wipe dry. Allow to air dry for 24 h.
- Cut and weigh polymer samples in atmosphere.
- Document material type, sample name, and weight.
- Place polymer pieces in stainless steel retort; label retort with sample name.
- Bolt container to conflat flange using a copper gasket and six bolts.
- Store retorts near Despatch oven until testing could be conducted.
- Select random retort for test; use nickel gasket to connect container to flexible tubing inside oven.
- Record pressures from baratrons measuring ambient and experimental pressures; these should be equivalent before test.
- Open National Instruments program and establish data collection mode and sampling rate (in data points per minute).
- Check data readout from signal conditioner and thermocouple.
- Check data download to personal computer via Labview program using Excel.
- Open sample retort valve.
- Turn oven on and load Profile 5; select Run.
- Periodically check system to ensure that data are being collected as planned.
- At end of test, record pressures according to both ambient and experimental baratrons; note oven temperature.
- Turn off oven and open oven door.
- Allow pressure to reach a new "ambient" equilibrium, and again record pressures.
- Close sample retort valve.
- Unbolt sample retort, and reserve for possible headspace gas analysis.
- Download data immediately in Excel *.csv format.
- Stop data collection program.

DATA AND RESULTS

The data were collected, then downloaded and analyzed using Microsoft Excel. The raw data were recorded as pressure in units torr as a function of time; temperature in degrees centigrade was also tracked as a function of time. For all materials, charts were later calculated to provide outgassing volume in cm^3(STP)/g and temperature in degrees Fahrenheit from ambient to 400°F, as a function of elapsed time (duration in hours). Blank data were used to calculate the moles of outgassed species

contributed by the sample container and other system components. Appendix 1, *Data Analysis*, provides additional detail on data processing.

BLANK OUTGASSING RESULTS

Two empty containers (blanks 1 and 3) were subjected to the same temperature profile in separate tests. Outgassing patterns shown in Figs. 6 and 7 provide a guide to the variation in (a) oven runs at different times and (b) blank outgassing under identical temperature profiles. The oven temperature was observed to vary as much as 5% at the same temperature setting. In concert with this, the blank outgassing pressures varied from each other by −0.25 to 4.2% in these tests. An analysis shows a 0.58 correlation of pressure to temperature variation between these two experiments. The other significant variable that can cause variation in outgassing between the two seemingly identical blanks is dimensional variations. The container volume difference (observed to be <2%) will lead to pressure discrepancies for identical gas quantities. In the current tests, molar quantities were calculated using container data developed through successive gas expansions to measure their volumes.

FOAM OUTGASSING RESULTS

The results from two red foam specimens are averaged in Fig. 8, where the specific volume of outgassing from each specimen is plotted with the temperature in degrees Fahrenheit. This normalized value is cited as specific volume at standard temperature and pressure (STP), providing the volume per specimen mass at standard temperature (273 K) and pressure (1 atm); the specific volume = $V/g = (nRT/p)g^{-1}$. It can be noted that the magnitude of outgassing is comparable to the 1991 data, but perhaps slightly less due to the material outgassing over time in storage. The experiment described here increases the temperature range and time of outgassing, so larger ultimate values than those of 1991 are observed. As well, the ramping and hold times were longer in the current experiment. The white foam outgassing quantities are shown in Fig. 7, and while on the same order of magnitude as the red PU, this material appears to produce only half the overall quantity of outgassed species. Both materials had continually increasing outgassing of volatiles at the highest test temperature, indicating that decomposition has started rather than outgassing has been seen at lower temperatures. The molecular structure of polyurethane includes an ester linkage that is subject to hydrolysis. Although some PU has a large moisture content, rigid foams typically have no more than 5% moisture. In this study, the red PU demonstrates about 1.2 wt % and the white foam 0.5 wt % moisture.

TEFLON AND POLYETHYLENE OUTGASSING RESULTS

The polytetrafluoroethylene and polyethylene materials outgassed relatively little, making it difficult to detect outgassing due to the heated container and that arising from the polymer alone. In other words, the final plots (Figs. 11–13) show a great deal of noise. It could be concluded that these materials would not present a large consideration for their outgassing potential in a heated situation. Their polyolefin structure does not attract moisture to the degree of the ester group in the PU structure. An interesting feature of the polyethylene materials is observable as the test vessel is cooled to room temperature. These experiments actually went into a negative pressure status, indicating that a reaction was taking place that consumed the gas phase inside the container. It is recognized that polyolefins degrade in air by oxidative reactions (Boenig). A mechanism for pressure decrease occurs if oxygen present in the original headspace reacts with the polymer and suppresses outgassing, even

during the heating cycle. Polymers also degrade by fragmentation, producing free radicals, which can then continue to react with one another (cross-linking). During a cooling of this system, these moieties would have reduced mobility, thereby increasing the probability of reaction with the gas phase. An analysis of the headspace would provide a means to study the remaining constituents.

OUTGASSING COMPARISONS

Figure 14 sets forth a straightforward comparison of outgassing quantities. The maximum and minimum amounts of gas are calculated for various samples after the background quantities are subtracted. These were weighted by the specimen mass and plotted on a bar chart as moles per gram of polymer specimen. The PUs demonstratedly have a larger outgassing of volatile species per mass, in comparison to PE and PTFE. Again, it is interesting to note the negative outgassing values in the case of PE minimums.

CONCLUSIONS

The next experimental procedure would be to conduct a gas analysis of the headspace on each container. The Y-12 National Security Complex Plant Laboratory is the best resource to complete this task. This would pinpoint the identity of outgassed species and provide a guide to ascertaining chemical reactions taking place in the solid–gas interface. This certainly would verify that reactions between the oxygen and polymer fragments have occurred.

Another stage would be to clearly identify the identity and manufacturer of each material, including the age, ingredients, and processing steps. Processing information for each polymer would assist in explaining the DSC and TGA output, if such an effort is desired. The response of a polymer to its environment involves its constituents, processing history, and treatment in storage. The large range of polymer properties, including outgassing, is due to these variables.

It can be concluded that PU foams absorb and outgas moisture to a larger extent than the polyolefins, as expected according to their respective molecular structures. This is also reflected in the literature absorption values. The white PU outgassing is no more likely to cause a shipping container breech than the red PU outgassing in the Nuclear Regulatory Commission (NRC) scenarios. The red PU outgassed a specific volume per mass similar to that quantity derived in the 1991 study.

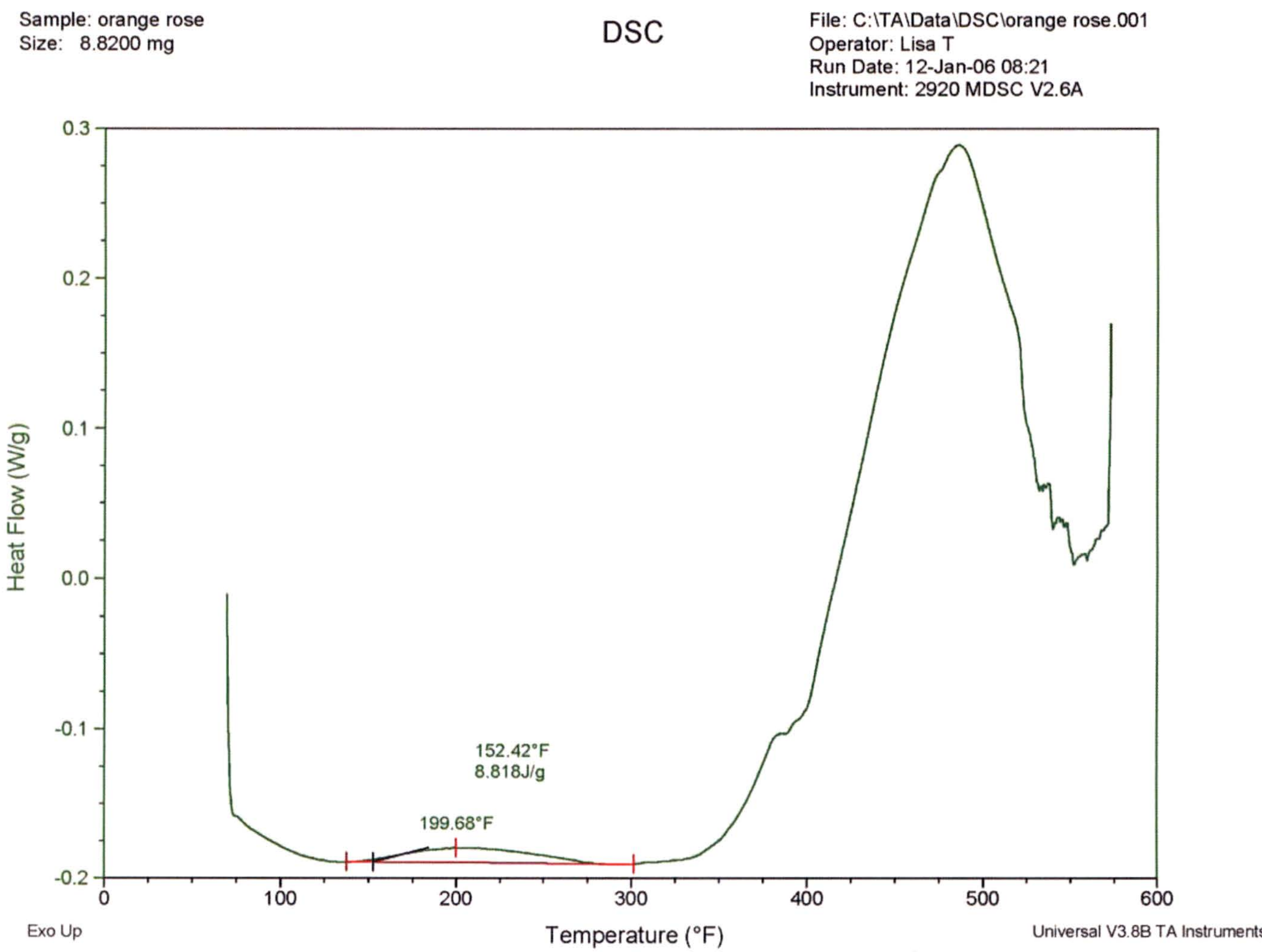

Fig. 2. Red PU thermogram showing thermal transitions at 200°C and 490°C.

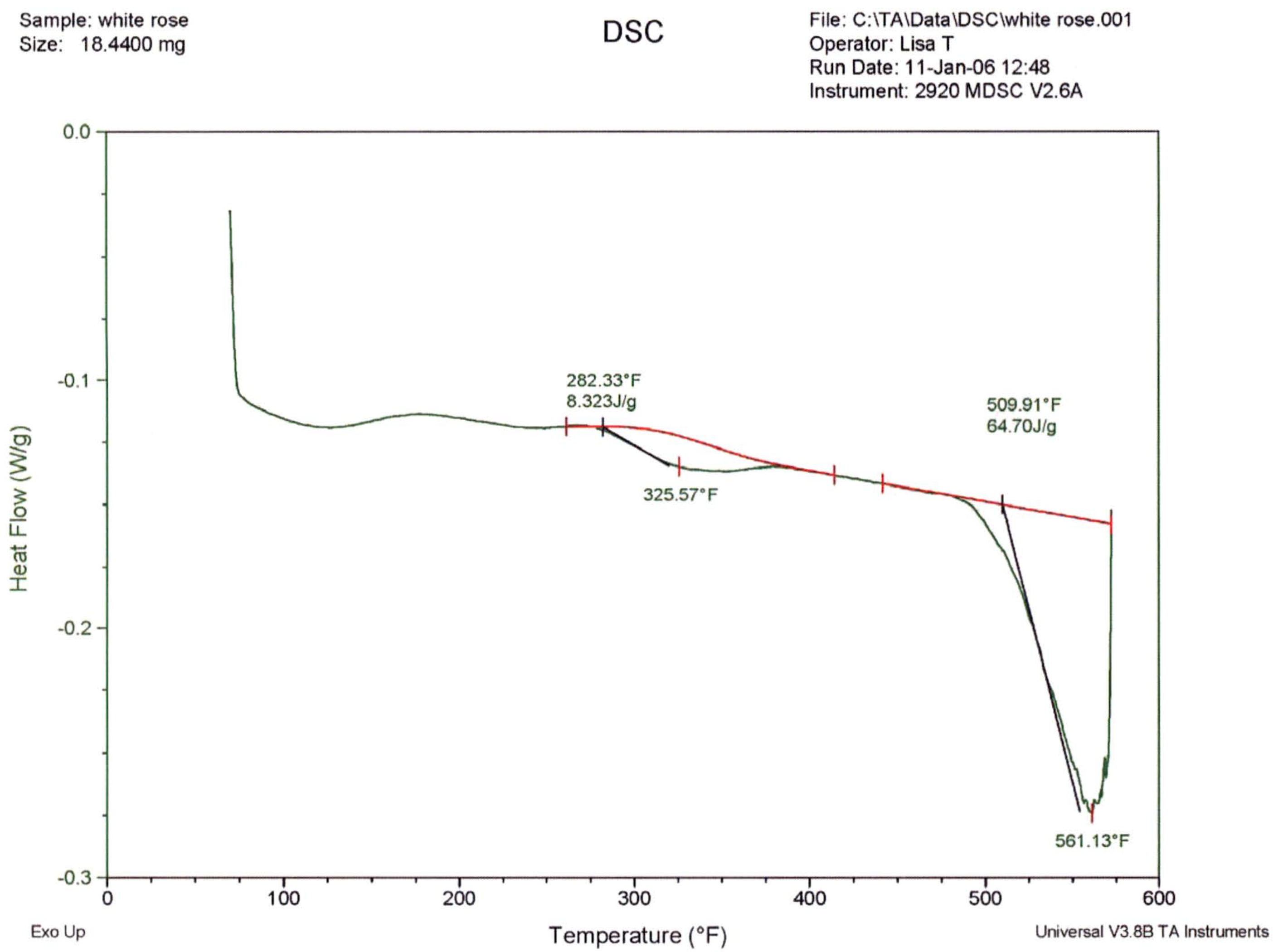

Fig. 3. White PU thermogram showing thermal transitions at 325°C and 560°C.

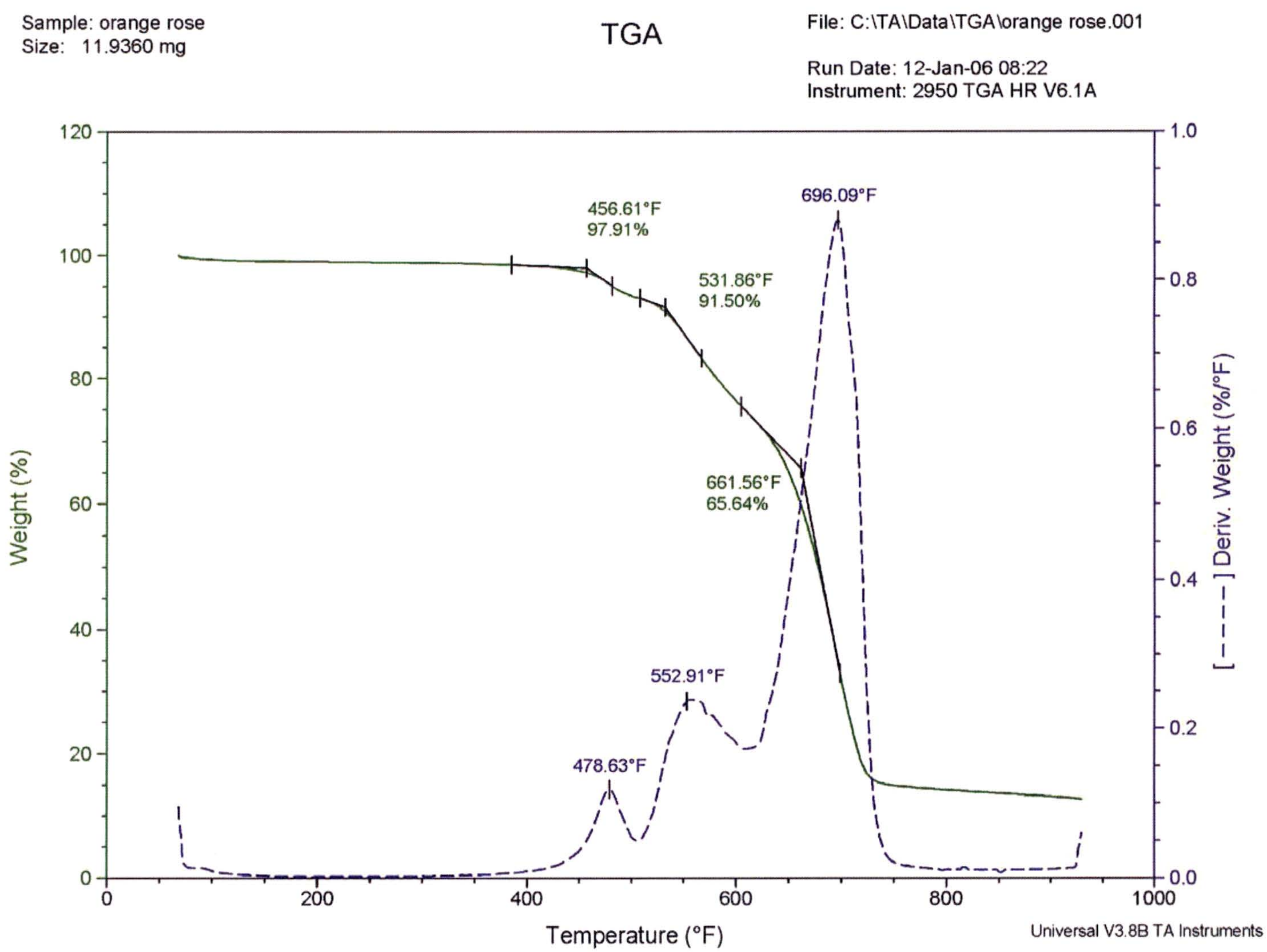

Fig. 4. Red PU foam showing three regions of thermal decomposition.

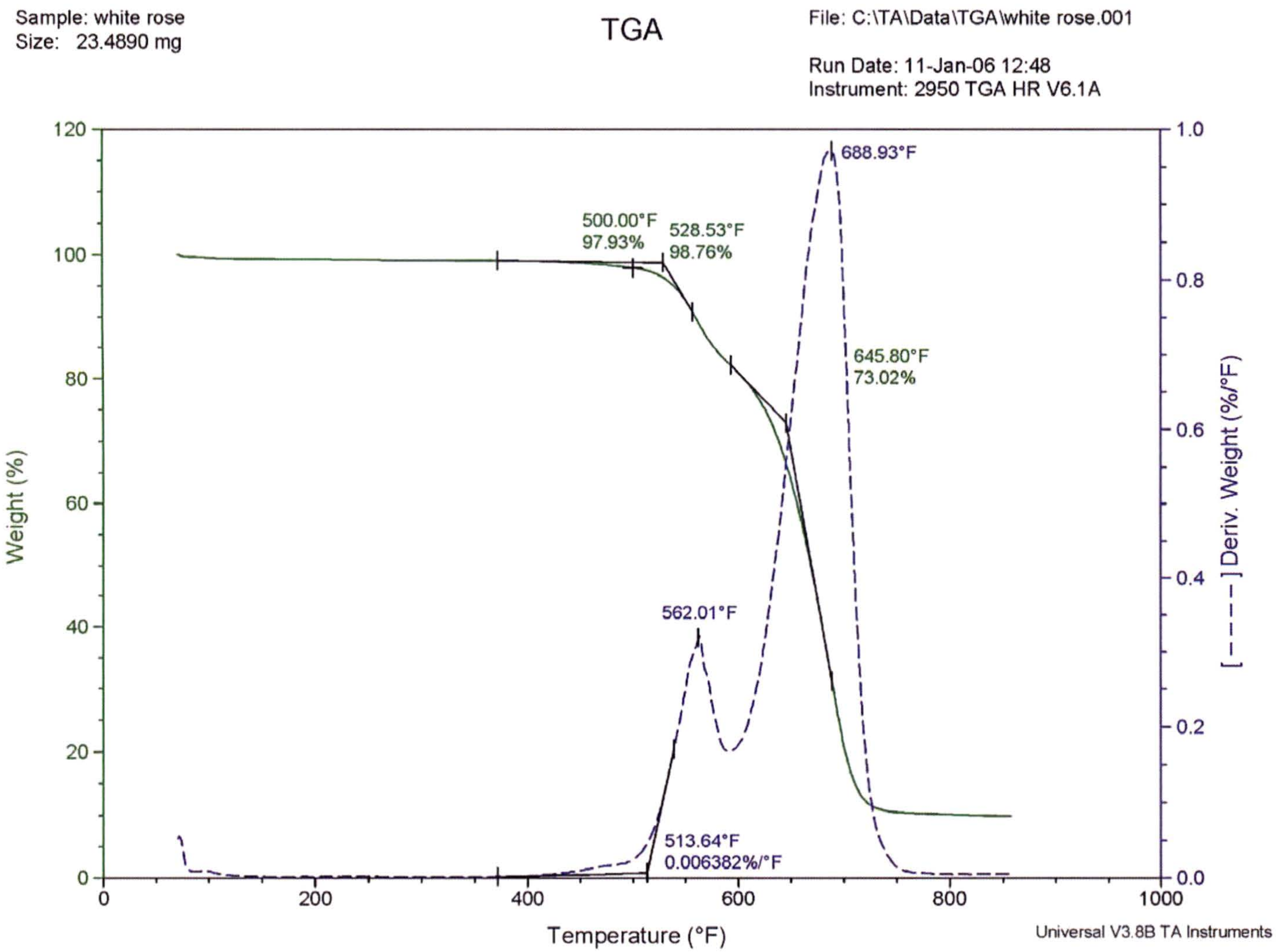

Fig. 5. White PU foam showing two regions of decomposition.

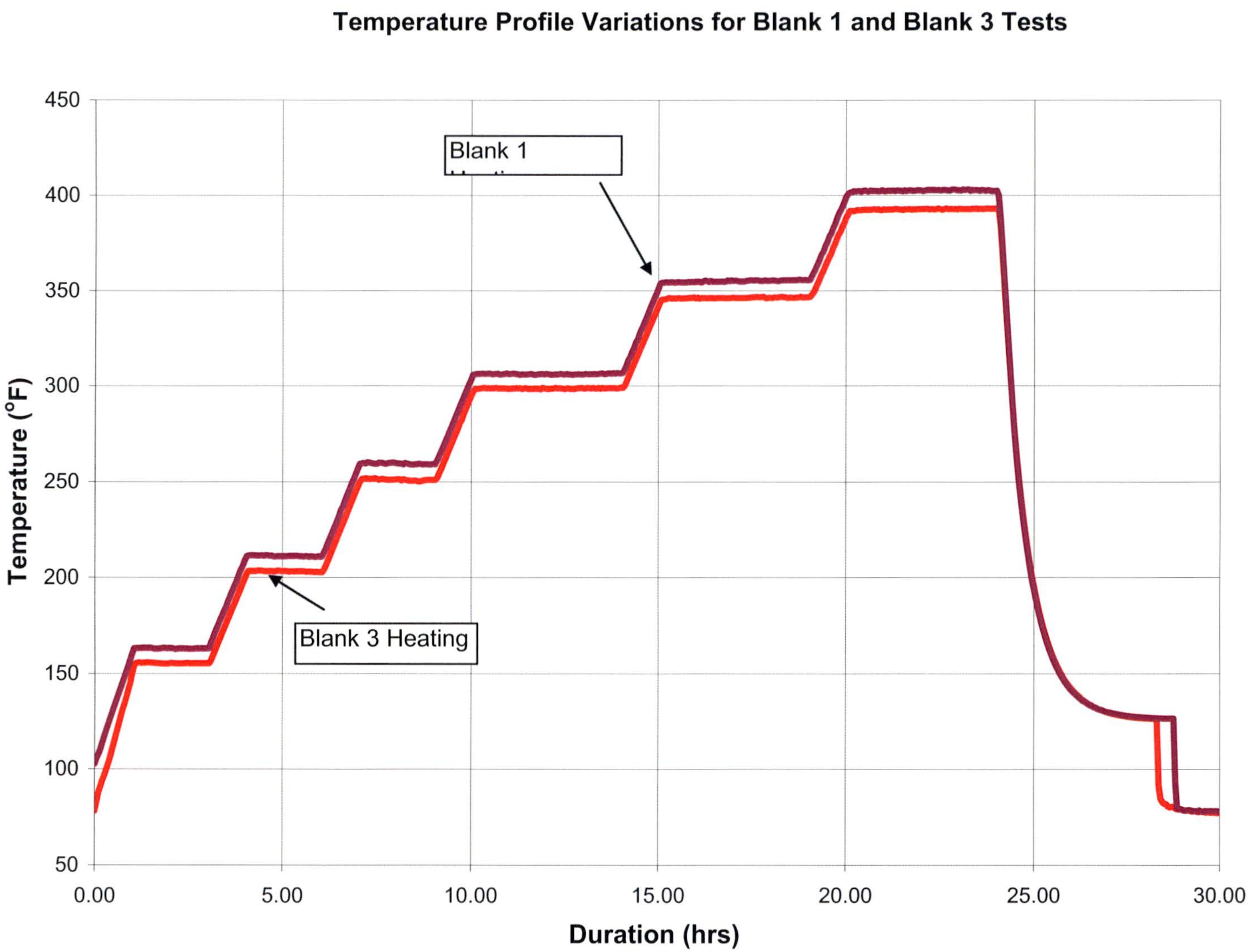

Fig 6. Variation in heating profile from oven may lead to variation in outgassing results.

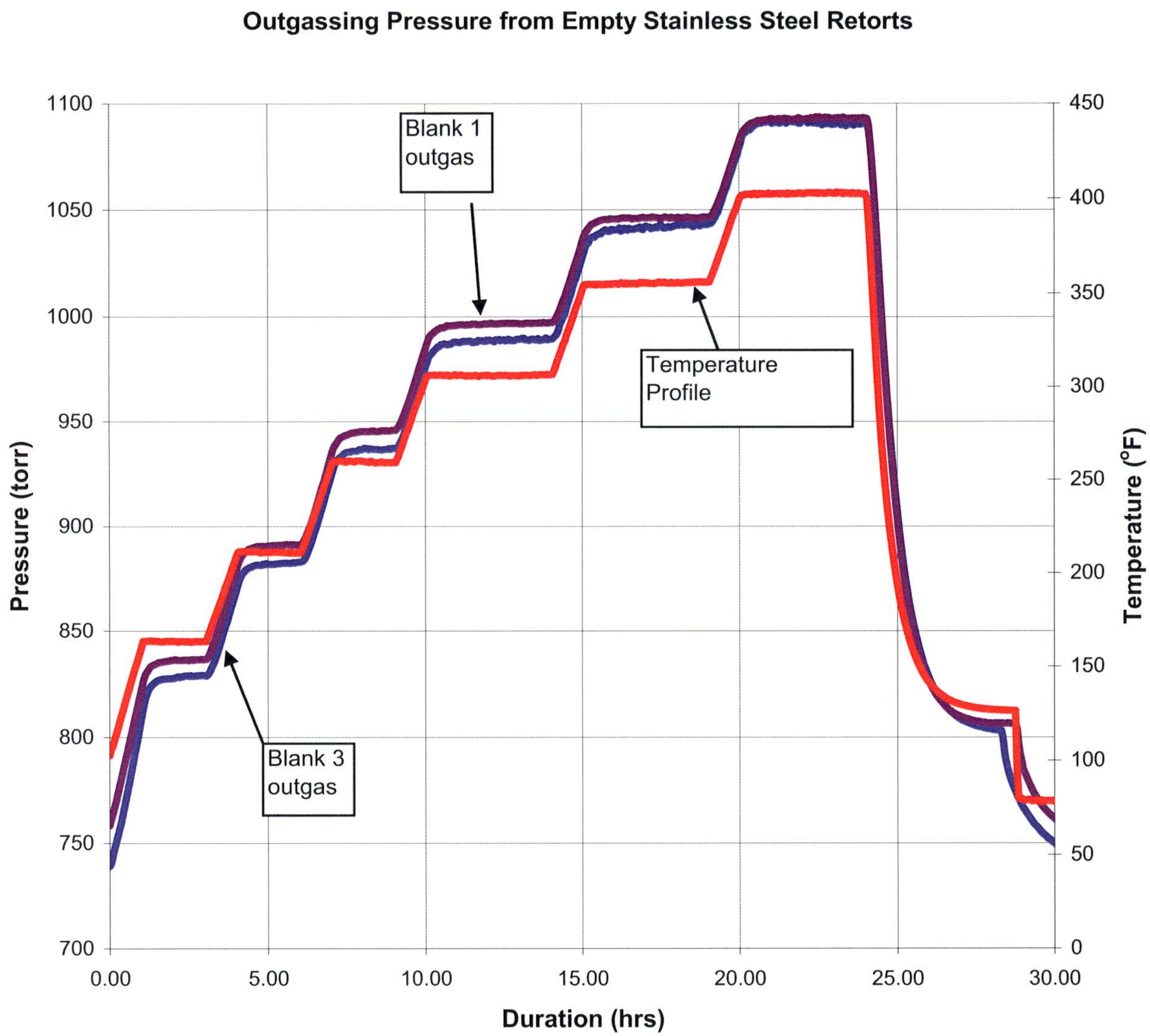

Fig. 7. Outgassing pressures from two stainless steel retorts.

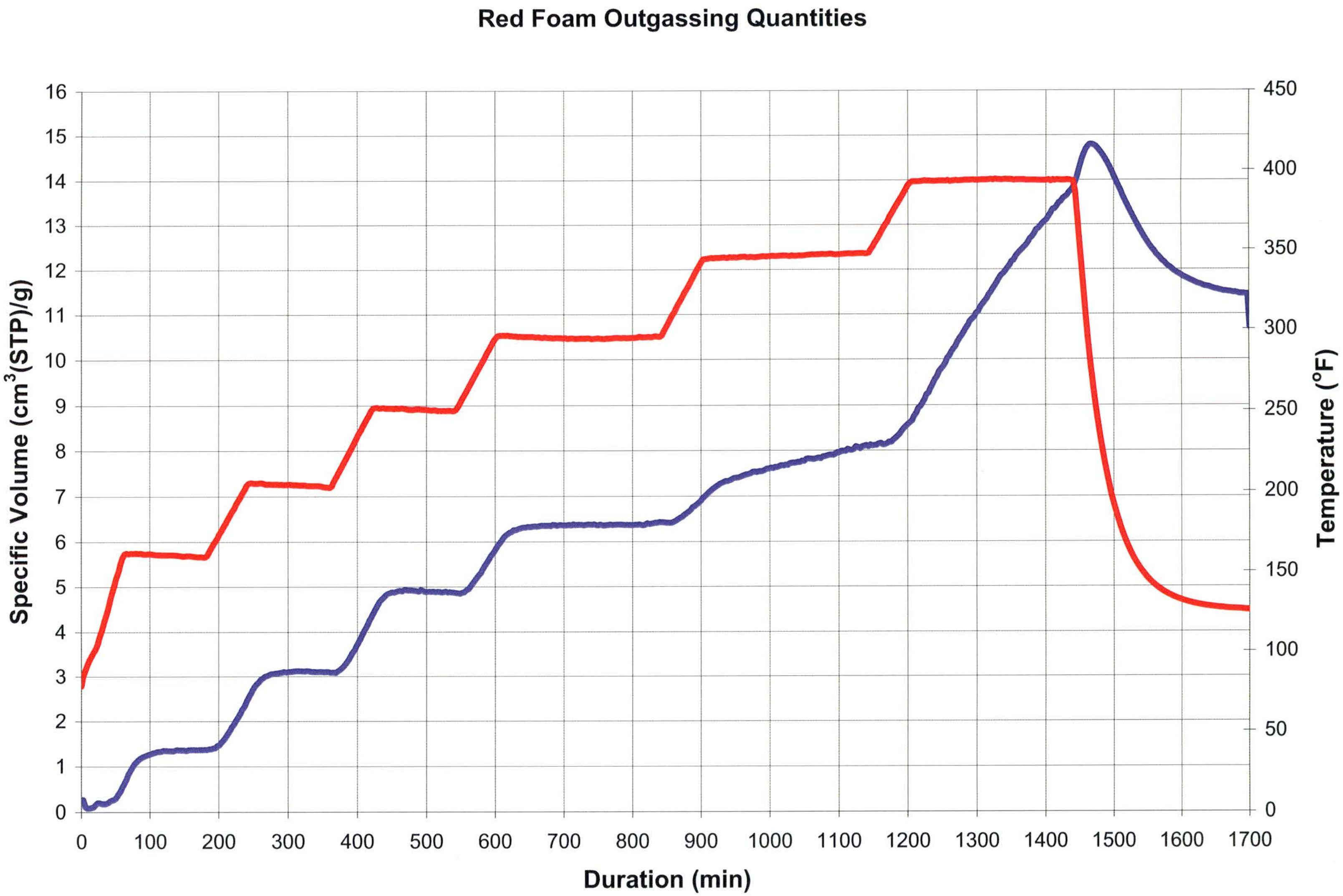

Fig. 8. Outgassing of two red PU foam specimens (8.88 g and 2.98 g).

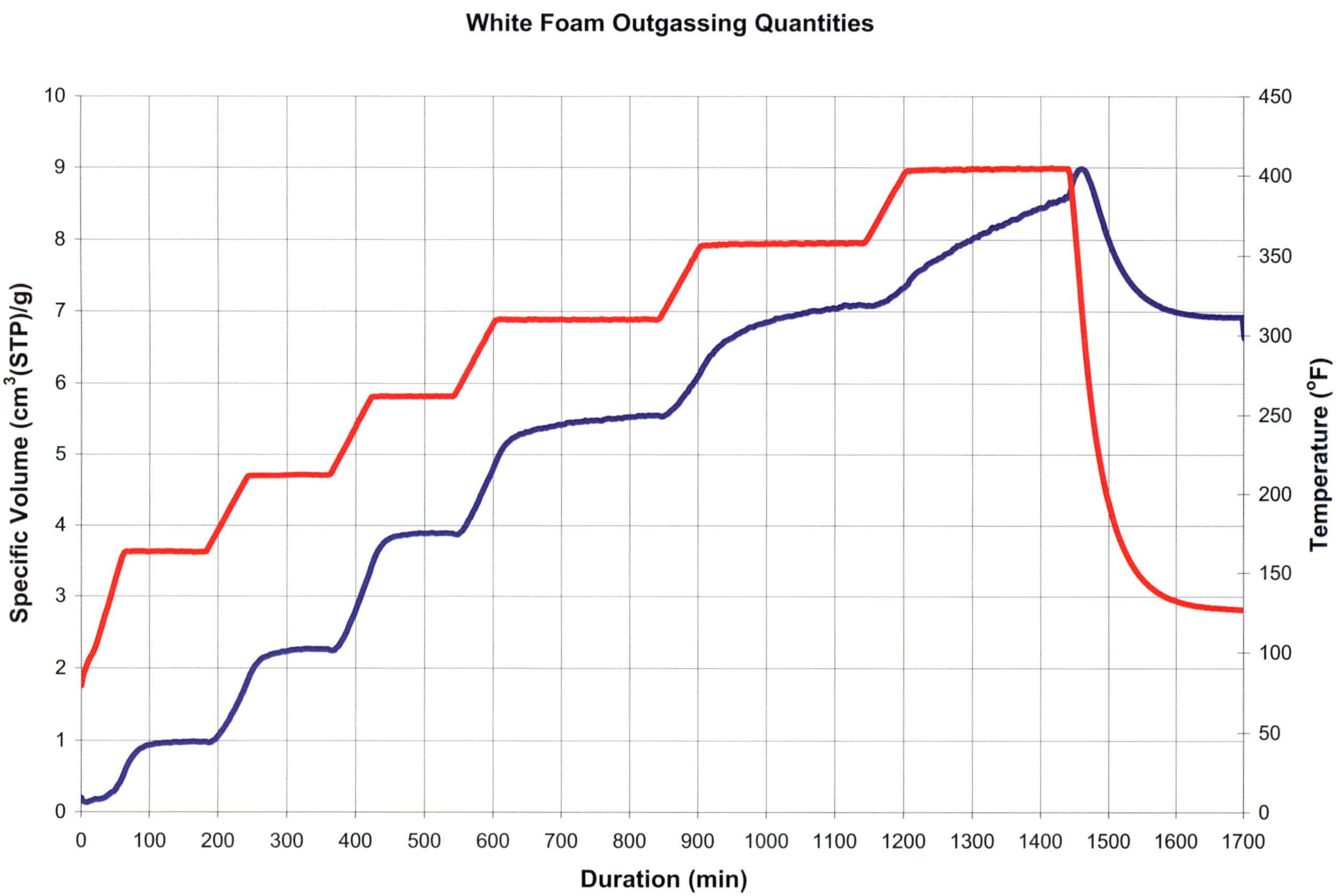

Fig. 9. Outgassing of an 11.06-g specimen of white PU foam.

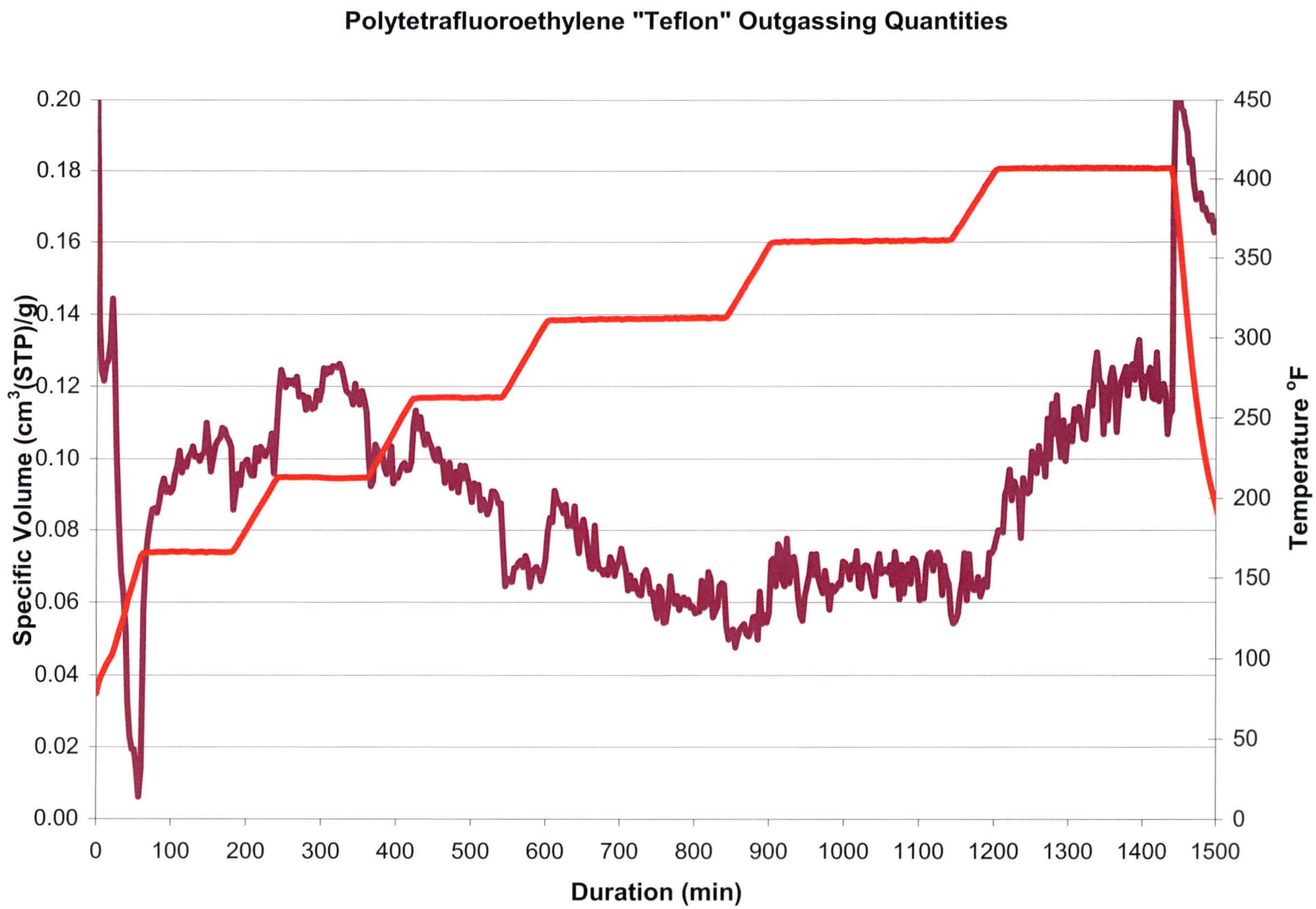

Fig 10. Outgassing of two polytetrafluoroethylene (Teflon) specimens (8.14 g and 12.41 g) competes with measurement noise.

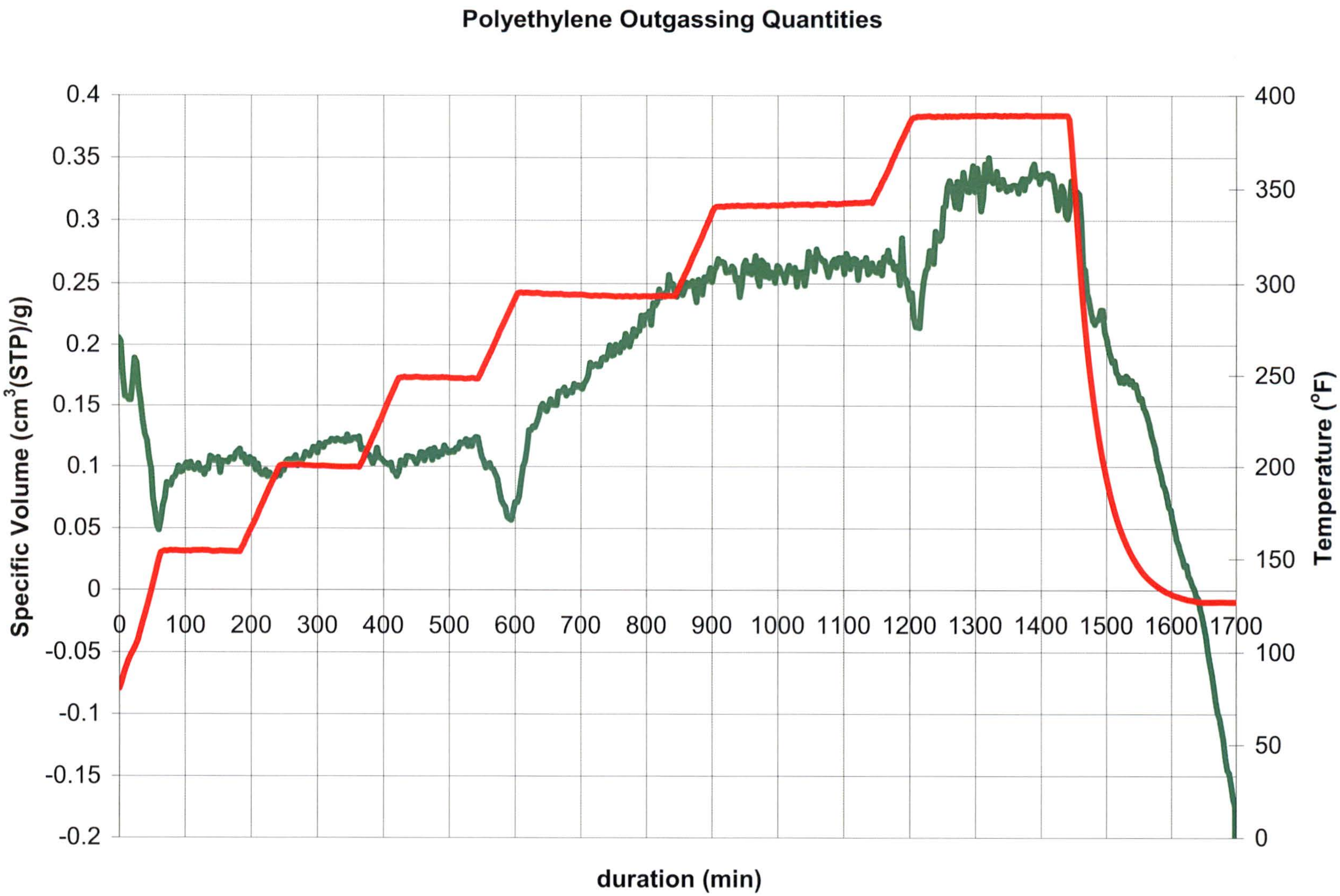

Fig. 11. Outgassing of an 8.18-g specimen of polyethylene bottle is at noise level and decreases rapidly upon cooling.

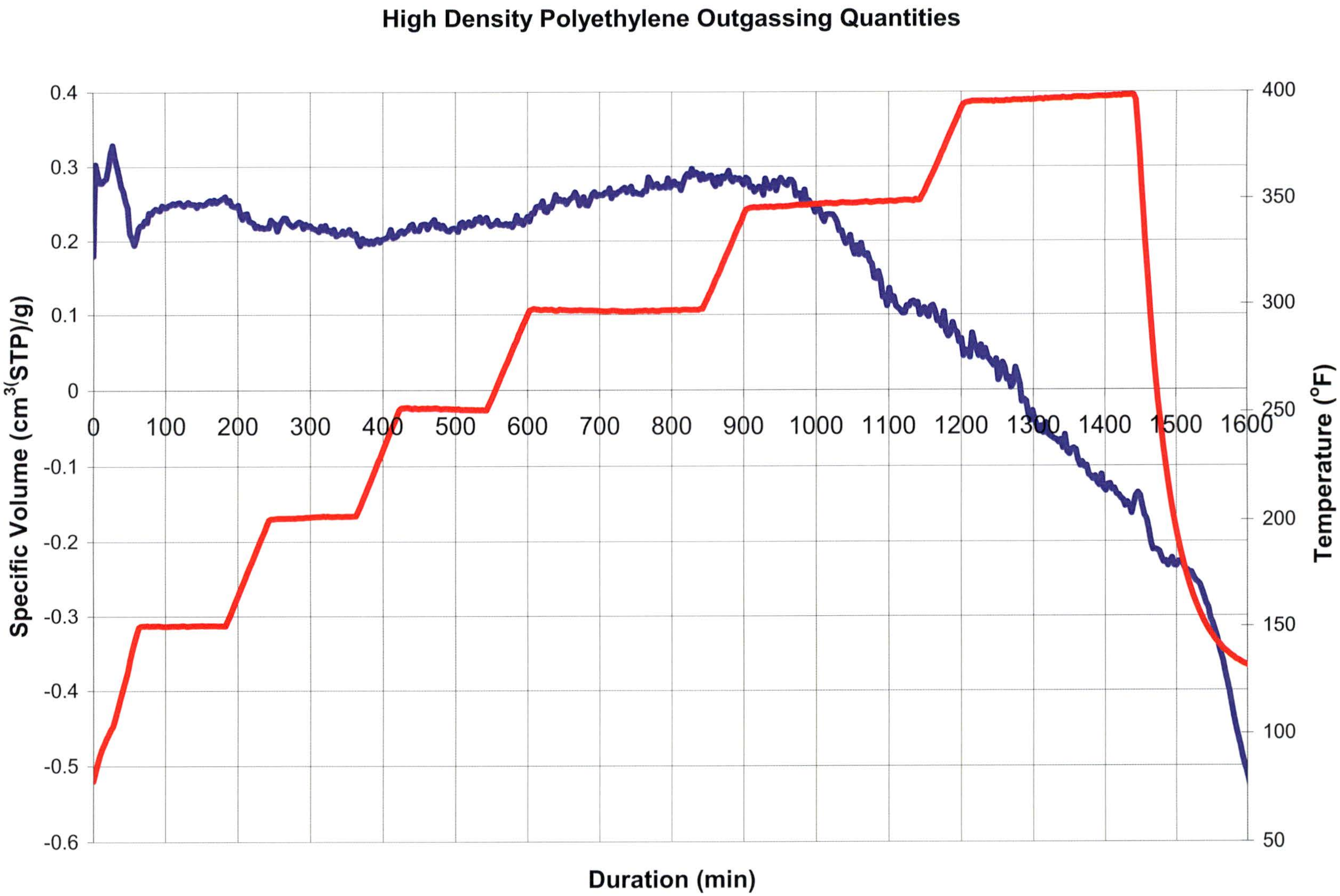

Fig. 12. Outgassing of an 8.3-g specimen of an HDPE bottle lid.

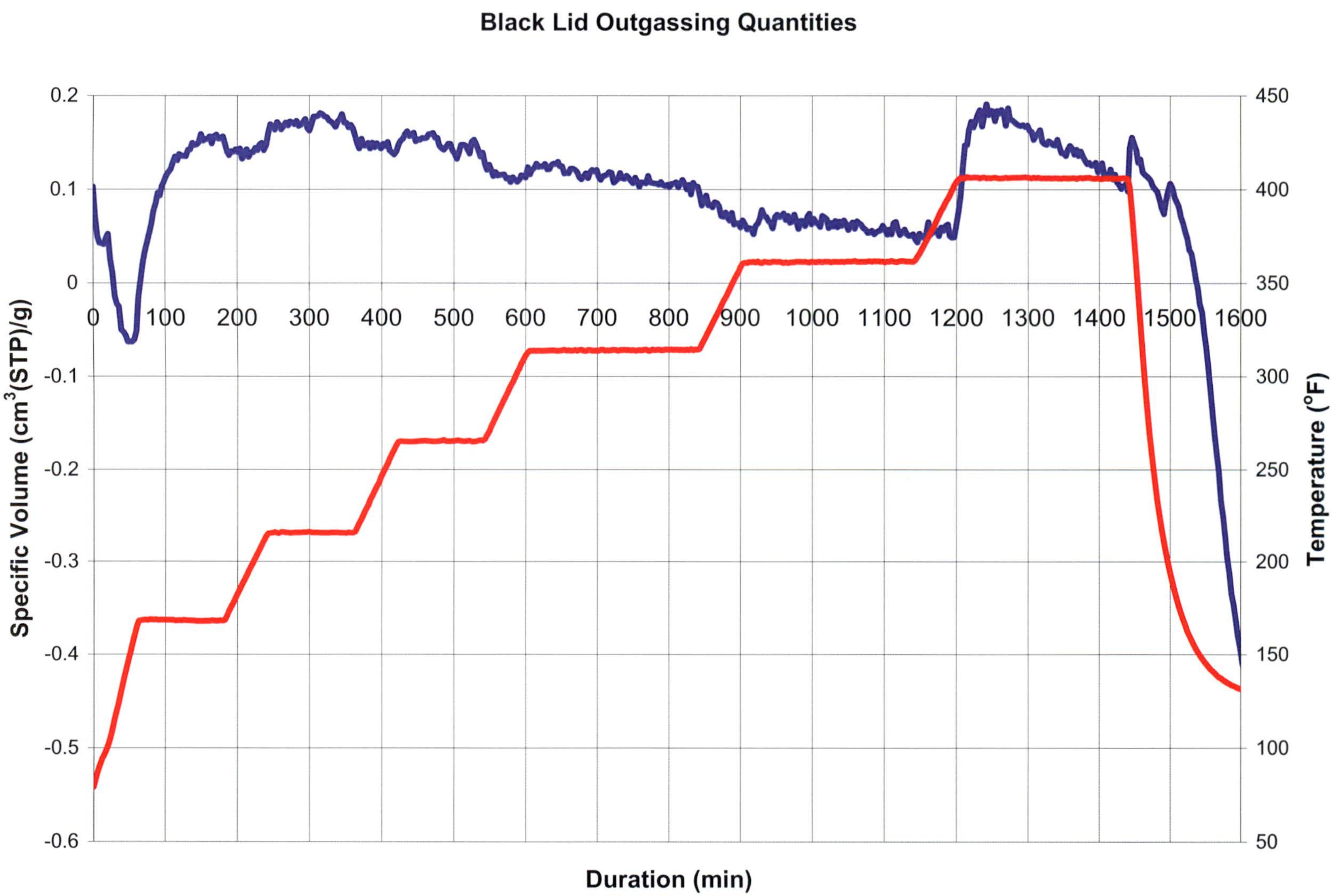

Fig. 13. Outgassing of an 8.90-g specimen of a black plastic bottle lid, possibly polyethylene.

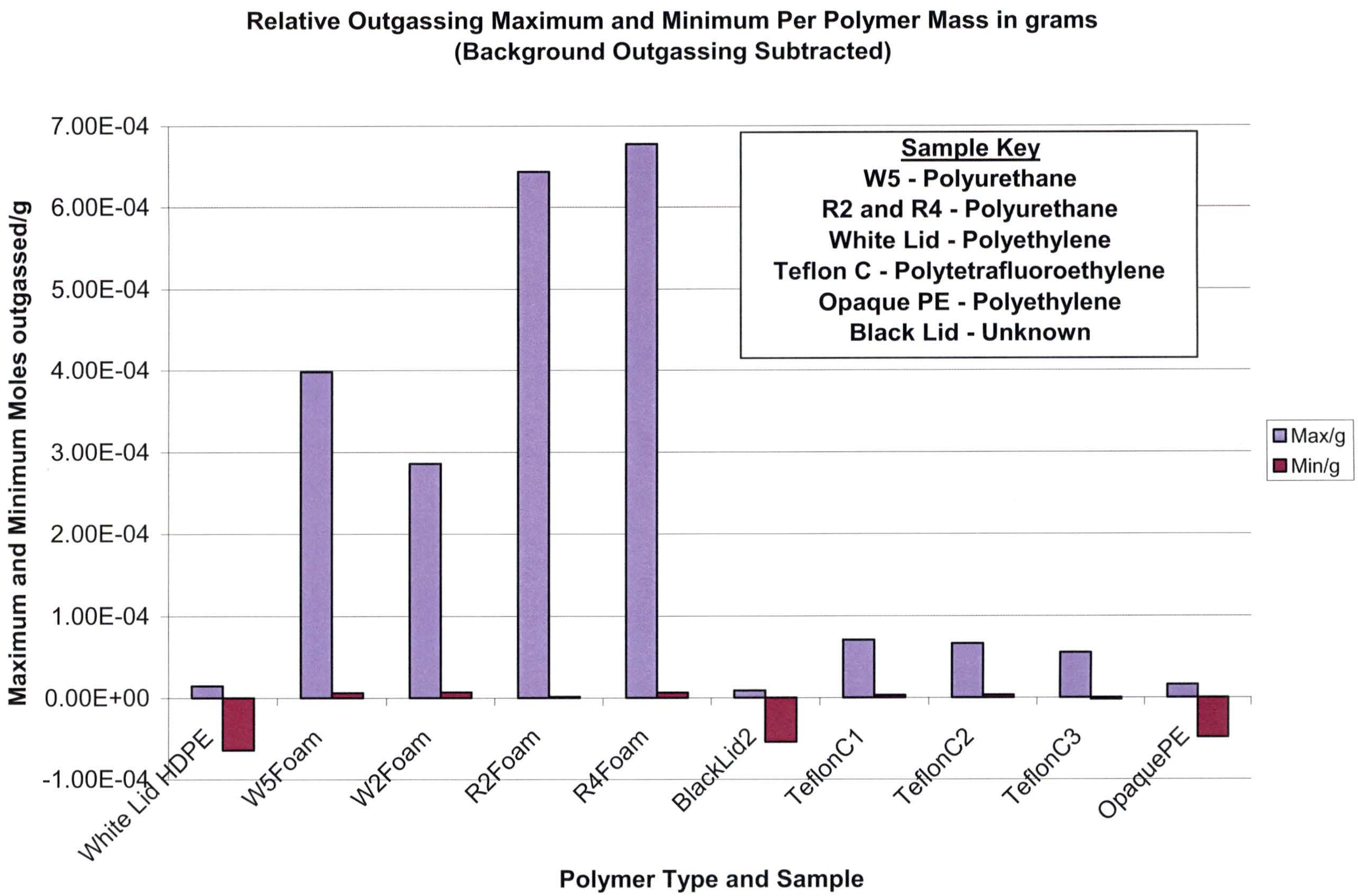

Fig. 14. Relative outgassing by polymer types examined.

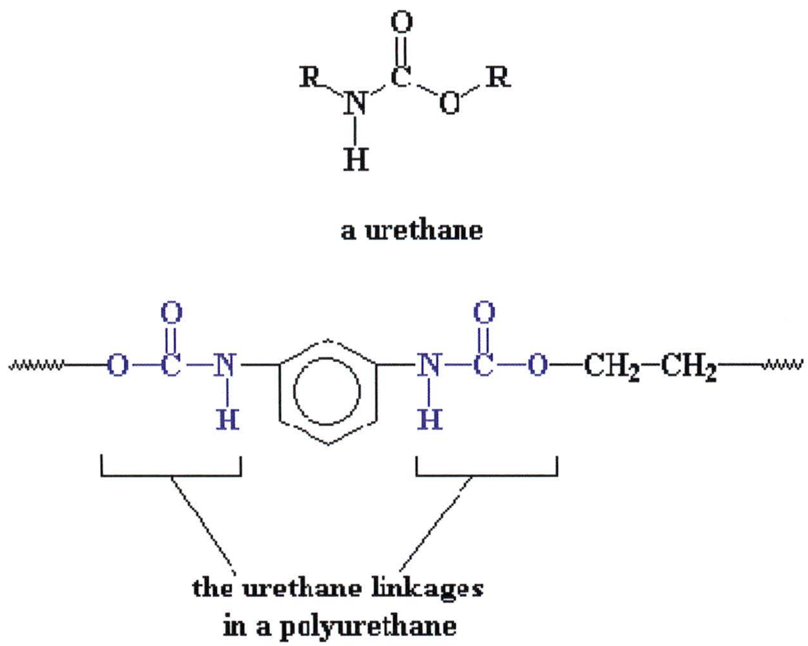

Fig. 15. Polyurethane molecular structure.

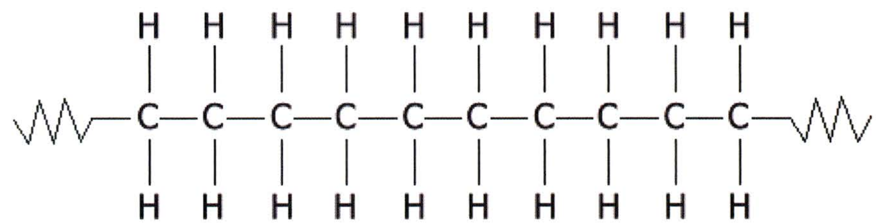

Fig. 16. Polyethylene molecular structure.

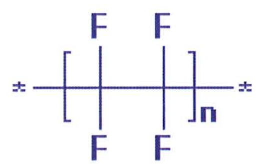

Fig. 17. Polytetrafluoroethylene (Teflon) molecular structure.

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APPENDIX 1: DATA ANALYSIS

This is a description of steps taken in Excel software to process data downloaded in the form of *.csv spreadsheets from National Instruments software. In general, new columns are set up for each calculation.

1. Open file
2. Data columns appear including Date and Time, Temperature, Pressure (torr)
3. Input sample name and weight (in grams) above pressure column
4. Insert column for duration—units can include days, hours, or minutes
5. Use CONVERT function to establish column of Fahrenheit temperatures
6. Input values for *R* (gas constant) and *V* (volume of container and flex hose) into cells on top of spreadsheet
7. Set up column to calculate the number of moles according to the Ideal Gas Law:
    a. $N = \{p(\text{torr})V(\text{cm}^3)/[R\ (82.057\ \text{atm-cm}^3/\text{K-mol})*T\ (T°\text{C} + 273)\text{K}]\} * (1\ \text{atm}/760\ \text{torr})$ using cell addresses for *p*, *V*, *R*, and *T* values
8. Paste column of blank outgassed moles
9. Subtract column of blank moles outgassed from specimen moles outgassed; this eliminates initial air and system outgassing
10. Calculate the volume of outgassed species at standard temperature and pressure (273 K and 1 atm) or by assuming an ideal gas that will have a volume of 22.4 liters per mole
11. Divide V_{STP} by specimen weight in grams; this column is Specific Volume
12. Plot T (°F) and Specific Volume vs Time (min), created separate axes for temperature and volume variables
13. Apply appropriate titles and formatting.

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Docket No. 71-9315
Volume 2

Safety Analysis Report, Y-12 National Security Complex, Model ES-3100 Package with Bulk HEU Contents

Consolidated Nuclear Security, LLC
P.O. Box 2009
Oak Ridge, Tennessee 37831

March 24, 2016

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Safety Analysis Report, Y-12 National Security Complex, Model ES-3100 Package with Bulk HEU Contents

Volume 2
Sections 3-8

March 24, 2016

Prepared by
Consolidated Nuclear Security, LLC
Management & Operating Contractor
for the
Y-12 National Security Complex and Pantex Plant
under Contract No. DE-NA0001942
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National Nuclear Security Administration

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APPROVALS

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ABBREVIATIONS

ALARA	as low as reasonably achievable
AM	as-manufactured
ANC	Average Net Count
ANSI	American National Standards Institute
AS	allowable stress
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
Cat 277-4	Thermo Electron Corporation (corporate name changed to Shieldwerx) Catalog No. 277-4™ (or Cat. No. 277-4)
CD	capacity discharge
CERCA	Compagnie pour l'Étude et la Realisation de Combustibles Atomiques
CFR	Code of Federal Regulations
CMTR	certified material test report
CoC	Certificate of Compliance
CSI	criticality safety index
CV	containment vessel
CVA	containment vessel arrangement
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPDM	ethylene-propylene-diene monomer
ETP	explicit triangular pack
FEA	finite element analysis
H/X ratio	hydrogen-to-fissile isotope ratio
HAC	Hypothetical Accident Conditions
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
k_{eff}	calculated neutron multiplication factor
LOD	loss on drying
LTL	lower tolerance limit
M.S.	margin of safety
MNOP	maximum normal operating pressure
MOCFR	moisture fraction inside the containment vessel
MOIFR	moisture fraction of the package external to the containment vessel
NCT	Normal Conditions of Transport
NLF	neutron leakage fraction
NRC	U.S. Nuclear Regulatory Commission
NTRC	National Transportation Research Center
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PGNAA	Prompt Gamma-ray Neutron Activation Analysis
ppb	parts per billion
ppm	parts per million
QA	quality assurance
QCPI	Quality Certification and Procurement
RCSB	Rackable Can Storage Box
SAR	safety analysis report
SCALE	Standardized Computer Analysis for Licensing Evaluation

ABBREVIATIONS

s_i	standard error
SRS	Savannah River Site
SS304	type 304 stainless steel
SST/SGT	Safe-Secure Trailer/Safeguards Transporter
TGA	thermogravimetric analysis
TI	transport index
TID	tamper-indicating device
TS	test sample
UNH	uranyl nitrate hexahydrate
UNX	uranyl nitrate crystals
USL	upper subcritical limit
VF	Volume Fraction
Y-12	Y-12 National Security Complex

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
2/25/05	0	Original issue	All
8/15/05	0, Page Change 1	Page changes resulting from *Responses to Request for Additional Information* #1, Y/LF-747	Title page, iv, xxiii, 1-4, 1-145, 2-2, 2-3, 2-6, 2-31, 2-32, 2-33, 2-34, 2-57, 2-59, 2-61, 2-107, 2-125, 2-131, 2-171, 2-173, 2-181, 2-183, 2-185, 2-186, 2-189, 2-367, 2-458, 2-675, 8-8, 8-9, 8-31
2/6/06	0, Page Change 2	Page changes resulting from *Responses to Request for Additional Information #2*, Y/LF-761	All sections
3/20/06	0, Page Change 3	Page changes resulting from *Responses to Request for Additional Information #3*, Y/LF-764	1.38, 1.48, Appendix 1.4.1, 2-120, Table 6.4
5/8/06	0, Page Change 4	Added polyethylene bottles and nickel alloy cans as convenience containers for authorized HEU contents (CoC Revision 1)	Various pages in Chaps. 1, 2, 3 and 4.
8/21/06	0, Page Change 5	Revised equipment specifications for Kaolite and 277-4 neutron absorber (CoC Revision 3)	Appendices 1.4.4 and 1.4.5.
11/15/06	1	• Updated definition of pyrophoric uranium • Evaluated air transport • Revised criticality safety calculations to remove bias correct factors • Added a CSI option of 3.2 • Increased mass of off-gassing material allowed in containment vessel • Increased carbon concentration in HEU contents • Increased Np-237 concentration is HEU contents • Added uranium zirconium hydride and uranium carbide as contents (TRIGA fuel) • Revised equipment specifications for 277-4 neutron absorber (CoC Rev. 3)	All sections

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
3/29/07	1, Page Change 1	Updated definition of TRIGA fuel for air transport and added TRIGA-related criticality safety cases	Title pages, viii, xi, xx, 1-12, 1-13, 1-20, 6-30, 6-54, 6-64, 6-66, 6-87, 6-119, 6-240 to 6-286, 6-385 to end
5/31/07	1, Page Change 2	Revised SAR in response to RAIs dated May 9, 2007 in reference to CoC Rev. 4	Title pages, xiii, xx, Sect. 1 and Sect. 6
6/30/07	1, Page Change 3	Revised SAR in response to RAIs dated May 9, 2007 in reference to CoC Rev. 5	Title pages, table of contents, Sect. 1, and Sect. 7
7/31/07	1, Page Change 4	Removed oxidation as an option for treating pyrphoric uranium metal	Title pages, xx, 1-12, 1-201, 1-203, 1-212, 2-26, 7-4
8/28/07	1, Page Change 5	Modified TRIGA fuel definition to include fuel pellets with cladding	Title page, xx, 1-13, 1-17, 2-4, 6-29, 6-30a, 6-66c, 6-66d, 6-73, 6-87, 6-119a
10/10/07	1, Page Change 6	• Revised criticality safety calculations to remove bias correction factors	Table 6.2a and supporting calculations
		• Added a CSI option of 3.2	Table 6.2a and supporting calculations
		• Increased mass of off-gassing material in containment vessel to allow Teflon bottles	Figure 1.4, page 1-15, and Appendices 3.6.4 and 3.6.5
		• Increased carbon and moisture concentration in HEU contents	Pages 1-10 and 1-11, Table 6.2a and pages 6-31 and 6-52
		• Increased Np-237 concentration is HEU contents	Pages 5-1 to 5-4, and supporting calculations
		• Revised equipment specifications for 277-4 neutron absorber	Pages 1-83 and 1-97
		• Details of alloys of uranium in contents definition	Page 1-12
		• More precise specification of maximum fissile mass in calculations (changed from 36 kg to 35.2 kg)	Administrative change affecting many pages. Removed round-off. No new calculations.

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
3/6/08	2	• Add the following contents for ground transport: – HEU oxides (U_3O_8-Al and UO_2-Mg) – Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg) • Add the following contents for air transport: – HEU oxides (UO_2, UO_2-Mg, U_3O_8, and U_3O_8-Al) – Broken HEU bulk metal and uranium-aluminum alloy of unspecified geometric form – Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg)	1-10 through 1-17, 1-20, 1-22, 2-1, 2-2, 2-4, 2-5, 2-15, 2-17, 2-18, 2-25, 2-26, 3-15 through 3-17, 3-22, 3-147, 3-149, 3-151 through 3-155, 3-157 through 3-161, 4-2, 6-1, 6-2, 6-4, 6-5, 6-30 through 6-34, 6-51, 6-56, 6-69, 6-78, 6-83, 6-87, 6-92, 6-93, 6-95, 6-119, 6-128 through 6-130, 6-168, 6-282 through 6-286, 6-303 through 6-305, and 6-488 through 6-501.
6/19/08	2, Page Change 1	Revised SAR in response to RAIs dated April 28, 2008 for review of CoC 9315, Rev. 8	i, ix, x, xxii, 1-15, 3-15 through 3-17, 3-154, 3-161, 4-3, 6-1, 6-3, 6-3a, 6-3b, 6-4, 6-5, 6-9 through 6-12, 6-29, 6-30, 6-35, 6-36, 6-67, 6-69, 6-70, 6-73, 6-74, 6-80, 6-81, 6-84, 6-96, 6-97, 6-99, 6-101, 6-103, 6-103a, 6-103b, 6-104a through 6-104n, 6-167, 6-188 through 6-197, 6-316 through 6-320, 6-320a through 6-320d, 6-321 through 6-324, 6-351 through 6-354, 6-354a through 6-354b, 6-355 through 6-362, 6-503 through 6-642, and 6-644.

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
8/28/08	2, Page Change 2	Revised SAR in response to RAIs dated April 28, 2008, for review of CoC 9315, Rev. 8	i, vi, viii, xii, xxiii, xxiv, 1-10, 1-14 through 1-16, 1-22, 2-1, 2-25 through 2-28, 2-894, 3-15, 3-16, 3-165 through 3-290, 4-1, 4-2, 6-1 through 6-3, 6-20 through 6-28, 6-30 6-32 through 6-34, 6-68 through 6-70, 6-70a, 6-70b, 6-75 through 6-77, 6-77a, 6-77b, 6-78, 6-81 through 6-83, 6-85, 6-86, 6-101 through 6-103, 6-103a through 6-103j, 6-104, 6-123 through 6-126, 6-167 through 6-170, 6-177, 6-177a, 6-177b, 6-218a through 6-218f, 6-219 through 6-234, 6-303 through 6-305, 6-331, 6-332, 6-332a, 6-332b, 6-333, 6-394 through 6-398, 6-501, 6-502, 6-502a through 6-502dd
2/26/09	2, Page Change 3	Revised SAR in response to RAIs dated January 12, 2009, for review of CoC 9315, Rev. 9	i, viii, ix, xxiv, 1-7, 1-10, 1-12 through 1-16, 1-21 through 1-23, 1-29 1-31, 1-33, 1-35, 1-37, 1-39, 1-41, 1-135, 1-157, 1-177, 2-6, 2-9, 2-18, 2-36 through 2-38, 2-41 through 2-43, 2-53, 2-78, 2-80, 3-15 through 3-17, 3-27, 3-28, 3-30, 3-32, 3-39, 3-41, 3-147, 3-149 through 3-154, 3-154a, 3-154b, 3-155, 3-158 through 3-161, 3-165 through 3-174, 3-289 through 3-344, 4-2, 4-7, 4-9, 4-27 through 4-34, 6-5, 6-29, 6-30, 6-34, 6-73 through 6-86, 6-86a through 6-86d, 6-96, 6-103a through 6-103c, 6-104b, 6-104c, 6-123, 6-124, 6-168, 6-219 through 6-221, 6-221a, 6-221b, 6-222, 7-7, 7-8, 7-10

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
5/6/09	3	This revision was issued to match Amendment 9 of the CoC. • Remove the following contents for ground transport that were not reviewed by NRC: – HEU oxides (U_3O_8-Al and UO_2-Mg) – Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg) • Remove the following contents for air transport that were not reviewed by NRC: – HEU oxides (UO_2, UO_2-Mg, U_3O_8, and U_3O_8-Al) – Broken HEU bulk metal and uranium-aluminum alloy of unspecified geometric form – Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg)	All
4/14/10	3, Page Change 1	Revised SAR to do the following: • Add uranium oxide loading with a CSI value of 0.4 • Remove the 8-lb minimum payload weight • Add stainless-steel option for can spacers • Revise allowable weight changes for drum body and top plug • Revise Drawing M2E801580A005 to clarify marking requirements on drum hex nuts • Allow methods other than sieving for establishing minimum content sizes for pyrophoric purposes • Revise the purity of the cover gas used for pyrophoric material	i, x, xxv, 1-13, 1-16, 1-22, 1-23, 1-24, 1-27, 1-89 through 1-126, 1-126a, 1-126b, 1-135, 1-147, 1-178a, 1-178b, 1-221, 2-1, 2-14, 2-24, 6-1, 6-3, 6-4, 6-31, 6-35, 6-57, 6-67 through 6-69, 6-104, 6-105, 6-195, 6-717 through 6-892, 7-3, 7-4, 8-9, 8-10

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
4/14/10 (cont.)		**Note:** The NRC performed an acceptance review of Page Change 1 and generated several Requests for Supplemental Information (RSIs). Therefore, Page Change 1 will be superseded by Page Change 2, which incorporates the responses to the RSIs.	
7/22/10	3, Page Change 2	Reissue of Page Change 1 with RSI responses incorporated	i, x, xiv, xxv, xxvi, 1-13, 1-16, 1-22, 1-23, 1-24, 1-27, 1-89 through 1-126, 1-126a, 1-126b, 1-135, 1-147, 1-178a, 1-178b, 1-221, 2-1, 2-6, 2-14, 2-24, 2-26, 3-8a, 3-8b, 3-9, 3-10, 3-12, 3-13, 3-18, 3-23, 3-27, 3-27a, 3-27b, 3-100, 3-104, 3-105, 3-115, 3-116, 3-140, 6-1, 6-3, 6-4, 6-31, 6-35, 6-57, 6-67 through 6-69, 6-104, 6-105, 6-195, 6-717 through 6-892, 7-3, 7-4, 8-9, 8-10
1/27/11	3, Page Change 3	Revised SAR in response to RAIs dated October 12, 2010, for review of CoC 9315, Rev. 10	i, vi, xiv, xxvi, 2-6, 2-11, 2-36, 2-37, 2-41 through 2-43, 2-53, 2-78, 2-80, 3-16 through 3-18, 3-23, 3-27, 3-27a through 3-27d, 3-28, 3-30, 3-39, 3-147, 3-153 through 3-157, 3-160 through 3-164, 4-7, 4-9, 4-23, 4-25 through 4-34, 7-2, 7-6, 7-7, 7-11
3/3/11	4	This SAR revision matches Rev. 10 of the CoC. Incorporated Page Changes 1–3 and revised MNOP value in two additional locations (Sects. 1.2.3.5 and 3.5.1)	All

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
3/24/16	5	Revised the SAR for recertification, which included the following changes: • Updated contractor name • Increased the Teflon bottle mass for CVA 7 • Removed the carbon steel option for can spacers • Updated the revision of package engineering drawings, specifications, and regulatory requirements • Added Appendix 1.4.11 for EPDM containment vessel O-ring requirements • Made editorial corrections, as necessary	Front covers, i, iii, v, xxvii, xxviii, 1-1, 1-4, 1-6, 1-15, 1-16, 1-22 through 1-24, 1-27, 1-55 through 1-66, 1-137, 1-139, 1-149, 1-157, 1-167, 1-175, 1-177, 1-179, 1-229 through 1-247, 2-6, 2-11, 2-14, 2-17, 2-24, 2-26, 2-28 through 2-30, 2-35 through 2-37, 2-41 through 2-43, 2-53, 2-80, 2-893, 3-16 through 3-19, 3-29 through 3-31, 3-33, 3-35, 3-149, 3-151 through 3-159, 3-161 through 3-166, 3-349, 4-2, 4-7, 4-9, 4-23, 4-27 through 4-35, 5-39, 6-1, 6-30, 6-35, 6-891, 7-6, 7-13, 8-11, 8-12

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3. THERMAL EVALUATION

Design analysis, similarity, and full-scale testing (see Sect. 2) have demonstrated that the ES-3100 shipping package is in compliance with the applicable requirements of Title 10 Code of Federal Regulations (CFR) 71 (10 CFR 71) when used to ship highly enriched uranium (HEU) having a maximum gross weight up to 35.2 kg (77.60 lb). The ES-3100 has a nominal gross shipping weight that ranges from 146.88 kg (323.79 lb) to 187.81 kg (414.05 lb) for the empty and maximum weight containment vessel configurations shown in Table 2.8, respectively.

3.1 DISCUSSION

The drum assembly of the shipping package is defined as the structure that maintains the position of and provides the impact and thermal barrier surrounding the containment boundary. Preserving the location of the containment boundary within the packaging prevents reduction of the shielding and subcriticality effectiveness. The drum assembly for the ES-3100 consists of an internally flanged Type 304L stainless-steel 30-gal modified drum with two Type 304L stainless-steel inner liners, one filled with noncombustible cast refractory insulation and impact limiter and one filled with noncombustible cast neutron poison; a stainless-steel top plug with noncombustible cast refractory insulation; silicone rubber pads; silicon bronze hex-head nuts; and a stainless-steel lid and bottom (Drawing M2E801580A031, Appendix 1.4.8). The nominal weight of these components is 131.89 kg (290.76 lb).

The drum's diameters (inner diameter of 18.25 in.) and corrugations meet the requirements of Military Standard, MS27683-7. All other dimensions are controlled by Drawing M2E801580A004 (Appendix 1.4.8). Modifications to the drum from MS27683-7 include the following: (1) the overall height was increased; (2) the drum was fabricated with two false wire open ends; and (3) a 0.27-cm (12-gauge, 0.1046-in.)-thick concave cover was welded to the bottom false wire opening (Drawing M2E801508A005, Appendix 1.4.8). Four 0.795-cm (0.313-in.)-diam equally spaced holes are drilled in the top external sidewall to prevent a pressure buildup between the drum and inner liner. The holes are filled with a plastic plug to provide a moisture barrier for the cast refractory insulation during Normal Conditions of Transport (NCT). The cavity created by the inner liners is a three-tiered volume with a 37.52-cm (14.77-in.) inside diameter 13.26 cm (5.22 in.) deep, a 21.84-cm (8.60-in.) inside diameter 5.59 cm (2.20 in) deep, and an additional 15.85-cm (6.24-in.) inside diameter 78.31-cm (30.83 in.) deep. The volume between the drum and mid liner is filled with a lightweight noncombustible cast refractory material called Kaolite 1600 (Thermal Ceramics, Appendix 2.10.3). The material is composed of portland cement, water, and vermiculite and has an average density of 358.8 kg/m^3 (22.4 lb/ft^3). The procedure for manufacturing and documenting the insulation, JS-YMN3-801580-A003 (Appendix 1.4.4), is referenced on Drawings M2E801580A002 and M2E801580A008 (Appendix 1.4.8) for the drum body weldment and top plug weldment, respectively. The insulation has a maximum continuous service temperature limit of 871 °C (1600 °F) due to the presence of the vermiculite and portland cement. The volume between the most internal liner and the mid liner is filled with a noncombustible cast neutron poison (absorber) material called Cat 277-4 from Thermo Electron Corporation. The material is composed of aluminum, magnesium, calcium, boron, carbon, silicone, sulfur, sodium, iron, and water. The final mixture will have an average density of 1681.9 kg/m^3 (105 lb/ft^3). The procedure for manufacturing and documenting this material, JS-YMN3-801580-A005 (Appendix 1.4.5), is referenced on Drawing M2E801580A002 (Appendix 1.4.8). This neutron poison material has a maximum continuous service temperature limit of 150.0 °C (302 °F). At this temperature,

the moisture inside the Cat 277-4 material remains an integral part of the composite material, and moisture content loss is negligible.

The top plug is fabricated in accordance with Drawing M2E801580A008 (Appendix 1.4.8), with an overall diameter of 36.50 cm (14.37 in.) and a height of 13.41 cm (5.28 in.). The plug's rim, bottom sheet, and top sheet are fabricated from 0.15-cm (16-gauge, 0.0598-in.)-thick Type 304/304L stainless-steel sheet per ASME SA240. Four lifting inserts are welded into the top sheet for loading and unloading operations. The internal volume of the top plug assembly is filled with Kaolite 1600 in accordance with JS-YMN3-801580-A003 (Appendix 1.4.4).

Three silicone rubber pads complete the drum assembly. One pad is placed on the bottom of the most inward liner to support the containment vessel during transport. Another pad is placed on the top shelf of the mid liner to support the top plug during transport. The final plug is placed over the top of the containment vessel lid and closure nut interface. The pads are molded to the shapes as defined on Drawing M2E801580A009 (Appendix 1.4.8). The material is silicone rubber with a Shore A durometer reading of 22 ±5.

The ES-3100 package is evaluated for a maximum heat source of 0.4 W (Sect. 1.2.3.7); however, no active cooling systems or specific thermal design features are required. A lightweight cast refractory insulation between the inner liner and the drum provides thermal protection of the contents from external heat sources.

Thermal criteria are applied to the package in accordance with 10 CFR 71 for NCT and Hypothetical Accident Conditions (HAC). These requirements specify that each package design provide containment, shielding, and criticality safety at temperatures ranging from −40 to 38°C (−40 to 100°F) with full insolation. Also, in accordance with *Packaging and Transportation of Radioactive Material* [10 CFR 71.43(g)], a package must be designed, constructed, and prepared for transport so that in still air at 38°C (100°F) and in the shade no accessible surface of a package would have a temperature exceeding 50°C (122°F) in a nonexclusive use shipment, or 85°C (185°F) in an exclusive use shipment. In addition, each package will experience no significant reduction in effectiveness as the result of being exposed to a thermal radiation environment of 800°C (1475°F) for 30 min with an emissivity coefficient of at least 0.9.

The maximum internal pressures and thermal stresses for both NCT and HAC are discussed and calculated (Sects. 3.4.2, 3.4.3, and 3.5.3) for use in the structural evaluation. The calculated pressures are well below the design pressures of the package components, and the effect of thermal stresses on the package is negligible (Sects. 2.6.1.2 and 2.7.4.2).

Compliance with the NCT thermal requirements is shown by analysis (Sect. 3.3.1). Since the components to be shipped have a maximum decay heat load of 0.4 W, a thermal analysis was conducted for the ES-3100 package (Appendix 3.6.2). Since the decay heat load is so meager, the maximum predicted temperature of the entire package, while stored at 38°C (100°F) in the shade, is 38.52°C (101.33°F) [Table 3.5]. The analysis shows that no accessible surface of the package would have a temperature exceeding 50°C (122°F). Therefore, the requirement of 10 CFR 71.43(g) would be satisfied. If the package is exposed to solar radiation at 38°C (100°F) in still air, the conservatively calculated temperatures at the top of the drum, center of containment vessel lid, and on the containment vessel near the O-ring sealing surfaces are 117.72°C (243.89°F), 87.81°C (190.06°F), and 87.72°C (189.90°F), respectively (Sect. 3.4.2 and Table 3.6). For conservatism, the O-ring sealing surface temperature will be assumed to be 87.81°C (190.06°F). At the low-temperature range and neglecting

decay heating, the package components would stabilize at −40°C (−40°F), which is within normal operating limits of the packaging materials (Sect. 2.2).

Five full-scale packages were subjected to the HAC thermal test following the drop, crush and puncture tests (Sects. 2.7.1 through 2.7.3). All of these test packages were exposed to a thermal radiation environment of >800°C (>1475°F) for well over 30 min in a furnace. Other temperature conditions before and during the thermal testing are given in *Test Report of the ES-3100 Package* for the furnace, test packages, and package supports. The maximum temperature recorded during the tests on the external surface of any of the containment vessels was 127.2°C (261°F). This containment vessel maximum temperature reading is the highest value shown in Table 3.9. This temperature was recorded on Test Units-4 and -5 on the containment vessel sealing lid. The maximum internal temperature adjacent to the O-rings was 116°C (241°F). Temperature adjustments are then added to the containment vessel's maximum recorded temperature to correct for measuring accuracy, internal decay heating, insolation heating during cool down, location of crush plate damage, neutron poison substitution, thermal capacitance difference between mockups and actual contents, and material density variations. Detailed discussion of each temperature adjustment is provided in Sect. 3.5.3. Since Test Unit-5 was tested with a mock-up that represented the lightest proposed content, no temperature correction was needed for mass differences. The containment vessel's recorded temperature values were lower on all other test units, which consisted of much heavier mock-up contents.

3.1.1 Design Features

The drum assembly for the ES-3100 consists of an internally flanged Type 304L stainless-steel 30-gal modified drum with two Type 304L stainless-steel inner liners, one filled with noncombustible cast refractory insulation and impact limiter and one filled with noncombustible cast neutron poison; a stainless-steel top plug with noncombustible cast refractory insulation, silicone rubber pads, silicon bronze hex-head nuts, and a stainless-steel lid and bottom (Drawing M2E801580A031, Appendix 1.4.8). The drum's diameter (inner diameter of 18.25 in.) and corrugations meet the requirements of Military Standard, MS27683-7. All other dimensions are controlled by Drawing M2E801580A004 (Appendix 1.4.8). Modifications to the drum from MS27683-7 include the following: (1) the overall height was increased; (2) the drum was fabricated with two false wire open ends; and (3) a 0.27-cm (12-gauge, 0.1046-in.)-thick concave cover was welded to the bottom false wire opening (Drawing M2E801508A005, Appendix 1.4.8). Four 0.795-cm (0.313-in.)-diam equally spaced holes are drilled in the top external sidewall to prevent a pressure buildup between the drum and inner liner. The cavity created by the inner liners is a three-tiered volume with a 37.52-cm (14.77-in.) inside diameter 13.26 cm (5.22 in.) deep, a 21.84-cm (8.60-in.) inside diameter 5.59 cm (2.20 in) deep, and an additional 15.85-cm (6.24-in.) inside diameter 78.31 cm (30.83 in.) deep. Drum and inner liner wall thickness is 0.15 cm (16 gauge, 0.0598 in.).

The volume between the drum and mid liner is filled with a lightweight noncombustible cast refractory material called Kaolite 1600 (Thermal Ceramics, Appendix 2.10.3). The material is composed of portland cement, water, and vermiculite and has an average density of 358.8 kg/m^3 (22.4 lb/ft^3). The procedure for manufacturing and documenting the insulation, JS-YMN3-801580-A003 (Appendix 1.4.4), is referenced on Drawings M2E801580A002 and M2E801580A008 (Appendix 1.4.8) for the drum body weldment and top plug weldment, respectively.

The volume between the most internal liner and the mid liner is filled with a noncombustible cast neutron poison material from Thermo Electron Corporation (Cat 277-4). The material is composed of aluminum, magnesium, calcium, boron, carbon, silicone, sulfur, sodium, iron, and water. This mixture will have an average density of 1681.9 kg/m^3 (105 lb/ft^3). The procedure for manufacturing and documenting this material, JS-YMN3-801580-A005 (Appendix 1.4.5), is referenced on Drawing M2E801580A002 (Appendix 1.4.8).

Three silicone rubber pads complete the drum assembly. One pad is placed on the bottom of the most inward liner to support the containment vessel during transport. Another pad is placed on the top shelf of the mid liner to support the top plug during transport. The final plug is placed over the top of the containment vessel lid and closure nut assembly. Pads are molded to the shapes as defined on Drawing M2E801580A009 (Appendix 1.4.8) using silicone rubber with a Shore A durometer reading of 22 ± 5.

3.1.2 Content's Decay Heat

The maximum decay heat and radioactivity of the contents (Sect. 4) are based on a maximum of 35.2 kg of HEU in the isotopic and mass distribution at fabrication as shown in Table 3.1.

Table 3.1. Isotopic mass and weight percent for the HEU contents [a]

Nuclide	Weight percent	Mass (g)
^{232}U	0.000004	0.001408
^{233}U	0.600000	211.200000
^{234}U	2.000000	704.000000
^{235}U	54.895996	19,323.390592
^{236}U	40.000000	14,080.000000
^{238}U	0.000000	0.000000
Transuranic	0.004000	1.408000
^{237}Np	2.500000	880.000000
Total	100.000000	35,200.000000

[a] Weight percent values of individual isotopes are those that generate the largest activity within the allowable ranges presented in Sect. 1.2.3.

Using the ORIGEN-S program for determining decay heat values and predicting the isotopic decay patterns from 0 to 70 years from original fabrication, the following decay heat loads are predicted and shown in Table 3.2. Isotopic mass distribution has been calculated in Sect. 4 and shown in Table 2 of Appendix 4.6.1. The maximum decay heat load is rounded up from 0.3954 to 0.4 W, and 0.4 W is used in subsequent analyses for temperature predictions. Contributions from the transuranics and ^{237}NP at the bottom of Table 3.2 remain constant for the time period evaluated. The decay heat per gram value used for the transuranic isotopes was an average of the decay heat values for ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu and ^{241}Am.

Table 3.2. Decay heat for 35.2 kg of HEU content (watts)

Decay Heat (Watts per gram)	Isotope	DECAY TIME								
		0 years	5 years	10 years	20 years	30 years	40 years	50 years	60 years	70 years
1.7920E-02	Pb-210	0.0000E+00	2.5360E-12	1.9556E-11	1.4635E-10	4.5799E-10	1.0156E-09	1.8547E-09	3.0280E-09	4.5294E-09
2.6280E+03	Pb-212	0.0000E+00	4.7733E-05	5.3284E-05	4.9583E-05	4.4773E-05	4.0703E-05	3.6781E-05	3.3302E-05	3.0157E-05
2.8650E+02	Bi-210	0.0000E+00	2.5008E-11	1.9280E-10	1.4339E-09	4.5175E-09	1.0003E-08	1.8312E-08	2.9848E-08	4.4570E-08
2.4500E+05	Bi-212	0.0000E+00	4.2147E-04	4.6984E-04	4.3875E-04	3.9729E-04	3.5929E-04	3.2578E-04	2.9503E-04	2.6705E-04
1.4420E+02	Po-210	0.0000E+00	3.4726E-10	2.6806E-09	1.9902E-08	6.2751E-08	1.3911E-07	2.5486E-07	4.1327E-07	6.1939E-07
5.1130E+03	Rn-222	0.0000E+00	7.2355E-09	2.8942E-08	1.1555E-07	2.5990E-07	4.6077E-07	7.1995E-07	1.0331E-06	1.4075E-06
1.8230E+03	Ra-223	0.0000E+00	1.1907E-08	4.5091E-08	1.6416E-07	3.3642E-07	5.4602E-07	7.8557E-07	1.0463E-06	1.3210E-06
5.4700E+03	Ra-224	0.0000E+00	8.6260E-04	9.6272E-04	9.0111E-04	8.1639E-04	7.3783E-04	6.6774E-04	6.0459E-04	5.4760E-04
2.8380E+01	Ra-225	0.0000E+00	5.9942E-07	1.2947E-06	2.5895E-06	3.8842E-06	5.1730E-06	6.4737E-06	7.7325E-06	9.0512E-06
2.8600E-02	Ra-226	0.0000E+00	6.3026E-09	2.5170E-08	1.0068E-07	2.2553E-07	4.0071E-07	6.2624E-07	9.0009E-07	1.2243E-06
1.5200E-02	Ra-228	0.0000E+00	3.1241E-15	1.0485E-14	3.1241E-14	5.4992E-14	7.9599E-14	1.0442E-13	1.2946E-13	1.5449E-13
2.0290E+03	Ac-225	0.0000E+00	3.4282E-05	6.2564E-05	1.2513E-04	1.8769E-04	2.4983E-04	3.1239E-04	3.7453E-04	4.3709E-04
3.5000E-02	Ac-227	0.0000E+00	1.6165E-10	6.1483E-10	2.2253E-09	4.5656E-09	7.4402E-09	1.0687E-08	1.4204E-08	1.7924E-08
1.7460E+04	Ac-228	0.0000E+00	4.3760E-13	1.4701E-12	4.3760E-12	7.6949E-12	1.1161E-11	1.4652E-11	1.8143E-11	2.1659E-11
1.1250E+03	Th-227	0.0000E+00	1.2065E-08	4.5869E-08	1.6630E-07	3.4130E-07	5.5434E-07	7.9781E-07	1.0609E-06	1.3413E-06
2.6850E+01	Th-228	0.0000E+00	8.2427E-04	9.1879E-04	8.5830E-04	7.7889E-04	7.0327E-04	6.3900E-04	5.7850E-04	5.2178E-04
6.0870E-03	Th-229	0.0000E+00	3.8569E-05	5.5025E-05	1.0992E-04	1.6456E-04	2.1984E-04	2.7384E-04	3.2912E-04	3.8440E-04
5.8220E-04	Th-230	0.0000E+00	5.6970E-06	1.1353E-05	2.2747E-05	3.4100E-05	4.5494E-05	5.6970E-05	6.8037E-05	7.9513E-05
5.7940E+02	Th-231	0.0000E+00	4.5568E-05	4.5568E-05	4.5568E-05	4.5568E-05	4.5568E-05	4.5568E-05	4.5568E-05	4.5568E-05
2.6590E-09	Th-232	0.0000E+00	5.4281E-12	1.0894E-11	2.1787E-11	3.2681E-11	4.3425E-11	5.4281E-11	6.5512E-11	7.6368E-11
9.5900E+00	Th-234	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.4390E-03	Pa-231	0.0000E+00	1.3457E-07	2.6942E-07	5.3940E-07	8.0910E-07	1.0760E-06	1.3457E-06	1.6154E-06	1.8823E-06
5.2710E+01	Pa-233	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
7.0800E-01	U-232	9.9686E-04	9.4702E-04	9.0216E-04	8.1743E-04	7.3967E-04	6.6989E-04	6.0709E-04	5.4927E-04	4.9744E-04
2.8070E-04	U-233	5.9280E-02	5.9278E-02	5.9278E-02	5.9275E-02	5.9273E-02	5.9270E-02	5.9268E-02	5.9265E-02	5.9263E-02
1.7910E-04	U-234	1.2609E-01	1.2609E-01	1.2609E-01	1.2609E-01	1.2608E-01	1.2608E-01	1.2608E-01	1.2607E-01	1.2607E-01
6.0000E-08	U-235	1.1594E-03	1.1594E-03	1.1594E-03	1.1594E-03	1.1594E-03	1.1594E-03	1.1594E-03	1.1594E-03	1.1594E-03
2.0000E-06	U-236	2.4656E-02	2.4656E-02	2.4656E-02	2.4656E-02	2.4656E-02	2.4656E-02	2.4656E-02	2.4656E-02	2.4656E-02
8.5111E-09	U-238	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.1580E-01	transuranic	1.6306E-01	1.6306E-01	1.6306E-01	1.6306E-01	1.6306E-01	1.6306E-01	1.6306E-01	1.6306E-01	1.6306E-01
2.0100E-05	Np-237	1.7688E-02	1.7688E-02	1.7688E-02	1.7688E-02	1.7688E-02	1.7688E-02	1.7688E-02	1.7688E-02	1.7688E-02
	Total watts	3.9293E-01	3.9517E-01	3.9542E-01	3.9530E-01	3.9514E-01	3.9500E-01	3.9489E-01	3.9480E-01	3.9473E-01

3.1.3 Summary Tables of Temperatures

3.1.3.1 NCT summary tables

The ES-3100 shipping container has been conservatively evaluated empty of all containment vessel internal components for NCT. Prior to the change of neutron absorber from BoroBond4 to Cat 277-4, parameters, such as Kaolite 1600 density, BoroBond4 thermal conductivity, and decay heat loads, were varied to encompass the range of potential variations in material properties. The available thermal conductivity information on BoroBond4 was limited to moderate temperatures in the range of -3.89°C (25°F) to 40°C (104°F) [Eagle-Picher presentation excerpts sent to Gerry Byington via e-mail from Jim Hall on March 12, 2004]. Using the available thermal conductivity data for BoroBond4, thermal analyses for NCT and HAC have been performed and are documented in DAC-PKG-801699-A001 (summarized in Appendix 3.6.1). Nodal locations for temperatures presented are shown in Fig. 3.1. Based on the results reported in the above document and shown in Tables 3.3 and 3.4, it was determined that the higher temperatures occurred when the lowest density of the Kaolite 1600 was used. Therefore, subsequent analysis using the proposed Cat 277-4 neutron absorber during NCT uses a Kaolite 1600 density of 19.4 lb/ft^3. The results for the steady state condition at 38°C (100°F) in the shade, and the transient condition of applying solar insolation are shown in Tables 3.5 and 3.6 for the proposed configuration (package with Cat 277-4 neutron absorber).

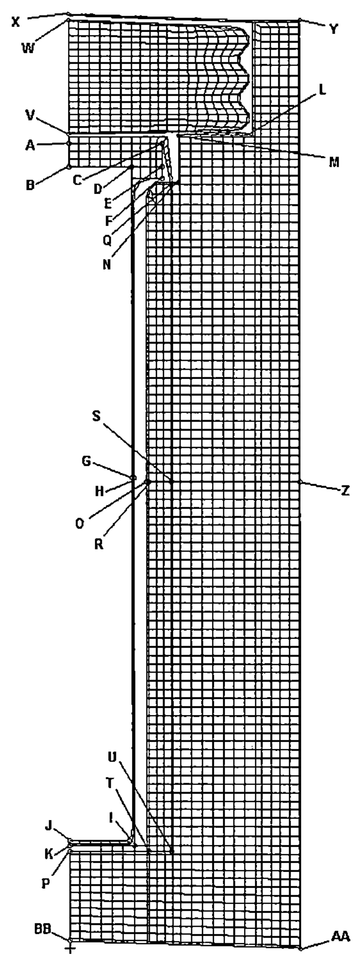


Fig. 3.1. MSC.Patran axisymmetric finite element model of the ES-3100 shipping container with BoroBond 4—nodal locations of interest (elements representing air not shown for clarity).

Table 3.3. Maximum "quasi steady-state" temperatures during NCT for the ES-3100 shipping container with various content heat loads—Kaolite density of 19.4 lb/ft^3 and BoroBond4

Node[a]	Location	Maximum "quasi steady-state" temperature, °C (°F)			
		0 W	0.4 W	20 W	30 W
A	CV lid, top, center	88.30 (190.95)	88.62 (191.52)	103.84 (218.91)	111.35 (232.42)
B	CV lid, bottom, center	88.28 (190.90)	88.60 (191.48)	103.90 (219.03)	111.45 (232.62)
C	CV lid, top, outer	88.32 (190.97)	88.63 (191.54)	103.61 (218.50)	111.00(231.80)
D	CV flange at interface, inner[b]	88.24 (190.83)	88.56 (191.41)	103.87 (218.96)	111.42 (232.55)
E	CV flange at interface, outer[b]	88.25 (190.84)	88.56 (191.41)	103.77 (218.78)	111.27 (232.28)
F	CV flange, bottom, outer	88.24 (190.82)	88.55 (191.39)	103.75 (218.75)	111.25 (232.24)
G	CV shell, mid-height, inner	83.04 (181.47)	83.61 (182.50)	110.50 (230.89)	123.46 (254.23)
H	CV shell, mid-height, outer	83.04 (181.47)	83.61 (182.50)	110.49 (230.88)	123.45 (254.21)
I	CV bottom, outer	83.36 (182.04)	83.75 (182.74)	102.58 (216.64)	111.99 (233.59)
J	CV bottom, center, inner	88.37 (182.07)	83.76 (182.77)	102.70 (216.86)	112.17 (233.91)
K	CV bottom, center, outer	88.37 (181.07)	83.76 (182.77)	102.69 (216.84)	112.15 (233.87)
L	Drum liner, plug cavity, outer	98.72 (209.70)	98.80 (209.85)	102.63 (216.73)	104.58 (220.24)
M	Drum liner, plug cavity, inner	94.43 (201.97)	94.58 (202.24)	101.92 (215.46)	105.65 (222.16)
N	Drum liner, CV flange cavity, outer	89.43 (192.97)	89.63 (193.34)	99.83 (211.70)	105.01 (221.02)
O	Drum liner, CV cavity, mid-height, inner	83.12 (181.62)	83.43 (182.18)	98.63 (209.54)	106.40 (223.52)
P	Drum liner, CV cavity, bottom, inner	83.62 (182.52)	83.96 (183.13)	100.36 (212.65)	108.60 (227.48)
Q	Borobond4, top, outer	88.82 (191.88)	89.04 (192.27)	99.65 (211.38)	105.04 (221.07)
R	Borobond4, mid-height, inner	83.12 (181.62)	83.43 (182.18)	98.63 (209.53)	106.39 (223.51)
S	Borobond4, mid-height, outer	83.03 (181.46)	83.33 (182.00)	97.91 (208.23)	105.36 (221.65)
T	Borobond4, bottom, inner	83.55 (182.39)	83.85 (182.93)	98.58 (209.45)	106.03 (222.86)
U	Borobond4, bottom, outer	83.51 (182.31)	83.80 (182.83)	97.82 (208.07)	104.90 (238.82)
V	Drum plug liner, bottom, center	112.01 (233.62)	112.05 (233.69)	113.95 (237.11)	114.90 (238.82)
W	Drum plug liner, top, center	92.09 (197.77)	92.31 (198.16)	102.93 (217.27)	108.26 (226.87)
X	Drum lid, top, center	118.01 (244.42)	118.03 (244.45)	118.77 (245.79)	119.15 (246.47)
Y	Drum lid, top, outer	107.33 (225.19)	107.34 (225.22)	108.22 (226.80)	108.67 (227.60)
Z	Drum, mid-height, outer	92.27 (198.08)	92.30 (198.14)	93.81 (200.86)	94.58 (202.24)
AA	Drum bottom, outer	91.70 (197.06)	91.74 (197.13)	93.61 (200.49)	94.54 (202.18)
BB	Drum bottom, center	88.82 (191.88)	88.93 (192.07)	93.84 (200.91)	96.30 (205.35)

[a] See Fig. 3.1.
[b] Approximate location of the CV O-rings.

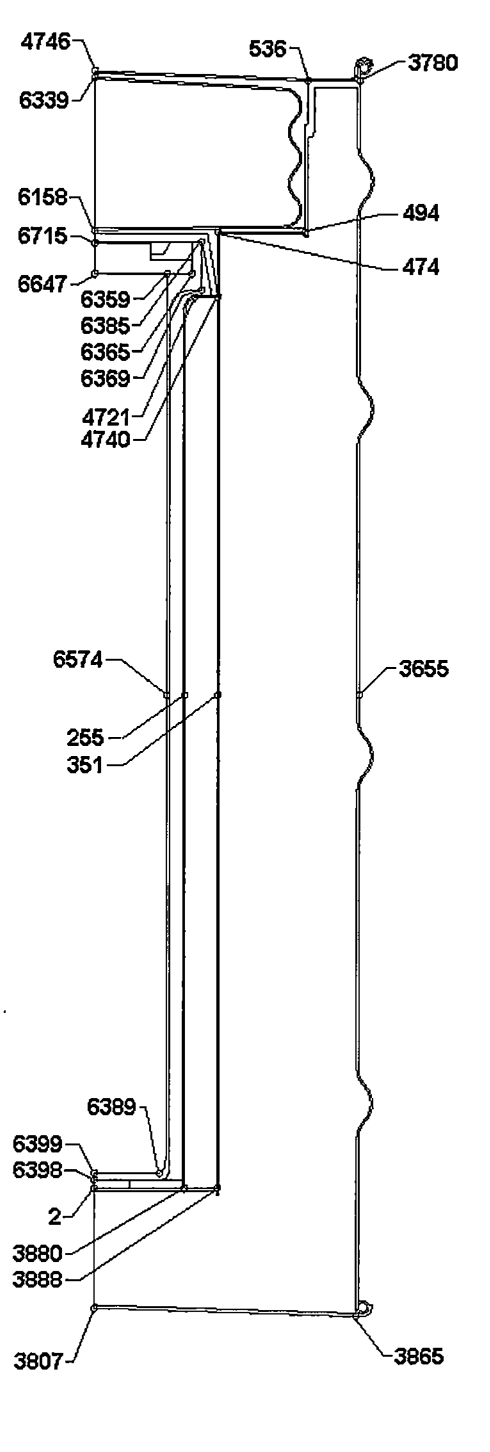
Table 3.4. Maximum "quasi steady-state" temperatures during NCT for the ES-3100 shipping container with various content heat loads—Kaolite density of 30 lb/ft³ and BoroBond4

Node[a]	Location	Maximum "quasi steady-state" temperature, °C (°F)			
		0 W	0.4 W	20 W	30 W
A	CV lid, top, center	86.56 (187.81)	86.88 (188.38)	102.98 (215.74)	109.59 (229.26)
B	CV lid, bottom, center	86.56 (187.80)	86.88 (188.38)	102.16 (215.90)	109.71 (229.47)
C	CV lid, top, outer	86.54 (187.78)	86.86 (188.34)	101.89 (215.41)	109.31 (228.75)
D	CV flange at interface, inner[b]	86.47 (187.64)	86.79 (188.21)	102.09 (215.77)	109.67 (229.40)
E	CV flange at interface, outer[b]	86.44 (187.59)	86.76 (188.16)	102.00 (215.61)	109.53 (229.15)
F	CV flange, bottom, outer	86.42 (187.56)	86.74 (188.13)	101.99 (215.58)	109.51 (229.12)
G	CV shell, mid-height, inner	81.52 (178.74)	82.09 (179.76)	109.01 (228.21)	121.98 (251.57)
H	CV shell, mid-height, outer	81.52 (178.74)	82.09 (179.76)	109.00 (228.19)	121.97 (251.55)
I	CV bottom, outer	81.32 (178.37)	81.71 (179.08)	100.57 (213.02)	109.99 (229.99)
J	CV bottom, center, inner	81.37 (178.47)	81.77 (179.18)	100.73 (213.31)	110.21 (230.38)
K	CV bottom, center, outer	81.37 (178.47)	81.77 (179.18)	100.72 (213.29)	110.19 (230.34)
L	Drum liner, plug cavity, outer	97.74 (207.93)	97.82 (208.07)	101.65 (214.96)	103.59 (218.47)
M	Drum liner, plug cavity, inner	92.91 (199.23)	93.06 (199.50)	100.40 (212.72)	104.13 (219.43)
N	Drum liner, CV flange cavity, outer	87.69 (189.84)	87.90 (190.21)	98.09 (208.57)	103.27 (217.43)
O	Drum liner, CV cavity, mid-height, inner	81.30 (178.35)	81.61 (178.90)	96.82 (206.27)	104.13 (219.43)
P	Drum liner, CV cavity, bottom, inner	81.52 (178.74)	81.86 (179.35)	98.30 (208.94)	106.56 (223.80)
Q	Borobond4, top, outer	87.36 (189.25)	87.58 (189.64)	98.19 (208.74)	103.57 (218.43)
R	Borobond4, mid-height, inner	81.30 (178.35)	81.61 (178.90)	98.81 (206.26)	104.58 (220.24)
S	Borobond4, mid-height, outer	81.37 (178.46)	81.66 (178.99)	96.24 (205.23)	103.69 (218.64)
T	Borobond4, bottom, inner	81.67 (179.01)	81.98 (179.56)	96.73 (206.12)	104.19 (219.55)
U	Borobond4, bottom, outer	81.78 (179.21)	82.07 (179.72)	96.11 (205.00)	103.23 (217.81)
V	Drum plug liner, bottom, center	111.30 (232.35)	111.34 (232.42)	113.25 (235.85)	114.21 (237.57)
W	Drum plug liner, top, center	90.70 (195.26)	90.92 (195.66)	101.53 (214.76)	106.87 (224.36)
X	Drum lid, top, center	117.74 (243.93)	117.75 (243.96)	118.50 (245.30)	118.88 (245.98)
Y	Drum lid, top, outer	107.04 (224.68)	107.06 (224.71)	107.94 (226.29)	108.39 (227.10)
Z	Drum, mid-height, outer	91.86 (197.36)	91.90 (197.41)	93.42 (200.15)	94.18 (201.53)
AA	Drum bottom, outer	91.00 (195.79)	91.04 (195.86)	92.92 (199.26)	93.87 (200.96)
BB	Drum bottom, center	87.21 (188.97)	87.31 (189.15)	92.26 (198.07)	94.74 (202.54)

[a] See Fig. 3.1.
[b] Approximate location of the CV O-rings.

Table 3.4a. ES-3100 shipping container finite element model nodal map

Node map[a]

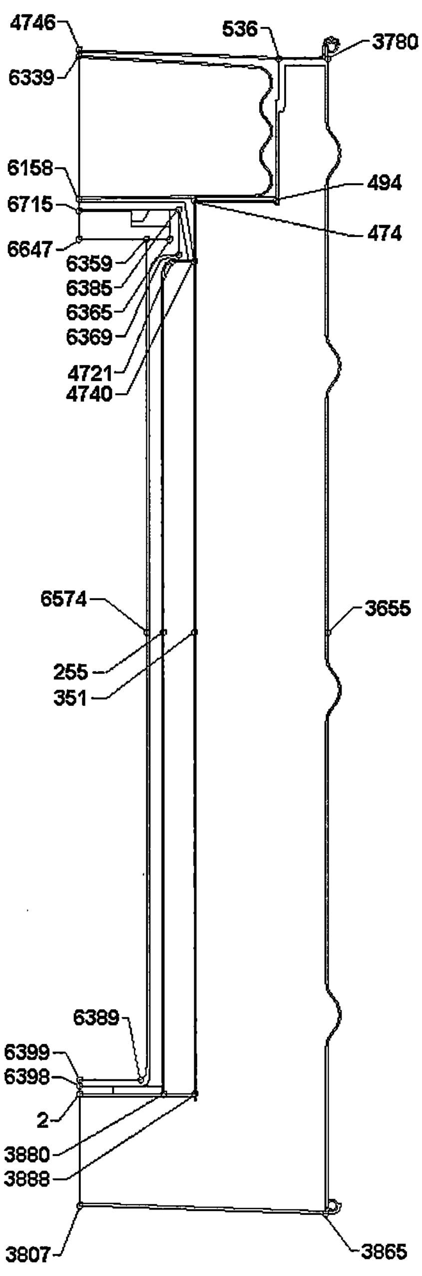


Node location and coordinates (in.)			
No.	Location description	r	z
2	Drum liner, CV cavity, bottom, inner	0.000	4.505
255	Drum liner, CV cavity, mid-height, outer	3.180	21.528
351	Cat. 277-4, mid-height, outer	4.300	21.528
474	Drum liner, plug cavity, inner	4.300	37.535
494	Drum liner, plug cavity, outer	7.325	37.525
536	Drum liner, flange, inner	7.385	42.755
3655[c]	Drum, mid-height, outer	9.185	21.528
3780[c]	Drum lid, top, outer	9.185	42.755
3807[c]	Drum, bottom, center, outer	0.000	0.320
3865[c]	Drum, bottom, edge, outer	9.185	0.008
3880	Cat. 277-4, bottom, inner	3.178	4.505
3888	Cat. 277-4, bottom, outer	4.300	4.505
4721	Cat. 277-4, top, inner	3.500	35.275
4740	Cat. 277-4, top, outer	4.300	35.275
4746[c]	Drum lid, top, center, outer	0.000	43.065
6158	Top plug liner, bottom, center, outer	0.000	37.579
6339	Top plug liner, top, center, outer	0.000	42.859
6359[b]	CV flange at lid interface, inner	2.530	36.075
6365[b]	CV flange at lid interface, outer	3.425	36.075
6369	CV flange, bottom, outer	3.750	35.525
6385	CV lid, top, outer	3.750	37.175
6389	CV bottom edge, inner	2.310	5.025
6398	CV bottom, center, outer	0.000	4.775
6399	CV bottom, center, inner	0.000	5.025
6574	CV shell, mid-height, inner	2.530	21.528
6647	CV lid, bottom, center	0.000	36.075
6715	CV lid, top, center	0.000	37.135

[a] See Figs. 8 through 11 in Appendix 3.6.2 for details of node locations.
[b] Approximate location of the CV O-ring.
[c] These nodes are at the accessible surfaces of the package (i.e., the drum, drum lid, and drum bottom plate).

Table 3.5. ES-3100 shipping container maximum steady-state temperatures with Cat 277-4 (100°F ambient temperature, no insolation)

Node map[a]

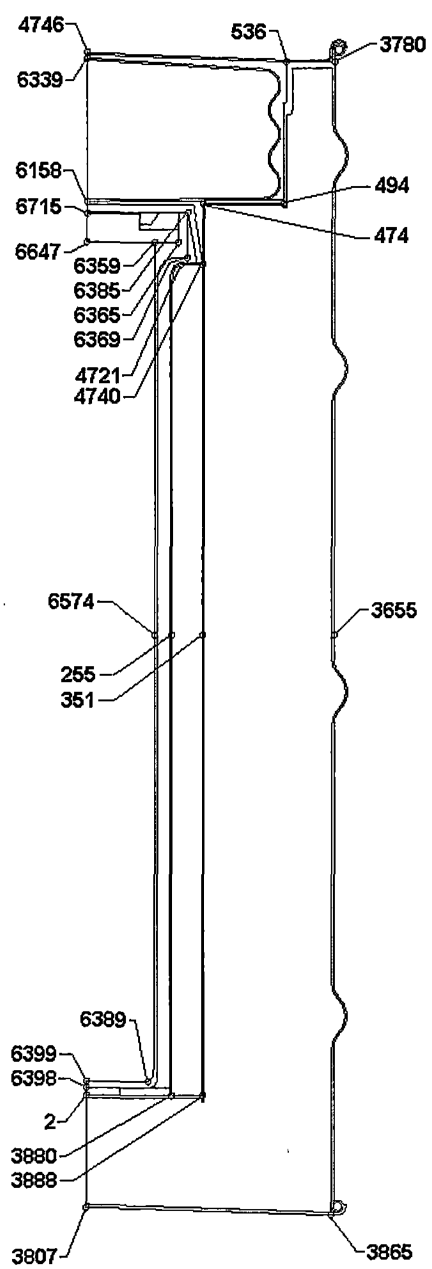


Node coordinates (in.)			Maximum "quasi steady-state" temperature (°F)		
No.	r	z	0.4 W	20 W	30 W
2	0.000	4.505	100.83	134.54	150.15
255	3.180	21.528	100.75	131.57	146.21
351	4.300	21.528	100.71	129.45	142.87
474	4.300	37.535	100.46	117.90	125.67
494	7.325	37.525	100.32	110.87	115.19
536	7.385	42.755	100.21	105.50	107.19
3655[c]	9.185	21.528	100.28	107.58	109.92
3780[c]	9.185	42.755	100.21	105.29	106.89
3807[c]	0.000	0.320	100.43	114.39	120.08
3865[c]	9.185	0.008	100.32	108.97	111.97
3880	3.178	4.505	100.74	130.48	144.23
3888	4.300	4.505	100.71	128.60	141.42
4721	3.500	35.275	100.59	124.08	134.90
4740	4.300	35.275	100.57	122.92	133.15
4746[c]	0.000	43.065	100.20	104.99	106.43
6158	0.000	37.579	100.57	123.14	133.42
6339	0.000	42.859	100.25	107.42	110.04
6359[b]	2.530	36.075	100.80	133.51	148.56
6365[b]	3.425	36.075	100.79	133.33	148.28
6369	3.750	35.525	100.79	133.27	148.20
6385	3.750	37.175	100.78	132.85	147.58
6389	2.310	5.025	100.97	141.27	160.06
6398	0.000	4.775	100.96	140.91	159.55
6399	0.000	5.025	100.96	140.94	159.60
6574	2.530	21.528	101.33	157.70	183.56
6647	0.000	36.075	100.80	133.56	148.63
6715	0.000	37.135	100.79	133.40	148.40

[a] See Table 3.4a and Figs. 8–11 in Appendix 3.6.2 for details of node locations.
[b] Approximate location of the CV O-ring.
[c] These nodes are at the accessible surfaces of the package (i.e., the drum, drum lid, and drum bottom plate).

Table 3.6. ES-3100 shipping container maximum "quasi steady-state" temperatures during NCT with various content heat loads and Cat 277-4 (100°F ambient temperature, with insolation)

Node map[a]



Node coordinates (in.)			Maximum "quasi steady-state" temperature (°F)			
No.	r	z	0 W	0.4 W	20 W	30 W
2	0.000	4.505	180.59	181.23	210.15	224.69
255	3.180	21.528	179.33	179.93	207.32	221.43
351	4.300	21.53	179.59	180.14	204.73	217.27
474	4.300	37.54	198.88	199.20	212.72	219.58
494	7.325	37.53	207.40	207.56	214.4	217.87
536	7.385	42.76	226.44	226.49	228.31	229.24
3655	9.185	21.528	198.09	198.15	200.81	202.16
3780	9.185	42.755	223.47	223.51	225.13	225.95
3807	0.000	0.320	190.48	190.70	199.84	204.43
3865	9.185	0.008	195.87	195.97	199.91	201.90
3880	3.178	4.505	180.72	181.28	206.65	219.52
3888	4.300	4.505	181.03	181.55	205.08	217.01
4721	3.500	35.275	189.45	189.90	209.53	219.47
4740	4.300	35.275	190.56	190.98	209.37	218.68
4746	0.000	43.065	243.86	243.89	245.32	246.03
6158	0.000	37.579	198.42	198.84	217.12	226.32
6339	0.000	42.859	233.98	234.06	237.32	238.95
6359[b]	2.530	36.075	189.28	189.90	217.07	230.51
6365[b]	3.425	36.075	189.27	189.88	216.88	230.23
6369	3.750	35.525	189.23	189.85	216.79	230.12
6385	3.750	37.175	189.39	190.00	216.57	229.72
6389	2.310	5.025	179.94	180.70	215.75	233.27
6398	0.000	4.775	179.99	180.76	215.52	232.92
6399	0.000	5.025	179.99	180.76	215.55	232.96
6574	2.530	21.528	179.27	180.35	229.19	252.87
6647	0.000	36.075	189.40	190.02	217.24	230.72
6715	0.000	37.14	189.44	190.06	217.14	230.54

[a] See Table 3.4a and Figs. 8–11 in Appendix 3.6.2 for details of node locations.
[b] Approximate location of the CV O-ring.

3.1.3.2 HAC temperature summary tables

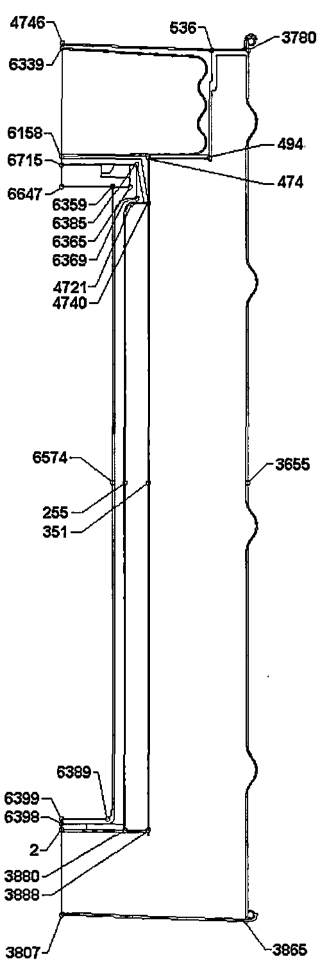
In order to predict the maximum temperature for the packaging components during HAC, a transient thermal analyses was performed on the finite element model of the ES-3100 shipping container (undamaged configuration) to simulate HAC as prescribed by 10 CFR 71.73(c)(4). A 30-min fire of 800°C (1475°F) was simulated by applying natural convection and radiant exchange boundary conditions to all external surfaces of the drum (assuming the drum is in a horizontal orientation) with content heat loads of 0, 0.4, 20, and 30 W. There are no heat flux boundary conditions simulating insolation applied to the model before and during the 30-minute fire. The initial temperature distribution within the package having content heat loads of 0.4, 20, and 30 W is obtained from their respective steady-state analyses (Table 3.5). The initial temperature distribution within the package having no content heat load (0 W) is assumed to be at a uniform temperature equal to the ambient temperature of 38°C (100°F). The content heat load is simulated by applying a uniform heat flux to the internal surfaces of the elements representing the containment vessel.

Following the 30-min fire transient analyses, 48-h cool-down transient thermal analyses are performed using the temperature distribution at the end of the fire as the initial temperature distribution. During post-fire cool-down, natural convection and radiant exchange boundary conditions are applied to all external surfaces of the drum (assuming the drum is in a horizontal orientation). Additionally, cases are analyzed in which insolation is included during the post-fire cool-down. For the cases in which insolation is applied to the model during cool-down, insolation is applied during the first 12-h period following the 30-min fire, and then alternated (off, then on) as was done for NCT.

Based on the previous analysis of the ES-3100 package using BoroBond4 (Appendix 3.6.1), it was noted that using the low-end density of Kaolite 1600 results in higher containment vessel temperatures than using the high-end density of Kaolite 1600. For this reason, the NCT and HAC thermal analyses were run using a density of 19.4 lb/ft^3. Similarly, the low-end density of the Cat 277-4 material (100 lb/ft^3) was also used in these analyses. However, while using these low-end densities will result in higher temperatures to the containment vessel, using the high-end densities for these two materials will result in higher temperature differences from the baseline case. Thus, HAC runs are also made for heat loads of 0, 0.4, 20, and 30 W using a Kaolite 1600 density of 30 lb/ft^3 and a Cat 277-4 density of 110 lb/ft^3.

The maximum temperatures calculated for the ES-3100 shipping container for HAC are summarized in Table 3.7 for the analyses using a Kaolite 1600 density of 19.4 lb/ft^3 and a Cat 277-4 density of 100 lb/ft^3. The maximum temperatures calculated for the ES-3100 shipping container for HAC are summarized in Table 3.8 for the analyses using a Kaolite 1600 density of 30 lb/ft^3 and a Cat 277-4 density of 110 lb/ft^3. The thermal analyses that use the low-end density values for Kaolite 1600 and Cat 277-4 achieve the higher package temperatures (see Table 3.7).

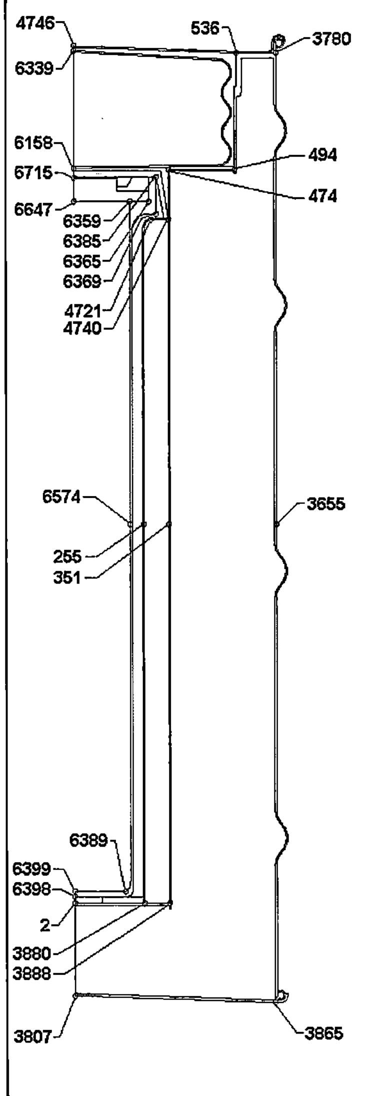
Table 3.7. ES-3100 shipping container HAC maximum temperatures (Kaolite 1600 density of 19.4 lb/ft^3 and Cat 277-4 density of 100 lb/ft^3)



Node map [a]	Node coordinates (in.)			HAC maximum temperature (°F)							
				0 W		0.4 W		20 W		30 W	
	No.	r	z	Insolation during cool-down?		Insolation during cool-down?		Insolation during cool-down?		Insolation during cool-down?	
				No [b]	Yes	No	Yes	No	Yes	No	Yes
	2	0.000	4.505	225.5	232.1	226.2	232.8	255.5	261.7	269.5	275.7
	255	3.180	21.528	194.5	212.5	195.2	213.2	223.8	241.3	237.8	255.3
	351	4.300	21.528	195.8	211.9	196.4	212.5	222.3	237.8	234.8	250.3
	474	4.300	37.535	392.9	395.0	393.2	395.4	407.6	409.7	414.2	416.3
	494	7.325	37.525	671.2	672.0	671.4	672.3	679.1	680.0	682.5	683.3
	536	7.385	42.755	1380.4	1380.4	1380.4	1380.4	1380.9	1380.9	1381.1	1381.1
	3655	9.185	21.528	1457.8	1457.8	1457.8	1457.8	1458.0	1458.0	1458.1	1458.1
	3780	9.185	42.755	1427.8	1427.8	1427.9	1427.9	1428.1	1428.1	1428.2	1428.2
	3807	0.000	0.320	1454.5	1454.5	1454.5	1454.5	1454.9	1454.9	1455.0	1455.0
	3865	9.185	0.008	1470.1	1470.1	1470.1	1470.1	1470.1	1470.1	1470.2	1470.2
	3880	3.178	4.505	230.6	236.4	231.2	237.0	257.1	262.5	269.4	274.8
	3888	4.300	4.505	236.9	241.7	237.5	242.3	261.5	266.1	272.9	277.5
	4721	3.500	35.275	245.7	252.8	246.2	253.3	266.8	273.8	276.6	283.6
	4740	4.300	35.275	258.4	263.5	258.8	264.0	278.1	283.1	287.1	292.1
	4746	0.000	43.065	1448.0	1448.0	1448.0	1448.0	1448.2	1448.2	1448.3	1448.3
	6158	0.000	37.579	308.7	311.6	309.1	312.0	328.3	331.2	337.3	340.2
	6339	0.000	42.859	1335.1	1335.1	1335.2	1335.2	1336.4	1336.4	1336.9	1336.9
	6359 [c]	2.530	36.075	236.7	247.6	237.3	248.3	266.2	276.6	279.8	289.9
	6365 [c]	3.425	36.075	236.6	247.6	237.3	248.3	266.0	276.4	279.5	289.7
	6369	3.750	35.525	236.5	247.6	237.2	248.2	265.8	276.2	279.3	289.5
	6385	3.750	37.175	237.3	248.2	237.9	248.8	266.1	276.4	279.4	289.5
	6389	2.310	5.025	219.0	227.4	219.9	228.2	255.3	263.1	272.2	279.9
	6398	0.000	4.775	219.7	227.9	220.5	228.7	255.6	263.3	272.5	280.0
	6399	0.000	5.025	219.7	227.9	220.5	228.7	255.6	263.3	272.5	280.0
	6574	2.530	21.528	196.1	214.9	197.3	216.0	246.7	263.8	269.9	286.5
	6647	0.000	36.075	237.2	248.0	237.9	248.6	266.8	277.0	280.4	290.4
	6715	0.000	37.135	237.4	248.1	238.0	248.8	266.8	277.0	280.4	290.4

[a] See Table 3.4a and Figs. 8–11 in Appendix 3.6.2 for details of node locations.
[b] Baseline case for ΔT comparisons.
[c] Approximate location of the CV O-ring.

Table 3.8. ES-3100 shipping container HAC maximum temperatures (Kaolite 1600 density of 30 lb/ft^3 and Cat 277-4 density of 110 lb/ft^3)

Node map [a]	Node coordinates (in.)			HAC maximum temperature (°F)							
				0 W		0.4 W		20 W		30 W	
	No.	r	z	Insolation during cool-down?		Insolation during cool-down?		Insolation during cool-down?		Insolation during cool-down?	
				No [b]	Yes	No	Yes	No	Yes	No	Yes
	2	0.000	4.505	209.9	218.9	210.6	219.6	240.4	248.8	254.6	262.8
	255	3.180	21.528	185.5	207.7	186.1	208.4	215.1	236.6	229.3	250.6
	351	4.300	21.528	185.6	207.4	186.2	208.0	212.3	233.3	225.0	245.9
	474	4.300	37.535	342.9	345.5	343.3	345.9	358.1	360.7	365.0	367.5
	494	7.325	37.525	596.3	597.4	596.5	597.6	604.7	605.8	608.3	609.4
	536	7.385	42.755	1366.8	1366.8	1366.8	1366.8	1367.4	1367.4	1367.6	1367.6
	3655	9.185	21.528	1452.8	1452.8	1452.8	1452.8	1453.0	1453.0	1453.1	1453.1
	3780	9.185	42.755	1420.8	1420.8	1420.8	1420.8	1421.0	1421.0	1421.2	1421.2
	3807	0.000	0.320	1449.4	1449.4	1449.4	1449.4	1449.8	1449.8	1449.9	1449.9
	3865	9.185	0.008	1467.3	1467.3	1467.3	1467.3	1467.4	1467.4	1467.4	1467.4
	3880	3.178	4.505	213.1	221.4	213.7	222.0	240.0	247.9	252.5	260.3
	3888	4.300	4.505	217.0	224.4	217.6	225.0	242.1	249.1	253.8	260.7
	4721	3.500	35.275	228.0	237.5	228.5	238.0	249.7	259.0	259.7	269.0
	4740	4.300	35.275	236.5	243.8	236.9	244.3	256.7	263.9	266.0	273.2
	4746	0.000	43.065	1441.8	1441.8	1441.8	1441.8	1442.0	1442.0	1442.1	1442.1
	6158	0.000	37.579	277.3	281.8	277.8	282.3	297.5	302.0	306.7	311.2
	6339	0.000	42.859	1299.5	1299.5	1299.6	1299.6	1301.1	1301.1	1301.7	1301.7
	6359 [c]	2.530	36.075	225.1	237.3	225.8	237.9	254.7	266.1	268.3	279.6
	6365 [c]	3.425	36.075	225.0	237.3	225.7	237.9	254.5	266.0	268.1	279.3
	6369	3.750	35.525	224.9	237.2	225.6	237.8	254.3	265.8	267.9	279.2
	6385	3.750	37.175	225.5	237.6	226.2	238.3	254.6	266.1	268.0	279.2
	6389	2.310	5.025	205.3	215.9	206.2	216.8	242.0	251.9	259.2	268.9
	6398	0.000	4.775	205.8	216.3	206.7	217.1	242.2	252.0	259.2	268.8
	6399	0.000	5.025	205.8	216.3	206.7	217.1	242.2	252.0	259.3	268.8
	6574	2.530	21.528	187.8	209.1	189.0	210.2	238.9	258.4	262.4	281.3
	6647	0.000	36.075	225.6	237.7	226.3	238.3	255.2	266.5	268.9	280.0
	6715	0.000	37.135	225.8	237.8	226.4	238.4	255.2	266.5	268.9	280.0

[a] See Table 3.4a and Figs. 8–11 in Appendix 3.6.2 for details of node locations.
[b] Baseline case for ΔT comparisons.
[c] Approximate location of the CV O-ring.

Table 3.9. Maximum HAC temperatures recorded on the test packages' interior surfaces

Temperature patch location [a]	ES-3100 Test Unit				
	1	2	3	4	5
	°C (°F)	°C (°F)	°C (°F)	°C (°F)	°C (°F)
Top plug bottom	149 (300)	163 (325)	177 (350)	177 (350)	177 (350)
Inner liner					
Flange step wall	135 (275)	163 (325)	135 (275)	135 (275)	135 (275)
BoroBond4 step	107 (225)	135 (275)	107 (225)	177 (350)[b]	121 (250)
Adjacent to CV body wall high	99 (210)	99 (210)	99 (210)	99 (210)	104 (219)
Adjacent to CV body wall middle	99 (210)	93 (199)	116 (241)	93 (199)	99 (210)
Bottom flat portion	104 (219)	99 (210)	99 (210)	127 (261)	110 (230)
Containment boundary					
Lid (external top)	116 (241)	110 (230)	116 (241)	127 (261)	127 (261)
Lid (internal)	104 (219)	104 (219)	110 (230)	110 (230)	116 (241)
Flange (external)	116 (241)	110 (230)	110 (230)	116 (241)	121 (250)
Flange (internal)	104 (219)	99 (210)	116 (241)[b]	104 (219)	116 (241)
Body wall mid height	99 (210)	88 (190)	99 (210)	82 (180)	93 (199)
Bottom end cap (center)	99 (210)	99 (210)	88 (190)	110 (230)	99 (210)
Mock-up					
Side top	82 (180)	77 (171)	77 (171)	77 (171)	99 (210)
Side middle	77 (171)	77 (171)	77 (171)	77 (171)	93 (199)
Side bottom	77 (171)	77 (171)	77 (171)	77 (171)	88 (190)

[a] Refer to figures for exact locations and to Tables 5.3 through 5.7 in ORNL/NTRC-013, Vol. 1 for recorded values.
[b] Temperature indicating patch may have been damaged due to impact with surrounding structure.

3.1.4 Summary Tables of Maximum Pressures

3.1.4.1 Maximum NCT pressures

Table 3.10 summarizes the results from Appendix 3.6.4 in which the pressure of the containment vessel when subjected to the tests and conditions of NCT per 10 CFR 71.71 has been determined for the most restrictive containment vessel arrangements (CVAs) shipped in the ES-3100. The most restrictive CVAs are those in which the void volume inside the containment vessel is minimized based on content volumes and those CVAs that carry the largest mass of items that offgas at the predicted temperatures during NCT. Several convenience container heights are proposed for shipment (Fig. 1.4). Shipping configurations will use these containers in any configuration as long as it does not exceed the HEU weight limit and form and does not exceed the height constraint of the containment vessel. However, in order to determine the worst-case shipping configuration, the arrangements that minimize the void volume inside the containment vessel are analyzed as follows:

1. one shipment will contain six cans with external dimensions of 10.8 cm (4.25 in.) diameter by 12.38 cm (4.875 in.) high cans;

2. one shipment will contain five cans with external dimensions of 10.8 cm (4.25 in.) diameter by 12.38 cm (4.875 in.) high cans and three can spacers;

3. one shipment will contain three cans with external dimensions of 10.8 cm (4.25 in.) diameter by 22.23 cm (8.75 in.) high and two can spacers;

4. one shipment will contain three cans with external dimensions of 10.8 cm (4.25 in.) diameter by 25.4 cm (10 in.) high;

5. one shipment will contain six nickel cans with external dimensions of 7.62 cm (3.00 in.) diameter by 12.07 cm (4.75 in.) high;

6. one shipment will contain three polyethylene bottles with external dimensions of 12.54 cm (4.94 in.) diameter by 22.1 cm (8.7 in.) high; and

7. one shipment will contain three Teflon bottles (~400 g Teflon each) with external dimensions of 11.91 cm (4.69 in.) diameter by 23.88 cm (9.4 in.) high, limited to 1600 g of offgassing material.

Table 3.10. Total pressure inside the containment vessel at 87.81°C (190.06°F) [a]

CVA	n_a [b] (lb-mole)	n_v [b] (lb-mole)	n_{po} [b] (lb-mole)	n_{bo} [b] (lb-mole)	n_{tf} [b] (lb-mole)	n_{H2} [b] (lb-mole)	n_{O2} [b] (lb-mole)	n_T [b] (lb-mole)	P_T (psia)
2	5.7148E-04	1.8626E-05	0.0000E+00	0.0000E+00	0.0000E+00	3.1895E-05	1.5948E-05	6.3795E-04	19.238
7	4.5819E-04	2.4843E-04	0.0000E+00	0.0000E+00	2.7025E-05	2.5572E-05	1.2786E-05	7.7200E-04	29.036

[a] This assumes that the internal convenience cans, polyethylene or Teflon FEP bottles, and Cat 277-4 spacer cans are not sealed.

[b] n_a –molar quantity of dry air in the gas mixture;
n_v –molar quantity of water vapor in the gas mixture due primarily from efflorescence;
n_{po} –molar quantity of gas due to offgassing of the silicone rubber pads;
n_{bo} –molar quantity of gas due to offgassing of the polyethylene bags, bottles, and lifting sling;
n_{tf} –molar quantity of gas due to offgassing of the Teflon bottles;
n_{H2} –molar quantity of hydrogen gas due to radiolysis of water;
n_{O2} –molar quantity of oxygen gas due to radiolysis of water;
n_T –total molar quantity in the gas mixture.

These arrangements are shown in Fig. 1.4. To determine the ES-3100's maximum normal operating pressure, the following assumptions have been used in the calculations:

1. The HEU contents are loaded into convenience cans, and convenience cans are placed inside the containment vessel at standard temperature (T_{amb}) and pressure (P_t) [25°C (77°F) and 101.35 kPa (14.7 psia)] with air at a maximum relative humidity of 100%;

2. The convenience cans and bottles are assumed to not be sealed to maximize the void volume inside the containment vessel;

3. Convenience can and bottle geometry does not change during pressure increase inside containment vessel;

4. If metal convenience cans are used, the total amount of polyethylene bagging and lifting slings is limited to 500 g per containment vessel shipping arrangement;

5. The mass of offgassing material (polyethylene bagging or bottles, Teflon bottles, silicone pads, lifting slings) is assumed to be 1600 g for the offgassing evaluation of CVA 7. Teflon bottles (~400 g Teflon each) contribute ~1200 g total, therefore the other offgassing material is limited to 400 g; and

6. Containment vessel arrangements that utilize closed convenience cans with a diameter greater than 10.8 cm (4.25 in.) will not contain any materials that off gas at the temperatures associated with Normal Conditions of Transport (NCT).

The offgassing material limits identified in assumptions 4 and 5 have been established based on the needs of shippers. All configurations except CVA 7 are limited to 500 g of polyethylene in the form of bags, slings, and/or bottles. The upper limit of 1600 g of offgassing material is a combination of three Teflon bottles (400 g Teflon per bottle) and a 400 g allowance for the other offgassing material. These offgassing material limits have been used in calculations pertaining to containment vessel pressure, radioactive material leakage criteria, and criticality control. Therefore, portions of the safety basis for this shipping package have been based on these material limits.

NUREG-1609, Sect. 4.5.2.3, requires the applicant to demonstrate that any combustible gases generated in the package during a period of one year do not exceed 5% (by volume) of the free gas volume in any confined region of the package. No credit should be taken for getters, catalysts, or other recombination devices. The analysis conducted in Appendix 3.6.7 evaluates the different packaging arrangements for the generation of hydrogen gas due to the radiolysis of water vapor, free water, interstitial water, polyethylene bags, and polyethylene or Teflon bottles. By limiting the mass and the material composition as shown in Appendix 3.6.7, the combustible gas concentration limit stated in NUREG-1609 is not exceeded. These limits are further discussed and shown in Tables 1.3 and 1.3a. Getters, catalysts, or other recombination devices are not employed in any of the containment vessel packaging arrangements. The analysis conducted in Appendix 3.6.4 predicts the maximum normal operating pressure inside the containment vessel for the various packaging arrangements and masses discussed previously. This appendix also includes the hydrogen gas generation predicted by Appendix 3.6.7.

3.1.4.2 Maximum HAC pressures

Table 3.11 summarizes the results from Appendix 3.6.5 in which the pressure of the containment vessel when subjected to the tests and conditions of HAC per 10 CFR 71.73 has been determined for the most restrictive CVAs shipped in the ES-3100. The shipping configurations discussed in Sect. 3.1.4.1 are evaluated for HAC. To determine the maximum pressure generated inside the ES-3100's containment vessel due to HAC conditions, the following assumptions have been used in the calculations:

1. The initial pressure inside the containment vessel is the maximum normal operating pressure shown in Table 3.10 for each CVA at standard temperature [25°C (77°F)];

2. The convenience cans and bottles are assumed to not be sealed in order to maximize the void volume inside the containment vessel;

3. Convenience can and bottle geometry does not change during pressure increase inside containment vessel or because of damage from compliance testing;

4. If metal convenience cans are used, the total amount of polyethylene bagging and lifting slings is limited to 500 g per containment vessel shipping arrangement;

5. The mass of offgassing material (polyethylene bagging or bottles, Teflon bottles, silicone pads, lifting slings) is assumed to be 1600 g for the offgassing evaluation of CVA 7. Teflon bottles (~400 g Teflon each) contribute ~1200 g total, therefore the other offgassing material is limited to 400 g; and

6. Containment vessel arrangements that utilize closed convenience cans with a diameter greater than 10.8 cm (4.25 in.) will not contain any materials that off gas at the temperatures associated with Hypothetical Accident Conditions (HAC).

Table 3.11. Total pressure inside the containment vessel at 123.85°C (254.93°F) [a]

CVA	n_{MNOP} [b] (lb-mole)	n_{po} [b] (lb-mole)	n_{bo} [b] (lb-mole)	n_{tf} [b] (lb-mole)	n_{r-H2} (lb-mole)	n_{r-O2} (lb-mole)	n_{wv} [b] (lb-mole)	n_T [b] (lb-mole)	P_T (psia)
2	7.7228E-04	1.7302E-05	3.1529E-04	0.0000E+00	3.1895E-05	1.5948E-05	0.0000E+00	1.1527E-03	38.236
7	9.3452E-04	0.0000E+00	2.5223E-04	2.7025E-05	2.5572E-05	1.2786E-05	7.8472E-04	2.0369E-03	84.255

[a] This assumes that the internal convenience cans, polyethylene or Teflon FEP bottles, and Cat 277-4 spacer cans are not sealed.

[b] n_{MNOP} –molar quantity of the gas mixture at maximum normal operating pressure at standard temperature [25°C (77°F)];
n_{po} –molar quantity of gas due to offgassing of the silicone rubber pads;
n_{bo} –molar quantity of gas due to offgassing of the polyethylene bags, bottles, and lifting sling;
n_{tf} –molar quantity of gas due to offgassing of the Teflon bottles;
n_{r-H2} –molar quantity of hydrogen gas due to radiolysis of water;
n_{r-O2} –molar quantity of oxygen gas due to radiolysis of water;
n_{wv} –molar quantity of water vapor due to efflorescence of UNX crystals; and
n_T –total molar quantity in the gas mixture.

The offgassing material limits identified in assumptions 4 and 5 have been established based on the needs of shippers. All configurations except CVA 7 are limited to 500 g of polyethylene in the form of bags, slings, and/or bottles. The upper limit of 1600 g of offgassing material is a combination of three Teflon bottles (400 g Teflon per bottle) and a 400 g allowance for the other offgassing material. These offgassing material limits have been used in calculations pertaining to containment vessel pressure, radioactive material leakage criteria, and criticality control. Therefore, portions of the safety basis for this shipping package have been based on these material limits.

3.2 SUMMARY OF THERMAL PROPERTIES OF MATERIALS

3.2.1 Material properties

Thermal properties at various temperatures for the stainless steel used in the fabrication of the drum, noncombustible cast refractory (Kaolite 1600), noncombustible neutron poison (BoroBond 4 or Cat 277-4), silicone rubber pads, and air are listed in Table 3.12. Properties used to evaluate thermal stresses due to differences in coefficient of thermal expansion are listed in Table 3.13.

3.2.2 Component Specifications

Component specifications are listed in Tables 3.14 and 3.15.

3.3 GENERAL CONSIDERATIONS

Thermal evaluation of the package design for NCT was performed by analysis. Evaluation of the package design for HAC was performed by a combination of testing and analysis.

3.3.1 Evaluation by Analysis

A description of the method and calculations used to perform the thermal and thermal stress analyses of the package for NCT and HAC is presented in detail in Appendices 3.6.1, 3.6.2 and 3.6.3.

Table 3.12. Thermal properties of the materials used in the thermal analysis

Material	Temperature (°F)	Thermal conductivity (Btu/h-in.-°F)	Density (lbm/in.^{3})	Specific heat (Btu/lbm-°F)	Emissivity
Stainless steel	-279.67	0.443 [a]	0.285 [a]	0.065 [a]	0.22 [a]
	-99.67	0.607	–	0.096	–
	260.33	0.799	–	0.123	–
	620.33	0.953	–	0.133	–
	980.33	1.088	–	0.139	–
	1340.33	1.223	–	0.146	–
	1700.33	1.348	–	0.153	–
	2240.33	1.526	–	0.163	–
Kaolite 1600	68	0.0093 [b]	0.011 [c]	0.2 [d]	–
	212	0.0091	–	–	–
	392	0.0081	–	–	–
	572	0.0072	–	–	–
	1112	0.0082	–	–	–
Neutron poison (Cat 277-4)	-31	0.0457 [e]	0.0579 [f]	0.125 [e]	–
	73.4	0.0485	–	0.186	–
	140	0.04	–	0.239	–
	212	0.0295	–	0.242	–
	302	0.0305	–	0.291	–
Neutron poison (BoroBond4)	25	0.0450 [g]	0.0683 [g]	0.2160 [g]	-
	77	0.0576	-	-	-
	100	0.0632	-	-	-
	104	0.0642	-	-	-
Silicone rubber	–	0.0161 [h]	0.047 [h]	0.300 [h]	1.0 [i]
Air	-9.67	1.074×10^{-3} [a]	$4.064 \times 10 - 5$ [a,j]	0.240 [a]	–
	80.33	1.266×10^{-3}	–	0.241	–
	170.33	1.445×10^{-3}	–	0.241	–
	260.33	1.628×10^{-3}	–	0.242	–
	350.33	1.796×10^{-3}	–	0.244	–
	440.33	1.960×10^{-3}	–	0.246	–
	530.33	2.114×10^{-3}	–	0.248	–
	620.33	2.258×10^{-3}	–	0.251	–
	710.33	2.393×10^{-3}	–	0.254	–
	800.33	2.523×10^{-3}	–	0.257	–
	890.33	2.644×10^{-3}	–	0.260	–
	980.33	2.759×10^{-3}	–	0.263	–
	1070.33	2.870×10^{-3}	–	0.265	–
	1160.33	2.985×10^{-3}	–	0.268	–
	1250.33	3.096×10^{-3}	–	0.270	–
	1340.33	3.212×10^{-3}	–	0.273	–
	1520.33	3.443×10^{-3}	–	0.277	–

[a] F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 2nd edition, John Wiley & Sons, New York, 1985.

[b] Hsin Wang, *Thermal Conductivity Measurements of Kaolite*, ORNL/TM-2003/49 (Appendix 2.10.3).

[c] Based on a baked density of 19.4 lbm/ft^3 (0.011 lbm/in^3). Specification JS-YMN3-801580-A003 (Appendix 1.4.4) requires a baked density of 22.4 ± 3 lbm/ft^3. Using a lower value for the Kaolite density results in higher temperatures on the containment vessel because the heat capacity of the Kaolite is minimized-allowing more heat to flow to the containment vessel; therefore, the thermal analyses are performed using a low-end density of 19.4 lbm/ft^3. The HAC analyses also consider a high-end density of 30 lbm/ft^3.

[d] FAX communication from J. W. Breuer of Thermal Ceramics, Engineering Department, August 11, 1995.

[e] Hsin Wang, *Thermophysical Properties of Heat Resistant Shielding Material*, ORNL/TM-2004/290 (Appendix 2.10.4). Specific heat values are presented in MJ/m^3-K in ORNL/TM-2004/290-converted to mass-based units using a density of 105 lbm/ft^3.

[f] Based on a cured density of density of 100 lbm/ft^3 (0.0579 lbm/in^3). B. F. Smith and G. A. Byington, *Mechanical Properties of 277-4*, Y/DW-1987, January 19, 2005 (Appendix 2.10.4), presents a range of measured densities between approximately 100 and 110 lbm/ft^3 for Catalog No. 277-4. Therefore, in order to minimize the heat capacity of the material and allow more heat to be transferred to the containment vessel, the lower-bound value is used. The HAC analyses also consider a high-end density of 110 lbm/ft^3.

[g] E-mail communication with presentation attachment, Jim Hall (Eagle-Picher) to Jerry Byington (BWXT Y-12), 3/12/2004.

[h] THERM 1.2, thermal properties database by R. A. Bailey.

[i] Conservatively modeled as 1.0.

[j] Constant density value evaluated at 100°F.

Table 3.13. Mechanical properties of the materials used in the static stress analyses

Material	Temperature (°F)	Modulus of Elasticity (psi)	Poisson's Ratio	Density (lbm/in.^{3})	Coefficient of thermal expansion (in./in./°F)
Stainless steel	-40	28.6×10^6 [a]	0.29 [b]	0.285 [d]	8.2×10^{-6} [e]
	100	28.14×10^6	—	—	8.6×10^{-6}
	200	27.6×10^6	—	—	8.9×10^{-6}
	300	27.0×10^6	—	—	9.2×10^{-6}
Kaolite	—	29,210 [c]	0.01 [c]	0.013 [f]	5.04×10^{-6} [g]
Neutron absorber (Cat 277-4)	-40	1.991×10^6 [h]	0.33 [h]	0.0608 [h]	7.056×10^{-6} [i]
	-4	—	—	—	7.222×10^{-6}
	32	—	—	—	7.222×10^{-6}
	70	0.984×10^6	0.28	—	—
	100	0.403×10^6	0.25	—	—
	104	—	—	—	7.000×10^{-6}
	140	—	—	—	6.444×10^{-6}
	176	—	—	—	5.778×10^{-6}
	212	—	—	—	5.389×10^{-6}
	248	—	—	—	5.056×10^{-6}
	284	—	—	—	4.889×10^{-6}
	302	—	—	—	4.833×10^{-6}

[a] *ASME Boiler and Pressure Vessel Code*, Sect. II, Part D, Subpart 2, Tables TE-1, B column, and TM-1.
[b] R. A. Bailey, *Strain - A Material Database*, Lawrence Livermore National Laboratory, 1989.
[c] The Poisson's Ratio of Kaolite is assumed to be a small value of 0.01 (Appendix 2.10.2).
[d] F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 2nd edition, John Wiley & Sons, New York, 1985.
[e] *Metallic Materials and Elements for Aerospace Vehicle Structures*, MIL-HDBK-5H, May 1986.
[f] Specification JS-YMN3-801580-A003 (Appendix 1.4.4) requires a baked density of 22.4 ± 3 lbm/ft^3.
[g] E-mail communication, Ken Moody (Thermal Ceramics, Inc.) to Paul Bales (BWXT Y-12), December 9, 2004.
[h] B. F. Smith and G. A. Byington, *Mechanical Properties of 277-4*, Y/DW-1987, January 19, 2005 (Appendix 2.10.4).
[i] W. D. Porter and H. Wang, *Thermophysical Properties of Heat Resistant Shielding Material*, ORNL/TM-2004/290, Oak Ridge National Laboratory, Oak Ridge, Tenn., December 2004 (Appendix 2.10.4). Coefficient of thermal expansion at each temperature taken as the maximum of values for Runs #2, #3, and #5.

Table 3.14. Packaging material technical specifications

Component	Specifications
	Drum assembly
Drum washers	1.375 OD × 0.812 ID × 0.25-in. thick, 300 Series stainless steel
Drum threaded weld studs	⅝-11 × ⅞ long, fabricated per ASME SA-193, using Type 304/304L stainless-steel per ASME 479
Drum hex nuts	⅝-11 UNC-2B, silicon bronze C65100, ASTM F-467
Drum lid weldment	Modified 30-gal, 16-gauge (MS27683-61) lid, type 304 or 304L stainless steel; and a 11-gauge thick sheet, type 304 or 304L stainless steel, ASME SA-240
Drum weldment	Modified 30-gal, 16-gauge (MS27683-7), type 304 or 304L stainless steel, ASME SA-240, manufactured per Drawing M2E801580A004 (Appendix 1.4.8)
Drum plugs	Nylon plastic plug, Micro Plastic, Inc.
	Impact limiter, insulation enclosure, neutron absorber, and drum packing material
Insulation and impact limiter (not removable)	Lightweight cast refractory insulation, Kaolite 1600, 358.8 kg/m^3 (22.4 lb/ft^3) density, cast in stainless-steel shells in the drum and top plug
Neutron absorber	Cat 277-4, 1681.9 +240/-80 kg/m^3 (105 +15/- 5 lb/ft^3) density
Top plug (removable)	Type 304 or 304L stainless steel, ASME SA-240 (body), ASME SA-79 (lifting inserts),
Inner liners	Type 304 or 304L stainless steel, ASME SA-240 (body), ASME SA-79 (modified angle)
Aluminum tape	
Silicone pads	Silicone rubber, 22 ± 5 Shore A, color black/gray
	Containment boundary
Containment vessel plug	Part # 04-2126, Modified VCO threaded plug, brass
Containment vessel swivel hoist ring	3052T56, Swivel hoist ring, alloy steel (not used for shipment)

Table 3.14. Packaging material technical specifications

Component	Specifications
Containment vessel	Method 1: Type TP304L stainless steel ASME SA-312 (welded or seamless pipe body); type F304L, stainless steel, ASME SA-182 (flange, and end cap); type 304, stainless steel, ASME SA-479 (sealing lid), Nitronic 60 SST per ASME SA-479, UNS-S21800 (closure nut) Method 2: Type F304L stainless ASME SA-182 (body, flange, and end cap); type 304, stainless steel, ASME SA-479 (sealing lid), Nitronic 60 SST per ASME SA-479, UNS-S21800 (closure nut) All components per *ASME Boiler and Pressure Vessel Code*, Sect. II, Part D, Table 2A
Containment vessel O-rings	Elastomer, ethylene propylene, normal service temperature range of −40 to 150°C, Specification M 3BA712A14B13F17 in ASTM D-2000, per OO-PP-986, Rev. D
Containment vessel lid assembly retaining ring	Part # WSM-400-S02, type 302 stainless steel
Containment vessel O-ring lubricant	Clear dimethyl siloxane polymer
Containment vessel closure nut lubricant	Krytox #240AC
Containment vessel body dowel pins	0.2501/0.2503 OD × 0.50 long, 18-8 stainless steel
	Containment vessel packing material
Convenience cans	Stainless steel or tin plated carbon steel with stainless-steel can handles and nylon coated stainless-steel wire, or passivated nickel
Silicone rubber pads	Silicone rubber, 22 ±5 Shore A, color black/gray
Spacers	Stainless-steel can filled with Cat 277-4
Bottles	Polyethylene or Teflon FEP
Bagging	Polyethylene
Metal scrubbers	Stainless steel, McMaster Carr Part # 7361T13

Table 3.15. Component allowable service temperature and pressure

Component	Allowable service temperature range °C (°F)	Allowable pressure range kPa (psi) gauge
Drum assembly		
Stainless-steel drum and lid	−40 to 871 (−40 to 1600)[a]	48.3 (7)
Silicon bronze nuts	−40 to 871 (−40 to 1600)[a]	N/A
Stainless-steel washers	−40 to 871 (−40 to 1600)[a]	N/A
Stainless-steel mid liner	−40 to 871 (−40 to 1600)[a]	N/A
Stainless-steel inner liner	−40 to 871 (−40 to 1600)[e]	N/A
Stainless-steel top plug weldment	−40 to 871 (−40 to 1600)[a]	
Kaolite 1600	−40 to 871 (−40 to 1600)[a]	N/A
Cat 277-4	-40 to 150 (−40 to 302)[b] -40 to 161 (−40 to 320)[g]	N/A
Silicone rubber pads	−40 to 232 (−40 to 450)[f]	N/A
Containment vessel		
Stainless-steel body and sealing lid	−40 to 427 (−40 to 800)[c]	149.62 (21.7) external 699.82 (101.5) internal
Nitronic 60 closure nut	−40 to 427 (−40 to 800)[c]	149.62 (21.7) external 699.82 (101.5) internal
Stainless-steel retaining ring	−40 to 427 (−40 to 800)[c]	N/A
Dowel pins	−40 to 427 (−40 to 800)[c]	N/A
Brass VCO fitting (Viton O-rings)	−40 to 204 (−40 to 400)[d]	N/A
Ethylene propylene O-rings	−40 to 150 (−40 to 302)[d]	5.52×10^3 (800) with no backing rings
Containment vessel silicone pads	−40 to 232 (−40 to 450)[f]	N/A

[a] In accordance with *Kaolite SuperLightweight Insulating Castables* (Appendix 2.10.3), the recommended use limit temperature for Kaolite 1600 material is 871°C (1600°F). This temperature is the established limit for material in immediate contact with the Kaolite 1600 material and is based on continuous service.
[b] This limit is established based on criticality limits of moisture loss for NCT. It is based on continuous service.
[c] This limit is established by the *ASME Boiler and Pressure Vessel Code.*
[d] This limit is provided by the *Parker O-Ring Handbook* for each material's continuous service limit.
[e] This limit is established based on the fact that the inner liner material is identical to the drum material.
[f] This represents the allowable service temperature limit listed in the McMaster-Carr catalog description for this material.
[g] This limit is established based on criticality limits of moisture loss for HAC. It is based on four hours at this temperature.

3.3.2 Evaluation by Test

Full-scale testing of five ES-3100 test units was conducted in accordance with 10 CFR 71.73 for HAC. A single full-scale ES-3100 (TU-4) was assembled and subjected to both NCT testing and the sequential tests specified in 10 CFR 71.73(c). The furnace used for thermal testing was the No. 3 furnace at Timken Steel Company in Latrobe, Penn., which is a gas-fired furnace. This furnace employs "pulsed" fire burners, in which the natural gas flow rate is varied based on furnace controller demands, but the flow of air through the burners is constant, even when no gas is flowing. This ensures a very rich furnace atmosphere capable of supporting any combustion of package materials of construction.

Oxygen content was not monitored in stack gases of the furnace because it was not anticipated that any of the package's materials of construction were combustible. There was some burning of the silicone pads which are placed between the inner liner and the top plug of the package.

The most significant change to the definition of the HAC thermal test in the current 10 CFR 71 is the requirement for calculation purposes to base convective heat input on "that value which may be demonstrated to exist if the package was exposed to the fire specified." This is not especially significant for this package because it was tested in the gas-fired furnace with burners placed in an attitude which produced a strong convective swirl. Careful examination of the thermal test data indicates that the total heat imparted to the packages was significantly greater than the required total heat specified in 10 CFR 71.73(c)(4).

Compliance with ASTM E-2230-02, *Standard Practice for Thermal Qualification of Type B Packages for Radioactive Materials* (ASTM E-2230-02), was accomplished by the method described in Sect. 7.3 of this standard. This standard is in general agreement with Paragraph 2.2.1 ("Steady-state Method of Compliance") of SG 140.1 entitled *Combination Test Analysis/ Method Used to Demonstrate Compliance to DOE Type B Packaging Thermal Test Requirements (30 Minute Fire Test)*. The data from each of the thermal tests, as shown in the test report, show that five of the six thermocouple-instrumented exterior surfaces of each package reached temperatures well in excess of 800°C (1475°F) during the 30-min thermal testing. Similarly, all other surfaces of the furnace, including the support stand, exceeded 800°C (1475°F) during the timed portion of the thermal test. For the test specified in the regulations, regardless of the amount of heat input by convection, radiation, or conduction, the maximum temperature the skin of the package could reach would be 800°C (1475°F). That is, the source of the heat in the regulatory-specified test is at 800°C (1475°F). Heat can only be transferred from a hotter source to a colder source. Thus, regardless of the mode of heat transfer, the greatest temperature a specimen exposed to the 10 CFR 71.73,(c)(4) thermal test can attain is 800°C (1475°F). The thermal performance of the packaging components as an assembled unit has been demonstrated through full-scale tests. Actual tests and procedures followed are described in Sect. 4.5 of ORNL/NTRC-013, Vol. 1. Figures 3.2 through 3.5 show the general testing arrangements.

Since full-scale testing in accordance with 10 CFR 71.73 for HAC was conducted on prototypical packages. No analyses were conducted to show compliance with the HAC thermal test. However, to determine the thermal impacts of (1) an internal heat source, (2) application of insolation during cool down, (3) thermal capacitance differences between test mock-ups and actual contents, and (4) the change in neutron absorbing material, analyses were conducted and are summarized in Appendices 3.6.1 and 3.6.2. Further discussion of these issues is found in Sect. 3.5.3.

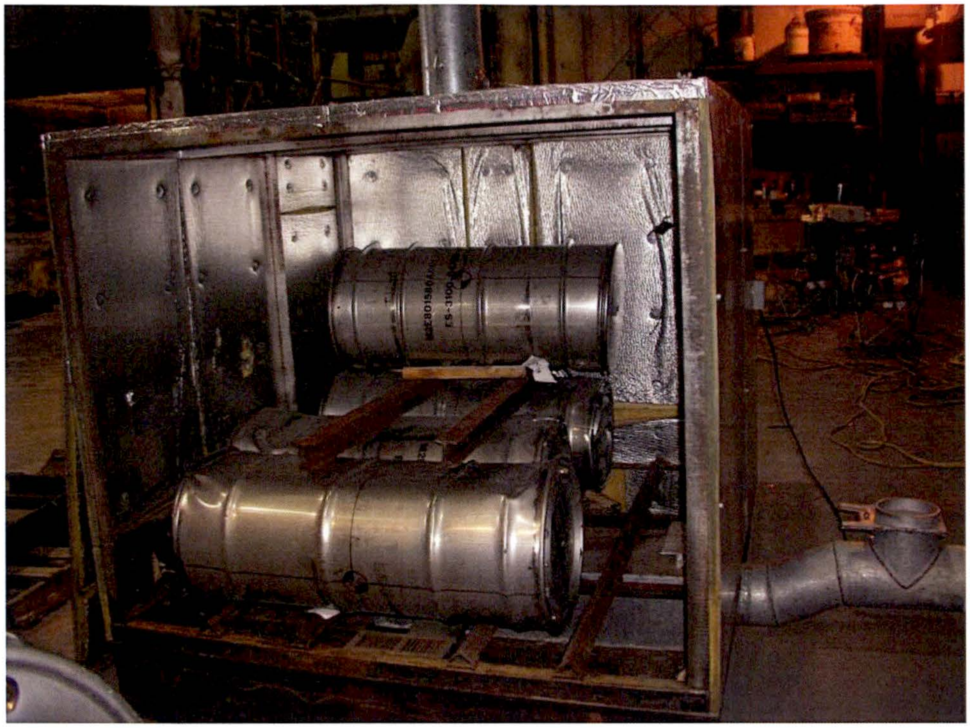


Fig. 3.2. Test units preheat arrangement.

Fig. 3.3. Test unit insertion into furnace.

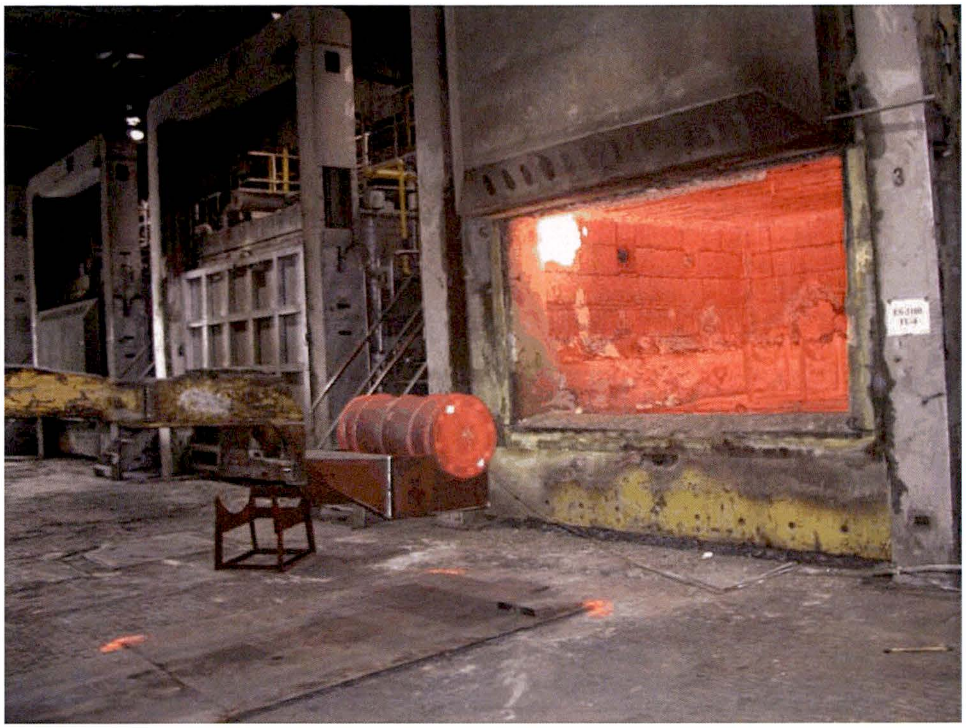


Fig. 3.4. Test unit removal from furnace.

Fig. 3.5. Test unit cool down and monitoring arrangement.

3.3.3 Margins of Safety

Tables 3.16 and 3.17 summarize the results of thermal analysis and testing in accordance with NCT and HAC regulatory requirements. Margins of safety have not been calculated. However, the predicted or calculated results of individual components are compared with their allowable continuous service limit for NCT in Table 3.16 and for HAC in Table 3.17. For all components, the values calculated during NCT (Table 3.16) do not approach their allowable limits stated in Table 3.15. The temperature values predicted or calculated for the Kaolite 1600 material, the top plug stainless steel, the silicon bronze nuts, and the Cat 277-4 neutron poison do approach and/or exceed their allowable continuous service limits during HAC thermal testing. However, short-term excursions above these allowable limits as shown in ORNL/NTRC-013/V1 do not reduce the ability of the packaging components to provide their safety functions during HAC. Justification of this statement is provided by the following information:

1. As discussed in Sect. 3.5.2, the thermal tests were conducted in compliance with ASTM E 2230-02 and SG 140.1 using the steady state environmental method to comply with 10 CFR 71.73(c)(4). In order to maintain a 800°C thermal environment at all locations inside the furnace and on all external surfaces of the shipping package, the set point of the furnace had to be adjusted upward to 871°C (1600°F). A direct result of this action was that some of the external thermocouples on the package surface exceeded 871°C (1600°F) for short periods of time during the timed thermal test.

2. In accordance with National Bronze & Metals, Inc., the silicon bronze nuts remain solid or crystalline in nature up to a temperature of 1032°C (1890°F). Their only safety function during and following the thermal test is to keep the lid attached to the drum assembly. By remaining solid during and following HAC testing, the silicon bronze nuts performed their safety function. All lids remained attached to the drum assembly following HAC thermal testing.

3. In accordance with ASM Aerospace Specification Metals Inc., Type 304/304L stainless steel has a continuous service temperature of 927°C (1700°F). During the thermal test, the safety function of the stainless steel in the top plug is to encapsulate the Kaolite 1600 insulating material. As shown in ORNL/NTRC-013/V1, the external temperature does intermittently exceed the continuous service limit of the Kaolite 1600 material. However, these short-term temperature excursions do not diminish the ability of the stainless steel to maintain the boundary around the insulating material. The solidus temperature for stainless steel is ~1399°C (2550°F); therefore, there is a significant thermal margin of safety in the stainless steel. All top plugs were intact following HAC thermal testing.

4. As documented in Appendix 2.10.3, the recommended use limit temperature for Kaolite 1600 is 871°C (1600°F) and the melting point is 1260°C (2300°F). This use limit temperature is also the established limit for material in immediate contact with the Kaolite 1600 material and is based on continuous service at this temperature. As previously stated, the external temperature does intermittently exceed the continuous service limit of the Kaolite 1600 material during the thermal test, but it remains well below its melting point. The safety function of the Kaolite 1600 material is to keep the containment vessel as cool as possible and to meet the leaktight criteria established in ANSI N14.5-1997. Based on temperature and pressure calculations, the containment vessel maintains containment during and after thermal testing to the above criteria. Therefore, short-term temperature excursions above 871°C do not diminish the ability of the Kaolite 1600 material to perform its safety function.

Table 3.16. Summary of results of evaluation for the ES-3100 under NCT

Conditions	Calculated results	Allowable limit	SARP reference
Minimum package temperature, °C (°F)	-40 (-40)	-40 (-40)	Sect. 3.4.1
Maximum drum assembly stress due to cold conditions per 10 CFR 71.71(c)(2), kPa (psia)	61,150 (8,869)	132,379 (19,200)	Appendix 3.6.3
Minimum containment vessel pressure, kPa (psia)	76.74 (11.13)	0.0 (0.0)	Sect. 3.4.1
Maximum drum temperature with insolation, °C (°F)	117.72 (243.89) [a]	N/A	Appendix 3.6.2 Sect. 3.4.1
Maximum drum assembly stress due to hot conditions per 10 CFR 71.71(c)(1), kPa (psia)	66,934 (9,708)	132,379 (19,200)	Appendix 3.6.3
Containment vessel temperature with insolation, °C (°F)	87.81 (190.06) [a]	427 (800) [b]	Appendix 3.6.2 Sect. 3.4.1
Maximum ethylene propylene O-ring temperature, °C (°F)	87.81 (190.06)	150 (302) [c]	Appendix 3.6.2 Sect. 3.4.1
Maximum containment vessel pressure, kPa (psia)	200.20 (29.036) [d]	801.2 (116.2) [e]	Appendix 3.6.4 Sect. 3.4.2
Maximum silicone bronze nut temperature with insolation, °C (°F) [Node 536]	~108.05 (226.49)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum stainless-steel washer temperature with insolation, °C (°F) [Node 536]	~108.05 (226.49)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum stainless-steel mid liner temperature with insolation, °C (°F) [Node 474]	92.89 (199.20)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum stainless-steel inner liner temperature with insolation, °C (°F) [Node 4721]	87.72 (189.90)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum top plug temperature with insolation, °C (°F) [Node 6339]	112.26 (234.06)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum Kaolite 1600 temperature with insolation, °C (°F) [Node 6339]	112.26 (234.06)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum Cat 277-4 temperature with insolation, °C (°F) [Node 4740]	88.32 (190.98)	150 (302) [f]	Sect. 3.1.3.1 Table 3.6
Maximum silicone rubber pad temperature with insolation, °C (°F) [Node 494]	97.53 (207.56)	232 (450) [f]	Sect. 3.1.3.1 Table 3.6
Maximum Viton O-ring temperature with insolation, °C (°F) [Node 6715]	~87.81 (190.06)	204 (400) [f]	Sect. 3.1.3.1 Table 3.6
Maximum brass VCO fitting temperature with insolation, °C (°F) [Node 6715]	~87.81 (190.06)	204 (400) [f]	Sect. 3.1.3.1 Table 3.6

[a] Appendix 3.6.2.
[b] *ASME Boiler and Pressure Code*, Sect. II, Part D, maximum allowable temperature for Sect. III, Div. 1, Subsection NB vessel.
[c] Maximum O-ring seal life up to 150°C (302°F) for continuous service (*Parker O-ring Handbook*, Fig. 2-24).
[d] Appendix 3.6.4 for CVA 7.
[e] Appendix 2.10.1 allowable limit.
[f] See Table 3.15.

Table 3.17. Summary of results of evaluation under HAC for the ES-3100 shipping arrangement using bounding case parameters

Condition with HAC temperature adjustments	Calculated results	Allowable limit	SARP references
Maximum adjusted containment vessel temperature during testing, °C (°F)	152.22 (306.00)	426.67 (800) [a]	Sect. 3.5.3
Maximum containment vessel pressure during testing, kPa (psia)	580.92 (84.255) [b]	801.2 (116.2) [c]	Appendix 3.6.5 Sect. 3.5.3
Maximum adjusted ethylene propylene O-ring temperature, °C (°F)	141.22 (286.20)	150 (302) [d]	Sect. 3.5.3
Maximum silicone bronze nut temperature, °C (°F) [Node 536]	<871 (<1600)	871 (1600) [e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum stainless-steel drum washer temperature, °C (°F) [Node 536]	<871 (<1600)	871 (1600) [e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum stainless-steel mid liner temperature, °C (°F) [Node 474]	~204 (400) [f]	871 (1600) [e]	Sect. 3.1.3.2 Tables 3.6, 3.7, 3.8, and 3.9
Maximum stainless-steel inner liner temperature, °C (°F) [Node 4721]	~203 (397) [g]	871 (1600) [e]	Sect. 3.1.3.2 Tables 3.6, 3.7, 3.8, and 3.9
Maximum top plug temperature, °C (°F) [Node 6339]	<871 (<1600)	871 (1600) [e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum Kaolite 1600 temperature, °C (°F)	>871 (>1600)	871 (1600) [e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum Cat 277-4 temperature, °C (°F) [Node 4721]	~161 (320) [g]	161 (320) [e]	Sect. 3.1.3.2 Table 3.6, 3.7, 3.8, and 3.9
Maximum silicone rubber pad temperature, °C (°F) [Node 494]	>232 (450)	NSS [h]	Sect. 3.1.3.2 Figure 5.4 of ORNL/NTRC-013/V1
Maximum Viton O-ring temperature, °C (°F) [Node 6715]	~152 (306)	204 (400) [e]	Sect. 3.1.3.2 Tables 3.20 and 3.21
Maximum brass VCO fitting temperature, °C (°F) [Node 6715]	~152 (306)	204 (400) [e]	Sect. 3.1.3.2 Tables 3.20 and 3.21

[a] *ASME Boiler and Pressure Code*, Sect. II, Part D, max allowable temperature for Sect. III, Div. 1, Subsection NB vessel.
[b] Appendix 3.6.5 for CVA 7.
[c] Appendix 2.10.1 at 148.89°C (300°F).
[d] Maximum O-ring seal life up to 150°C (302°F) for continuous service (*Parker O-ring Handbook,* Fig. 2-24).
[e] See Table 3.15.
[f] Maximum HAC temperature adjustments for this location are 6.1°C for blackout readings, 6.1°C for crush plate location differences, 1.4°C for decay heat and insolation after thermal test, and 27.8°C for variation in Kaolite 1600 and Cat. 277-4 densities.
[g] Maximum HAC temperature adjustments for this location are 6.1°C for blackout readings, 6.1°C for crush plate location differences, 4.2°C for decay heat and insolation after thermal test, and 9.8°C for variation in Kaolite 1600 and Cat. 277-4 densities.
[h] Considered a non-safety significant (NSS) component. Therefore, maximum allowable temperature limit during HAC is unknown.

5. By using the appropriate temperature adjustments shown in Table 3.20, the maximum recorded HAC temperature shown in Table 3.9, and the data for Node 4740 in Fig. 21 of Appendix 3.6.2, the 277-4 material reaches its peak temperature (~320°F) ~2 h following the thermal test. Figure 21 in Appendix 3.6.2 also shows that this peak temperature drops ~15°F ~4 h after furnace removal and continuously drops thereafter. The maximum temperature in the 277-4 material occurs at the top of neutron absorber cavity (Node 4740 in the analytical models). As shown in Tables 3.7 and 3.8, the temperature in other regions of the 277-4 (e.g., Nodes 351 and 3888) is well below this maximum temperature for the entire length of time associated with the thermal test and cool-down period. For HAC criticality safety analysis, the entire mass of the 277-4 material is conservatively assumed to have the properties resulting from exposure to 320°F for 4 h.

Based on these results, the ES-3100 components will perform their safety functions during both NCT and HAC.

3.4 THERMAL EVALUATION UNDER NORMAL CONDITIONS OF TRANSPORT

3.4.1 Heat and Cold

The ambient temperature requirement for NCT is 38°C (100°F). The 35.2 kg of HEU shipped in the ES-3100 package generates a maximum bounding heat load of 0.4 W. The insolation heat flux stipulated in 10 CFR 71.71(c)(1) was used in the calculations. If the package is exposed to solar radiation at 38°C (100°F) in still air, the conservatively calculated temperatures at the top of the drum, on the top surface of the containment vessel, and on the containment vessel near the O-ring sealing surfaces, are 117.72, 87.81, and 87.72°C (243.89, 190.06, 189.90°F), respectively, for the ES-3100. Nevertheless, these temperatures are within the service limits of all packaging components, including the O-rings. The normal service temperature range of the O-rings used in the containment boundary is −40 to 150°C (−40 to 302°F), in accordance with B&PVC, Sect. III; thus, the seal will not be affected by this maximum normal operating temperature.

Using the temperatures calculated for the conditions of 10 CFR 71.71(c)(1), Appendix 3.6.4 predicts that the maximum normal operating pressure inside the containment vessel will be 200.20 kPa (29.036 psia). The design absolute pressure of the containment vessel is 801.17 kPa (116.2 psia), and the hydrostatic test pressure is 1135.57 kPa (164.7 psia). Thus, increasing the internal pressure of the containment vessel to a maximum of 200.20 kPa (29.036 psia) during NCT would have no detrimental effect. Stresses generated in the containment vessel at this pressure are insignificant compared to the materials of construction allowable stress. Table 2.20 provides a summary of the pressure and temperature for the various shipping configurations. As discussed in Sect. 2.6.1.4, the containment vessel and vessel closure nut stresses for these pressure conditions are below the allowable stress values.

Summarizing 10 CFR 71.43(f), the tests and conditions of NCT shall not substantially reduce the effectiveness of the packaging to withstand HAC sequential testing. The effectiveness of the ES-3100 to withstand HAC sequential testing is not diminished through application of the tests and conditions stipulated in 10 CFR 71.71. The justification for this statement is provided by physical testing of both the ES-2M and ES-3100 test packages. Due to the similarities in design, fabrication, and material used in construction of both the ES-2M and the ES-3100 package, the Kaolite 1600 physical characteristics will hold true for both designs. The integrity of the Kaolite 1600 is not significantly affected by the NCT vibration and 1.2-m (4-ft) drop tests.

Prior to testing the ES-2M design (a similarly constructed shipping package), each test unit was radiographed to determine the integrity of the Kaolite 1600 impact and insulation material. Following

casting of the material inside the drum, some three-dimensional curving cracks were seen in some packages near the top thinner sections from the bottom of the liner to the bottom drum edge. After vibration testing, radiography of the ES-2M Test Unit-4 showed that the lower half of the impact limiter was broken into small pieces (Byington 1997). To evaluate these findings, Test Unit-4 was reassembled and subjected to HAC sequential testing (Byington 1997). After vibration and impact testing, many three-dimensional curving cracks were seen around the impact areas, and the inner liner was also visibly deformed. Nevertheless, temperatures at the containment boundary were also similar to other packages not subjected to vibration testing prior to HAC testing. No inleakage of water was recorded following immersion. Also, Test Unit-4 of the ES-3100 shipping package was subjected to the full NCT test battery including vibration.

Following these tests, the containment vessel of the ES-2M Test Unit-4 was removed, and a full body helium leak check was performed. The test unit passed the leak-tight criteria in accordance with ANSI N14.5-1997. The containment vessel was then reassembled into the previously tested drum assembly and subjected to the complete HAC testing. Based on the success of this unit and the similar design of the ES-2M, it can be concluded that vibration normally incident to transport does not reduce the effectiveness of the ES-3100 packaging during HAC testing. The ES-3100 has been tested to determine the effectiveness of the package following a sequential NCT 1.2-m (4-ft) drop test and HAC test battery. Throughout all of the vibration and structural testing, the effectiveness of the Kaolite 1600 material as an impact limiter and thermal insulation was not substantially reduced.

Since the components to be shipped have an assumed decay heat load of 0.4 W, a thermal analysis was conducted for the ES-3100 package with and without full solar insolation. The package was analyzed using the ABAQUS/Standard computer code, and the finite element geometry was constructed for each model using MSC.Patran 2004. The predicted temperature, while stored at 38°C (100°F) in the shade, for the drum lid center and the containment vessel flange near the inner O-ring, is 37.89°C (100.20°F) and 38.22°C (100.80°F), respectively. The analysis shows that no accessible surface of the package would have a temperature exceeding 50°C (122°F). Therefore, the requirement of 10 CFR 71.43(g) would be satisfied for either transportation mode (exclusive use or nonexclusive use).

Also, in accordance with 10 CFR 71.71(c)(2), the containment vessel pressure must be calculated at −40°C (−40°F). Given the initial conditions of temperature, relative humidity, no silicone rubber or polyethylene bag offgassing, the pressure is calculated as follows:

$$P_1 @ 25°C = P_a + P_v + P_{fo},$$

where,

P_a	=	98.15 kPa (14.236 psia)	(Appendix 3.6.4)
P_v	=	3.20 kPa (0.464 psia)	(Appendix 3.6.4)
P_{fo}	=	0	(no offgassing, Appendix 3.6.4)

At −40°C (−40°F), the partial pressure of the water vapor is conservatively assumed to be zero. Therefore, the final pressure of the mixture at −40°C (−40°F) is calculated according to the ideal gas law based solely on the partial pressure of the air.

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

where,

P_1 = 98.15 kPa (14.236 psia)
T_1 = 25°C (298.15 K)

$$T_2 = -40°C\ (233.15\ K)$$
$$V_1 = V_2$$

rearranging and solving for P_2,

$$P_2 = P_1\ (T_2/T_1)$$
$$= (98.15)(233.15/298.15)$$
$$P_2 = 76.76\ kPa\ (11.13\ psia).$$

The cold condition for NCT specified in 10 CFR 71.71 is an ambient temperature in still air and shade of −40°C (−40°F). The 35.2 kg (77.60 lb) of HEU contents in the ES-3100 package generates a maximum bounding decay heat load of 0.4 W. However, in accordance with Regulatory Guide 7.8, the thermal effects of this internal heat source are neglected during evaluation of the package performance at −40°C (−40°F). When exposed to this condition, the package component temperatures will stabilize over time at a temperature approaching −40°C (−40°F). The package has been examined for use at −40°C (−40°F) (Sect. 2.6.2). No detrimental effects on the package structure or sealing capability result from this minimum temperature requirement. The normal service temperature range of the O-rings used in the containment boundary is −40 to 150°C (−40 to 302°F), in accordance with the *Parker O-ring Handbook*; thus, the seal will not be affected by this minimum package temperature in accordance with 10 CFR 71.71(c)(2). Leak testing conducted on Test Unit-2 to the leak tight criteria stipulated by ANSI N14.5-1997 following compliance testing provides justification of the above statements.

3.4.2 Maximum Normal Operating Pressure

The stainless-steel drum and cast refractory system will not pressurize as a result of temperature increases because of four ventilation holes (0.795 cm [0.313 in.] in diameter) drilled in the drum side wall 3.81 cm (1.5 in.) from the flanged top and equally spaced around the drum. The holes are filled with nylon plugs, but they are not hermetically sealed. The inner liner encapsulating the noncombustible neutron poison (Cat 277-4) will not pressurize as a result of temperature increases because of three ventilation holes (0.635 cm [0.25 in.] in diameter) and a slot (1.63 cm [0.64 in.] in width and 4.17 cm [1.64 in.] in length) drilled into this inner liner. These features are covered during transport with aluminum tape to prevent contamination of the neutron poison. This tape does not represent a hermetic seal.

The maximum normal operating pressure is defined in 10 CFR 71.4 as the maximum gauge pressure that would develop in the containment system in a period of one year under the heat conditions specified in 10 CFR 71.71(c)(1). The internal pressure developed under these conditions in the ES-3100 containment vessel is calculated in Appendix 3.6.4 for the most restrictive containment vessel configurations. For conservatism, the decay heat of 0.4 W was used for the maximum internal heat load in evaluating the package for NCT. The maximum calculated internal absolute pressure in the containment vessel with solar insolation and the bounding case parameters is 200.20 kPa (29.036 psia) CVA 7. This pressure incorporates offgassing of the silicone rubber pads, polyethylene bottles, Teflon bottles, and polyethylene bagging and hydrogen gas generation from the radiolysis of water and/or other packing materials. The initial environment inside the containment vessel when assembled is at ambient temperature and pressure with 100% relative humidity. The heat-transfer capability of the packaging is not degraded due to gap creation caused by differences in the fabrication material's coefficient of thermal expansion. Modeling assumed nominal gaps and position based on the engineering drawings of Appendix 1.4.8.

3.4.3 Maximum Thermal Stresses

The temperature of the package under NCT will vary from a low of −40°C (−40°F) throughout the package to a maximum of 117.72 and 87.81°C (243.89 and 190.06°F) (Appendix 3.6.2) on the surface of the drum and the containment vessel, respectively (Sect. 3.4.1). The slow temperature increase or decrease experienced in normal conditions between these limits will result in an essentially uniform temperature change throughout the package. All materials of construction are within this operating temperature range (Table 3.15). Thermal stresses due to differences in thermal expansion are insignificant, as discussed in Sects. 2.6.1.2 and 2.6.2.

Most of the components of the packaging are completely unrestrained. Therefore, any thermal stresses in the packaging components as the temperature varies between the extremes listed above will have no effect on the ability of the packaging to maintain containment, shielding integrity, and nuclear subcriticality. The maximum stresses due to pressure under NCT for the containment vessel are given in Tables 2.21 and 2.22. These values are significantly below the allowable stresses for the packaging components. The Kaolite 1600 insulation and Cat 277-4 materials are poured and cast in place during the fabrication of the drum weldment (Drawing M2E801508A002, Appendix 1.4.8). This situation produces a zero gap between the these materials and the bounding drum and inner liners. Due to differences in coefficients of thermal expansion, some radial and axial interference is expected due to thermal growth or contraction of the inner liners. These radial and axial interferences and induced stresses are calculated in Appendix 3.6.3. The results show that the stresses induced are minimal and do not reduce the effectiveness of the drum assembly.

The containment vessel, which is Type 304L austenitic (iron-nickel-chromium) stainless steel, is designed and fabricated in accordance with Sects. III SubSect. NB and IX of the *ASME Boiler and Pressure Vessel Code* (B&PVC Sect. III and B&PVC Sect. IX). The two sealing surfaces of each containment boundary are joined together by torquing the closure nut inside the containment vessel body to 162.7 ±6.8 N·m (120 ±5 lbf-ft). The O-ring material is ethylene-propylene elastomer.

The design temperature range of the containment vessel is −29 to 148.89°C (−20 to 300°F) (Appendix 2.10.1). However, the package has been evaluated to −40°C (−40°F) (Sect. 2.6.2). The thermal properties of the stainless-steel container body, lid, and closure nut are not critical at these temperatures. The O-ring seal is important for the containment properties of the containment vessel. The normal service temperature range for the elastomer O-ring is −40 to 150°C (−40 to 302°F) for continuous service and up to 165°C (329°F) for 72 h (*Parker O-ring Handbook*). The maximum adjusted HAC temperature of the ES-3100 containment vessel was based upon the thermal testing results in the vicinity of the O-rings. The maximum temperature recorded in the vicinity of the ES-3100 O-rings (241°F) is shown in Table 3.9. As shown in Sect. 3.5.3, the maximum temperature for the containment vessel at the O-ring location was adjusted for the ES-3100 package to 141.22°C (286.20°F). Hence, no damage would be expected to the O-rings during HAC.

The test packages were all preheated to above 38°C (100°F) prior to being placed in the furnace, which was heated to over 800°C (1475°F). As noted in the test report (Appendix 2.10.7), the temperatures recorded on the containment vessels of all the test units were fairly uniform, both vertically and circumferentially. The maximum temperature variation on the containment vessels was ~50°F (from the test temperatures reported in Table 3.9). No damage would be expected on the containment vessel from thermal stresses resulting from a temperature differential of this magnitude. This conclusion is based on the guidelines given in B&PVC, Sect. III. Thermal stress is defined as a self-balancing stress produced by a nonuniform distribution of temperature (Paragraph NB-3213.13 of B&PVC, Sect. III). This paragraph further states that there are two types of thermal stresses: general thermal stress and local thermal stress. An example of a general stress is that produced by an axial temperature distribution in a

cylindrical shell (Paragraph NB-3213.9). This general stress is further classified (Paragraph NB-3213.9) as a secondary stress (that is, a normal stress or a shear stress developed by the constraint of adjacent materials or by self-constraint of the structure). Paragraph NB-3213.9 further states that the basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions that cause the stress to occur, and failure from a single application would not be expected. An example of a local thermal stress is a small hot spot in the wall of a pressure vessel (Paragraph NB-3213.13). Local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses are considered only from a fatigue standpoint. Fatigue will not result from a one-time cyclic event such as an accidental fire.

Following the thermal test, the volume between the O-rings on the five containment vessels (Sect. 2.7.4) was then leak tested and met the air leak-rate criterion of 10^{-4} ref-cm^3/s. Following the O-ring leak check, the five containment vessels were drilled and tapped for full body helium leak testing. All five containment vessels passed the leak rate criteria for leaktightness per ANSI N14.5-1997. The containment vessels were then submerged under a pressure equivalent to 0.9 m (3 ft) of water for 8 h, with no leakage noted. (Sect. 2.7.5). Visual inspection following testing and disassembly also indicated that no distortion or damage occurred in the containment vessel wall, sealing lid, closure nut, O-rings, or sealing surfaces. These tests and observations demonstrate that thermal stresses produced during testing did not affect the containment capability of the containment vessel.

3.5 HYPOTHETICAL ACCIDENT THERMAL EVALUATION

3.5.1 Initial Conditions

Five full-scale packages were tested in the sequence shown in Table 2.19. Each ES-3100 test package was subjected to the 1.2-m (4-ft) drop test in accordance with 10 CFR 71.71(c)(5) prior to the sequential HAC tests in accordance with 10 CFR 71.73 (free drop, crush, puncture, thermal, and immersion tests). One of these units (Test Unit-4) had previously completed the tests and conditions stipulated in 10 CFR 71.71(c)(5) through (c)(10), excluding (c)(8). Two different mock-up configurations were used to represent the minimum and maximum proposed shipping weight and to simulate various center of gravity locations. The structural and thermal interface between the mock-up component and the containment vessel was designed to match that of the actual hardware proposed for transport. Based on LS-DYNA-3D drop simulations (Appendix 2.10.2) the five test units with their associated test weights represent the worst drop orientations for the ES-3100 package. Test Unit-5 used a near replicate of the lightest weight contents for its mock-up component. NCT free-drop, 9 m (30 ft) free drop, 9 m (30 ft) crush and puncture tests were made as specified in 10 CFR 71.71(c)(1), and 73(c)(1) through (c)(3) on all five full-scale test packages prior to thermal testing. The results of this testing are discussed in Sects. 2.7.1, 2.7.2, and 2.7.3. The 1.2-m (4-ft), 9-m (30-ft) drop and crush test orientations were as follows: two tests with the long axis of drum at an oblique angle of 12° to impact surface; a center of gravity over the corner of the drum lid; a drop with the long axis of drum parallel with the impact surface; and a vertical drop on to the drum's lid. The subsequent 40-in. puncture drops were made at various orientations as shown in Table 2.19.

Prior to the thermal test, each test unit was preheated to the maximum temperature extreme in accordance with 10 CFR 71.73(b)(1). Since the containment vessels were initially assembled at ~101.35 kPa (14.7 psia) at 25°C (77°F), the initial internal containment vessel pressure was ~105.70 kPa (15.33 psia) at 38°C (100°F) using the ideal gas law. In accordance with 10 CFR 71.73(b)(1), the internal pressure should be that calculated for the maximum normal operating pressure or 200.20 kPa (29.036 psia). This slight pressure differential has little or no effect on the thermal test results. The maximum decay heat load of the contents is calculated to be 0.4 W based on 35.2 kg of HEU. Analysis

of the ES-3100 package after thermal HAC tests both with and without the decay heat load has been performed. The maximum projected temperature differential between the two packages following furnace exposure, as calculated in Appendix 3.6.2, would be 0.4°C (0.7°F) at the top center of the containment vessel lid , 0.4°C (0.7°F) at the containment vessel flange near the O-rings, 0.45°C (0.8°F) at the containment vessel bottom center, and 0.6°C (1.1°F) at the containment vessel mid body. These temperature differentials are representative for both the Kaolite 1600 densities evaluated.

3.5.2 Fire Test Conditions

Full-scale testing in accordance with 10 CFR 71.73 for HAC was conducted on prototypical packages. Therefore, no analyses were conducted to show compliance with the HAC thermal test. However, analyses were conducted and are discussed in Sect. 3.5.3 to determine the thermal impacts of an internal heat source, application of insolation during cool down, location of crush plate impact on test unit, and thermal capacitance differences between test hardware and proposed shipping hardware.

Full-scale testing of five ES-3100 test units was conducted in accordance with 10 CFR 71.73(c)(4) for HAC. A single full-scale ES-3100 test unit (TU-4) was assembled and subjected to both NCT and to the sequential tests specified in 10 CFR 71.73(c). The furnace used for thermal testing was the No. 3 Furnace at Timken Steel Company in Latrobe, Penn., which is a gas-fired furnace. Oxygen content in stack gases from the furnace were not monitored because it was not anticipated that any of the package's materials of construction were combustible. There was some burning of the silicone pads which are placed between the inner liners and the top plugs of the packages. However, it should be noted that this furnace employs "pulsed" fire burners. This type of burner is unique in that the natural gas flow rate is varied based on furnace controller demands, but the flow of air through the burners is constant, even when no gas is flowing, thereby ensuring a very rich furnace atmosphere capable of supporting any combustion of package materials of construction.

The most significant change to the definition of the HAC thermal test in the current 10 CFR 71 is the requirement for calculation purposes to base convective heat input on "that value which may be demonstrated to exist if the package was exposed to the fire specified." This is not especially significant for this package because it was tested in the gas-fired furnace with burners placed in an attitude which produced a strong convective swirl. Careful examination of the thermal test data indicates that the total heat imparted to the packages was significantly greater than the required total heat specified in 10 CFR 71.73(c)(4). Compliance with ASTM E-2230-02, *Standard Practice for Thermal Qualification of Type B Packages for Radioactive Materials*, was accomplished by the method described in Sect. 7.3 of this standard. This standard is in general agreement with Paragraph 2.2.1 ("Steady-state Method of Compliance") of SG 140.1 entitled *Combination Test Analysis/ Method Used to Demonstrate Compliance to DOE Type B Packaging Thermal Test Requirements (30 Minute Fire Test).*

Prior to the beginning of the thermal test, the furnace was characterized for temperature and heat recovery times. The support stand was welded to a large steel plate which had been placed on the floor of the furnace prior to heating. This steel plate acted as the radiating surface at the bottom of the furnace, as well as providing the ability to hold the test stand rigidly in place. Before heating the furnace, workers practiced loading and unloading test packages from the cold furnace to ensure that the furnace door would not remain open >90 s during each loading. In fact, the maximum time the door was open during any loading was 64 s. As discussed in *Test Report of the ES-3100 Package* (Appendix 2.10.7), six thermocouples were affixed to the drum assembly's exterior surface. Metal retainer clips were welded to the exterior surface to hold the thermocouples in place. The thermocouple tips were inserted underneath the metal clips, and the wire was wrapped around the metal clip. To eliminate any radiant heat exchange between the thermocouples and the furnace walls, the tips and metal clips were covered with a ceramic

coating. Three thermocouples were mounted on each of the walls of the furnace, as well as on the furnace floor, on the furnace door, and three thermocouples were mounted on the test stand.

A minimum of 24 h prior to the beginning of all testing, the furnace was turned on with a set-point temperature of 871 °C (1600 °F). Following each test, the furnace set point was adjusted to 871 °C (1600 °F) for at least 45 min prior to the beginning of the next test. The furnace control data recorder ran continuously for the entire duration of the preheat cycle test. Each test unit was preheated to over 38 °C (100 °F) by placing the packages in an environmental chamber. The environmental chamber was heated by a torpedo-type kerosene space heater controlled by a mechanical bulb thermostat with a control range of 38 to 93 °C (100 to 200 °F). The environmental chamber is a welded steel frame with fiberglass insulation panels. It was heated from the bottom with four floor register vents located around the perimeter and a 20.32-cm (8-in.)-diam manual dampened center venting stove pipe.

The set point temperature of the environmental chamber was monitored and adjusted for the duration of the preheat cycle. Initially, the thermostat was set to 66 °C (150 °F) for ~23 h. The thermostat set point was then reduced to 43 °C (110 °F) for the remainder of the preheat cycle (24 h). All packages were preheated for at least 47 h. No test package was loaded into the furnace until 15 of the 18 thermocouples monitoring the furnace had a reading of 800 °C (1475 °F) or higher. All packages were placed in the preheated furnace on the support stand with the long axis positioned horizontally, and the package lid facing toward a furnace side wall. During the testing of each package, the thermocouple temperature data recorder was set to record every 15 s.

These packages were exposed to the radiation environment for a minimum of 30 min after all functioning furnace thermocouples and at least five of the six test package exterior surface thermocouples reached a temperature of 800 °C (1475 °F). During the testing, the package thermocouple temperature data were recorded every 15 s.

After each test, the furnace was allowed to reheat for a minimum of 45 min after obtaining the set point temperature before testing the next unit. The furnace control temperature data recorder ran continuously for the duration of the preheat. No test package was loaded into the furnace until all functioning thermocouples on the furnace walls and support stand had again reached a temperature of 800 °C (1475 °F) or higher.

All units were tested in a horizontal attitude with the top end of the package facing to the right side wall of the furnace and the 0° mark on the drum facing the floor of the furnace. The data from each of the thermal tests, as shown in the test report, show that at least four of the six external drum thermocouples reached temperatures well in excess of 800 °C (1475 °F) and remained above 800 °C (1475 °F) during the 30-min thermal testing. Similarly, all other surfaces of the furnace, including the support stand, exceeded 800 °C (1475 °F) during the timed portion of the thermal test. For the test specified in the regulations, regardless of the amount of heat input by convection, radiation, or conduction, the maximum temperature the skin of the package could reach would be 800 °C (1475 °F). That is, the source of the heat in the regulatory specified test is at 800 °C (1475 °F). Heat can only be transferred from a hotter source to a colder source. Thus, regardless of the mode of heat transfer, the greatest temperature a specimen exposed to the 10 CFR 71.73,(c)(4) thermal test can attain is 800 °C (1475 °F). Therefore, the fact that these test packages attained temperatures well in excess of 800 °C (1475 °F) is an excellent indication that the thermal tests performed not only met the requirements of 10 CFR 71.73(c)(4) but actually exceeded them markedly. The results of these tests are provided in the test report (Appendix 2.10.7).

Each test package was removed from the furnace and placed in an area where it was not exposed to artificial cooling. As the furnace door was opened for each test unit, flaming or smoking was visible at

the tamper indicating device (TID) holes in the drum/lid interface. Flaming continued on some of the packages for a short duration; the longest flame duration was 22 min after removal from the furnace. Smoke was also visible from each of the packages and continued after flames were no longer visible. The packages continued to smoke between 12 and 60 min after removal from the furnace. All the packages were allowed to cool naturally to room temperature. The post-thermal testing weights of each unit are summarized in Table 3.18. The drums were disassembled, and the damage was photographed. Each package was visually inspected, and the condition of the package and any observations were recorded.

Table 3.18. ES-3100 test package weights before and after 10 CFR 71.73(c)(4) HAC thermal testing

Test Unit	Pre-test[a] weight kg (lb)	Post-test[a] weight kg (lb)	Thermal test weight loss kg (lb)	BoroBond4 original weight[b] kg (lb)	Water weight in BoroBond4[c] kg (lb)	Water loss percent[d] (%)
1	202.3 (446)	202.3 (446)	0.0 (0)	20.7 (45.64)	4.91 (10.82)	0.00
2	202.8 (447)	202.8 (447)	0.0 (0)	20.5 (45.19)	4.86 (10.72)	0.00
3	203.7 (449)	203.2 (448)	0.45 (1)	20.5 (45.19)	4.87 (10.74)	9.31
4	201.8 (445)	201.4 (444)	0.45 (1)	20.4 (44.97)	4.84 (10.66)	9.38
5	157.4 (347)	156.9 (346)	0.45 (1)	20.6 (45.42)	4.89 (10.77)	9.29

[a] Data from ORNL/NTRC-013.
[b] Weight of BoroBond4 and water obtained from casting data. (ES-3100 Weldments 2004)
[c] This weight is based on TGA measurements and calculation showing that the minimum water percent is 23.71%.
[d] All weight loss attributed to loss of water in BoroBond4.

3.5.3 Maximum Temperatures and Pressure

The five test unit's previously subjected to both NCT and HAC drop testing were thermal tested in accordance with 10 CFR 71.73(c)(4). To determine the maximum temperatures reached during thermal testing, temperature indicating patches were placed at various locations throughout the test package at assembly. The temperature range for each patch used is identified in Table 3.19. When the temperature of an indicator was reached, the color would change to black (i.e., blackout temperature). The range of possible blackout temperatures of the patches was from 51.67 to 260°C (125 to 500°F). For Test Units-1 through -5, Table 3.19 defines the number and location of the temperature indicating patches.

Since the structural and thermal interface between the various mock-ups and containment vessels is the same as the actual hardware, the use of steel mock-ups to simulate the contents is not expected to affect the results of the thermal test significantly. The total maximum weight of the test packages ranged from 157.4 kg (347 lb) to 203.7 kg (449 lb). The ES-3100 package has a nominal gross shipping weight that ranges from 146.88 kg (323.79 lb) to 187.81 kg (414.05 lb) for the minimum and maximum weight containment vessel configurations shown in Table 2.8, respectively. However, the effect on temperature is evaluated in the following paragraphs due to thermal capacitance differences between the mock-up and the actual contents.

Table 3.19. Thermax temperature indicating patches for test units

Patch Location	Internal surface	External surface	Temperature range °C (°F)	Test report figure[a]
Inner liner of drum assembly		17 (Full Range)	52–260 (125–500)	5.30
Top plug weldment		4 (Full Range)	52–260 (125–500)	5.31
Containment vessel body flange	8 (4B & 4C)	8 (4B & 4C)	"B" 77–127 (171–261) "C" 132–182 (270–360)	5.28
Containment vessel body (end cap and cylinder)		5 (B)	"B" 77–127 (171–261)	5.28
Containment vessel sealing lid	4 (B)	4 (B)	"B" 77–127 (171–261)	5.29
Test mock-up components		6 (B)	"B" 77–127 (171–261)	5.26 & 5.27

[a] ORNL/NTRC-013, Volume 1.

As previously stated, temperature indicators (patches) were placed on the surface of each containment vessel, inner liner, and mock-up component. The blackout temperatures that occurred during thermal testing are recorded for each test unit; the maximum blackout temperatures are listed in Table 3.9. A maximum blackout temperature of 116°C (241°F) was recorded in the vicinity of the O-rings on the containment vessel of Test Unit-5. As discussed below, this temperature will be conservatively adjusted to correlate the test conditions to shipping conditions with decay heat and solar insolation. The blackout temperatures are increased to account for (1) the temperature interval between blackout dots; (2) the ambient temperature of the package prior to insertion into the furnace; (3) the temperature increase due to the effects of applying solar insolation during post-HAC thermal test cool down; (4) the temperature increase due to the decay heat load of the actual contents being shipped; (5) effects of crushing at different locations along the body of the shipping package; (6) thermal capacitance difference in the proposed contents and hardware used during testing; (7) temperature difference occurring when using Borobond4 and Cat 277-4; and (8) temperature difference resulting from variations in Kaolite 1600 and Cat 277-4 material densities.

The initial adjustment for the blackout reading is an increase of 6.11°C (11.0°F) from the patch that blacked out. The highest blackout reading indicates that the actual temperature is somewhere between the highest temperature indicated and the next higher temperature.

The second adjustment compensates for thermal testing at package soak temperatures less than the maximum temperature of 38°C (100°F). In the case of the ES-3100 package, each test unit was thermally soaked to over 38°C (100°F) prior to insertion into the furnace. Therefore, there is no temperature adjustment required.

The third adjustment is a temperature increase to represent the effect of insolation heat flux on the package immediately following the conclusion of the thermal HAC test. Analyses of the ES-3100 package after thermal HAC tests both with and without insolation have been performed. Results from these analyses indicate an increase of ~5.94°C (10.7°F) at the containment vessel top (node 6715), ~6.06°C (10.9°F) at the containment vessel O-ring (node 6359), ~10.44°C (18.8°F) at the containment vessel mid body (Node 6574), and ~4.56°C (8.2°F) at the containment vessel bottom (node 6399), as a result of applying insolation following HAC thermal testing. These increases are extracted from Tables 3.7 and 3.8. The most pronounced effect of applying the insolation heat flux was that it increased the time required to cool the package to NCT type conditions. Nevertheless, the influence of insolation is included in the adjustments to the blackout temperatures.

The fourth temperature adjustment considered is the temperature increase due to the decay heat load of the actual contents being shipped. A maximum decay heat load of 0.4 W is calculated as the bounding case for 35.2 kg of HEU. HAC analysis of the ES-3100 package both with and without the decay heat load has been performed, with the results shown in Tables 3.7 and 3.8. The maximum projected temperature increase during HAC due to a 0.4-W heat source, as calculated in Appendix 3.6.2, would be ~0.39 °C (0.7 °F) at the containment vessel's top (node 6715), ~0.39 °C (0.7 °F) at the containment vessel's O-ring (node 6359), ~0.6 °C (1.1 °F) at the containment vessel's mid body (node 6574), and ~0.45 °C (0.8 °F) at the containment vessel bottom (node 6399).

The fifth temperature adjustment considered is the temperature increase to the containment vessel based on the location of impact from the 500 kg (1100 lb) crush plate. Based on the differences in location of the crush plate between Test Units-1 and -2, crushing the shipping package with the center of gravity of the plate directly above the containment vessel flange increases the containment vessel temperature on average ~6.11 °C (11 °F).

The sixth adjustment compensates for the shipment of only 3 kg of HEU rather than the steel mock-ups. The higher content weight was used for testing to cover the possibility of shipping larger components without retesting. The larger content weight gave conservative structural deformation test results to the drum assembly than would the actual shipping weight. One effect, however, of using the larger test mass could be to reduce the containment vessel's temperature rise during the thermal test because the mock-up acts like a heat sink. In order to eliminate this temperature adjustment, a mock-up of the lightest proposed shipment was used in Test Unit-5. The structural and thermal interface between the mock-up components and the containment vessel was designed to match that of the actual shipping hardware, thereby providing the same conductive heat path for thermal testing. As shown by the test results, both the containment vessel and mock-up components of Test Unit-5 recorded higher temperatures than the other test units. This supports the theory that the heavier mock-ups act as heat sinks for the containment vessel. Therefore, by testing the 3.6-kg (8-lb) mock-up representing the lightest assembly to be shipped, a more accurate prediction of actual temperatures reached during thermal testing was achieved. No further temperature adjustments due to differences in mock-up weight are needed.

The seventh temperature adjustment compensates for conducting the HAC compliance tests with BoroBond4 and substituting Cat 277-4 for the production shipping containers. This adjustment is determined by using an undamaged package and subjecting it to a thermal environment representative of that required by 10 CFR 71.73(c)(4). Based on the analytical results shown in Appendix 3.6.2, the containment vessel in a package using Cat 277-4 would be from 2.5 °F to 8. °F cooler than a package with BoroBond4. Conservatively, the temperatures will not be adjusted due to the neutron poison change.

The eighth and final temperature adjustment compensates for material density variation in the Kaolite 1600 and Cat 277-4 material during HAC compliance tests. Again, this temperature adjustment was predicted for an undamaged package using the finite element method. Based on the analytical results shown in Appendix 3.6.2 (Tables 3.7 and 3.8), the containment vessel temperature was predicted to be ~6.4 °C (11.6 °F) higher at the containment vessel's top (node 6715), ~6.4 °C (11.6 °F) higher at the containment vessel's O-ring (node 6359), ~4.6 °C (8.3 °F) higher at the containment vessel's mid body, and ~7.72 °C (13.9 °F) at the containment vessel's bottom (node 6399) when the lower density values for Kaolite 1600 and the neutron poison were used. Since actual compliance testing was conducted with these densities on the high side, the above adjustments must be added to the containment vessel temperatures.

Table 3.20 summarizes the numerous temperature adjustments needed for the containment vessel.

Table 3.20. Predicted temperature adjustments (°F) for containment vessel due to HAC

Node [a]	Analytical Temperature Adjustments								Total Temp Adjustment
	1	2	3	4	5	6	7	8	
6715	11.00	0.00	10.70	0.70	11.00	0.00	0.00	11.60	45.00
6359	11.00	0.00	10.90	0.70	11.00	0.00	0.00	11.60	45.20
6574	11.00	0.00	18.80	1.10	11.00	0.00	0.00	8.30	50.20
6399	11.00	0.00	8.20	0.80	11.00	0.00	0.00	13.90	44.90

[a] See Figs. 8 through 11 in Appendix 3.6.2 for details of node locations.

Table 3.21 shows the results of adding the eight temperature adjustments previously discussed to the black-out temperatures for the containment vessel with the 3.6-kg (8-lb) mock-up (Test Unit-5). These adjusted temperatures would not adversely affect the stainless-steel components or the O-ring materials of the containment vessel.

Table 3.21. Predicted temperatures of the containment vessel due to HAC (°F)

Node [a]	Analytical temperature adjustments (°F)	Maximum blackout temperature on Test Unit-5 (°F)	Final predicted CV temperature (°F)
6715	45.00	261	306.00
6359	45.20	241	286.20
6574	50.20	199	249.20
6399	44.90	210	254.90

[a] See Figs. 8 through 11 in Appendix 3.6.2 for details of node locations.

To determine the maximum pressure inside the containment vessel as a result of thermal testing, the average adjusted gas temperature must be calculated based on the above results. The approach used is to divide the containment vessel volume into three distinct equal regions and then average the three together. The first volume is represented by the gas adjacent to the containment vessel lid and flange region and the top convenience can. Based on the temperature recorded near the O-rings [116.11°C (241°F)] and the temperature recorded on the external surface of the convenience can [98.89°C (210°F)], the average temperature of the gas in this region is 107.50°C (225.50°F). Using the temperature adjustment of 25.11°C (45.20°F) for this region, the adjusted average temperature in the first region is 132.61°C (270.70°F). The second volume is represented by the gas adjacent to the second convenience can from the top. Based on the temperature recorded on the containment vessel wall and convenience can [92.78°C (199°F)], the average temperature of gas in this region is 92.78°C (199°F). Using the temperature adjustment of 27.89°C (50.20°F) for this region, the adjusted average temperature in the second region is 120.67°C (249.20°F). The third and final volume is represented by the gas adjacent to the bottom convenience can. Again based on the convenience can temperature [87.78°C (190°F)] and the containment vessel end cap temperature [98.89°C (210°F)], the average temperature of gas in this region is 93.33°C (200°F). Using the temperature adjustment of 24.94°C (44.90°F) for this region, the adjusted average temperature in the third region is 118.28°C (244.90°F). Averaging these

three temperatures, an average adjusted gas temperature of 123.85 °C (254.93 °F) is determined for the containment vessel.

As shown in Appendix 3.6.5, the maximum adjusted average gas temperature and pressure in the containment vessel during accident conditions was calculated to be 123.85 °C (254.93 °F) and 595.99 kPa (86.441 psia), respectively.

The maximum adjusted temperature on the surface of the containment vessel, adjacent to the O-rings, was 141.22 °C (286.20 °F). This is well within the design range for the packaging. The full body helium leak test on all test units following thermal testing meets the "leaktight" criteria in accordance with ANSI N14.5-1997. Visual inspection following testing and unloading indicated that no distortion or damage occurred in the containment vessel wall, sealing lid, closure nut, O-rings, or sealing surfaces. No water was visible inside the containment vessel following the 0.9-m (3-ft) water immersion test or the 15-m (50-ft) water immersion test on Test Unit-6.

The ES-3100 package satisfies the requirements of 10 CFR 71.73 for transport of the 35.2-kg (77.60-lb) arrangements shown in Table 2.8. Section 2.7 has additional details to support this conclusion.

3.5.4 Accident Conditions for Fissile Material Packages for Air Transport

The expanded fire test conditions specified in 10 CFR 71.55(f)(1)(iv) for fissile material package designs for air transportation was not conducted. The issue of subcriticality is addressed in Section 6 with content mass limits as addressed in Section 1 for air transport.

3.6 APPENDICES

Appendix	Description
3.6.1	THERMAL EVALUATION OF THE ES-3100 SHIPPING CONTAINER FOR NCT AND HAC (CONCEPTUAL DESIGN WITH BOROBOND4 NEUTRON ABSORBER)
3.6.2	THERMAL EVALUATION OF THE ES-3100 SHIPPING CONTAINER FOR NCT AND HAC (FINAL DESIGN WITH CATALOG 277-4 NEUTRON ABSORBER)
3.6.3	THERMAL STRESS EVALUATION OF THE ES-3100 SHIPPING CONTAINER DRUM BODY ASSEMBLY FOR NCT (FINAL DESIGN WITH CATALOG 277-4 NEUTRON ABSORBER)
3.6.4	CONTAINMENT VESSEL PRESSURE DUE TO NORMAL CONDITIONS OF TRANSPORT FOR THE PROPOSED CONTENTS
3.6.5	CONTAINMENT VESSEL PRESSURE DUE TO HYPOTHETICAL ACCIDENT CONDITIONS FOR THE PROPOSED CONTENTS
3.6.6	SILICONE RUBBER THERMAL PROPERTIES FROM THERM 1.2 DATABASE
3.6.7	ESTIMATES OF HYDROGEN BUILDUP IN THE ES-3100 PACKAGE CONTAINING HIGHLY ENRICHED URANIUM

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Appendix 3.6.1

THERMAL EVALUATION OF THE ES-3100 SHIPPING CONTAINER FOR NCT AND HAC (CONCEPTUAL DESIGN WITH BOROBOND4 NEUTRON ABSORBER)

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Appendix 3.6.1

THERMAL EVALUATION OF THE ES-3100 SHIPPING CONTAINER FOR NCT AND HAC (CONCEPTUAL DESIGN WITH BORBOND4 NEUTRON ABSORBER)

INTRODUCTION

Thermal analyses of the ES-3100 shipping container are performed to determine the temperature distribution within the packaging during Normal Conditions of Transport (NCT) as specified in 10 CFR 71.71(c)(1).[1] Transient thermal analyses are performed by treating the problem as a cyclic transient with the incident heat flux due to solar radiation applied and not applied in alternating 12-hour periods.

Additionally, thermal analyses of the ES-3100 shipping container are performed to determine the thermal response of the packaging to Hypothetical Accident Conditions (HAC) as specified in 10 CFR 71.73(c)(4).[1] Since physical testing of the ES-3100 shipping container will be conducted with no internal heat source or insolation during cool-down, temperature increases due to internal heat loads of 0.4, 20, and 30 W as well as temperature increases due to the application of insolation during cool-down following the HAC fire are calculated. Although earlier revisions of 10 CFR 71 specifically state that insolation does not need to be evaluated before, during, or after HAC, the current version of 10 CFR 71 and associated guidance are unclear regarding the need for consideration following HAC testing. Since the Nuclear Regulatory Commission (NRC) has taken the position that insolation must be considered and evaluated following fire testing, analyses are conducted to determine the effect of insolation following the HAC fire on the ES-3100 shipping container. The predicted temperature increases may be used to adjust physical test data for those loads not included in the tests.

FINITE ELEMENT MODEL DESCRIPTION

A two-dimensional axisymmetric (r-z) finite element model of the ES-3100 shipping container is constructed using MSC.Patran (2004, Version 12.0.044)[2] for evaluation for NCT. The actual contents of the ES-3100 shipping container are not specifically modeled—instead, the content source heat load (if desired) is modeled by applying a uniform heat flux to the inner surfaces of the containment vessel. This is a conservative approach in that package temperatures will not be reduced in a transient analysis by the heat capacity of the contents. A schematic of the finite element model is presented in Figure 1. The model consists of five materials: stainless steel (drum, liners, and containment vessel), Kaolite, Borobond4, silicone rubber, and air in the gaps between the drum liner and containment vessel and between the drum liner and top plug. Thermal properties of the materials used in the analysis are presented in Table 1.

Heat is transferred to the model from the contents (i.e., decay heat of the contents) via heat flux boundary conditions applied to the inner surface of the elements representing the containment vessel. Additionally, solar heat fluxes are applied to the model during NCT and HAC post-fire cool-down via heat flux boundary conditions. The heat applied to the model via the boundary conditions is transferred through the model via conduction and thermal radiation. Heat is rejected from the external surfaces of the model via natural convection and thermal radiation boundary conditions.

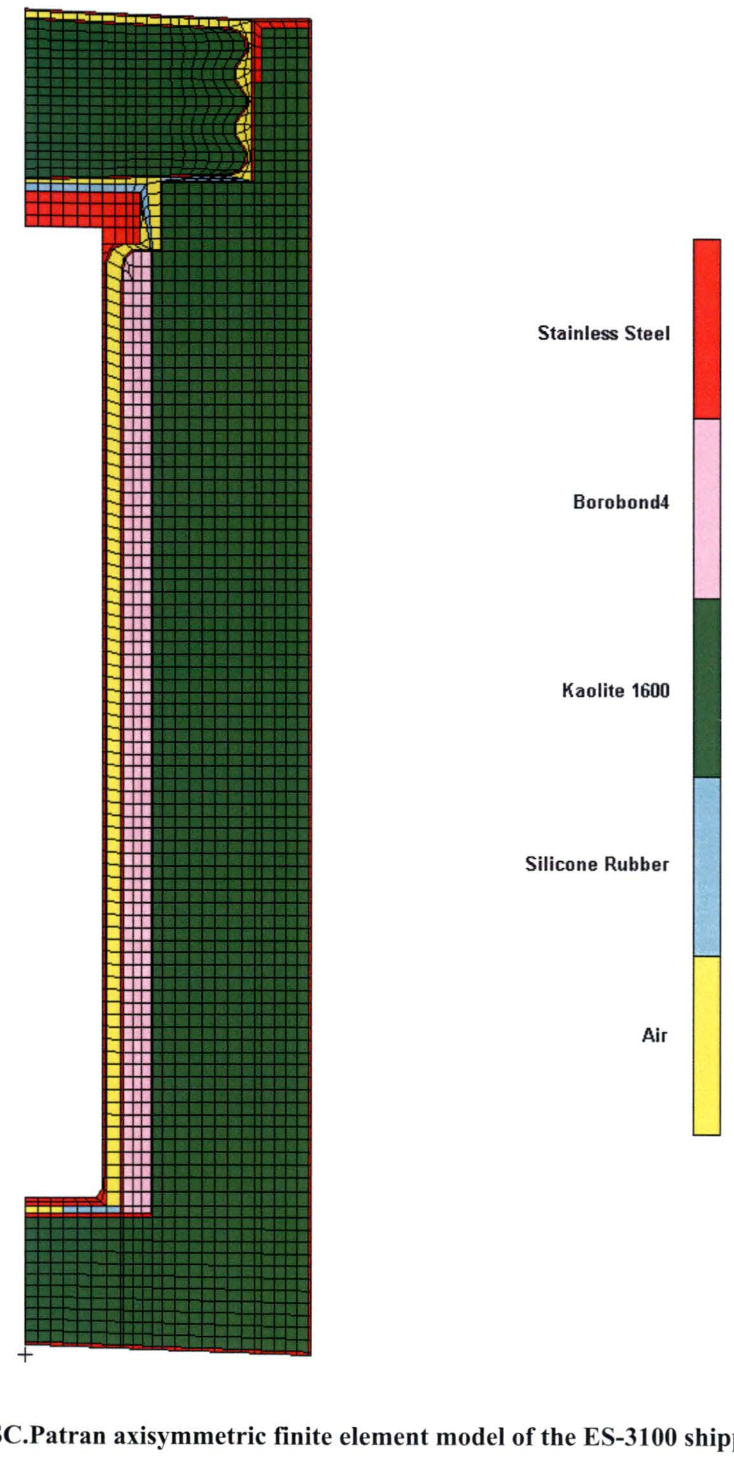


Figure 1. MSC.Patran axisymmetric finite element model of the ES-3100 shipping container.

Table 1. Thermal properties of the materials used in the thermal analysis.

Material	Temperature (°F)	Thermal conductivity (Btu/h-in.-°F)	Density (lbm/in.³)	Specific heat (Btu/lbm-°F)	Emissivity
Stainless steel	-279.67	0.443[(a)]	0.285[(a)]	0.065[(a)]	0.22[(a)]
	-99.67	0.607	–	0.096	–
	260.33	0.799	–	0.123	–
	620.33	0.953	–	0.133	–
	980.33	1.088	–	0.139	–
	1340.33	1.223	–	0.146	–
	1700.33	1.348	–	0.153	–
	2240.33	1.526	–	0.163	–
Kaolite 1600	68	0.0093[(b)]	0.011[(c)]	0.2[(d)]	–
	212	0.0091	–	–	–
	392	0.0081	–	–	–
	572	0.0072	–	–	–
	1112	0.0082	–	–	–
Borobond4	25	0.0450[(e)]	0.0683[(e)]	0.2160[(e)]	–
	77	0.0576	–	–	–
	100	0.0632	–	–	–
	104	0.0642	–	–	–
Silicone rubber	–	0.0161[(f)]	0.047[(f)]	0.300[(f)]	1.0[(g)]
Air	-9.67	1.074×10^{-3}[(a)]	4.064×10^{-5}[(a),(h)]	0.240[(a)]	–
	80.33	1.266×10^{-3}	–	0.241	–
	170.33	1.445×10^{-3}	–	0.241	–
	260.33	1.628×10^{-3}	–	0.242	–
	350.33	1.796×10^{-3}	–	0.244	–
	440.33	1.960×10^{-3}	–	0.246	–
	530.33	2.114×10^{-3}	–	0.248	–
	620.33	2.258×10^{-3}	–	0.251	–
	710.33	2.393×10^{-3}	–	0.254	–
	800.33	2.523×10^{-3}	–	0.257	–
	890.33	2.644×10^{-3}	–	0.260	–
	980.33	2.759×10^{-3}	–	0.263	–
	1070.33	2.870×10^{-3}	–	0.265	–
	1160.33	2.985×10^{-3}	–	0.268	–
	1250.33	3.096×10^{-3}	–	0.270	–
	1340.33	3.212×10^{-3}	–	0.273	–
	1520.33	3.443×10^{-3}	–	0.277	–

Notes:
(a) F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 2nd edition, John Wiley & Sons, New York, 1985.
(b) Hsin Wang, *Thermal Conductivity Measurements of Kaolite*, ORNL/TM-2003/49.
(c) Based on a baked density of 19.4 lbm/ft³ (0.011 lbm/in³). Specification JS-YMN3-801580-A003 requires a baked density of 22.4 ± 3 lbm/ft³. Using a lower value for the Kaolite density results in higher temperatures on the containment vessel because the heat capacity of the Kaolite is minimized—allowing more heat to flow to the containment vessel; therefore, the thermal analyses are performed using a low-end density of 19.4 lbm/ft³. The HAC analyses also consider a high-end density of 30 lbm/ft³.
(d) FAX communication from J. W. Breuer of Thermal Ceramics, Engineering Department, August 11, 1995.
(e) Data via email from Jim Hall (Eagle-Picher) to Jerry Byington (BWXT Y-12), March 12, 2004.
(f) THERM 1.2, thermal properties database by R. A. Bailey.
(g) Conservatively modeled as 1.0.
(h) Constant density value evaluated at 100°F.

MODELED HEAT TRANSFER MECHANISMS

The heat transfer mechanisms included in the thermal model such as thermal radiation, natural convection, and insolation (solar heat flux) are described in detail in the following sections.

Heat Transfer Between Package Exterior and Ambient

The heat transfer between the exterior of the package and the ambient (or fire) is modeled as a combination of radiant heat transfer and natural convection. The heat transfer due to radiant exchange with the environment is calculated as:[3]

$$q''_{rad} = \sigma F_e \left(T_s^4 - T_a^4\right), \tag{1}$$

where σ = Stefan-Boltzmann constant,
F_e = overall exchange factor,
T_s = container outer surface temperature (absolute), and
T_a = ambient or fire temperature (absolute).

The overall interchange factor is calculated as:[3]

$$F_e = \left[\frac{1}{\frac{1}{\varepsilon_p} + \frac{A_p}{A_s}\left(\frac{1}{\varepsilon_s} - 1\right)}\right], \tag{2}$$

where ε_p = emissivity of package surface,
A_p = surface area of the package,
A_s = surface area of the surroundings, and
ε_s = emissivity of surroundings.

For NCT and the cool-down period following the HAC fire, the area of the surroundings is assumed to be much larger than the surface area of the package; therefore, Eq. 2 reduces to:

$$F_e \approx \varepsilon_p . \tag{3}$$

An emissivity value of 0.22,[4] which is typical of clean stainless steel, is assumed for the outer surfaces of the drum during NCT and during the cool-down period following the HAC fire. In reality, the outer surfaces of the drum will have a much higher emissivity following the HAC fire; therefore, this assumption is conservative.

During the HAC fire, the area of the surroundings is assumed to be approximately equal to the surface area of the drum; therefore, Eq. 2 reduces to:

$$F_e = \left[\frac{1}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_s} - 1} \right]. \quad (4)$$

During the HAC 30-minute fire, an emissivity of 0.8 is assumed for the drum, and an emissivity of 0.9 is assumed for the fire per the guidance of 10 CFR 71.74(c)(4).[1] This results in an overall exchange factor of 0.7347 during the HAC fire using Eq. 4.

The natural convection heat transfer from the package surface to the ambient air is calculated as:

$$q''_{convection} = h\left(T_s - T_a\right). \quad (5)$$

where, h = natural convection heat transfer coefficient,
T_s = container outer surface temperature, and
T_a = ambient or fire temperature.

During the NCT transient thermal analyses and the steady-state thermal analyses (used to obtain the starting temperature distribution in the package for NCT and HAC when a content heat load is present), the shipping container is assumed to be in an upright (vertical) orientation. The top of the drum is modeled as a heated horizontal flat plate facing up using the following correlation:[5]

$$h = \left(\frac{k}{L}\right) C_1 \, Ra^{C_2}, \quad (6)$$

where, k = thermal conductivity of air,
L = characteristic length (= D/4 per Ref. 5),
D = diameter of the package,
Ra = Rayleigh number,
C_1 = constant (see Table 2), and
C_2 = constant (see Table 2).

The Rayleigh number in Eq. 6 is defined as:

$$Ra = \frac{g \beta \Delta T L^3}{\nu \alpha}, \quad (7)$$

where, g = acceleration of gravity,
β = coefficient of thermal expansion,
ΔT = temperature difference,
ν = kinematic viscosity [μ/ρ],
μ = absolute viscosity,
α = thermal diffusivity [$k/(\rho C_p)$],
ρ = density of air, and
C_p = specific heat of air.

The properties of air used in the natural convection calculations are presented in Table 3.

Table 2. Coefficients for natural convection correlations.

Coefficient	Rayleigh Number Range	Value
C_1	$2.6\times10^4 < Ra < 1.0\times10^7$ $1.0\times10^7 < Ra < 3.0\times10^{10}$	0.54 0.15
C_2	$2.6\times10^4 < Ra < 1.0\times10^7$ $1.0\times10^7 < Ra < 3.0\times10^{10}$	0.25 1/3
C_3	$Ra < 1.0\times10^9$ $Ra > 1.0\times10^9$	0.680 0.825
C_4	$Ra < 1.0\times10^9$ $Ra > 1.0\times10^9$	0.670 0.387
C_5	$Ra < 1.0\times10^9$ $Ra > 1.0\times10^9$	0.25 1/6
C_6	$Ra < 1.0\times10^9$ $Ra > 1.0\times10^9$	4/9 8/27
C_7	$Ra < 1.0\times10^9$ $Ra > 1.0\times10^9$	1 2
C_8	$1.0\times10^4 < Ra < 1.0\times10^9$ $1.0\times10^9 < Ra < 1.0\times10^{12}$	0.53 0.13
C_9	$1.0\times10^4 < Ra < 1.0\times10^9$ $1.0\times10^9 < Ra < 1.0\times10^{12}$	0.25 1/3

Source: *MSC.Patran Thermal User's Guide, Volume 1: Thermal/Hydraulic Analysis*, MSC.Software Corporation,Santa Ana, CA 92702, 2003.

Table 3. Properties of air used in natural convection calculations.

Temperature (K)	Thermal Conductivity (W/m-K)	Density (kg/m^3)	Specific heat (J/kg-K)	Absolute viscocity ($N\text{-}s/m^2$)	Coefficient of thermal expansion (K^{-1})
250	22.3×10^{-3}	1.3947	1006	159.6×10^{-7}	4.00×10^{-3}
300	26.3×10^{-3}	1.1614	1007	184.6×10^{-7}	3.33×10^{-3}
350	30.0×10^{-3}	0.9950	1009	208.2×10^{-7}	2.86×10^{-3}
400	33.8×10^{-3}	0.8711	1014	230.1×10^{-7}	2.50×10^{-3}
450	37.3×10^{-3}	0.7740	1021	250.7×10^{-7}	2.22×10^{-3}
500	40.7×10^{-3}	0.6964	1030	270.1×10^{-7}	2.00×10^{-3}
550	43.9×10^{-3}	0.6329	1040	288.4×10^{-7}	1.82×10^{-3}
600	46.9×10^{-3}	0.5804	1051	305.8×10^{-7}	1.67×10^{-3}
650	49.7×10^{-3}	0.5356	1063	322.5×10^{-7}	1.54×10^{-3}
700	52.4×10^{-3}	0.4975	1075	338.8×10^{-7}	1.43×10^{-3}
750	54.9×10^{-3}	0.4643	1087	354.6×10^{-7}	1.33×10^{-3}
800	57.3×10^{-3}	0.4354	1099	369.8×10^{-7}	1.25×10^{-3}
850	59.6×10^{-3}	0.4097	1110	384.3×10^{-7}	1.18×10^{-3}
900	62.0×10^{-3}	0.3868	1121	398.1×10^{-7}	1.11×10^{-3}
950	64.3×10^{-3}	0.3666	1131	411.3×10^{-7}	1.05×10^{-3}
1000	66.7×10^{-3}	0.3482	1141	424.4×10^{-7}	1.00×10^{-3}
1100	71.5×10^{-3}	0.3166	1159	449.0×10^{-7}	9.09×10^{-4}

Source: F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 2nd ed., John Wiley & Sons, New York, 1985.

During the NCT transient thermal analyses and the steady-state thermal analyses, the sides of the drum are modeled as a vertical flat plate using the following correlation:[5]

$$h=\left(\frac{k}{L}\right)\left[C_3+\frac{C_4\,Ra^{C_5}}{\left(1+\left[\frac{0.492}{Pr}\right]^{9/16}\right)^{C_6}}\right]^{C_7}, \qquad (8)$$

where
L = characteristic length = the drum height,
C_3 = constant (see Table 2),
C_4 = constant (see Table 2),
C_5 = constant (see Table 2),
C_6 = constant (see Table 2),
C_7 = constant (see Table 2), and
Pr = Prandtl number $[(C_p \times \mu)/k]$.

The bottom of the drum is conservatively modeled as adiabatic during the NCT transient analyses and the steady-state analyses.

During the HAC 30-minute fire and the post-fire cool-down, the shipping container is assumed to be in a horizontal orientation (as it is during furnace testing). As such, the top and bottom of the drum are modeled as vertical flat plates using Eq. 8 having a characteristic length, L, equivalent to the drum diameter, and the sides of the drum are modeled as a horizontal cylinder using the following correlation:[5]

$$h=\left(\frac{k}{D}\right)C_8\,Ra^{C_9}, \qquad (9)$$

where
D = diameter of the package,
C_8 = constant (see Table 2), and
C_9 = constant (see Table 2).

Insolation

The following insolation (incident solar radiation) data is required for NCT per 10 CFR 71.71(c)(1):[1]

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

The total insolation values specified in the previous table are for a 12-hour period. For analytical purposes, these values are "time-averaged" over the entire 12-hour period (i.e., divided by 12).

Therefore, the incident solar heat fluxes ($q''_{solar,i}$) used in the analyses for NCT and cool-down following the HAC fire are as follows:

During NCT, the drum is in an upright (vertical) orientation; therefore, the following heat fluxes are applied to the external surfaces of the drum to represent insolation:

Top $$q''_{solar,i} = 775.3\,W/m^2, \quad (10)$$

Sides $$q''_{solar,i} = 387.7\,W/m^2, \quad (11)$$

Bottom $$q''_{solar,i} = 0. \quad (12)$$

During the cool-down period following the HAC 30-minute fire, the drum is assumed to be in a horizontal orientation; therefore, the following heat fluxes are applied to the external surfaces of the drum to represent insolation:

Top $$q''_{solar,i} = 193.83\,W/m^2, \quad (13)$$

Sides $$q''_{solar,i} = 387.7\,W/m^2, \quad (14)$$

Bottom $$q''_{solar,i} = 193.83\,W/m^2. \quad (15)$$

The insolation is applied as a square-wave function (i.e., alternating on and off in 12-hour periods) in the thermal analysis. The heat flux values presented in Eqs. 10–15 represent the insolation absorbed by the package surface since a drum absorptivity of 1.0 was conservatively assumed. An analytical study has been performed on a similar shipping package that investigated three methods of applying the insolation.[6] The three methods consisted of 1) performing a steady-state analysis assuming the insolation is applied continuously by distributing the heat flux evenly throughout a 24-hour period, 2) performing a transient analysis assuming the insolation is represented by a step function (i.e., applied and then not applied in 12-hour cycles, and 3) performing a transient analysis where the incident insolation is represented by a sinusoidal function that varies throughout the day. The results of the study indicate that the method used in applying the insolation has a significant effect on the temperatures of the outermost portions of the package. However, since the total insolation over any 24-hour period is the same for all cases, internal package temperatures are relatively unaffected by the way in which the insolation is applied. Since containment vessel O-ring temperatures are of primary concern in this report, the step function method for applying the insolation is suitable.

Heat Transfer Across Gaps in the Package

Heat transfer across all gaps in the package is modeled by a combination of radiant exchange and conduction. Natural convection heat transfer is not included across the gaps in the model. Scoping studies performed for a similar shipping package indicate that the heat transfer due to natural convection in relatively small gaps is approximately a factor of 6 times less than the heat transfer due to radiant exchange.[6] These calculations assumed a temperature difference of 5°C across the gap. Based on these previous calculations, the effect of neglecting the natural convection in the gap regions is minimal. P/VIEWFACTOR[7] was used to calculate the view factors in all enclosures.

Content Heat Load

In order to simulate the decay heat generated by the ES-3100 shipping container contents, a uniform heat flux is applied to the inner surfaces of the elements representing the containment vessel in the model. Content heat loads of 0.4, 20, and 30 W as well as no content heat load are investigated in this report. The uniform heat flux (q''_{source}) for a given content heat load is calculated using the following equation:

$$q''_{source} = \frac{Q}{2\left(\frac{\pi D_i^2}{4}\right) + \pi(D_i)(H)}, \qquad (16)$$

where
- Q = content heat load,
- D_i = inside diameter of the containment vessel (0.12802 m),
- H = height of the containment vessel cavity (0.78867 m).

Using Eq. 16, a content heat load of 0.4 W results in a uniform heat flux of 1.1664 W/m^2, a content heat load of 20 W results in a uniform heat flux of 58.32 W/m^2, and a content heat load of 30 W results in a uniform heat flux of 87.48 W/m^2.

DISCUSSION OF ANALYTICAL RESULTS

All thermal analyses discussed in this report were performed using MSC.Patran Thermal (2004 Version 12.0.044)[8] on an Intel Pentium 4–based Microsoft Windows 2000 computer. Temperatures are monitored at selected locations in the model as shown in Figure 2.

Steady-state Conditions Analyses Results

Steady-state thermal analyses are performed on the finite element model of the ES-3100 shipping container for three cases having content heat loads of 0.4, 20, and 30 W. The temperature distribution results from these analyses are used as the starting temperature distribution within the model when performing the transient thermal analyses for NCT and the HAC 30-minute fire. The boundary conditions for these steady-state analyses include a combination of thermal radiation exchange and natural convection applied to the top and sides of the drum using an ambient temperature of 37.8°C (100°F). The bottom of the drum is modeled as an adiabatic surface (i.e., no heat transfer). Additionally, the content heat load is simulated by applying a uniform heat flux to the internal surfaces of the elements representing the containment vessel. The calculated steady-state temperature distribution with the model of the ES-3100 shipping container for content heat loads of 0.4, 20, and 30 W is presented in Table 4.

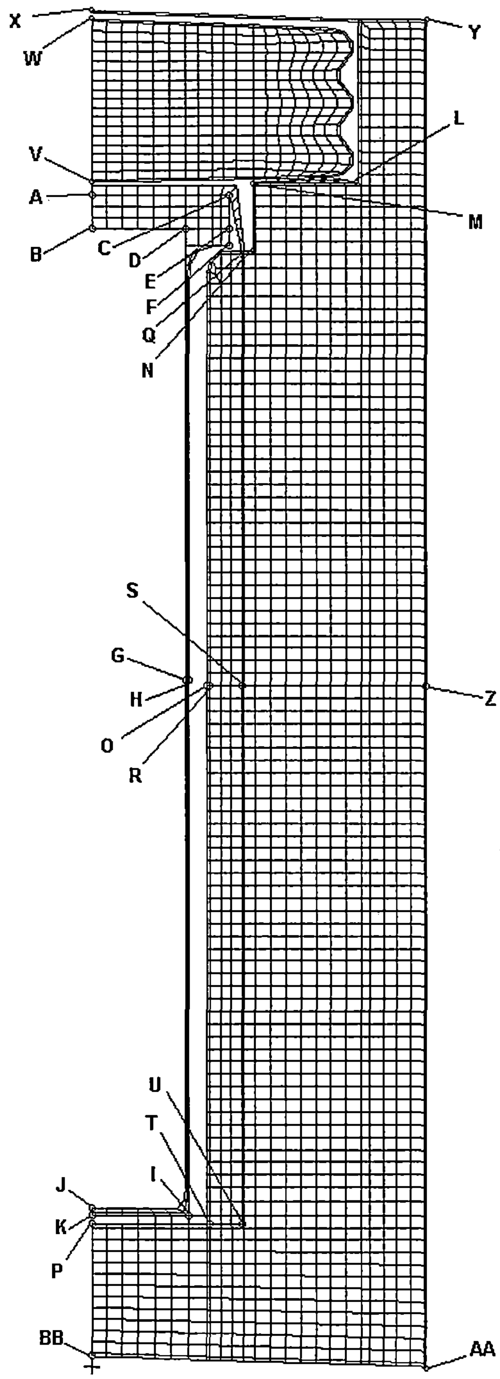


Figure 2. MSC.Patran axisymmetric finite element model of the ES-3100 shipping container—nodal locations of interest (elements representing air not shown for clarity).

Table 4. **ES-3100 shipping container steady-state temperatures (37.8°C ambient temperature, no insolation).**

Node[(a)]	Location	Steady-state temperature, °C (°F)		
		0.4 W	20 W	30 W
A	CV lid, top, center	38.09 (100.56)	56.06 (132.90)	64.65 (148.37)
B	CV lid, bottom, center	38.09 (100.56)	56.16 (133.08)	64.79 (148.63)
C	CV lid, top, outer	38.09 (100.55)	55.82 (132.47)	64.30 (147.73)
D	CV flange at interface, inner[(b)]	38.09 (100.57)	56.17 (133.10)	64.81 (148.66)
E	CV flange at interface, outer[(b)]	38.09 (100.56)	56.06 (132.90)	64.65 (148.37)
F	CV flange, bottom, outer	38.09 (100.56)	56.05 (132.88)	64.63 (148.34)
G	CV shell, mid-height, inner	38.36 (101.04)	69.36 (156.85)	83.91 (183.04)
H	CV shell, mid-height, outer	38.36 (101.04)	69.35 (156.83)	83.90 (183.01)
I	CV bottom, outer	38.18 (100.72)	59.56 (139.20)	69.97 (157.94)
J	CV bottom, center, inner	38.18 (100.72)	59.65 (139.38)	70.11 (158.20)
K	CV bottom, center, outer	38.18 (100.72)	59.64 (139.35)	70.09 (158.17)
L	Drum liner, plug cavity, outer	37.85 (100.13)	43.26 (109.87)	45.81 (114.46)
M	Drum liner, plug cavity, inner	37.91 (100.25)	46.93 (116.47)	51.29 (124.33)
N	Drum liner, CV flange cavity, outer	37.97 (100.34)	49.87 (121.77)	55.70 (132.26)
O	Drum liner, CV cavity, mid-height, inner	38.07 (100.52)	55.08 (131.15)	63.53 (146.36)
P	Drum liner, CV cavity, bottom, inner	38.12 (100.62)	56.87 (134.37)	66.02 (150.83)
Q	Borobond4, top, outer	37.97 (100.35)	50.31 (122.55)	56.35 (133.43)
R	Borobond4, mid-height, inner	38.07 (100.52)	55.08 (131.14)	63.53 (146.35)
S	Borobond4, mid-height, outer	38.12 (100.50)	54.45 (130.02)	62.59 (144.66)
T	Borobond4, bottom, inner	38.08 (100.55)	54.95 (130.91)	63.21 (145.79)
U	Borobond4, bottom, outer	38.07 (100.52)	54.16 (129.48)	62.05 (143.69)
V	Drum plug liner, bottom, center	37.82 (100.07)	41.36 (106.46)	42.96 (109.34)
W	Drum plug liner, top, center	37.98 (100.37)	50.51 (122.93)	56.59 (133.87)
X	Drum lid, top, center	37.79 (100.03)	39.82 (103.67)	40.67 (105.20)
Y	Drum lid, top, outer	37.79 (100.03)	40.08 (104.14)	41.06 (105.90)
Z	Drum, mid-height, outer	37.84 (100.11)	41.60 (106.88)	43.26 (109.86)
AA	Drum bottom, outer	37.85 (100.13)	41.94 (107.50)	43.76 (110.76)
BB	Drum bottom, center	37.91 (100.23)	45.14 (113.25)	48.51 (119.33)

Notes: (a) See Figure 2.
(b) Approximate location of the CV O-ring.

Normal Conditions of Transport Analyses Results

Transient thermal analyses are performed on the finite element model of the ES-3100 shipping container to simulate NCT with content heat loads of 0, 0.4, 20, and 30 W. The insolation required for NCT per 10 CFR 71.71(c)(1)[1] is applied to the top and sides of the drum in alternating 12-hour periods (i.e., 12 hours on and 12 hours off) with the drum bottom remaining adiabatic during the transient thermal analysis. An ambient temperature of 37.8°C (100°F) as stipulated in 10 CFR 71 is used in the NCT analysis. The initial temperature distribution within the package for the NCT transients was determined from steady-state analyses (with radiation and natural convection boundary conditions applied to the top and sides of the drum) for each internal heat load. For the case with no internal heat source (0 W), the initial temperature distribution within the package was assumed to be at a uniform 37.8°C (100°F).

The transient thermal analyses simulate a five-day period of cyclic solar loading with 12 hours of insolation being applied at the beginning of each day (i.e., onset of sunrise) followed by 12 hours in which there is no insolation to end the day (i.e., onset of sunset). This five-day period allows for "quasi

steady-state" conditions to be reached. While the temperature of a particular node within the model changes with respect to time in the transient analyses, the maximum temperature that node reaches from day-to-day does not change once a "quasi steady-state" condition is reached. In particular, the maximum temperature of the key location on the containment vessel (i.e., at the O-ring) on day 5 is within 0.01°C of the maximum temperature of the same location on day 4.

The maximum temperatures of several locations within the model are summarized in Table 5 and Table 6 for content heat loads of 0, 0.4, 20, and 30 W and Kaolite densities of 30 (maximum density) and 19.4 lbm/ft^3 (minimum density), respectively. The maximum temperatures reported in Table 5 and Table 6 represent "quasi steady-state." Temperature-history plots of several locations within the model are also depicted graphically in Figure 3 through Figure 10 for various content heat loads and Kaolite density. Additionally, temperature contours of the model at sunrise (0 hours) and sunset (12 hours) for day 5 of the transient are presented in Figure 11 through Figure 18 for various content heat loads and Kaolite density. The elements representing the air between the drum liner and containment vessel and between the drum liner and top plug liner are not shown in the temperature contours presented in these figures so that the containment vessel temperature contours can be more easily viewed.

The maximum temperature in the model occurs at the top center of the drum lid. This maximum temperature is 118.01°C (244.42°F), 118.03°C (244.45°F), 118.77°C (245.79°F), and 119.15°C (246.47°F) for content heat loads of 0, 0.4, 20, and 30 W, respectively, and occurs at sunset in each case (see Table 6, Kaolite density of 19.4 lbm/ft^3). The maximum temperature at the containment vessel O-ring is 88.25°C (190.84°F), 88.56°C (191.41°F), 103.87°C (218.96°F), and 111.42°C (232.55°F) for content heat loads of 0, 0.4, 20, and 30 W, respectively, and occurs at approximately 1 hour after sunset in each case (see Table 6, Kaolite density of 19.4 lbm/ft^3).

Table 5. Maximum "quasi steady-state" temperatures during NCT for the ES-3100 shipping container with various content heat loads (see Figure 2 for node locations)—Kaolite density of 30 lbm/ft^3.

Node[(a)]	Location	Maximum "quasi steady-state" temperature, °C (°F)			
		0 W	0.4 W	20 W	30 W
A	CV lid, top, center	86.56 (187.81)	86.88 (188.38)	102.98 (215.74)	109.59 (229.26)
B	CV lid, bottom, center	86.56 (187.80)	86.88 (188.38)	102.16 (215.90)	109.71 (229.47)
C	CV lid, top, outer	86.54 (187.78)	86.86 (188.34)	101.89 (215.41)	109.31 (228.75)
D	CV flange at interface, inner[(b)]	86.47 (187.64)	86.79 (188.21)	102.09 (215.77)	109.67 (229.40)
E	CV flange at interface, outer[(b)]	86.44 (187.59)	86.76 (188.16)	102.00 (215.61)	109.53 (229.15)
F	CV flange, bottom, outer	86.42 (187.56)	86.74 (188.13)	101.99 (215.58)	109.51 (229.12)
G	CV shell, mid-height, inner	81.52 (178.74)	82.09 (179.76)	109.01 (228.21)	121.98 (251.57)
H	CV shell, mid-height, outer	81.52 (178.74)	82.09 (179.76)	109.00 (228.19)	121.97 (251.55)
I	CV bottom, outer	81.32 (178.37)	81.71 (179.08)	100.57 (213.02)	109.99 (229.99)
J	CV bottom, center, inner	81.37 (178.47)	81.77 (179.18)	100.73 (213.31)	110.21 (230.38)
K	CV bottom, center, outer	81.37 (178.47)	81.77 (179.18)	100.72 (213.29	110.19 (230.34)
L	Drum liner, plug cavity, outer	97.74 (207.93)	97.82 (208.07)	101.65 (214.96)	103.59 (218.47)
M	Drum liner, plug cavity, inner	92.91 (199.23)	93.06 (199.50)	100.40 (212.72)	104.13 (219.43)
N	Drum liner, CV flange cavity, outer	87.69 (189.84)	87.90 (190.21)	98.09 (208.57)	103.27 (217.43)
O	Drum liner, CV cavity, mid-height, inner	81.30 (178.35)	81.61 (178.90)	96.82 (206.27)	104.13 (219.43)
P	Drum liner, CV cavity, bottom, inner	81.52 (178.74)	81.86 (179.35)	98.30 (208.94)	106.56 (223.80)
Q	Borobond4, top, outer	87.36 (189.25)	87.58 (189.64)	98.19 (208.74)	103.57 (218.43)
R	Borobond4, mid-height, inner	81.30 (178.35)	81.61 (178.90)	98.81 (206.26)	104.58 (220.24)
S	Borobond4, mid-height, outer	81.37 (178.46)	81.66 (178.99)	96.24 (205.23)	103.69 (218.64)
T	Borobond4, bottom, inner	81.67 (179.01)	81.98 (179.56)	96.73 (206.12)	104.19 (219.55)
U	Borobond4, bottom, outer	81.78 (179.21)	82.07 (179.72)	96.11 (205.00)	103.23 (217.81)
V	Drum plug liner, bottom, center	111.30 (232.35)	111.34 (232.42)	113.25 (235.85)	114.21 (237.57)
W	Drum plug liner, top, center	90.70 (195.26)	90.92 (195.66)	101.53 (214.76)	106.87 (224.36)
X	Drum lid, top, center	117.74 (243.93)	117.75 (243.96)	118.50 (245.30)	118.88 (245.98)
Y	Drum lid, top, outer	107.04 (224.68)	107.06 (224.71)	107.94 (226.29)	108.39 (227.10)
Z	Drum, mid-height, outer	91.86 (197.36)	91.90 (197.41)	93.42 (200.15)	94.18 (201.53)
AA	Drum bottom, outer	91.00 (195.79)	91.04 (195.86)	92.92 (199.26)	93.87 (200.96)
BB	Drum bottom, center	87.21 (188.97)	87.31 (189.15)	92.26 (198.07)	94.74 (202.54)

Notes: (a) See Figure 2.
(b) Approximate location of the CV O-ring.

Table 6. Maximum "quasi steady-state" temperatures during NCT for the ES-3100 shipping container with various content heat loads (see Figure 2 for node locations)—Kaolite density of 19.4 lbm/ft^3.

Node[(a)]	Location	Maximum "quasi steady-state" temperature, °C (°F)			
		0 W	0.4 W	20 W	30 W
A	CV lid, top, center	88.30 (190.95)	88.62 (191.52)	103.84 (218.91)	111.35 (232.42)
B	CV lid, bottom, center	88.28 (190.90)	88.60 (191.48)	103.90 (219.03)	111.45 (232.62)
C	CV lid, top, outer	88.32 (190.97)	88.63 (191.54)	103.61 (218.50)	111.00(231.80)
D	CV flange at interface, inner[(b)]	88.24 (190.83)	88.56 (191.41)	103.87 (218.96)	111.42 (232.55)
E	CV flange at interface, outer[(b)]	88.25 (190.84)	88.56 (191.41)	103.77 (218.78)	111.27 (232.28)
F	CV flange, bottom, outer	88.24 (190.82)	88.55 (191.39)	103.75 (218.75)	111.25 (232.24)
G	CV shell, mid-height, inner	83.04 (181.47)	83.61 (182.50)	110.50 (230.89)	123.46 (254.23)
H	CV shell, mid-height, outer	83.04 (181.47)	83.61 (182.50)	110.49 (230.88)	123.45 (254.21)
I	CV bottom, outer	83.36 (182.04)	83.75 (182.74)	102.58 (216.64)	111.99 (233.59)
J	CV bottom, center, inner	88.37 (182.07)	83.76 (182.77)	102.70 (216.86)	112.17 (233.91)
K	CV bottom, center, outer	88.37 (181.07)	83.76 (182.77)	102.69 (216.84)	112.15 (233.87)
L	Drum liner, plug cavity, outer	98.72 (209.70)	98.80 (209.85)	102.63 (216.73)	104.58 (220.24)
M	Drum liner, plug cavity, inner	94.43 (201.97)	94.58 (202.24)	101.92 (215.46)	105.65 (222.16)
N	Drum liner, CV flange cavity, outer	89.43 (192.97)	89.63 (193.34)	99.83 (211.70)	105.01 (221.02)
O	Drum liner, CV cavity, mid-height, inner	83.12 (181.62)	83.43 (182.18)	98.63 (209.54)	106.40 (223.52)
P	Drum liner, CV cavity, bottom, inner	83.62 (182.52)	83.96 (183.13)	100.36 (212.65)	108.60 (227.48)
Q	Borobond4, top, outer	88.82 (191.88)	89.04 (192.27)	99.65 (211.38)	105.04 (221.07)
R	Borobond4, mid-height, inner	83.12 (181.62)	83.43 (182.18)	98.63 (209.53)	106.39 (223.51)
S	Borobond4, mid-height, outer	83.03 (181.46)	83.33 (182.00)	97.91 (208.23)	105.36 (221.65)
T	Borobond4, bottom, inner	83.55 (182.39)	83.85 (182.93)	98.58 (209.45)	106.03 (222.86)
U	Borobond4, bottom, outer	83.51 (182.31)	83.80 (182.83)	97.82 (208.07)	104.90 (238.82)
V	Drum plug liner, bottom, center	112.01 (233.62)	112.05 (233.69)	113.95 (237.11)	114.90 (238.82)
W	Drum plug liner, top, center	92.09 (197.77)	92.31 (198.16)	102.93 (217.27)	108.26 (226.87)
X	Drum lid, top, center	118.01 (244.42)	118.03 (244.45)	118.77 (245.79)	119.15 (246.47)
Y	Drum lid, top, outer	107.33 (225.19)	107.34 (225.22)	108.22 (226.80)	108.67 (227.60)
Z	Drum, mid-height, outer	92.27 (198.08)	92.30 (198.14)	93.81 (200.86)	94.58 (202.24)
AA	Drum bottom, outer	91.70 (197.06)	91.74 (197.13)	93.61 (200.49)	94.54 (202.18)
BB	Drum bottom, center	88.82 (191.88)	88.93 (192.07)	93.84 (200.91)	96.30 (205.35)

Notes: (a) See Figure 2.
(b) Approximate location of the CV O-ring.

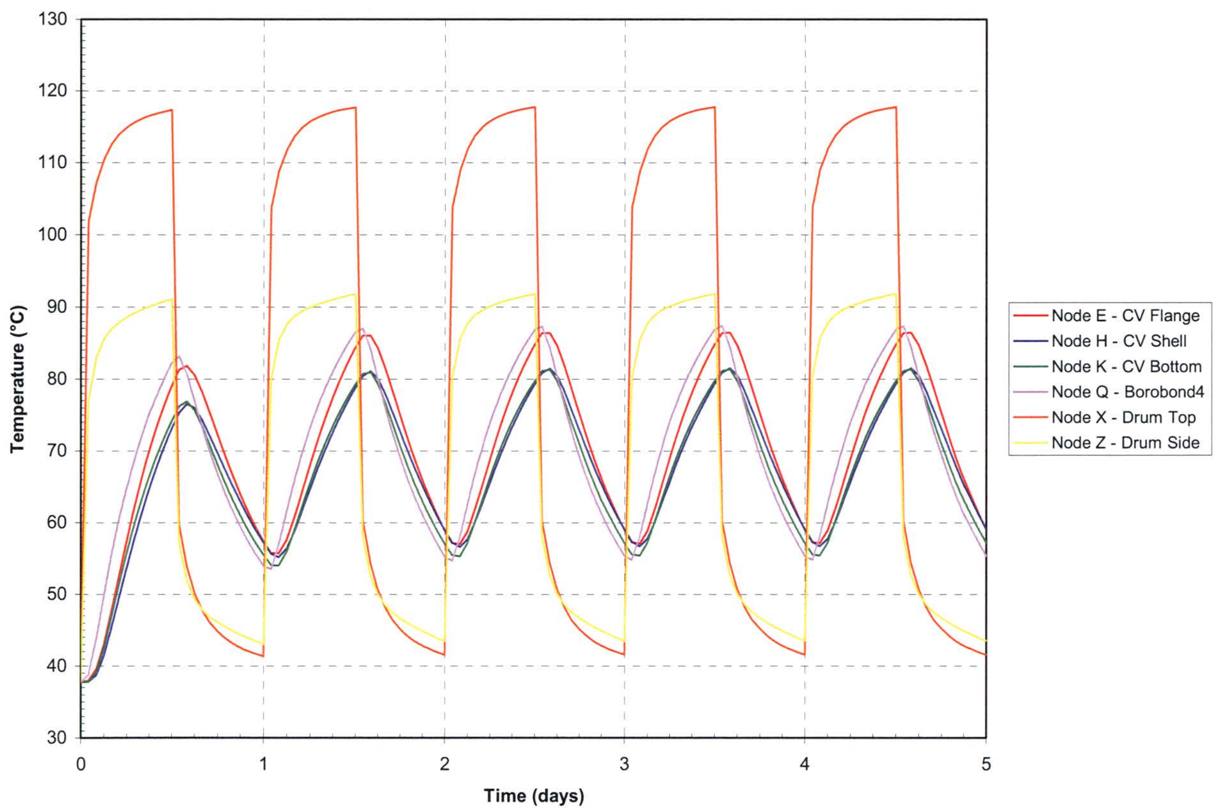


Figure 3. Transient temperatures of the ES-3100 shipping container for NCT (no content heat load) Kaolite density of 30 lbm/ft^3 (see Figure 2 for node locations).

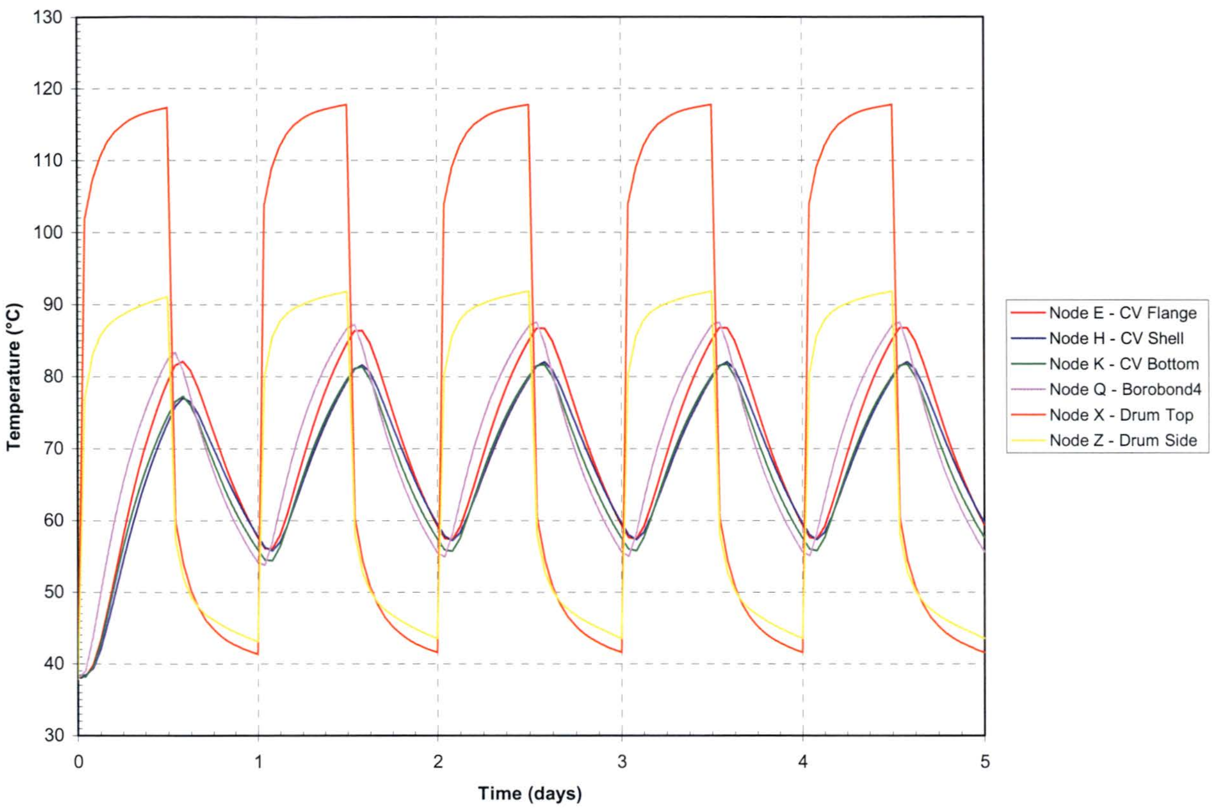


Figure 4. Transient temperatures of the ES-3100 shipping container for NCT (0.4 W content heat load) Kaolite density of 30 lbm/ft^3 (see Figure 2 for node locations).

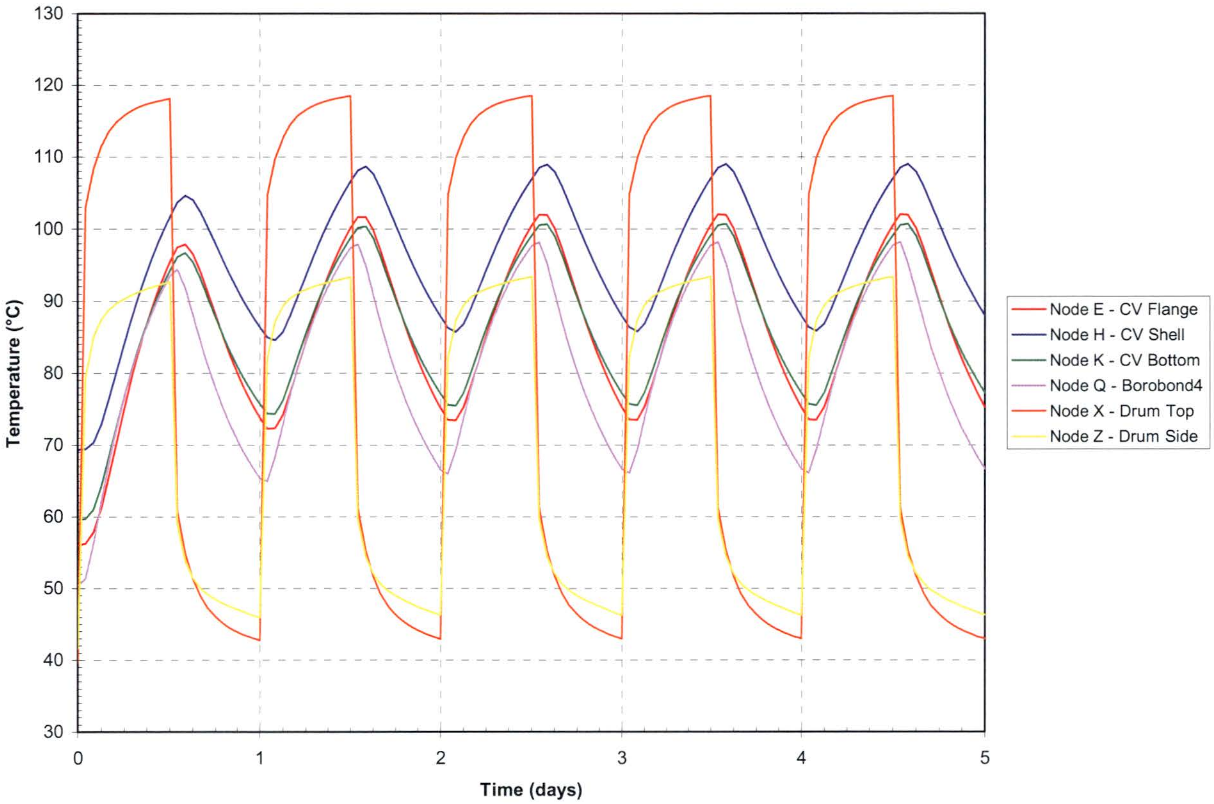


Figure 5. Transient temperatures of the ES-3100 shipping container for NCT (20 W content heat load) Kaolite density of 30 lbm/ft^3 (see Figure 2 for node locations).

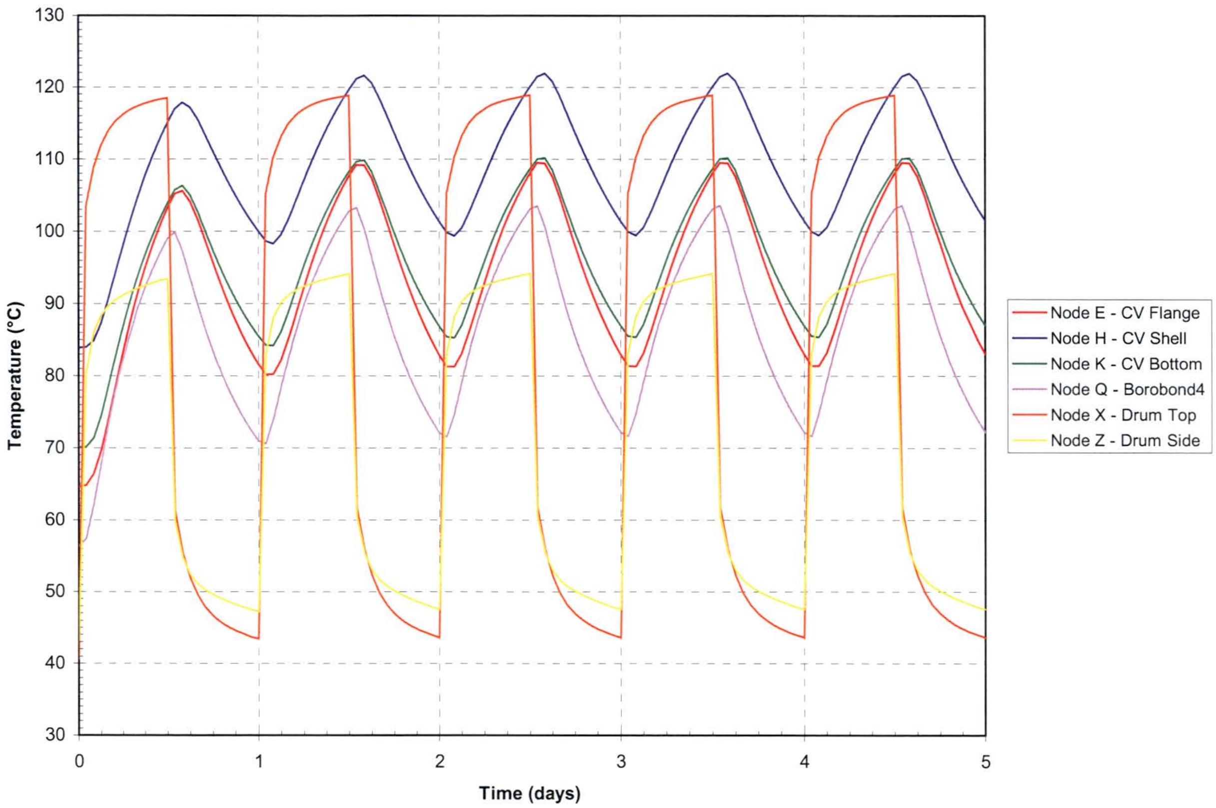


Figure 6. Transient temperatures of the ES-3100 shipping container for NCT (30 W content heat load)Kaolite density of 30 lbm/ft^3 (see Figure 2 for node locations).

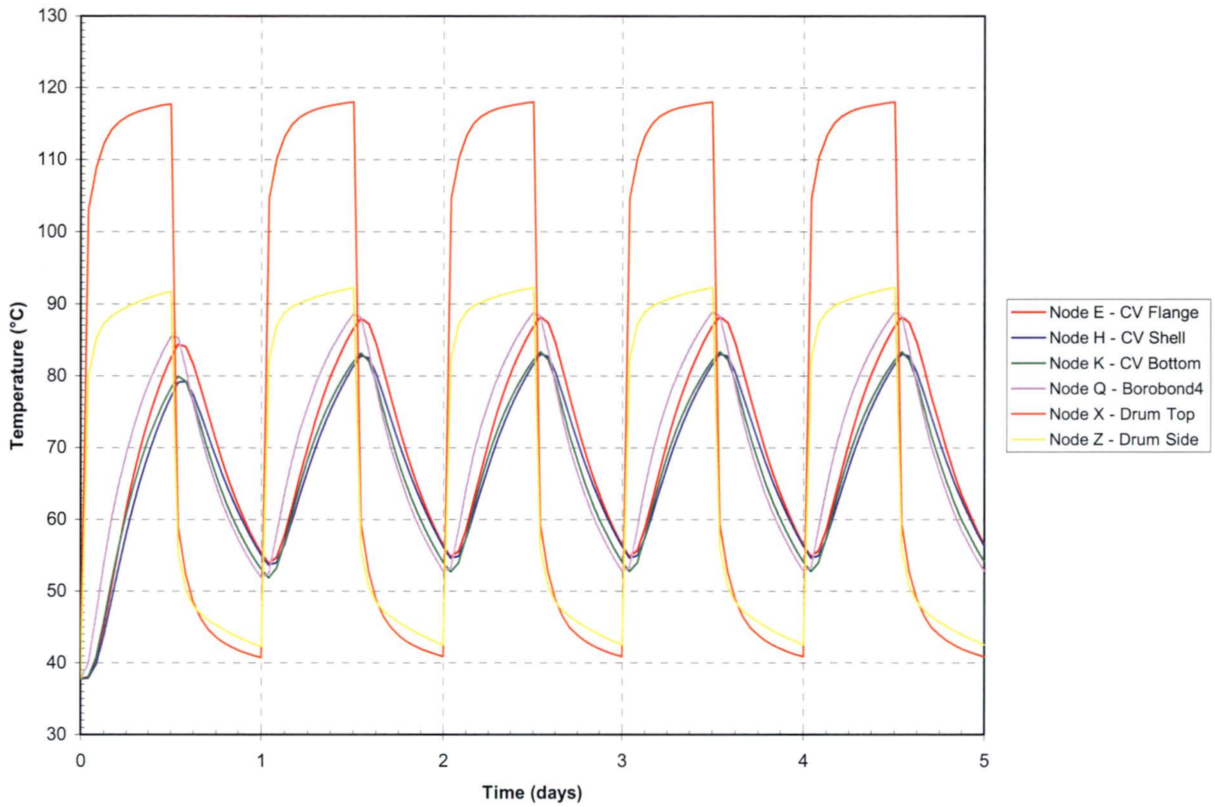


Figure 7. Transient temperatures of the ES-3100 shipping container for NCT (no content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).

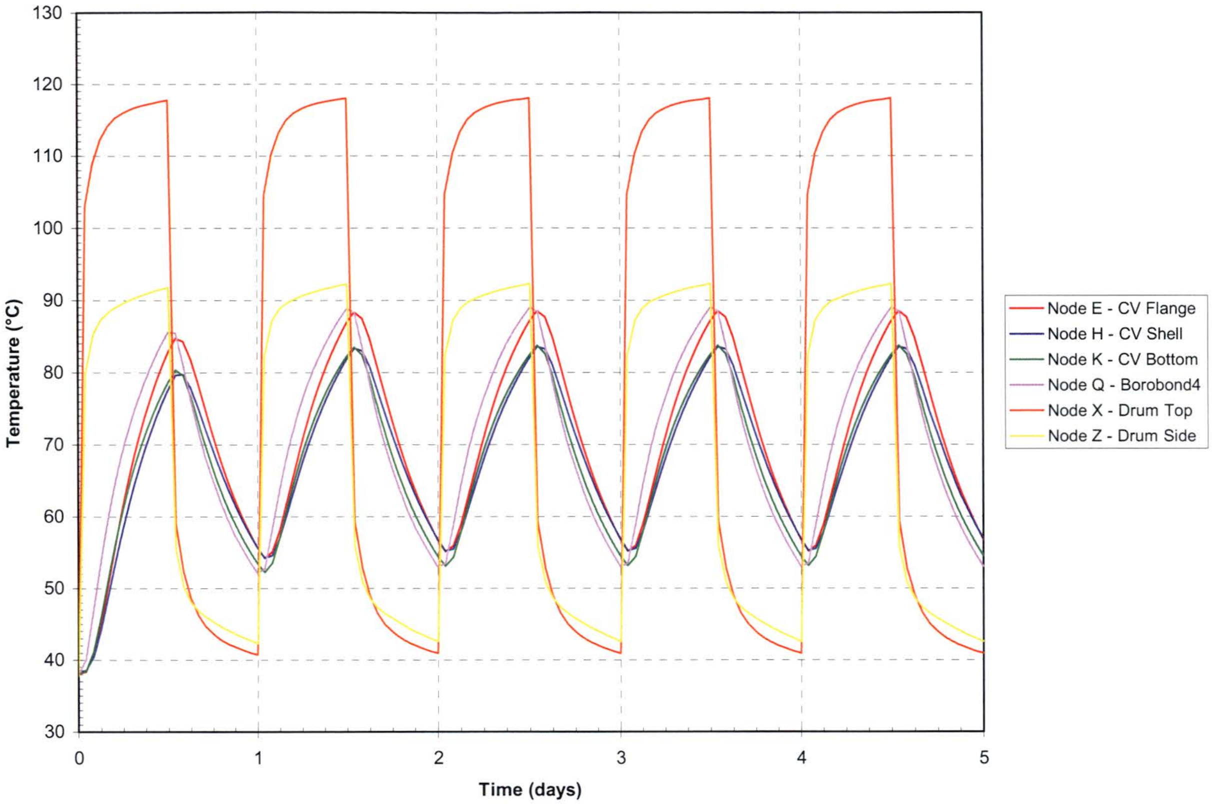


Figure 8. Transient temperatures of the ES-3100 shipping container for NCT (0.4 W content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).

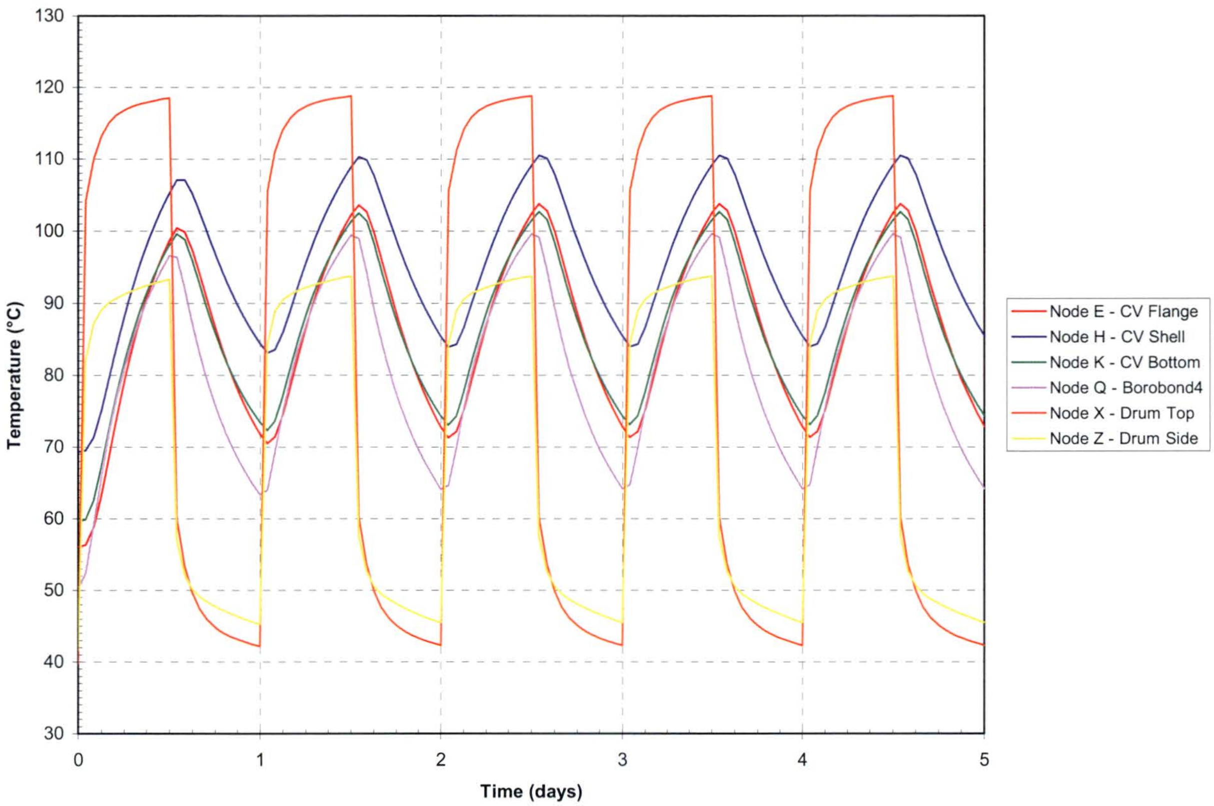


Figure 9. Transient temperatures of the ES-3100 shipping container for NCT (20 W content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).

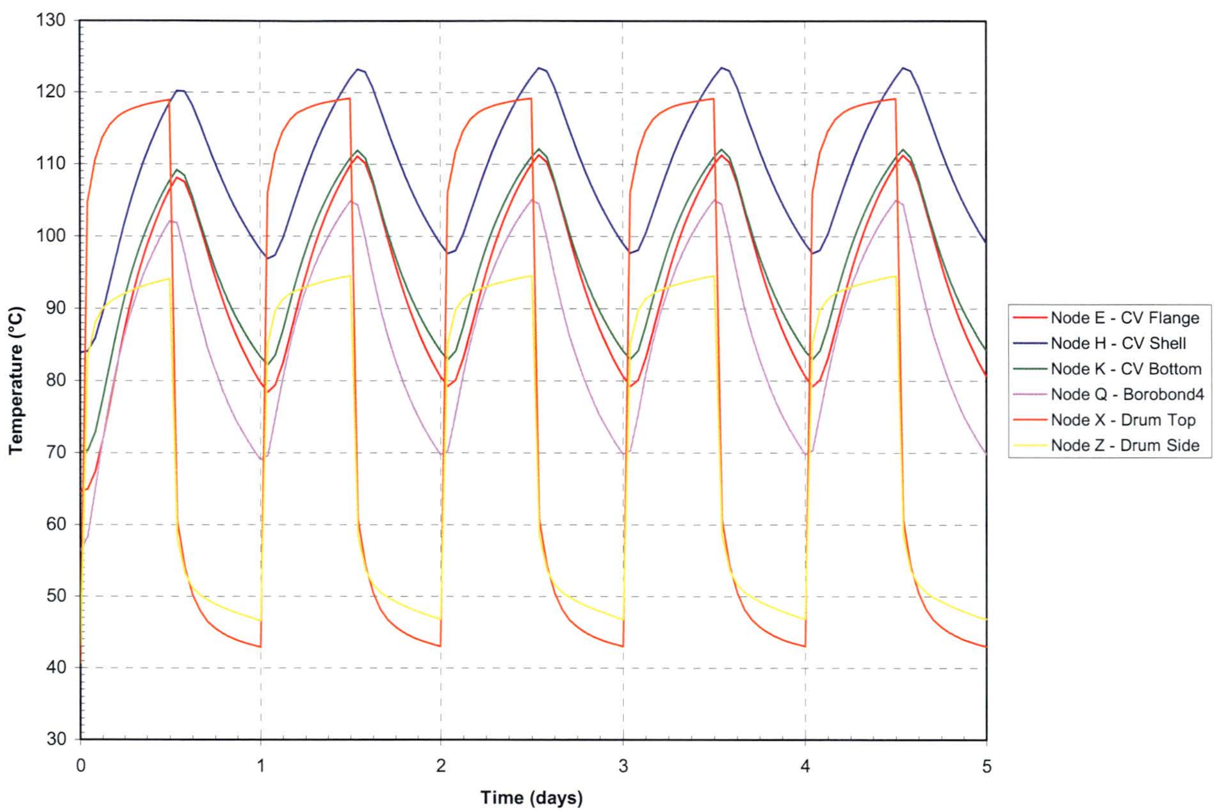


Figure 10. Transient temperatures of the ES-3100 shipping container for NCT (30 W content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).

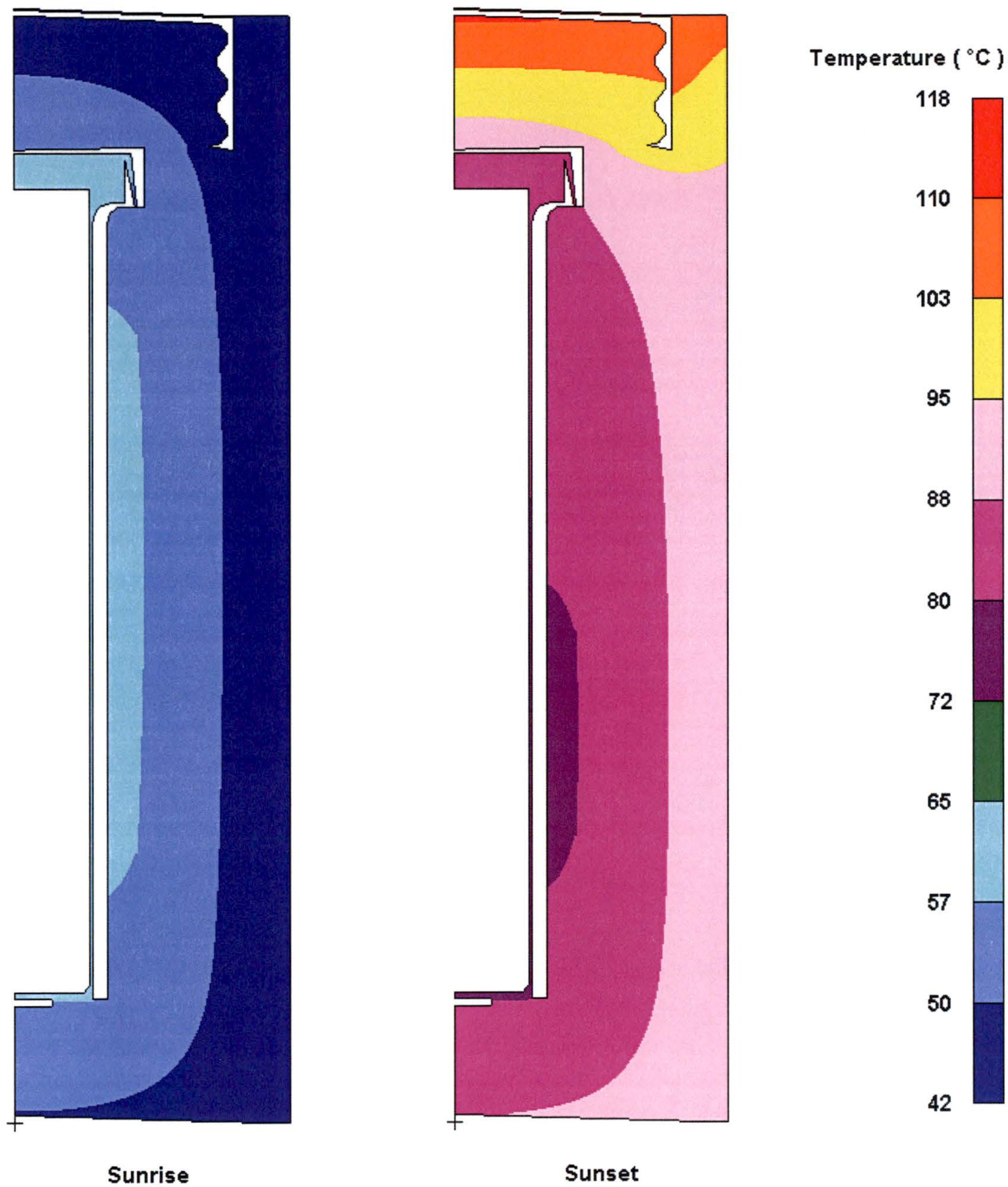


Figure 11. Temperature distribution in the ES-3100 shipping container for NCT (no content heat load)—Kaolite density of 30 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

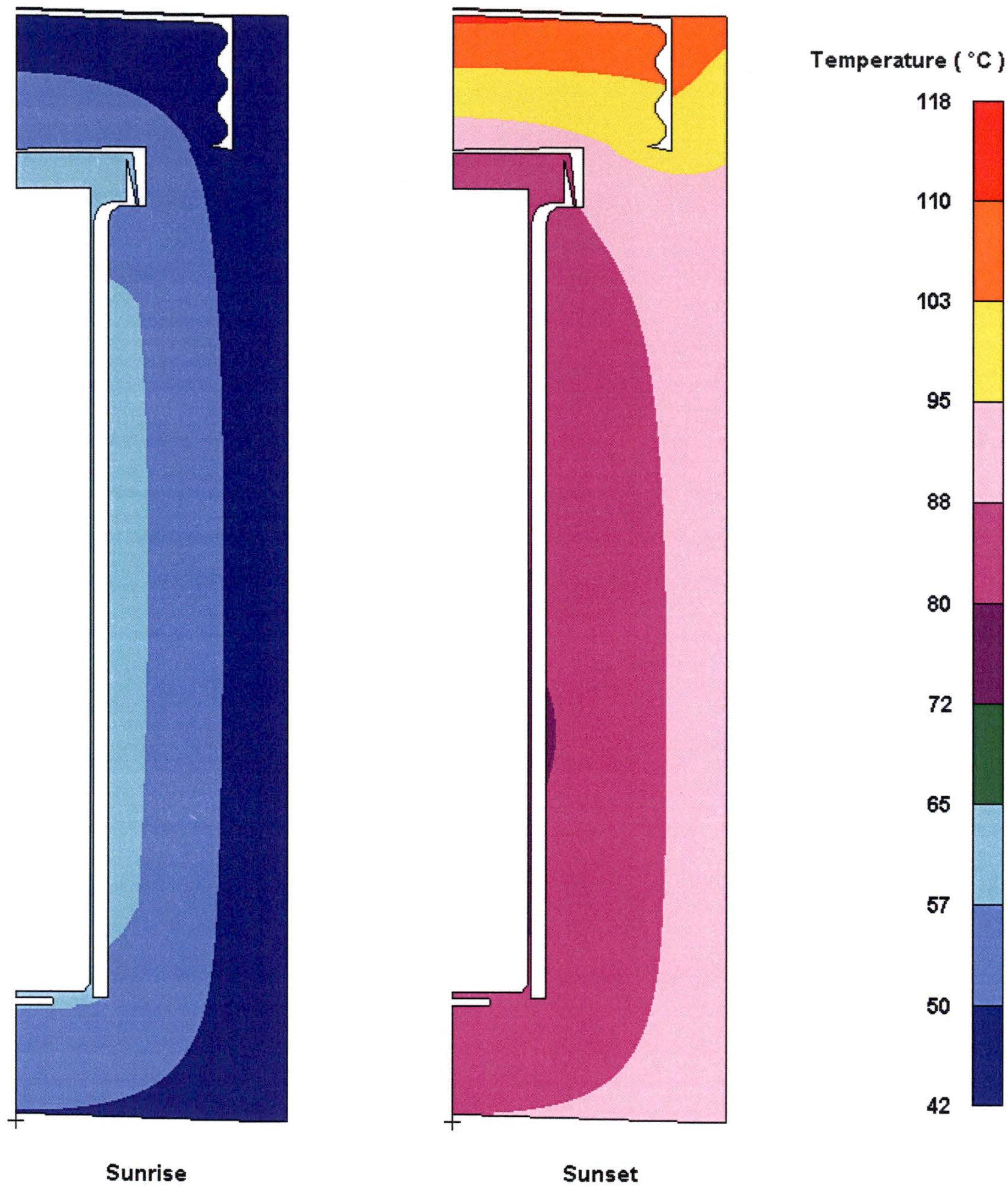


Figure 12. Temperature distribution in the ES-3100 shipping container for NCT (0.4 W content heat load)—Kaolite density of 30 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

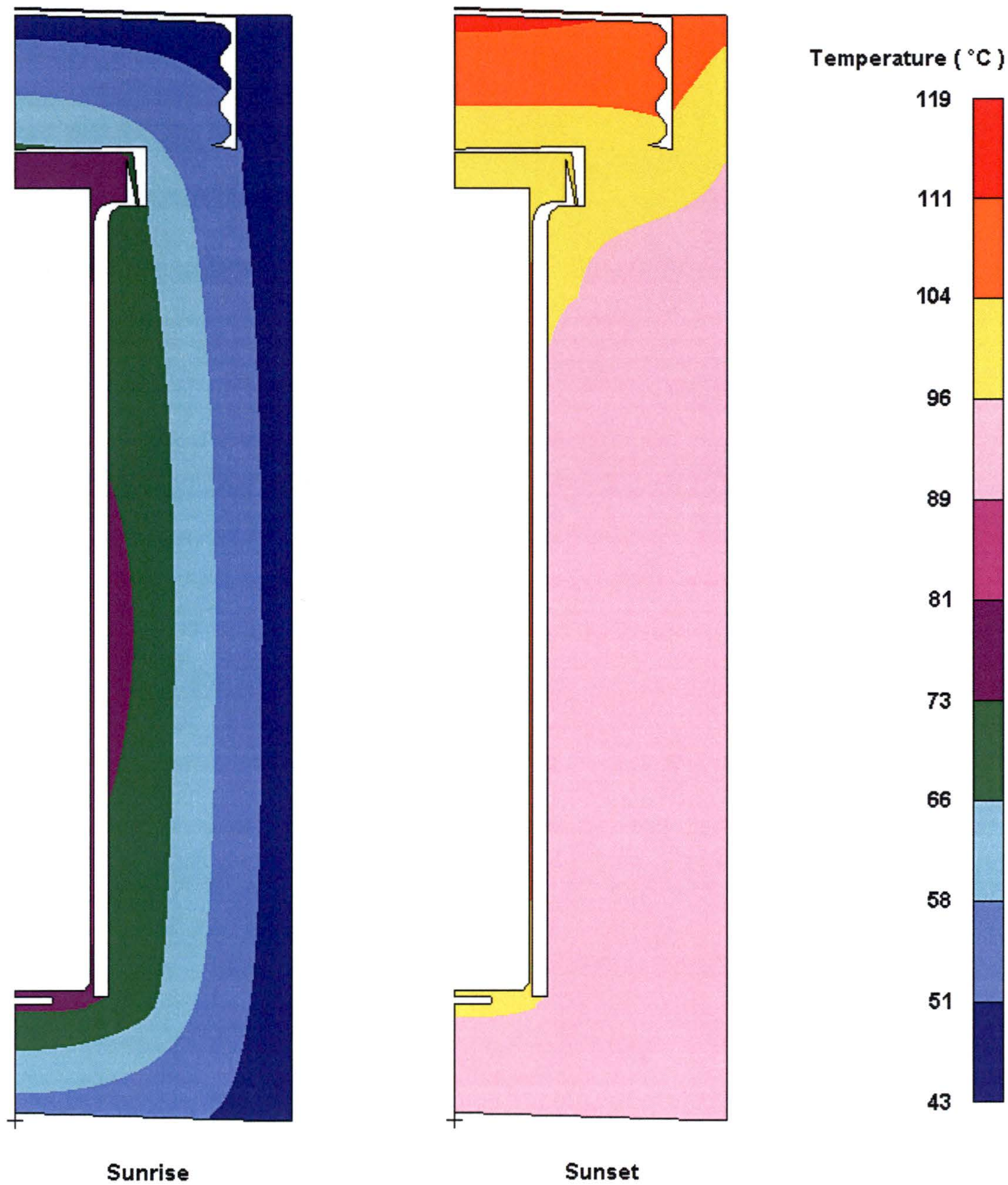


Figure 13. Temperature distribution in the ES-3100 shipping container for NCT (20 W content heat load)—Kaolite density of 30 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

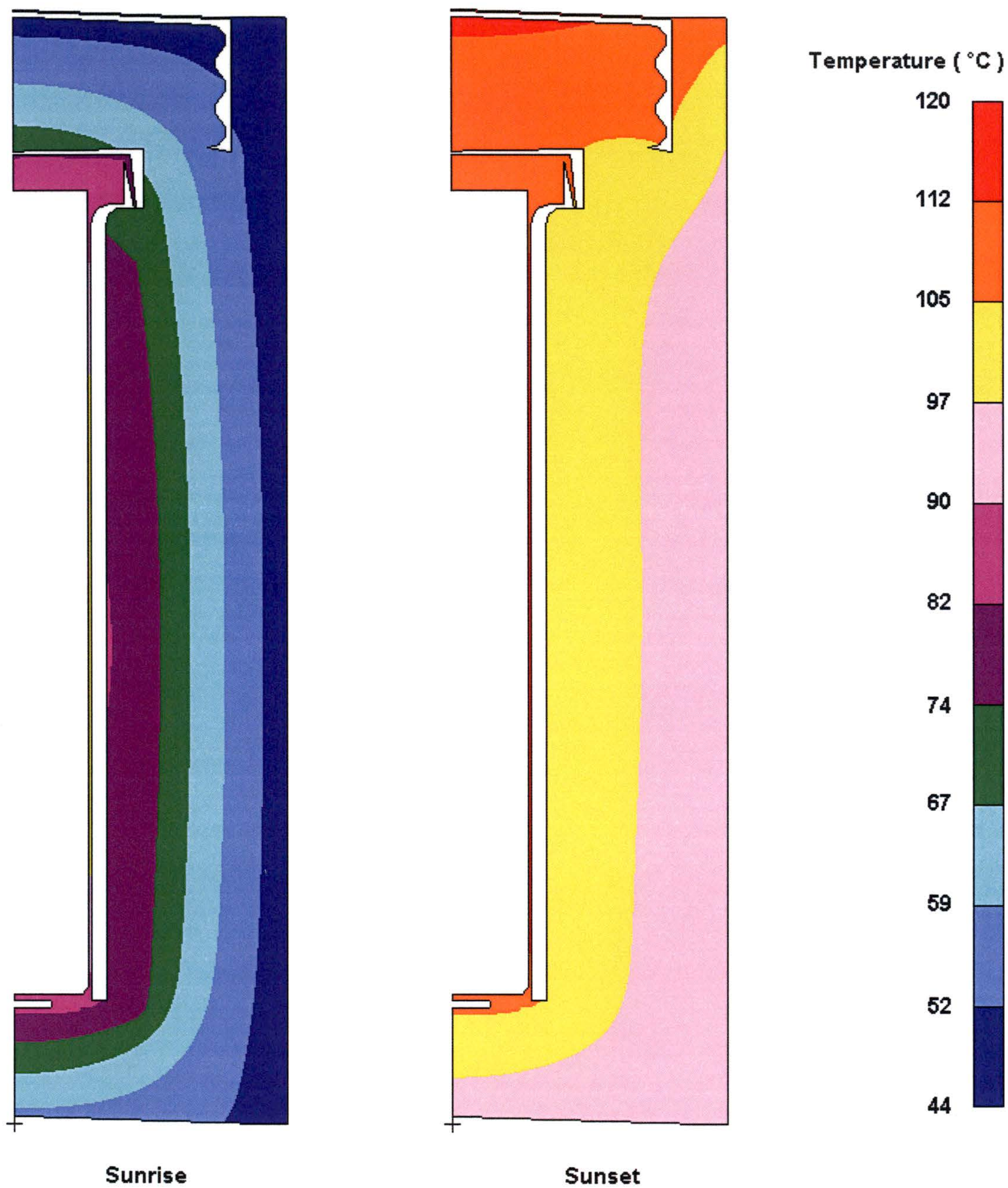


Figure 14. Temperature distribution in the ES-3100 shipping container for NCT (30 W content heat load)—Kaolite density of 30 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

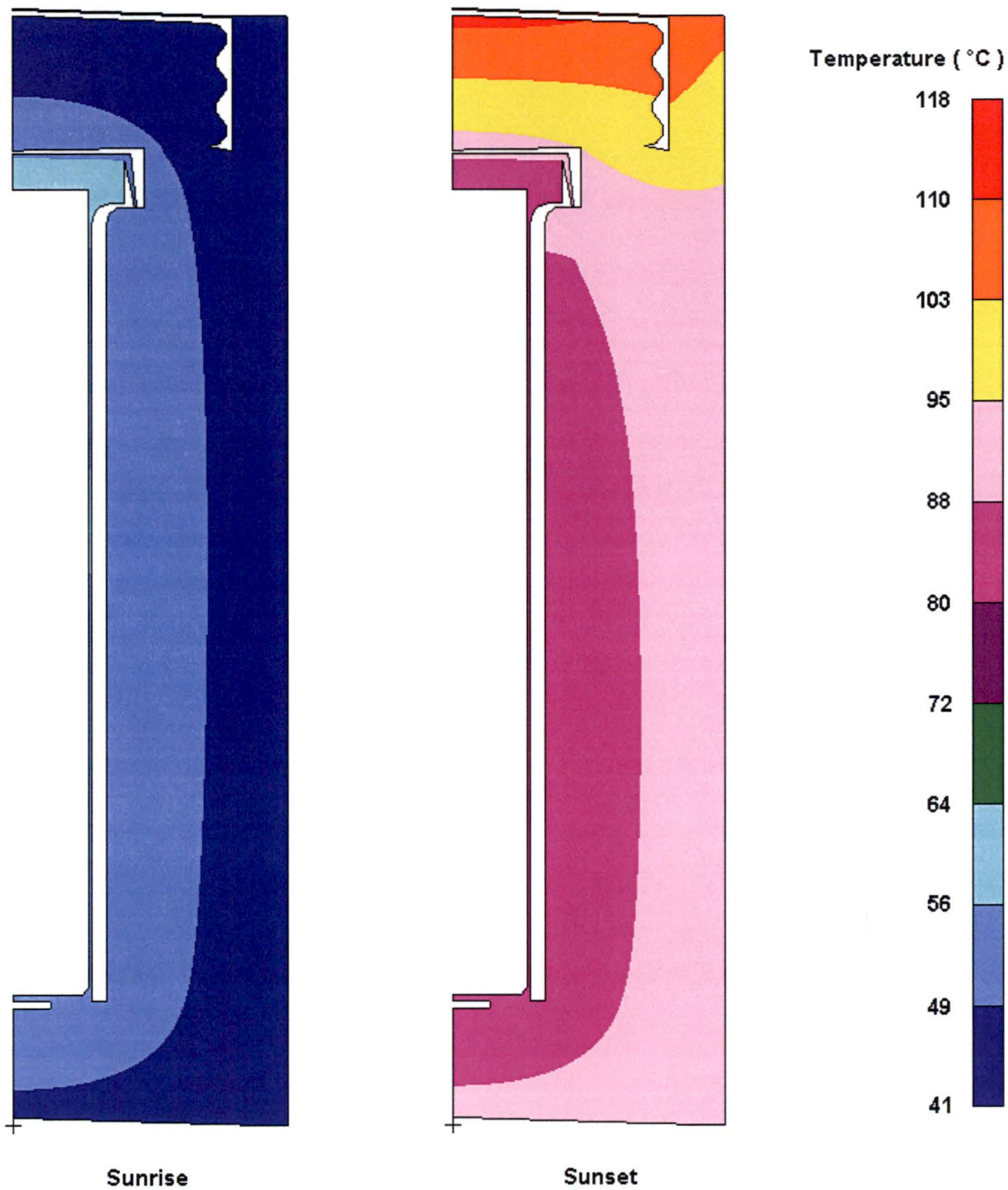


Figure 15. Temperature distribution in the ES-3100 shipping container for NCT (no content heat load)—Kaolite density of 19.4 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

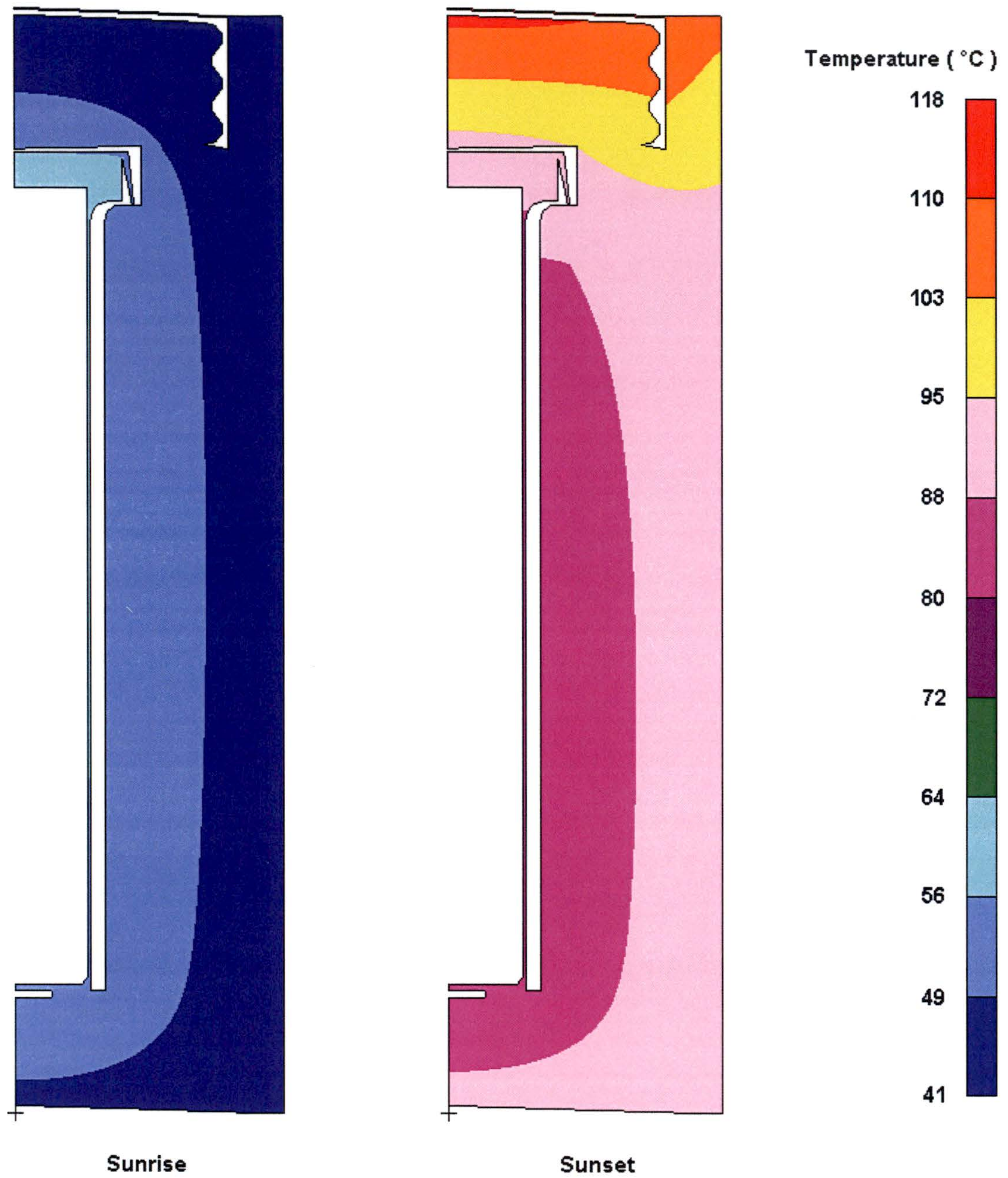


Figure 16. Temperature distribution in the ES-3100 shipping container for NCT (0.4 W content heat load)—Kaolite density of 19.4 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

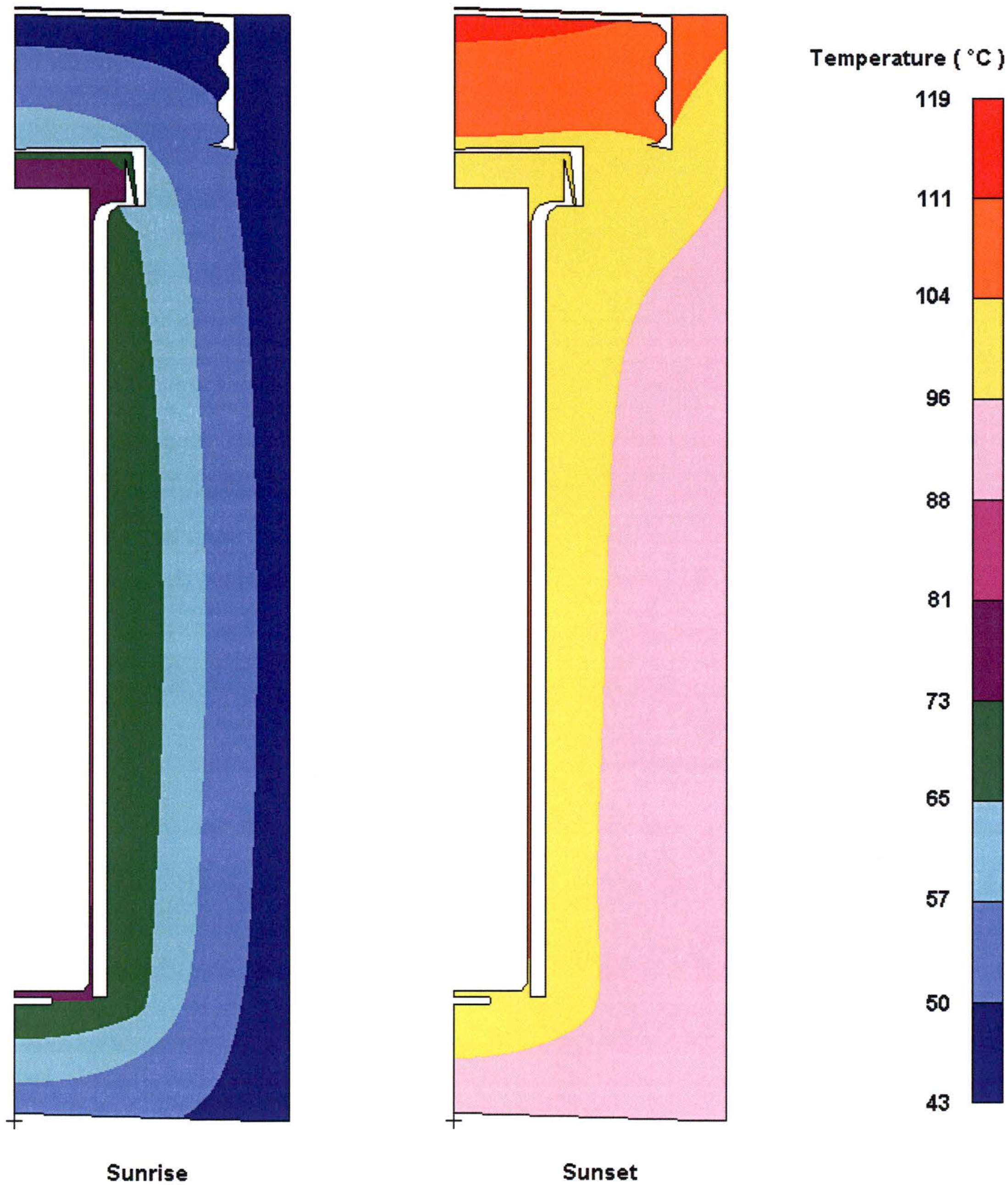


Figure 17. Temperature distribution in the ES-3100 shipping container for NCT (20 W content heat load)—Kaolite density of 19.4 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

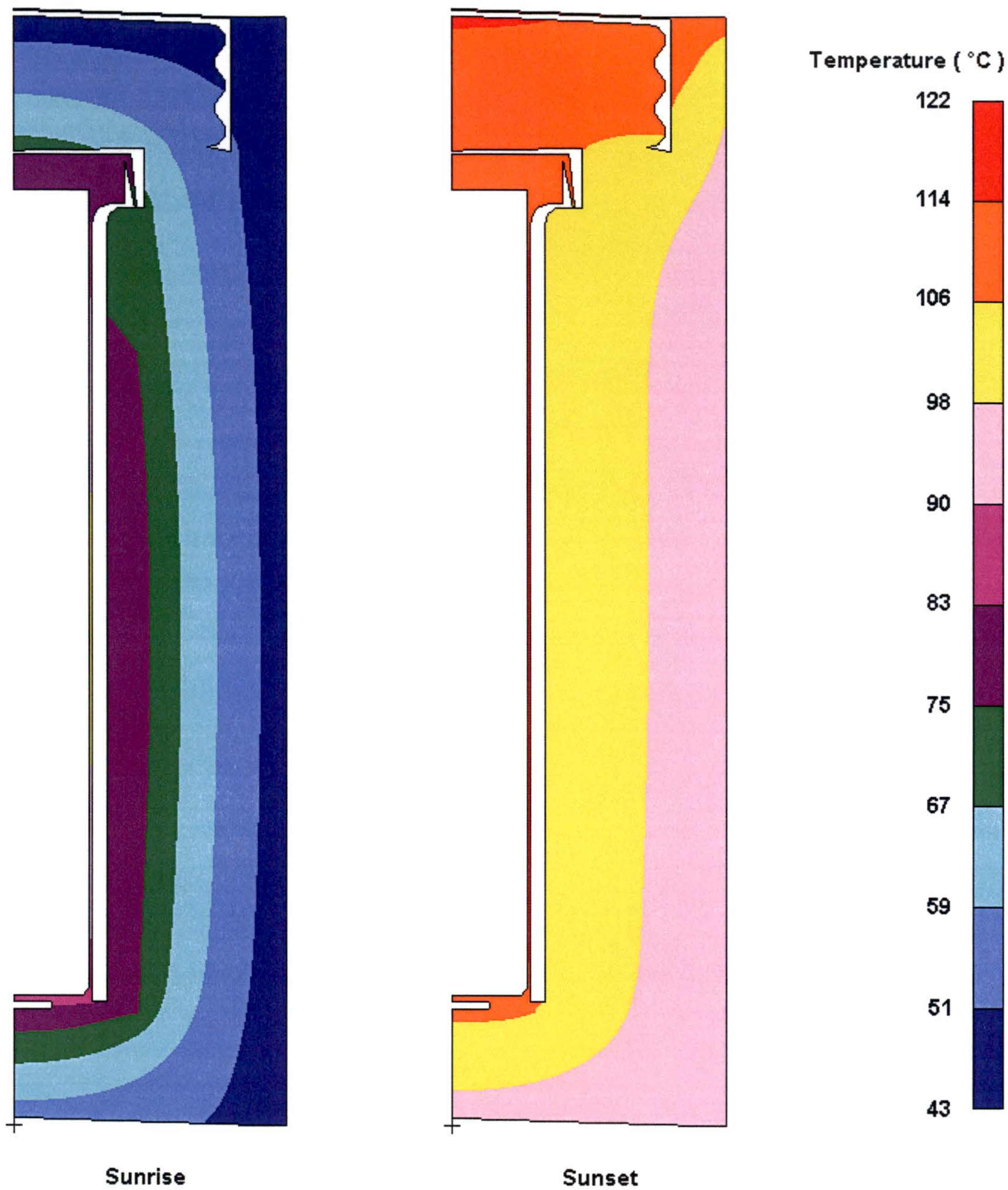


Figure 18. Temperature distribution in the ES-3100 shipping container for NCT (30 W content heat load)—Kaolite density of 19.4 lbm/ft^3—day 5 of transient analysis (elements representing air not shown for clarity).

Hypothetical Accident Conditions Analyses Results

Transient thermal analyses are performed on the finite element model of the ES-3100 shipping container (undamaged configuration) to simulate HAC as prescribed by 10 CFR 71.73(c)(4).[1] A 30-minute fire of 800°C (1472°F) is simulated by applying natural convection and radiant exchange boundary conditions to all external surfaces of the drum (assuming the drum is in a horizontal orientation) with content heat loads of 0, 0.4, 20, and 30 W and Kaolite densities of 30 (maximum density) and 19.4 lbm/ft^3 (minimum density). No heat flux boundary conditions simulating insolation are applied to the model during the 30-minute fire. The initial temperature distribution within the package having content heat loads of 0.4, 20, and 30 W is obtained from their respective steady-state analyses. The initial temperature distribution within the package having no content heat load (0 W) is assumed to be at a uniform temperature equal to the ambient temperature of 37.8°C (100°F).

Following the 30-minute fire transient analyses, 48-hour cool-down transient thermal analyses are performed using the temperature distribution at the end of the fire as the initial temperature distribution. During post-fire cool-down, natural convection and radiant exchange boundary conditions are applied to all external surfaces of the drum (assuming the drum is in a horizontal orientation). Additionally, cases are analyzed in which insolation is included during the post-fire cool-down. For the cases in which insolation is applied to the model during cool-down, insolation is applied during the first 12-hour period following the 30-minute fire, then alternated (off, then on) as was done for NCT.

The maximum temperatures calculated for the ES-3100 shipping container for HAC are summarized in Table 7 for the analyses using a Kaolite density of 30 lbm/ft^3 and Table 8 for the analyses using a Kaolite density of 19.4 lbm/ft^3. Temperature-history plots of several locations within the model are also depicted graphically in Figure 19 through Figure 22 for content heat loads of 0, 0.4, 20, and 30 W and a Kaolite density of 19.4 lbm/ft^3 (the graphs for the cases having a Kaolite density of 30 lbm/ft^3 are not shown because of their similarity to the presented graphs).

Table 7. ES-3100 shipping container HAC maximum temperatures—Kaolite density of 30 lbm/ft^3.

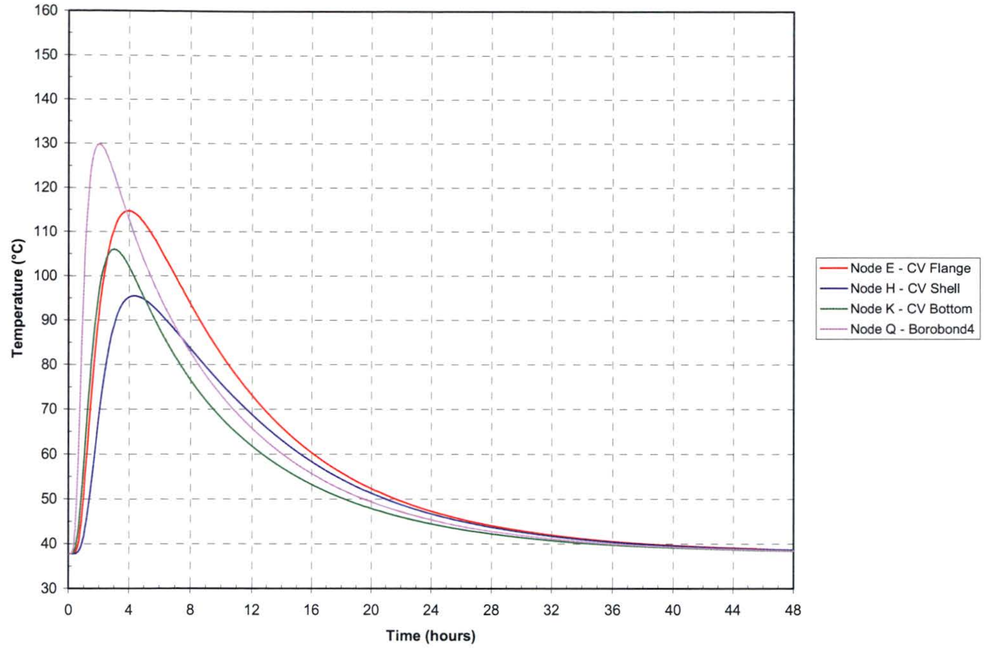
Content heat load (W)	Insolation during cool-down	Maximum temperature, °C (°F)						
		Node A[a] CV lid	Node E[a] CV flange at O-ring	Node H[a] CV shell (mid-elevation)	Node K[a] CV bottom (center)	Node Q[a] Borobond4 (top)	Node S[a] Borobond4 (mid-elevation)	Node T[a] Borobond4 (bottom)
0	No[b]	109.61 (229.29)	109.34 (228.81)	92.21 (197.98)	99.71 (211.47)	118.48 (245.26)	90.42 (194.76)	102.07 (215.73)
	Yes	116.91 (242.43)	116.74 (242.12)	104.22 (219.59)	106.13 (223.04)	122.46 (252.43)	103.28 (217.90)	107.63 (225.73)
0.4	No	109.93 (229.87)	109.66 (229.38)	92.78 (199.00)	100.11 (212.19)	118.69 (245.64)	90.73 (195.31)	102.38 (216.29)
	Yes	117.22 (243.00)	117.05 (242.68)	104.77 (220.58)	106.52 (223.74)	122.67 (252.81)	103.58 (218.45)	107.93 (226.28)
20	No	126.14 (259.05)	125.85 (258.53)	120.27 (248.48)	119.75 (247.56)	130.06 (266.11)	106.49 (223.67)	117.92 (244.25)
	Yes	133.07 (271.52)	132.85 (271.17)	131.38 (268.48)	125.90 (258.91)	134.05 (273.28)	118.96 (246.13)	123.31 (253.95)
30	No	134.00 (273.20)	133.69 (272.56)	133.41 (272.14)	129.43 (264.97)	135.69 (276.23)	114.38 (237.89)	125.62 (258.11)
	Yes	140.79 (285.42)	140.58 (285.05)	144.22 (291.59)	135.47 (275.85)	139.68 (283.42)	126.76 (260.17)	130.95 (267.71)

Notes: (a) See Figure 2 for node locations.
(b) Baseline case for ΔT comparisons.

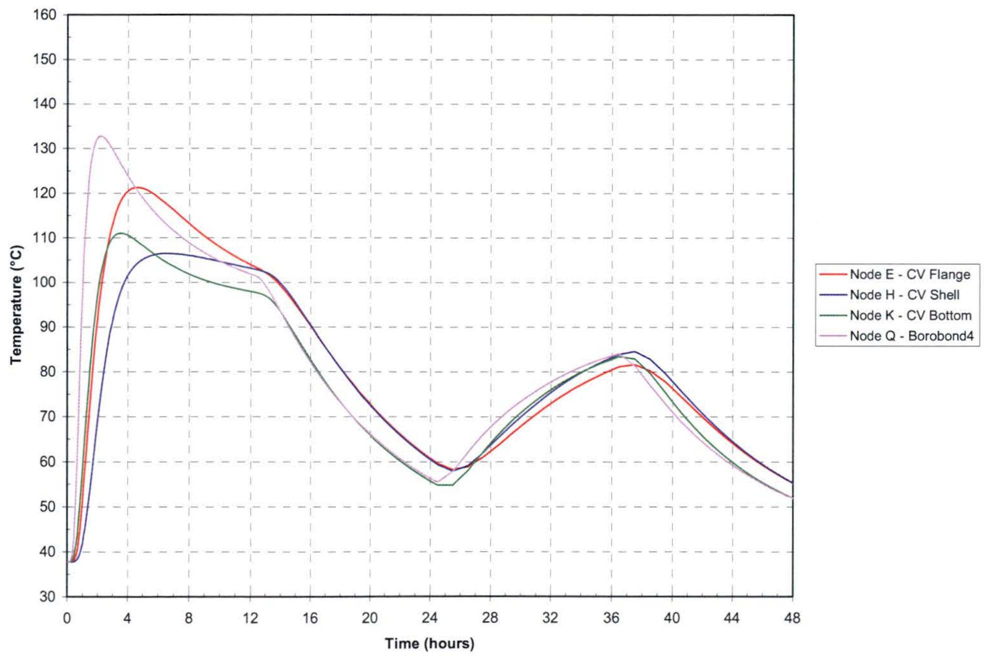
Table 8. ES-3100 shipping container HAC maximum temperatures—Kaolite density of 19.4 lbm/ft^3.

Content heat load (W)	Insolation during cool-down	Maximum temperature, °C (°F)						
		Node A[a] CV lid	Node E[a] CV flange at O-ring	Node H[a] CV shell (mid-elevation)	Node K[a] CV bottom (center)	Node Q[a] Borobond4 (top)	Node S[a] Borobond4 (mid-elevation)	Node T[a] Borobond4 (bottom)
0	No[b]	114.95 (238.92)	114.69 (238.43)	95.48 (203.86)	105.98 (222.77)	129.89 (265.79)	93.95 (201.11)	109.65 (229.36)
	Yes	121.44 (250.60)	121.27 (250.28)	106.43 (223.58)	111.02 (231.83)	132.73 (270.92)	105.10 (221.19)	113.62 (236.51)
0.4	No	115.27 (239.49)	115.00 (239.00)	96.04 (204.87)	106.37 (223.47)	130.09 (266.17)	94.25 (201.65)	109.95 (229.91)
	Yes	121.75 (251.16)	121.58 (250.85)	106.97 (224.57)	111.41 (232.53)	132.94 (271.30)	105.41 (221.73)	113.92 (237.06)
20	No	131.51 (268.71)	131.22 (268.19)	123.43 (254.17)	126.00 (258.80)	141.29 (286.32)	109.98 (229.96)	125.44 (257.80)
	Yes	137.69 (279.84)	137.49 (279.48)	133.54 (272.37)	130.83 (267.49)	144.13 (291.44)	120.84 (249.51)	129.33 (264.79)
30	No	139.39 (282.90)	139.08 (282.25)	136.53 (277.75)	135.66 (276.19)	146.82 (296.28)	117.85 (244.14)	133.11 (271.60)
	Yes	145.45 (293.82)	145.24 (293.44)	146.35 (295.43)	140.42 (284.75)	149.67 (301.41)	128.65 (263.57)	136.97 (278.55)

Notes: (a) See Figure 2 for node locations.
(b) Baseline case for ΔT comparisons.

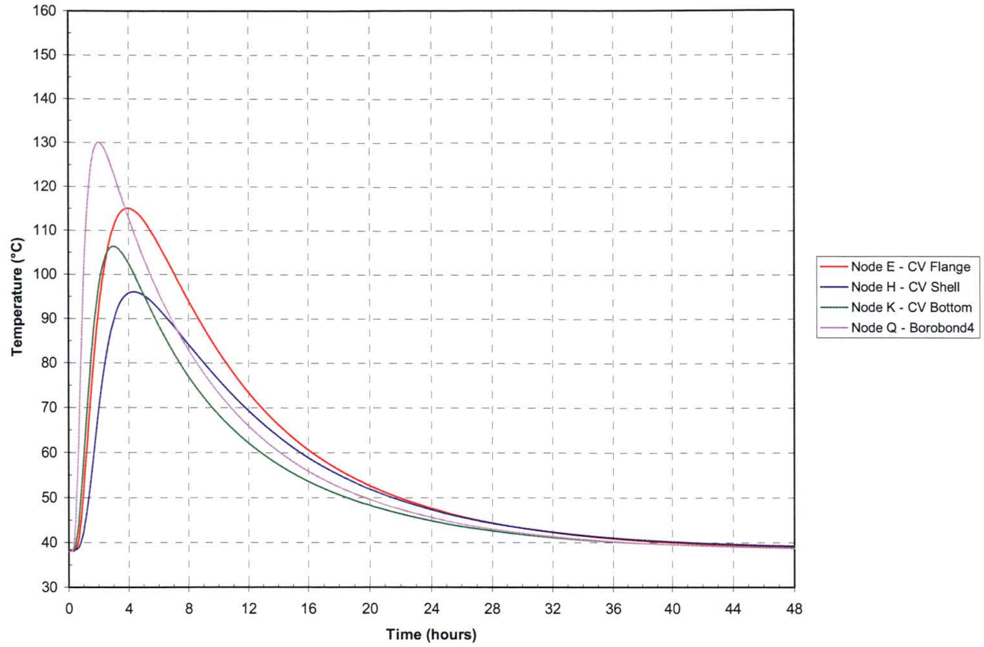


(a) No insolation during post-fire cool-down.

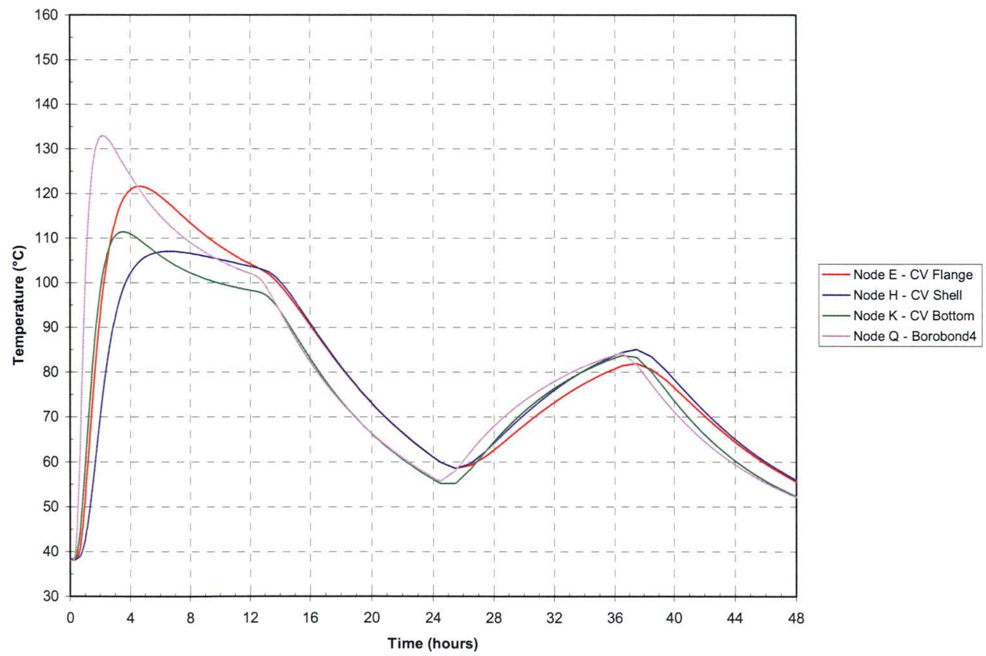


(b) Insolation during post-fire cool-down.

Figure 19. ES-3100 shipping container transient temperatures for HAC (no content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).

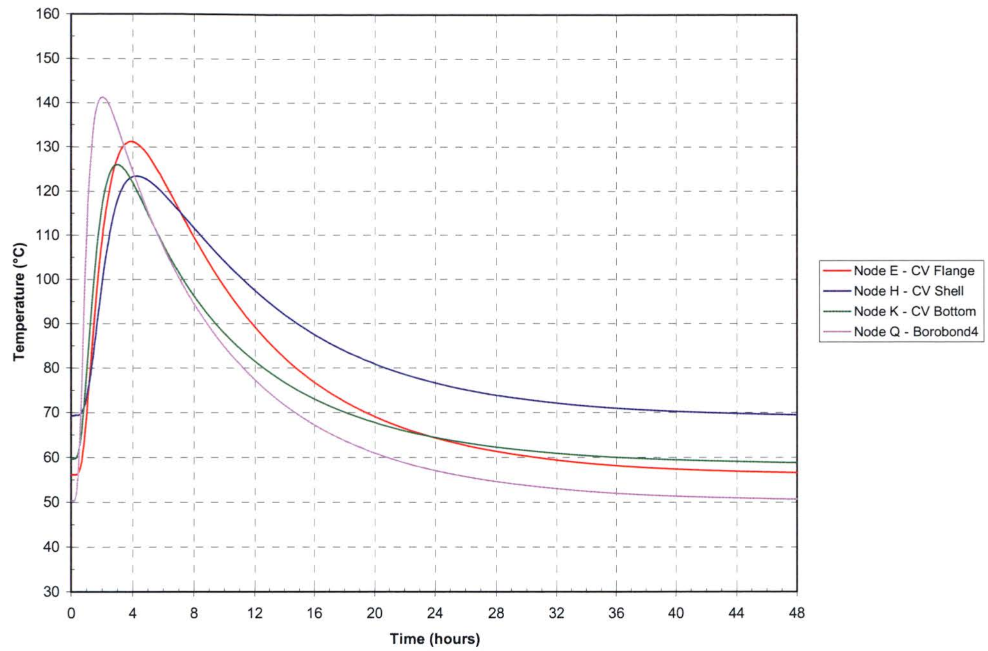


(a) No insolation during post-fire cool-down.

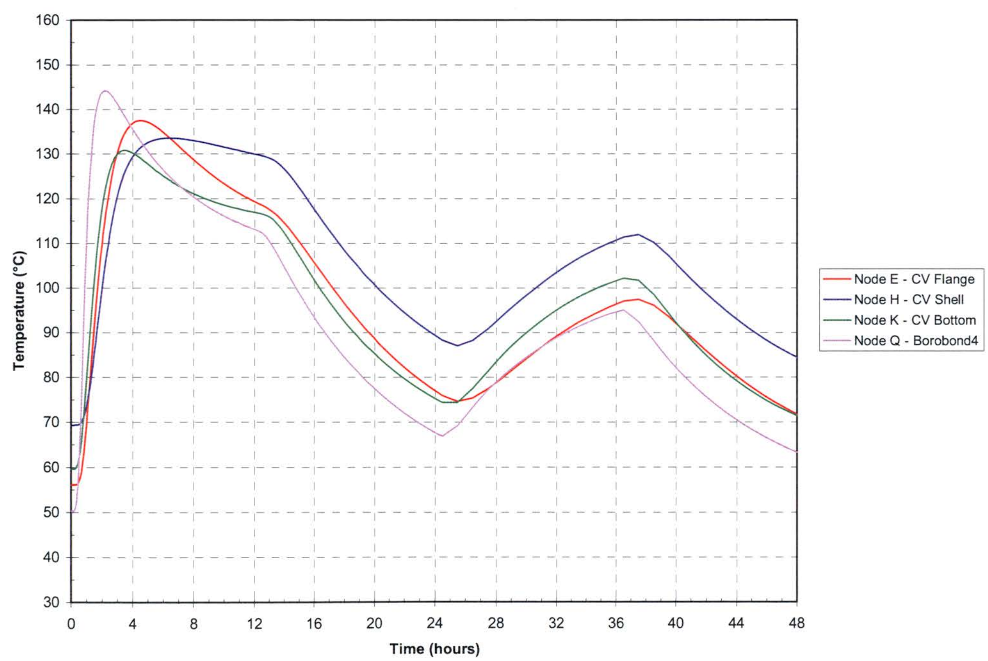


(b) Insolation during post-fire cool-down.

Figure 20. ES-3100 shipping container transient temperatures for HAC (0.4 W content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).

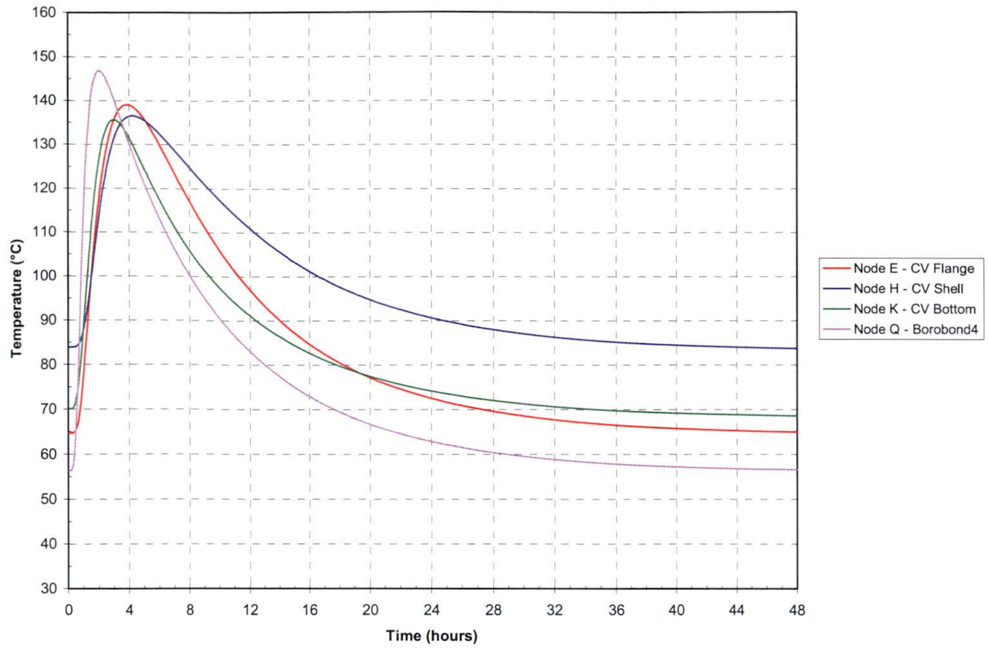


(a) No insolation during post-fire cool-down.

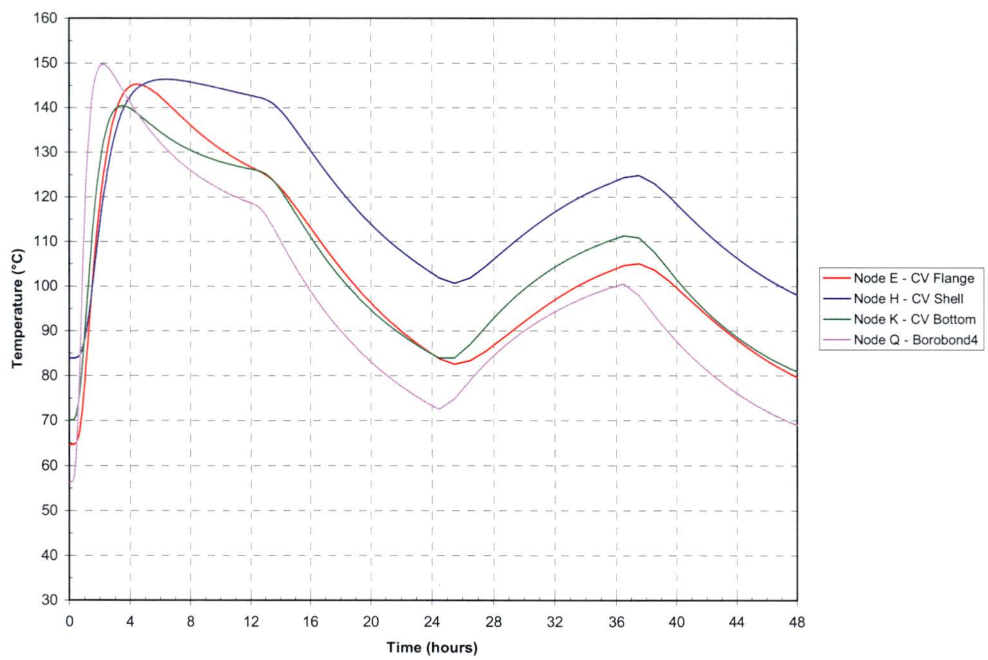


(b) Insolation during post-fire cool-down.

Figure 21. ES-3100 shipping container transient temperatures for HAC (20 W content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).



(a) No insolation during post-fire cool-down.



(b) Insolation during post-fire cool-down.

Figure 22. ES-3100 shipping container transient temperatures for HAC (30 W content heat load) Kaolite density of 19.4 lbm/ft^3 (see Figure 2 for node locations).

APPENDIX 3.6.1 REFERENCES

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