Prototype SAFKEG LS 3979A/0002

NCT and HAC Regulatory Test Report

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1 INTRODUCTION

The SAFKEG 3979A is being designed and licensed as a general purpose container for the transport of a range of non fissile and fissile excepted nuclides in solid, liquid and gaseous form. Evaluation of the design under Normal Conditions of Transport and Hypothetical Accident Conditions has been carried by a series of tests performed on a prototype 3979A package. All tests have been carried out in accordance with 10 CFR 71 by Croft Associates Ltd. This report provides detailed information regarding the prototype keg, the test series, test methods and the resultant effects on the keg.

2 DESCRIPTION OF TEST PACKAGE

The same test package was used for all the tests. The package was a full scale version of the SAFKEG LS package. The test package was manufactured for testing according to drawings listed in the drawing list DL-0C-6000 issue B with modifications for testing according to the drawings in drawing list DL-0C-6081 issue A. The prototype package consisted of keg 3979 serial number 002 and containment vessel 3980 serial number 002 listed under the Certificate of Conformity QAC 1382 [Ref 1].

Differences between the test package and the design specified by the licensing drawings are given in sections 2.1 and 2.2.

2.1 Modifications Required for Test

During the test series three different package test configurations were required. Each configuration is shown in figures 1 to 3. Figure 1 is the set up required for the steady state thermal test, figure 2 is the set up required for the drop tests and penetration tests and figure 3 is the set up required for the 800°C thermal test. Modifications were required to the package to allow test equipment such as accelerometers to be fitted and to provide access to the test cables.

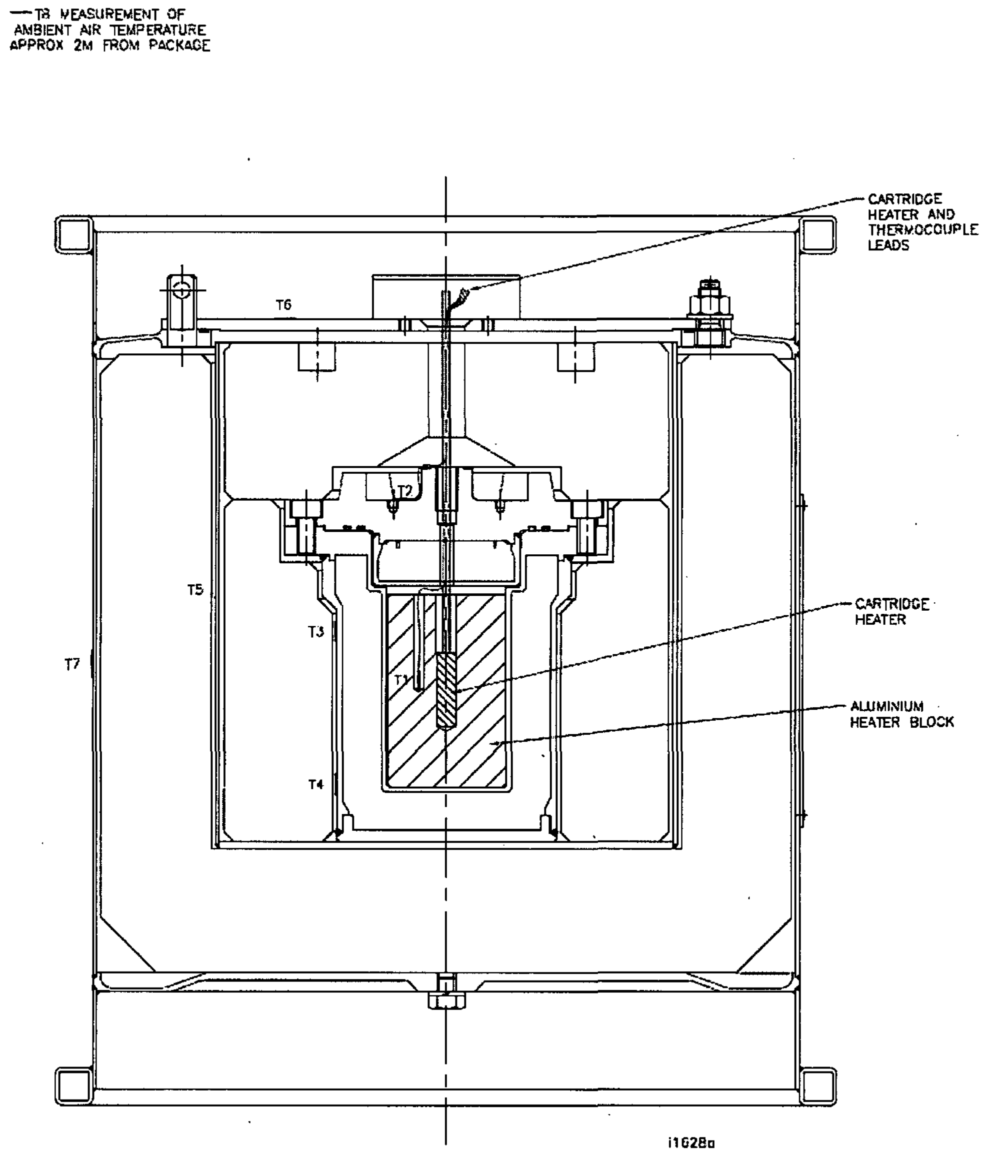


Figure 1 – Package Set Up for the Steady State Thermal Test

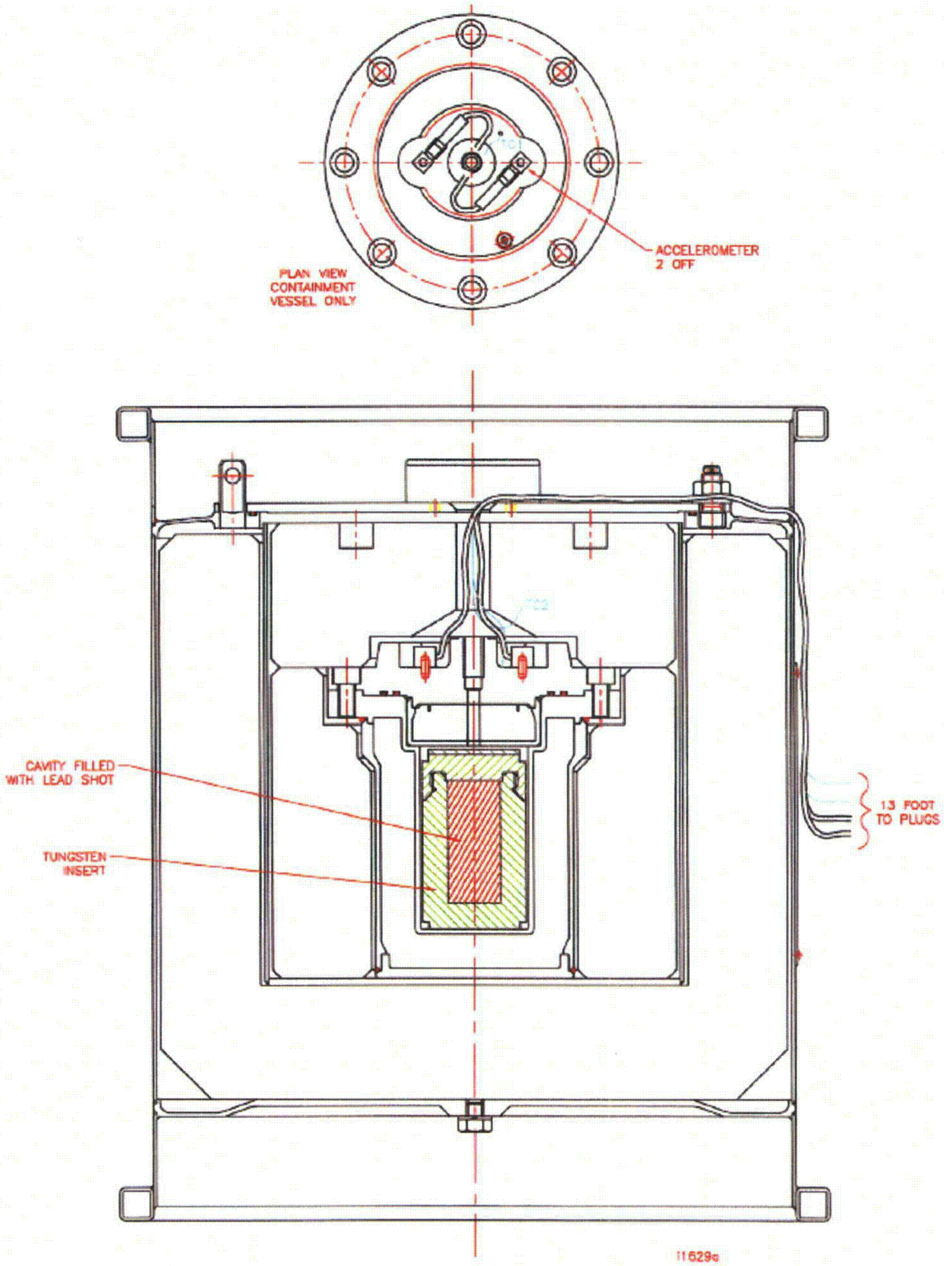


Figure 2 – Package Set up for Drop and Penetration Tests

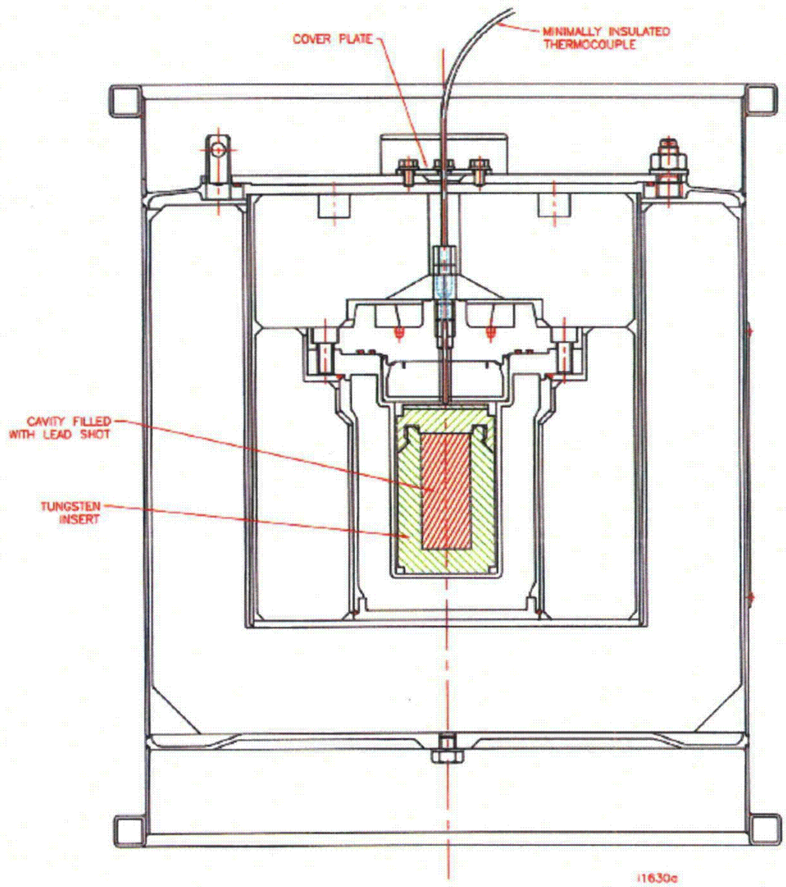


Figure 3 – Package Set Up for 800°C Thermal Test

2.1.1 Modifications to Containment Vessel

A hole of 7 mm in diameter was drilled through the center of the containment vessel lid to allow the thermocouple and heater wires to be fed through into the containment vessel during the steady state thermal test as shown in figure 1. This hole was also used to introduce the helium during the helium leak test.

In order to fit the accelerometers which were used during all the drop tests, two cavities were machined into the lid of the containment vessel as shown in figure 2. The accelerometers were screwed into position using two tapping holes machined into the lid. Thread locking compound was also applied to the accelerometers to keep them firmly attached in position during all the drop tests.

2.1.2 Modifications to Cork Packing

To accommodate the wiring from the accelerometers and thermocouples a 25 mm diameter hole was drilled 53 mm through the centre of the top cork. The 25 mm diameter was then widened to 77 mm over the final 15 mm. The modification to the top cork is shown in figures 1 to 3.

2.1.3 Modifications to Keg

To allow exit of the accelerometer and thermocouple wires a 25 mm diameter hole was drilled through the center of the keg lid. The wires were taped to the keg lid and fed through a hole in the keg body. This hole was a drain hole enlarged to accommodate the wires required for the testing instrumentation. The wiring was taped to the keg until half way down the body. Two stainless steel cable ties were tack welded to the lid of the keg to allow the umbilical cord to be tied to the keg.

For the thermal test the accelerometer wires were pushed down into the keg body. To hold these wires in place a cover plate was screwed over the 25 mm diameter hole in the keg lid as shown in figure 3. In order to accommodate the cover plate four holes were tapped into the keg lid. The cover plate was 3 mm thick stainless steel 60 mm by 60 mm. A hole was drilled in the centre with an 8 mm diameter in order to allow the information from the thermocouples to be logged during the thermal test.

2.2 Comparison of Test Package to Production Package

In comparing the test package with the design specified by the licensing drawings, the weight of the keg, cork, containment vessel and insert were considered along with the dimensions of the keg, containment vessel, liner and top cork.

Table 1 shows the design weights of the package compared to those taken from the test package. The weight of the test keg is 2% heavier than the calculated design weight and the containment vessel is 3% lighter than its design weight. Overall the tested package was 3% lighter than the design weight.

Item	Calculated Mass (kg)	Actual Mass (kg) of tested packaging[1]
Top & Bottom Rims (2 off)	2.87 total	-
Top Skirt	1.14	-
Bottom Skirt	1.04	-
Keg Top Flange	2.70	-
Keg Base Plate	3.22	-
Keg Outer Shell	6.47	-
Identification Label	0.12	-
Keg Closure Studs (8 off)	0.30 total	-
Lock Pin	0.04	-
Keg Lid	3.31	-
Keg Lid Handles (2 off)	0.17 total	-
Outer Cork	6.52	-
Keg Liner	3.41	-
Keg Liner Disc	1.51	-
Keg Closure Nuts & Washers (8 off)	0.24 total	-
Keg Body, Lid, Liner, Nuts & Washers	32.02	32.63
Inner Cork	1.62	1.52
Top Cork	1.09	1.04
CV Lid Top	3.90	-
CV Lid Shielding Casing	0.26	-

[1] From Reference 9

Item	Calculated Mass (kg)	Actual Mass (kg) of tested packaging[1]
CV Lid Shielding	1.02	-
Test Point Plug	negligible	-
CV Flange/Cavity Wall	3.07	-
CV Outer Wall	1.63	-
CV Base	0.52	-
CV Body Shielding	10.93	-
CV Closure Screws (8 off)	0.23 total	-
CV Body, Lid & Screws	21.56	20.97
Welds	0.50 estimate	-
12x65Tu Insert & contents	5.80 max	5.56
LS Safkeg Design No 3979A (excluding contents)	57.83	56.16
LS Safkeg Design No 3979A (including contents)	63.63	61.72

Table 1 – Comparison of Test Package Weight with Design Weights

The comparison of the dimensions between the tested package and the licensing drawings are shown in Table 2. All the dimensions are within expected manufacturing tolerances.

Item	Dimension on Licensing Drawings (mm)	Measured Dimension (mm)[Ref 9]	% diff
Keg Rim Diameter	424 [Ref 3]	420	-0.9434
Keg Body Diameter	382.5 [Ref 3]	382.25	-0.06536
Keg Height	483 [Ref 3]	480.71	-0.47412
Liner Height	270.5 [Ref 3]	275.6	1.885397
Liner Diameter	246 [Ref 3]	247.92	0.780488
Top Cork Diameter	241 [Ref 4]	239.56	-0.59751
Top Cork Height	85.5 [Ref 4	86.60	1.28655
Containment vessel Height	203.5 [Ref 5]	203.4	-0.04914
Containment vessel lower diameter	118.5 [Ref 6]	117.91	-0.49789
Containment vessel upper diameter	134.35 [Ref 6]	134.61	0.193524
Containment vessel lid diameter	175 [Ref 6]	174.98	-0.01143

Table 2 – Comparison of Test Package Dimensions with Licensing Drawings

2.3 Test Package Non-Conformance Reports

The prototype keg does not have any Non-Conformance Reports raised against its manufacture.

3 TEST FACILITY

Three test facilities were used in order to test the 3979A LS SAFKEG: Pipaway Engineering, Croft Associates Ltd and Hovel Ltd.

Pipaway Engineering testing facilities were used to carry out the 1.2m drop tests and the 1m penetration test series. A steel plate 1 m x 1 m x 65 mm and 500 kg in weight, located on a concrete floor, provided the drop target at this facility.

Croft Associates Ltd testing facility, located on the Southmead Industrial Estate, Didcot, was used for the 10.2 m drop tests and an additional -40°C penetration test. This facility has a test target consisting of a 50 mm thick non alloy structural steel plate of area 2000 mm x 1500 mm. This plate sits at ground level on a one piece, continuously poured, cast in situ concrete block. The mass of the target is 50 tonnes.

Hovel Ltd was used to carry out the 800°C thermal test. This facility provided a gas fired top hat furnace measuring 2.7 m x 2.1 m x 4 m. It has a fixed brick base and a ceramic lined removable hood. Two gas burners ensure that the load is uniformly heated throughout its cycle providing a temperature range of 0 – 1000°C.

4 REGULATORY TEST METHOD

4.1 Testing Sequence

The package was assembled, inspected and tested in the sequence shown in Table 3.

Sequence Number	Test Type	Test Number	Test
1	NCT	1	Steady state thermal test
2			Mark up datum lines. Inspect, measure and weigh all the test items
3	NCT	2	Compression test of keg at ambient temperature
4			Assemble containment vessel
5			Helium leakage test of containment vessel Note: The containment vessel shall remain closed until completion of the test programme.
6			Assemble the package. Note: The package shall remain closed until completion of the test programme (Test Number 13).
7	NCT	3	Penetration Test at ambient
8	NCT	4	1.2m drop test 1 at ambient, C of G over side.
9	NCT	5	1.2m drop test 2 at ambient, C of G over top end
10	NCT	6	1.2m drop test 3 at ambient, C of G over top rim edge
11	ACT	7	1m puncture test on side impact point at ambient
12	ACT	8	1m puncture test on bottom end impact point at ambient
13	ACT	9	1m puncture test on top rim edge impact point at ambient
14	ACT	10	10.2m drop test 1 at -40°C, C of G over side
15	ACT	11	10.2m drop test 2 at -40°C, C of G over top rim edge.
16	ACT	12	10.2m drop test 3 at -40°C, C of G over top end
17	ACT	12a	Optional: puncture test. The package shall be assessed after the 10.2 m drop test to determine if this further test is required
18	ACT	13	800°C thermal test
19			Inspect and weigh assembled package after completion of tests.
20			Disassemble the keg and inspect and weigh components.

Sequence Number	Test Type	Test Number	Test
21			Helium leakage test containment vessel after testing
22			Inspect and weigh the containment vessel, insert and contents

Table 3 - Test Sequence

The drop height requirement for the Hypothetic Accident Condition (HAC) test according to 10 CFR 71 [Ref 2] is 9 m. For this test sequence a 1.2m safety margin has been assumed for the HAC drop tests. Therefore the package has been dropped from 10.2 m as opposed to 9m. This height shows the combined effect of the Normal Conditions of Transport (NCT) test.

4.2 Test Methods

4.2.1 Test 1 – Steady State Thermal Test

The test keg was assembled according to figure 1, with a heater in place of the contents, in the containment vessel cavity. The heater provided a minimum wattage of 10 W. The seven calibrated thermocouples (T1, T2 etc) were positioned on and in the packaging to provide temperature readings over the package during the course of the test. A further thermocouple was used to measure the ambient temperature 2 meters from the package.

The package was positioned in the vertical upright position on a 16 mm thick piece of chipboard covered in aluminum foil as shown in photograph 1. The heater was set to 10 W. Temperatures were logged at 1 minute intervals until thermal equilibrium was reached. When the package reached equilibrium the surface temperature of the keg was mapped and the keg orientation changed to a horizontal position as shown in photograph 2. The test was repeated with the keg in the horizontal position until thermal equilibrium was reached and then the surface temperature of the keg was mapped.

4.2.2 Mark up and Inspection of Package

In order to determine if any dimensional changes occur during the NCT and HAC tests the constitutional parts of the packaging were indelibly marked with datum lines and measurement points as shown in photographs 3 to 6. Marking the components in this way ensured that the package was measured at the same points before and after testing.

4.2.3 Test 2 - Compression Test

The empty test keg was used for the compression test. The keg was weighed and the height and diameter of the keg measured using the marked datum points shown in photograph 6. A test load of 500 kg was placed on top of the keg and left for 24 hours. This load was well in excess of the required load of 340 kg, which is 5 x maximum weight of the complete package. On completion of the test the keg was weighed and measured using the marked datum points.

4:2.4 Package Assembly

The tungsten insert was filled with 42 g of 3mm lead shot. It was placed into the containment vessel according to Figure 4. The containment lid was fitted in the orientation shown in Figure 4 and the screws tightened to 10 ± 0.5 Nm. A helium leak test was carried out on the containment vessel as described in section 4.2.5.

Thermocouples to monitor the temperature of the package during the drop test and temperature sensitive labels for the thermal test were attached onto the containment vessel together with two accelerometers for the drop tests as shown in photograph 4. The package was assembled in the orientation shown in Figure 4 and demonstrated in photographs 8, 9 and 10, and then the keg nuts were tightened to 23 ± 1 Nm.

Once assembled the package was not opened until the completion of the testing program.

4.2.5 Helium Leak Test

A helium leak test was carried out prior to assembly of the keg on the containment vessel in accordance with ANSI N14.5-1997 as detailed in CP 390. The pass rate set for the test was 2 x 10^{-7} cm^3/s with a sensitivity of 5 x 10^{-8} cm^3/s helium at an upstream pressure of 1 atmosphere absolute and a downstream pressure of 0.01 atm or less. The helium leak test was repeated after the completion of the 800°C thermal test to determine if the containment boundary had been impaired during testing.

4.2.6 Test 3 – Penetration Test

A 6 kg steel bar of diameter of 3.2 cm was dropped 1.7 meters perpendicularly to the package onto the mid section of the long axis of the keg, as shown in photograph 11. The keg was stood on a flat horizontal surface and a guide tube was used to ensure the steel bar impacted the keg at the correct point.

4.2.7 Test 4 – 1.2m drop test 1 at ambient, C of G over side

On conclusion of the penetration test the keg underwent the first in the series of 1.2 m drop tests. The first test orientation was a free drop onto the side of the keg as shown in Figure 5. The test package was slung from lifting gear horizontally above the test pad as shown in photograph 12, it was then released to free fall onto the test pad.

4.2.8 Test 5 – 1.2m drop test 2 at ambient, C of G over top end

On completion of the first 1.2m drop test a second was then carried out. The test orientation was a free drop onto the top of the keg as shown in Figure 5. The test package was slung from lifting gear vertically above the test pad as shown in photograph 13; it was then released to free fall onto the test pad.

4.2.9 Test 6 – 1.2 m drop test 3 at ambient, C of G over top rim edge

On completion of the second 1.2m drop test a third was then carried out. The test orientation was a free drop onto the top rim of the keg as shown in Figure 5. The test package was slung from lifting gear so that the top rim of the keg was the lowest point above the test pad as shown in photograph 14. The height of the keg was checked to ensure the lowest point of the package was 1.2 m from the test pad. The package was then released to free fall onto the test pad.

4.2.10 Test 7 – 1 m puncture test at ambient on side impact point

On completion of the 1.2 m drop test series the first puncture test was carried out. The first puncture test was a free drop from 1 m onto the top end of a steel punch which had a diameter of 150 mm and length of 200 mm. The test orientation was so that the package dropped onto the side of the keg as shown in Figure 6.

As shown in photograph 15 the test package was slung from the lifting gear so that it was perpendicular to the punch. The height was checked to ensure the lowest point of the package was 1 m above the punch. The package was then released to free fall onto the punch.

4.2.11 Test 8 – 1 m puncture test at ambient on bottom impact point

On completion of the first puncture test the second was carried out. This test was a free drop from 1 m onto the steel punch described in section 4.2.10. The test orientation was so that the bottom of the package dropped onto the punch as shown in Figure 6.

As shown in photograph 16 the test package was slung from the lifting gear so that the bottom of the package was positioned over the punch. The height was checked to ensure the lowest point of the package was 1 m above the punch. The package was then released to free fall onto the punch.

4.2.12 Test 9 – 1 m puncture test at ambient on top rim edge

On completion of the second puncture test the third was carried out. This test was a free drop from 1 m onto the steel punch described in section 4.2.10. The test orientation was so that the top rim of the package dropped onto the punch as shown in Figure 6.

As shown in photograph 17 the test package was slung from the lifting gear so that the top rim of the package was positioned over the punch. The height was checked to ensure the lowest point of the package was 1 m above the punch. The package was then released to free fall onto the punch.

4.2.13 Test 10 – 10.2 m drop test 1 at -40°C, C of G over side

On completion of the puncture tests the first 10.2 m drop test was carried out at the Croft test facilities. The first test orientation was a free drop onto the side of the keg as shown in Figure 7.

The package was cooled to -40°C and the temperature of the package was recorded prior to the drop, using the thermocouples affixed in and on the package during assembly. The test package was horizontally slung from the crane 10.2 m above the test pad as shown in photograph 18. It was released to free fall onto the test pad which had been placed on the target.

On completion of the drop the damage to, and temperature of the package was recorded.

4.2.14 Test 11 – 10.2 m drop test 2 at -40°C, C of G over top rim

On completion of the first 10.2 m drop test the second 10.2 m drop test was carried out at the Croft test facilities. The second test orientation was a free drop onto the top rim of the keg as shown in Figure 7. The package was cooled to -40°C and the temperature was recorded prior to the drop using the thermocouples affixed in and on the package during assembly. The test package was then slung with the C of G over the top rim from a crane 10.2 m above the test pad as shown in photograph 19, it was released to free fall onto the test pad which had been placed on the target.

On completion of the drop the damage to, and temperature of the package was recorded.

4.2.15 Test 12 – 10.2 m drop test 2 at -40°C, on top end

On completion of the first 10.2 m drop test the second 10.2 m drop test was carried out at the Croft test facilities. The second test orientation was a free drop onto the top rim of the keg as shown in Figure 7. Prior to the test the package was cooled to -40°C, the temperature of the package was recorded using the thermocouples affixed in and on the package during its assembly before the package was positioned for the test.

The test package was then slung from a crane, vertically top down, 10.2 m above the test pad as shown in photograph 20. It was then released to free fall onto the test pad which had been placed on the target.

On completion of the drop the damage to, and temperature of the package was recorded.

4.2.16 Filtering of Acceleration Data

A filter has been used on the raw acceleration data to eliminate noise unrelated to the drop. Its use is recommended by the IAEA advisory material [Ref 7].

A low pass digital 4th order Iowpass Butterworth filter with a cut-off frequency of 500 Hz was applied to the raw data.

4.2.17 Test 12a – 1 m puncture test at -40°C on top end

On completion of the 10.2 m drop test series an extra puncture test was carried out in the worst case drop condition. The package was orientated so that the top end of the package was 1 m above a steel punch, which has a diameter of 150 mm and length of 200 mm. Before the package was positioned for the test the temperature of the package was recorded. As shown in photograph 21 the package was then slung from a crane in the correct orientation and the height checked to ensure it was 1m from the punch. The release mechanism was activated and the package free fell onto the punch.

The temperature of the package was taken and the damage resultant from the test recorded.

4.2.18 Test 13 – 800°C thermal test

On conclusion of test 12a, the extra puncture test, the package was subjected to the 800°C thermal test. The following alterations were required to the keg prior to the test. Six thermocouples were mounted on the keg surface one at each end, and 4 located half way down the body at 0°, 90°, 180° and 270°. The accelerometer wiring was removed along with the wiring for the thermocouples inside the keg. An additional thermocouple was inserted to rest on the CV lid. A cover plate was attached to the keg lid to reduce the wiring hole diameter in the lid from 25 mm to 8mm. The set up for the thermal test is illustrated in Figure 3. The keg was placed on a support cradle for the test so that it could be handled in and out of the furnace. Photograph 22 shows the test package on the support cradle prior to the thermal test.

The furnace at the Hoval test facilities, as described in section 3, was heated to 900°C. Data logging from the thermocouples was initiated and the package was placed in the furnace. Once the package surface temperature reached 800°C the test was initiated and the package remained inside the furnace for 30 minutes, with its temperature logged at 10 second intervals. On completion of the 30 minutes the package was removed from the furnace and allowed to cool naturally. The temperatures within the package were continuously logged until the internal temperature peaked and started to decrease.

4.2.19 Inspection of the Package

On completion of the NCT and HAC tests the package was disassembled. The package and packaging components were weighed and dimensions taken using the marked datum lines and measuring points. The results have been compared and are presented in Table 9.

Prior to opening the containment vessel a helium leakage test was carried out as detailed in section 4.2.5.

4.3 Deviations from Test Procedure

On completion of the steady state thermal test at 10W a further test was carried out for Croft information purposes only. This test was a thermal test with 20W heating. The test caused the inner cork to adhere to the keg liner which made any dimensional measurements of the inner cork impossible therefore these were not recorded. It must be noted this did not occur during the 10W steady state thermal test which has been reported in reference 1.

On completion of the 1.2 m drop tests and penetrations tests (Tests 4 to 9) it was apparent accelerometer 2 had failed during testing. In order to fix the fault the package had to be opened up, opening the package along with the loss of the accelerometer data made these tests invalid.

The faulty accelerometer was repaired and the test series from the point of completion of the helium leak test (sequence number 5) was repeated on the same package. Therefore the damage present from the original 1.2 m drop and penetration tests was present on the package when the tests were repeated. The results from the invalid tests were recorded in reference 12 to identify the damage caused by the invalid tests.

On the first 10.2 m drop test the package rotated during free fall (due to a 'kick' being given at the sling by the release mechanism) causing it to impact on the bottom rim rather than the side, coupled with that there was also a data logging failure so no acceleration data was captured. Therefore this test was considered invalid and repeated once the package had reached -40°C. The results from this test have been reported in reference 20.

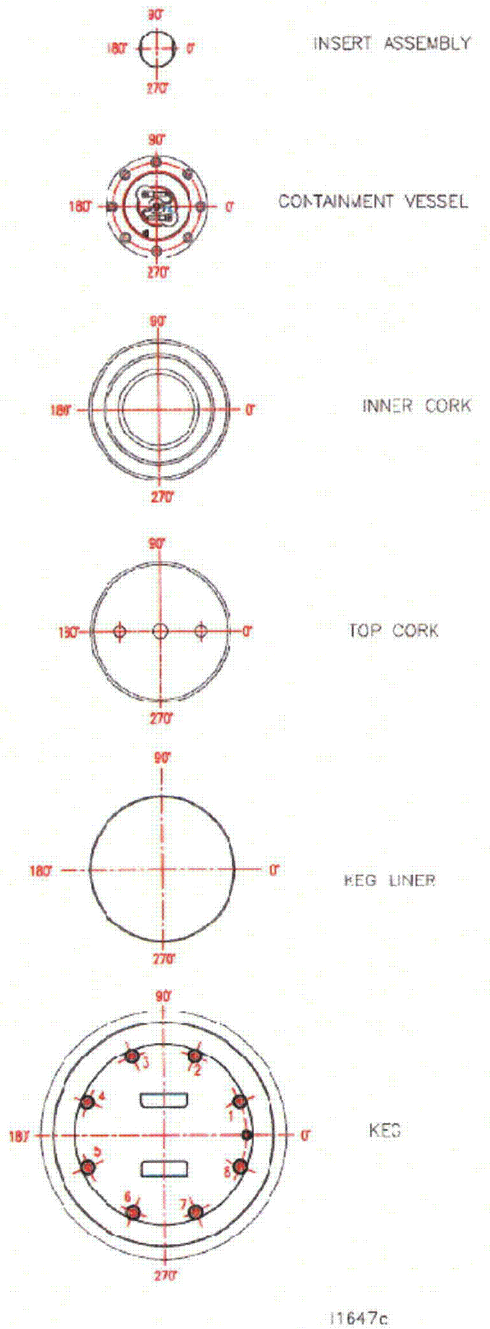


Figure 4 – Package Assembly Orientation

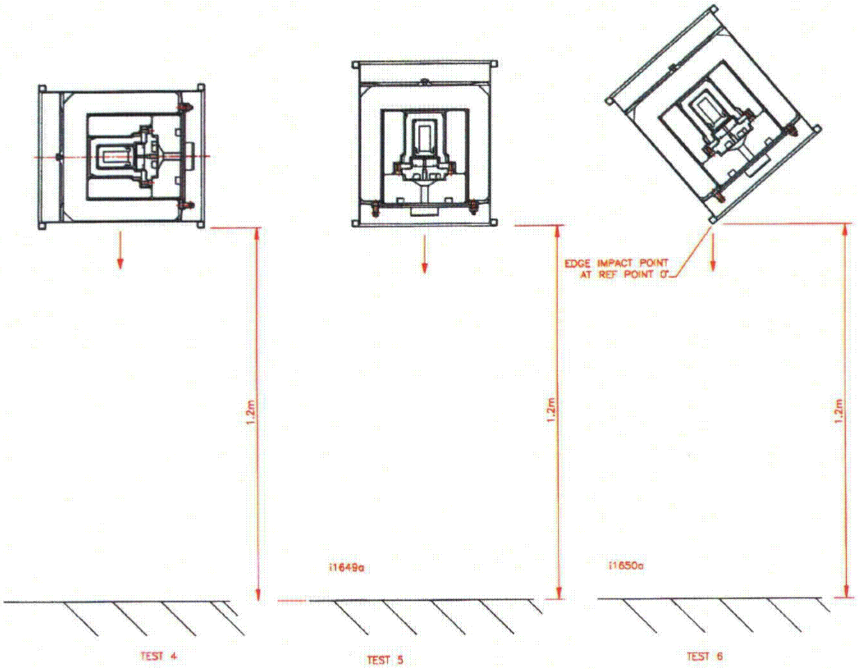


Figure 5 – 1.2 m Drop Tests

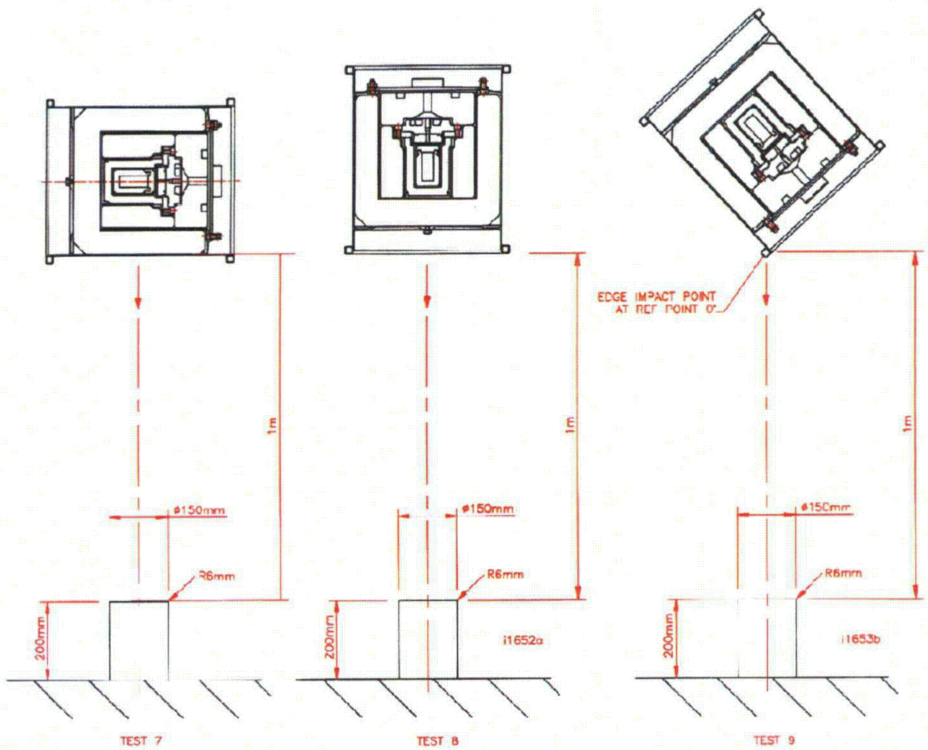


Figure 6 – Puncture tests

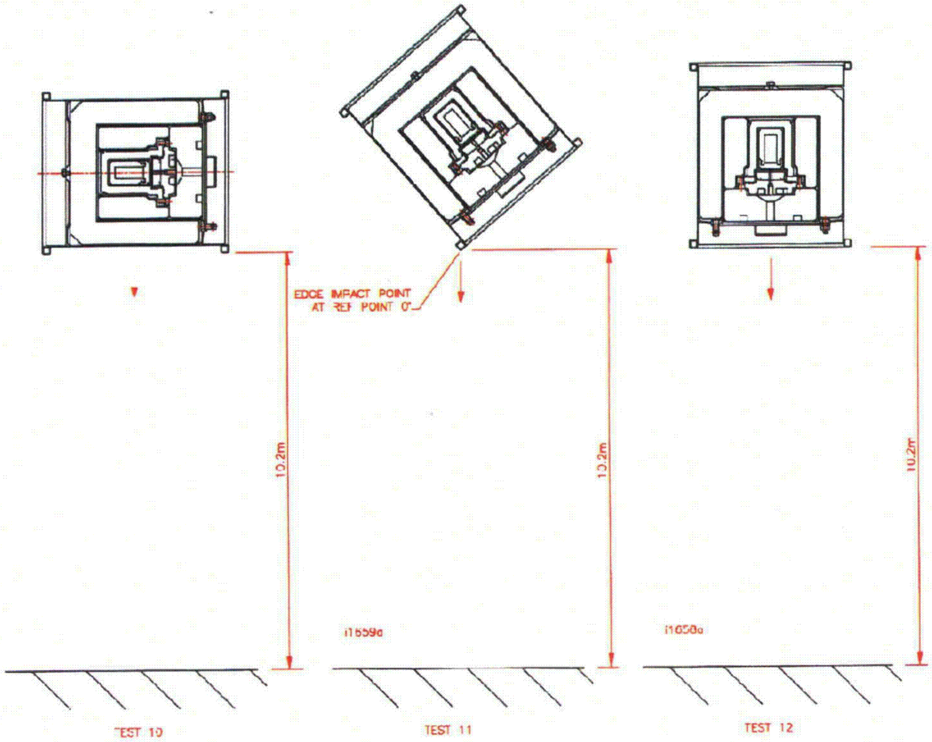


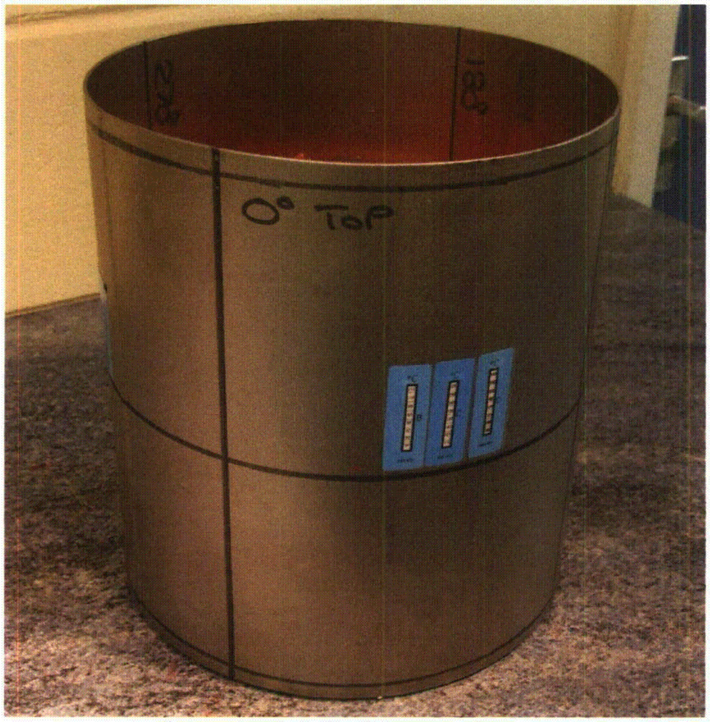
Figure 7 – 10.2 m Drop Tests

Photograph 1 – Vertical steady state thermal test

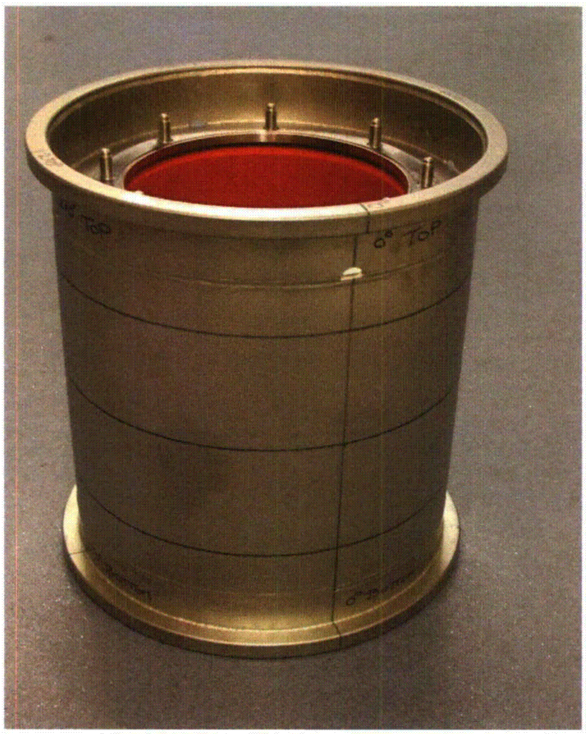
Photograph 2 – Horizontal steady state thermal test

Photograph 3 – Insert prior to testing

Photograph 4 – Containment vessel prior to testing

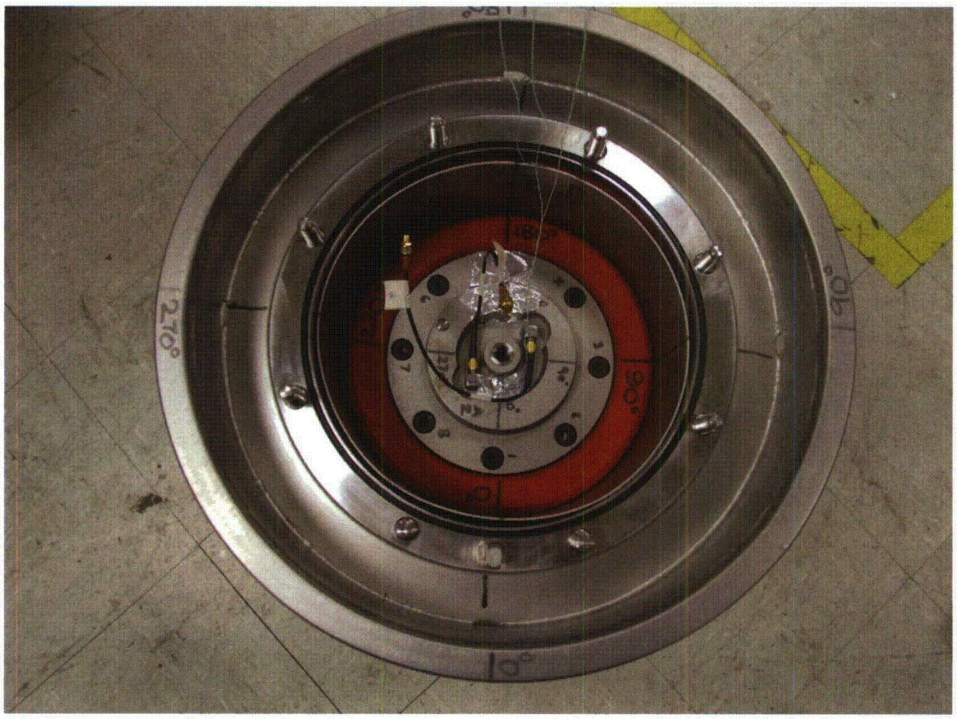


Photograph 5 – Keg liner prior to testing

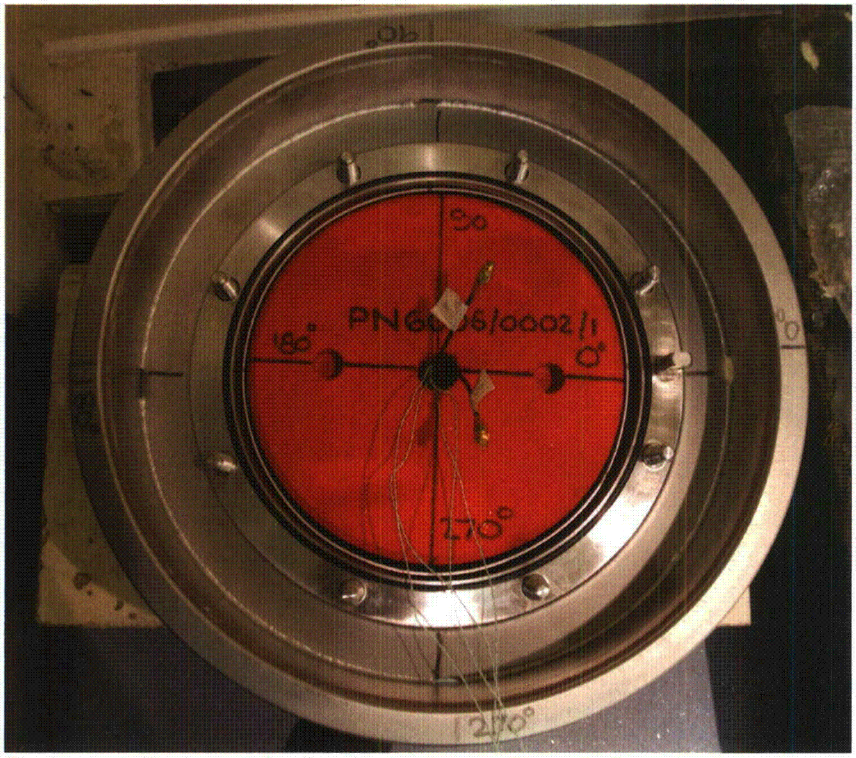


Photograph 6 – Keg prior to testing

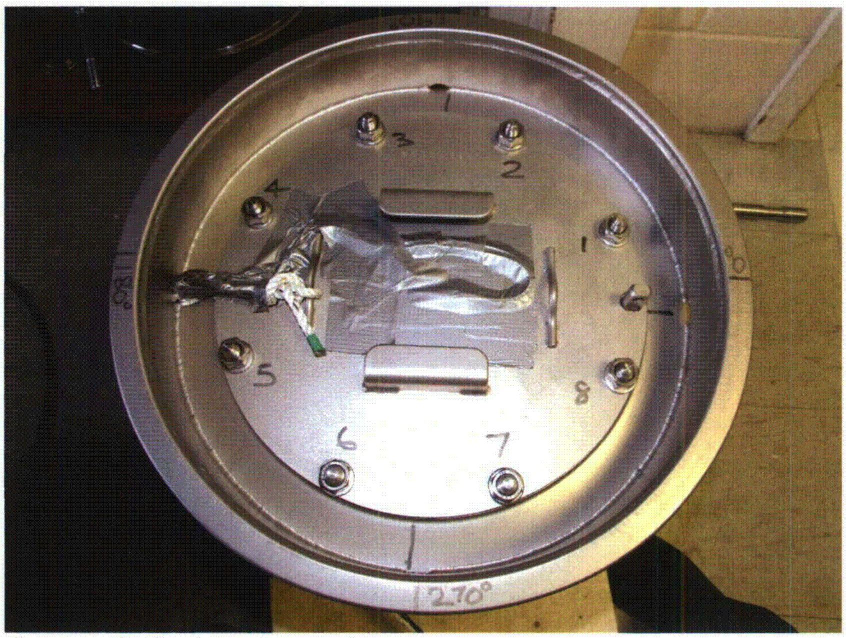
Photograph 7 – Compression test



Photograph 8 – Assembly of package



Photograph 9 – Assembly of package

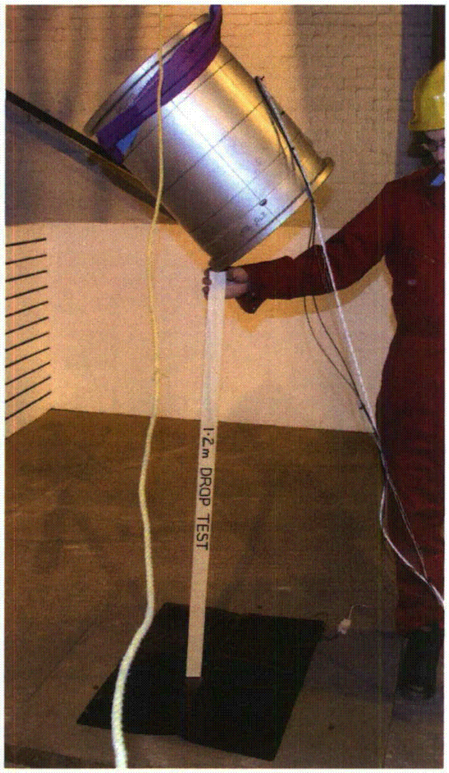


Photograph 10 – Assembled package

Photograph 11 – Penetration test

Photograph 12 – Test 4 1.2 m drop test onto side

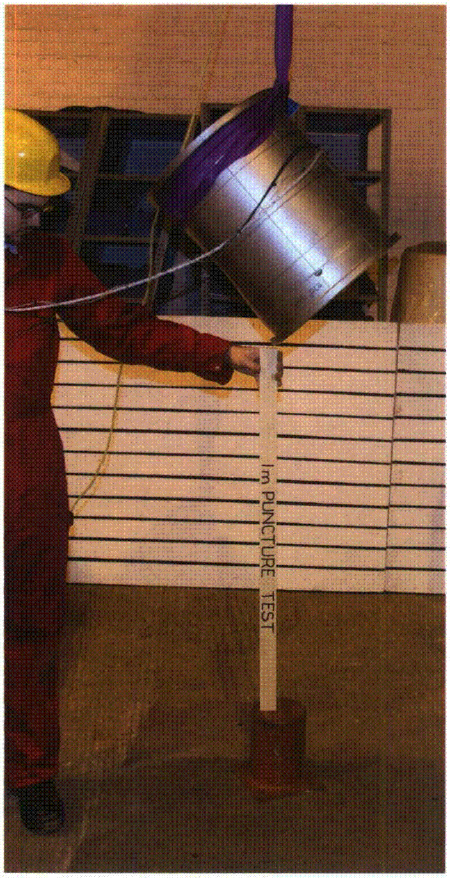
Photograph 13 – Test 5 1.2 m drop test onto top end



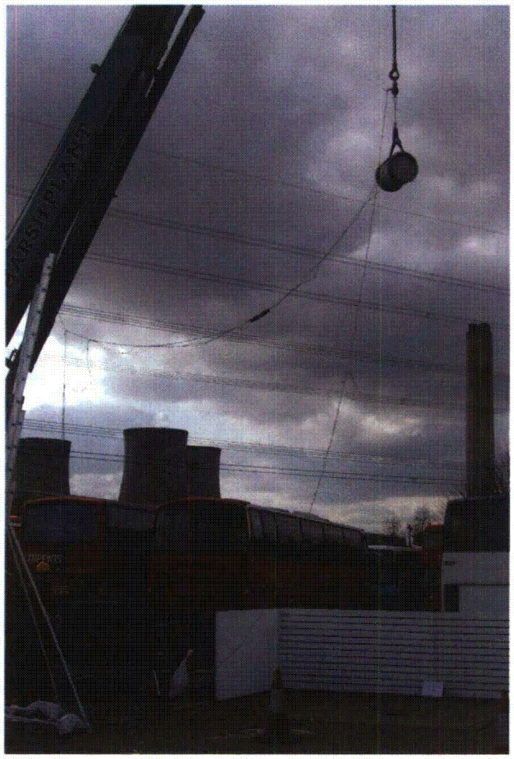
Photograph 14 – Test 6, 1.2 m drop test onto top rim edge

Photograph 15 – Test 7 1m puncture test over side

Photograph 16 – Test 8 1m puncture test over bottom

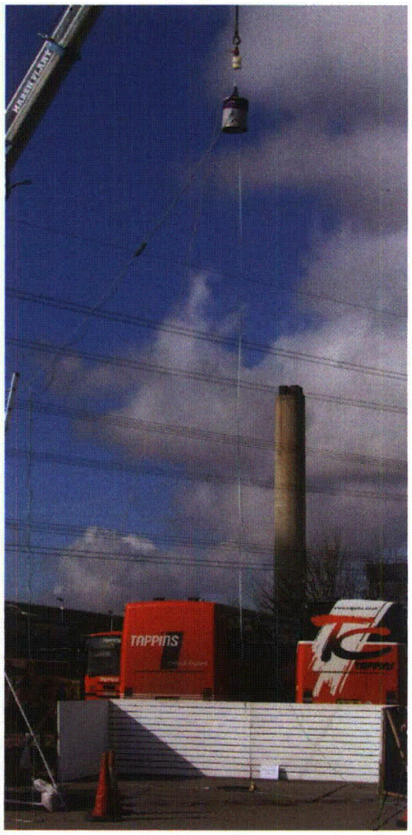


Photograph 17 – Test 9 1m puncture test over top rim edge



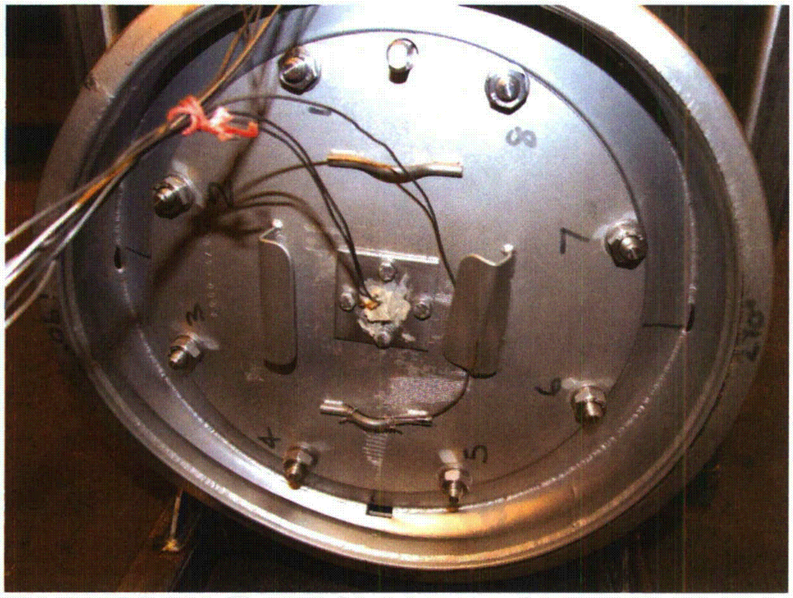
Photograph 18 – Test 10 10.2m drop test over side

Photograph 19 – Test 11 10.2 m drop test over top rim



Photograph 20 – Test 12 10.2 m drop test over top end.

Photograph 21 – Test 12a 1m puncture test on top end



Photograph 22 – Test package set up prior to thermal test

Photograph 23 – Test package on support cradle in preparation for thermal test

5 REGULATORY TEST RESULTS

5.1 Test 1 - Steady State Thermal Test [Reference 8]

In the vertical orientation the package took 67 hours to reach thermal equilibrium. The plot showing the thermocouple data over this time is given in Figure 8. The maximum temperature reached at each thermocouple position is given in Table 4. The surface temperature of the keg was measured at the points shown in Figure 9 and the resultant temperatures measured are given in Table 5.

The test continued for another 9.5 hours at which point the keg was turned into the horizontal position as indicated on the plot in Figure 8. It took a further 13.3 hours for the keg to reach equilibrium in this orientation. The test continued for another 12.9 hours, the maximum temperature obtained by the package over this time in the horizontal position is given in Table 4. The surface temperature of the keg was measured in the positions shown in Figure 10 and the resultant temperatures are given in Table 6.

The maximum surface temperature reached during both the vertical and horizontal tests was 28.6°C, which in an ambient of 24.1°C, is only a 4.5°C rise in the package surface temperature. During the tests the maximum temperature obtained over the containment vessel seals was 4.9°C.

5.2 Test 2 – Compression Test [Reference 10]

Table 7 presents the measurements taken from the keg before and after the compression test. The measurements show no change therefore the keg was unaffected by this test.

5.3 Test 3 – Penetration Test [Reference 11]

Photograph 24 shows the penetration test produced a dent in the keg skin. This dent was measured as 8.9 mm in depth and 105 mm wide, there was no puncture or tearing of the keg skin.

5.4 Test 4 – 1.2m drop test 1 at ambient C of G over side [Reference 14]

The package impacted the target slightly bottom down as shown in photograph 25 and experienced minimal damage to the rim as shown in photograph 26. The filtered acceleration data recorded during the drop test is presented in Figure 11.

5.5 Test 5 – 1.2 m drop test 2 at ambient, C of G over top end [Reference 15]

The package impacted the target over the top end however there was some sideways movement on impact as shown in photograph 27. The damage caused to the keg by the drop is minimal as shown in photograph 28. The filtered acceleration data recorded during the drop test is presented in Figure 12.

5.6 Test 6 – 1.2 m drop test 3 at ambient, C of G over top rim edge [Reference 16]

The package impacted the target over the top rim edge as shown in photograph 29. The damage caused to the keg by the drop is minimal as shown in photograph 30. The filtered acceleration data recorded during the drop test is presented in Figure 13.

5.7 Test 7 – 1 m Puncture test at ambient on side impact point [Reference 17]

The package impacted the punch over the side as shown in photograph 31. The impact caused a dent in the side of the keg of a depth of 14.61 mm as shown in photograph 32.

5.8 Test 8 – 1 m Puncture test at ambient on bottom impact point [Reference 18]

The package impacted the punch on the bottom of the package as shown in photograph 33. The impact caused minimal damage as shown in photograph 34.

5.9 Test 9 – 1 m Puncture test at ambient on top rim edge [Reference 19]

The package impacted the punch on the top rim edge of the package as shown in photograph 35. The impact caused minimal damage as shown in photograph 36.

5.10 Test 10 – 10.2 m drop test 1 at -40°C, C of G over side [Reference 21]

Due to an accelerometer failure discussed in section 4.3 this was the second 10.2 m drop test to be carried out, the results from the first test were discounted but the damage remained to the keg.

The temperature of the keg was recorded in Reference 21. The keg internals remained at < -40°C during the drop test. The point of impact was on the bottom rim as shown in photograph 37 with a secondary impact 40 milliseconds later on the top rim as shown in photograph 38. Photograph 39 shows the initial damage already present on the keg prior to the test, from the invalid drop. On repeating the drop the package impacted at the same point causing little additional damage to the primary impact point as shown in photograph 40. Minimal damage was caused to the keg from the secondary impact as shown in photograph 41. The filtered acceleration data taken during the drop test is shown in Figure 14. The maximum measured accelerations are given in Table 8.

5.11 Test 11 – 10.2 m drop test 2 at -40°C, C of G over top rim [Reference 22]

The temperature of the keg was measured before and after the drop, the results are recorded in Reference 22. The keg internals remained at < -40°C during the test.

The keg impacted the target on the top rim as shown in photograph 42 with the secondary impact shown in photograph 43. The impact caused 12 mm of deformation to the top rim of the keg as shown in photograph 44. The acceleration data recorded during the drop is shown in Figure 15. The maximum measured accelerations are given in Table 8.

5.12 Test 12 – 10.2 m drop test 3 at -40°C, on top end [Reference 23]

The temperature of the keg was measured before and after the drop, the results are recorded in Reference 23. The keg internals remained at < -40°C during the test.

The top of the keg impacted the target as shown in photograph 45. The impact caused minimal damage to the top of the keg as shown in photograph 46. However there was a degree of bellowing to the keg body beneath the rim as shown in photograph 47. The acceleration data recorded during the drop is shown in Figure 16. The maximum measured accelerations are given in Table 8.

5.13 Test 12a – 1 m puncture test on top at -40°C, on top end [Reference 24]

The temperature of the keg was measured before and after the drop, the results are recorded in Reference 24. The keg internals remained at < -40°C during the test.

The top of the keg impacted the punch causing damage to the handles as shown in photograph 48.

5.14 Test 13 – 800°C Thermal Test [Reference 25]

The test package was in the furnace for 47 minutes. During this time the furnace temperature remained above 800°C, with thermocouple 7 reading > 800°C for at least 30 minutes. The Time – Temperature traces from the thermocouples mounted on and in the package during the thermal test are shown in Figure 17. The maximum temperature of the CV lid boss was 101.8°C which was measured 262.83 minutes (approximately 4 hours) from the start of the test.

The effect on the thermal test on the package is illustrated in photographs 49 to 52. Photograph 49 and 50 shows the package as the furnace lid is lifted with photograph 51 showing the package 4 minutes after being removed from the furnace. The flames are caused by the gases emitted from the cork.

The flames continued for approximately 10 minutes after removal from the furnace at which point the flames self extinguished and the package continued to smoulder as shown in photograph 52.

The temperature sensitive strips indicated that the Containment vessel reached a maximum temperature of 110°C and the insert reached a maximum temperature of 90°C. Full details of the test can be found in reference 25.

5.15 Inspection Details Before and After NCT and HAC Testing [Reference 9]

The results of the dimensional inspection before and after testing are given in Table 9 with the weights presented in Table 10. Photographs 53 to 64 show the post test condition of the package and the individual components.

The outer surface of the keg suffered deformation from the drop and penetration tests. The majority of damage was caused to the rims of the keg. Table 9 and photograph 54 show that the keg height was reduced particularly at 0° and 270° due to the denting of the rim sustained during the 10.2 m drop tests. This denting has also caused the rim diameter to reduce. The penetration test did produce minor damage to the keg body causing the keg diameter to reduce 6.77 mm in the centre of the keg. Charring was also present on the outer surface of the keg due to the thermal test. There was however no puncture or tear on the keg surface.

On completion of the test the kegs nuts were no longer as tight as the assembly torque. On assembly the keg nuts were tightened to 23±1 Nm after testing the torque required to unscrew the keg nuts was ≤ 10 Nm. This was also borne out by the angular displacement data in Table 9 for the keg nuts. All nuts however were present.

Dimensional measurement of the containment vessel and insert has shown no change to either item on completion of the test series. The containment vessel nuts did not demonstrate any loosening. The containment vessel screws were tightened to 10 ± 0.5 Nm prior to testing. The torque required to remove the screws after testing was between 10 and 15 Nm. Photograph 62 shows that the insert has not caused any damage inside the containment vessel. The insert had loosened as demonstrated in photograph 63 and its O-ring had split as shown in photograph 64. This indicates that, liquid and gases would leak from the insert under HAC accident conditions

The thermal test caused charring to the cork within the package, photographs 57 and 58 show charring of the inner cork and Photographs 56 and 59 show charring of the top cork. The charring of the top cork was present for 30 mm below the upper surface. Below the charred line the cork is unaffected.

The weight measurements taken before and after the test series show a reduction in the overall package weight of 3.4 kg. The thermal test caused the cork to adhere to the steel liner therefore the change in the cork weights couldn't be accurately determined. No weight changes were observed to the containment vessel or insert. Therefore the likely cause of the weight decrease is due to the reduction is weight of the cork due to the effects of the thermal test.

5.16 Helium Leak Test Before and After NCT and HAC Testing

The helium leak test carried out prior to the NCT and HAC tests is detailed in Reference 13. The tested leak rate was 0.05×10^{-10} cm^3/sec which meets the acceptance criteria of 2×10^{-7} cm^3/sec.

The helium leak test carried out after the NCT and HAC tests is detailed in Reference 26. The tested leak rate was 1.92×10^{-10} cm^3/sec which meets the acceptance criteria of 2×10^{-7} cm^3/sec.

The results of the leak tests demonstrate that the containment vessel remained leak tight before and after the NCT and HAC tests. This indicates that the tests did not affect the containment vessel and its sealing system.

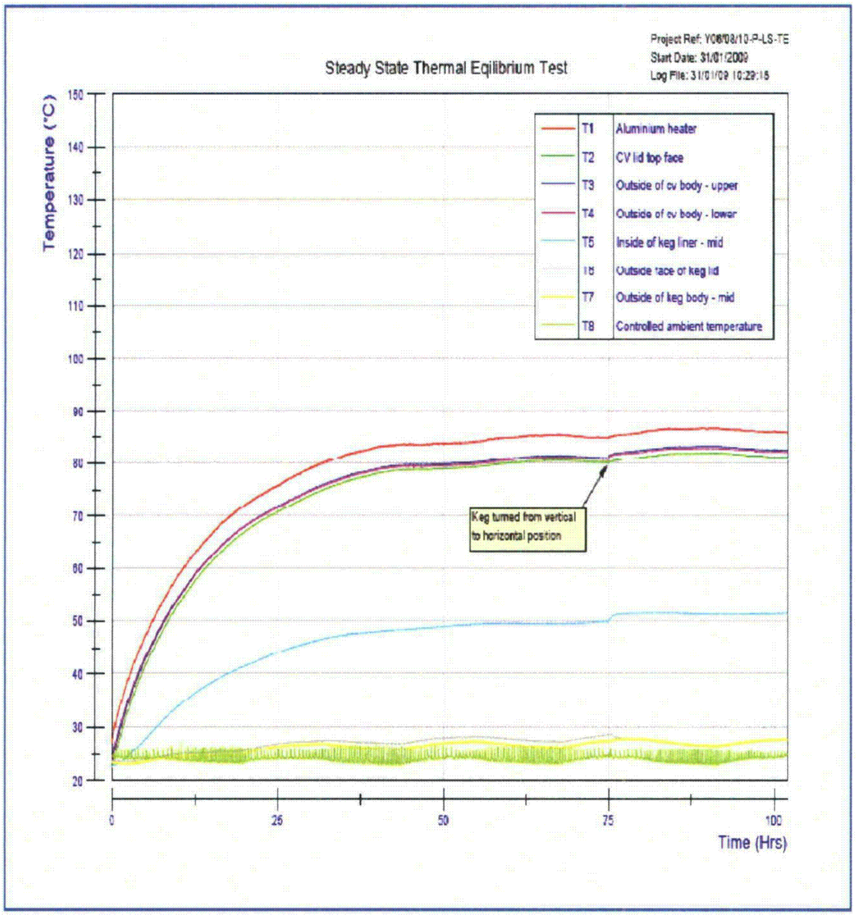


Figure 8 – Steady State Thermal Test Thermocouple Data

Thermocouple	Vertical Orientation Test 1a		Horizontal Orientation Test 2a	
	Max Temperature (°C)	Time (hrs)	Max Temperature (°C)	Time (hrs)
T1 Aluminium heater	85.4	66.07	86.7	90.55
T2 CV lid top face	80.5	66.07	81.9	89.55
T3 Outside of CV body upper	81.4	66.47	83.2	89.23
T4 Outside of CV body lower	81.1	66.82	82.9	89.32
T5 Inside of keg liner mid	49.6	58.60	51.4	89.02
T6 Outside face of keg lid	28.3	73.31	20.7	75.35
T7 Outside of keg body	27.9	79.30	27.9	79.33
T8 Controlled ambient temp.	24.1 (avg)		24.1 °C (avg)	

Table 4 – Maximum Temperatures Reached During Steady State Thermal Test

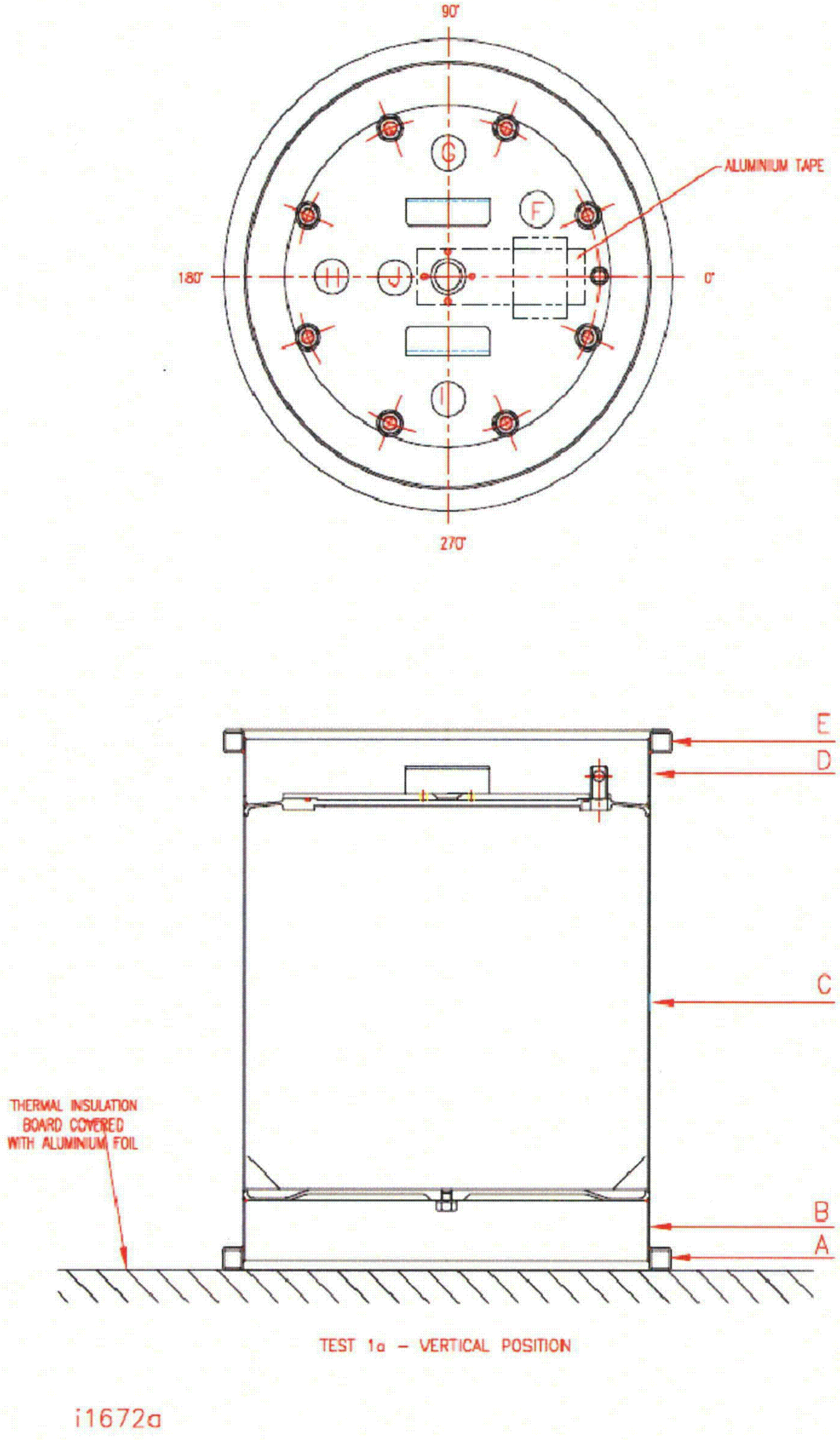


Figure 9 - Temperature Measurement Positions in the Vertical Orientation

Item	Measurement Position	Temperature (°C)
Keg Lid	F	28.4
	G	28.6
	H	28.0
	I	28.0
	J	28.4
Keg lid rim	E0	25.8
	E90	26.0
	E180	25.6
	E270	25.5
Keg Body – upper position	D0	26.2
	D90	26.6
	D180	26.0
	D270	25.9
Keg Body – Centre position	C0	27.0
	C90	27.5
	C180	26.8
	C270	26.4
Keg Body – Lower position	B0	24.9
	B90	24.9
	B180	24.7
	B270	24.6
Keg Base Rim	A0	23.7
	A90	23.8
	A180	23.6
	A270	23.4

Table 5 – Surface Temperatures with the Keg in the Vertical Position

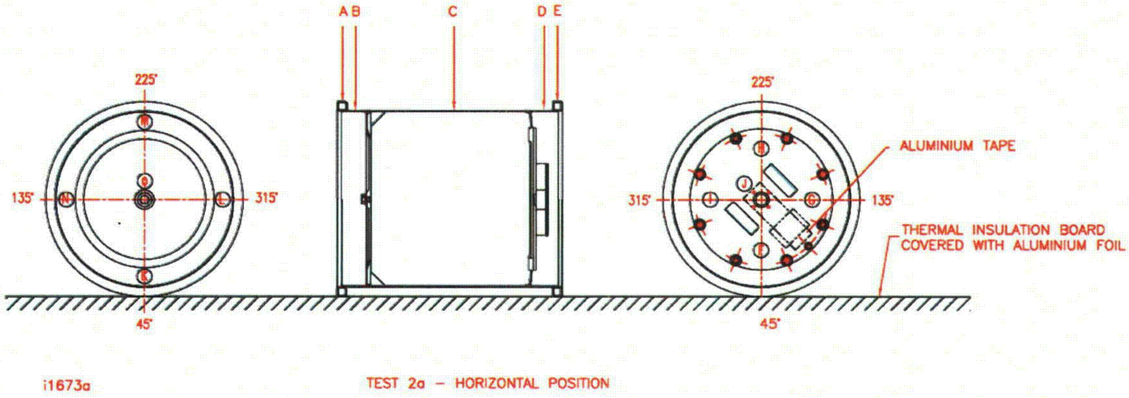


Figure 10 – Temperature Measurement Positions in the Horizontal Position

Item	Measurement Position	Temperature (°C)
Lid rim	E225	25.8
Keg body – lid end	D225	26.5
Keg body – mid	C225	27.7
Keg body – base end	B225	26.1
Base rim	A225	25.7
Base	M	26.8
Lid	I	28.0
	J	28.2
	G	27.5
	F	27.5
	H	28.5
Lid rim	E315	24.8
	E135	24.9
Keg Body – lid end	D315	25.3
	D135	25.6
Keg Body – mid	C315	26.6
	C135	27.1
Keg Body – base end	B315	25.8
	B135	25.4
Base rim	A315	24.9
	A135	25.0
Base	I	26.1
	O	27.7
	N	26.0
	K	25.7

Table 6 – Surface Temperatures with the Keg in the Horizontal Position

Component	Measurement Position	Free standing before test	*Free standing after test*
Keg weight		24.24 kg	24.24 kg
Keg height	A – A @ 0°	480.76 mm	480.76 mm
	A – A @ 90°	481.26 mm	481.26 mm
	A – A @ 180°	479.60 mm	479.60 mm
	A – A @ 270°	481.08 mm	481.08 mm
Keg rim dia	B – B	420.30 mm	420.30 mm
	C – C	420.10 mm	420.10 mm
Keg body dia	D – D	382.18 mm	382.18 mm

Table 7 – Measurements taken before and after the Compression Test

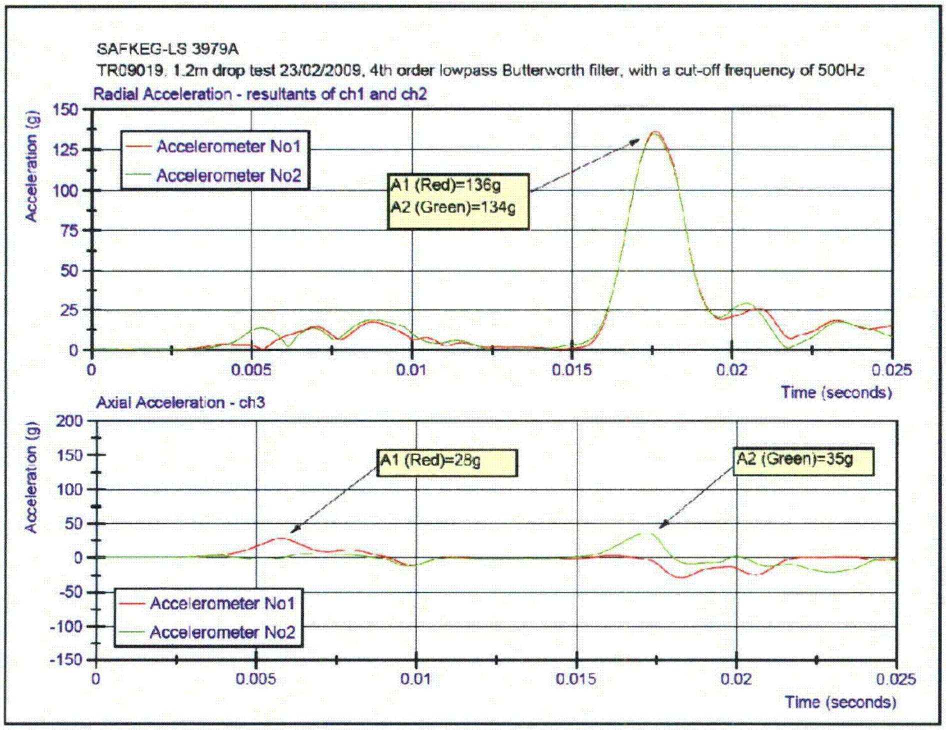


Figure 11 – Test 4 Filtered Acceleration Time History

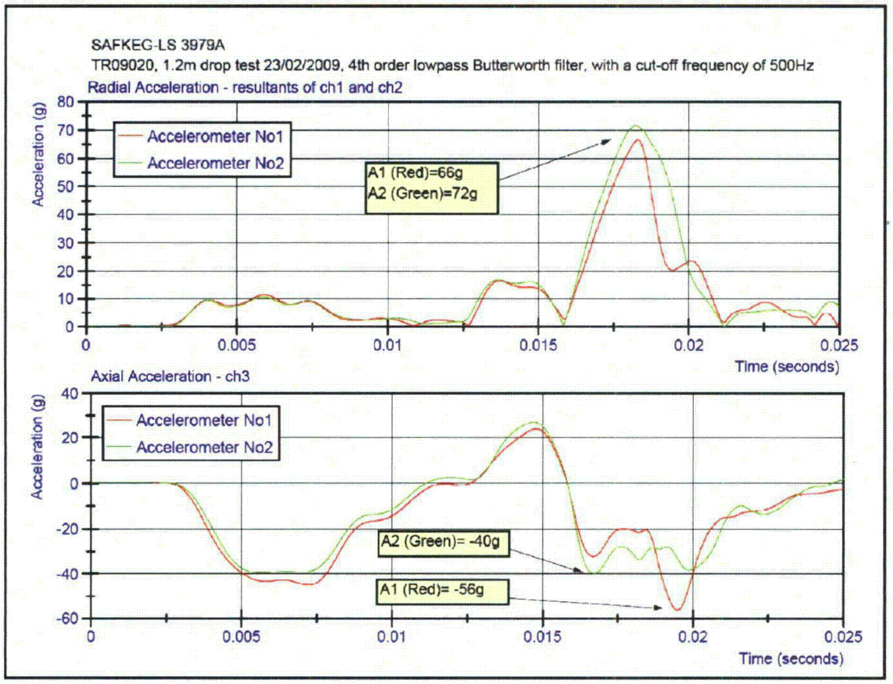


Figure 12 – Test 5 Filtered Acceleration Time History

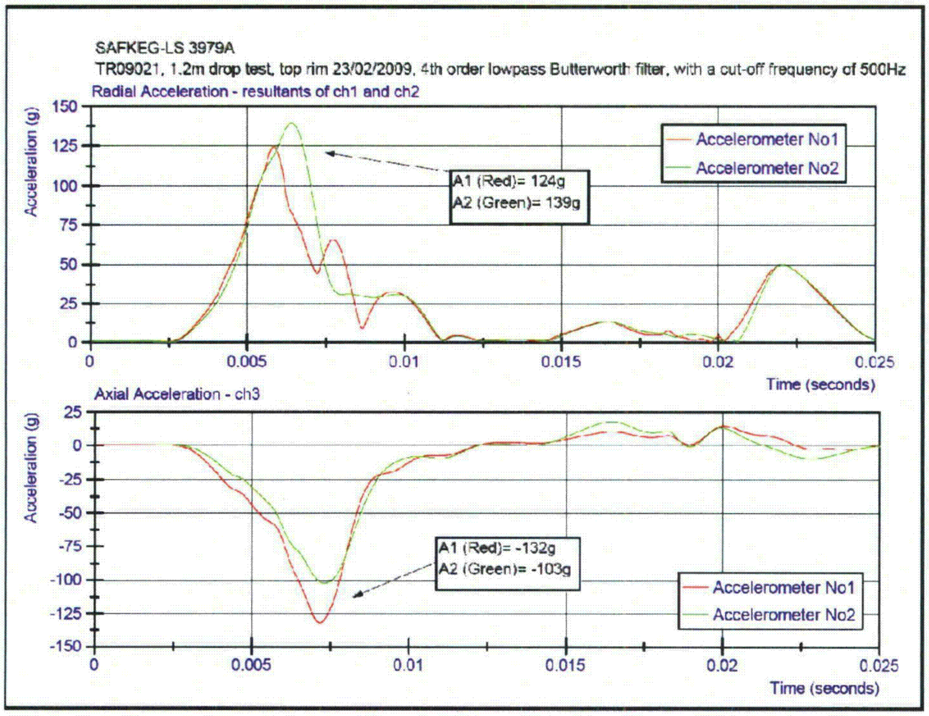


Figure 13 – Test 6 Filtered Acceleration Time History

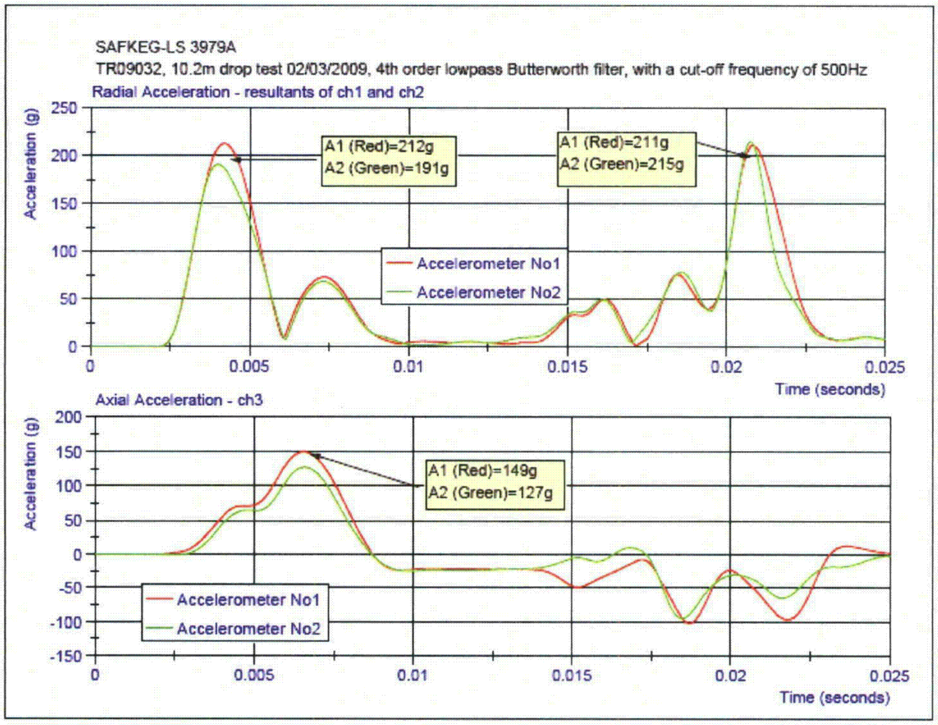


Figure 14 – Test 10 Filtered Acceleration Time History

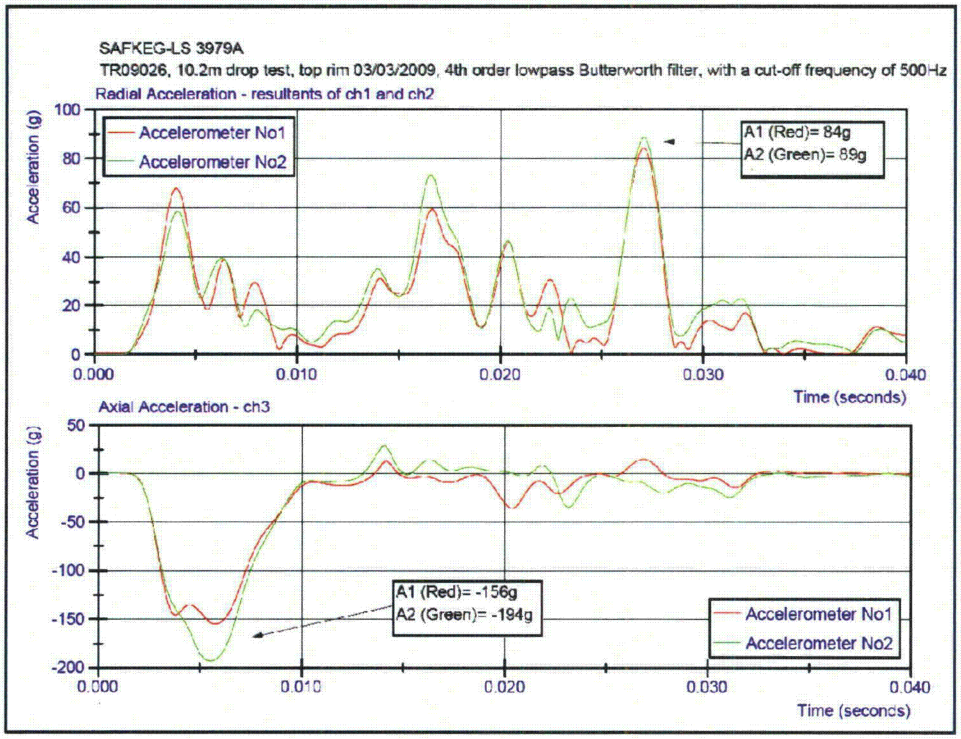


Figure 15 – Test 11 Filtered Acceleration Time History

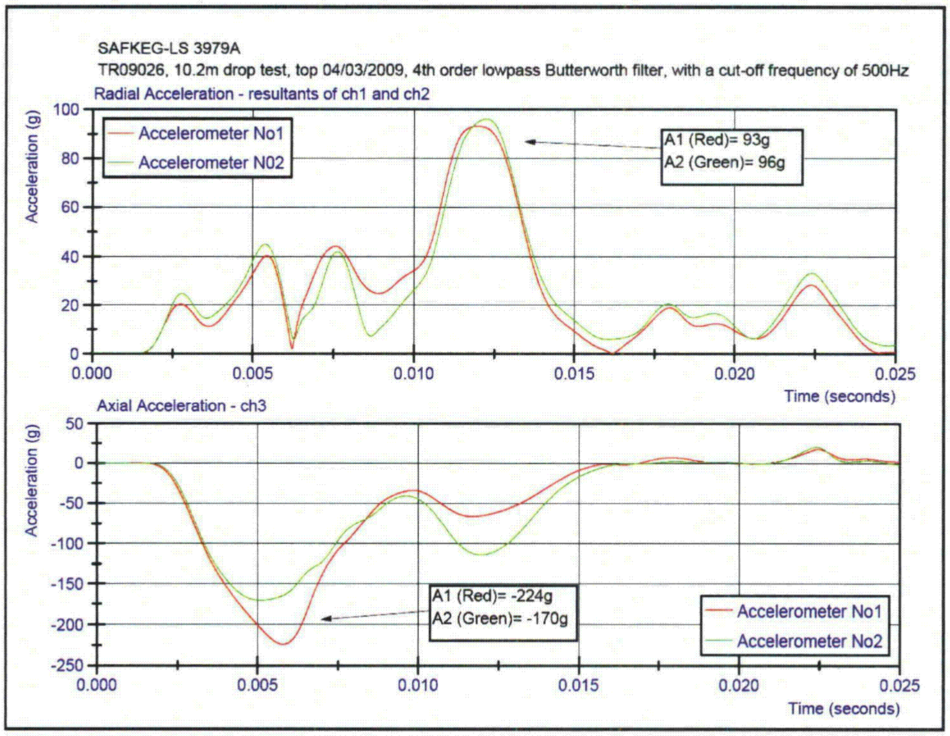


Figure 16 – Test 12 Filtered Acceleration Time History

Test			4	5	6	10	11	12
Drop Height			1.2	1.2	1.2	10.2	10.2	10.2
Velocity on impact (m/s)			4.85	4.85	4.85	14.15	14.15	14.15
Acceleration response pulse duration millisecond			23	20	8.5	21	40	23
Peak Acceleration	Axial (g)	Accelerometer 1	136	56	132	149	156	224
		Accelerometer 2	134	40	103	127	194	170
	Radial (g)	Accelerometer 1	28	66	124	212	84	93
		Accelerometer 2	35	72	139	215	89	96
Displacement of CV at the end of acceleration pulse (mm)			36	37	10	148	381	201

Table 8 – Acceleration data from drop tests

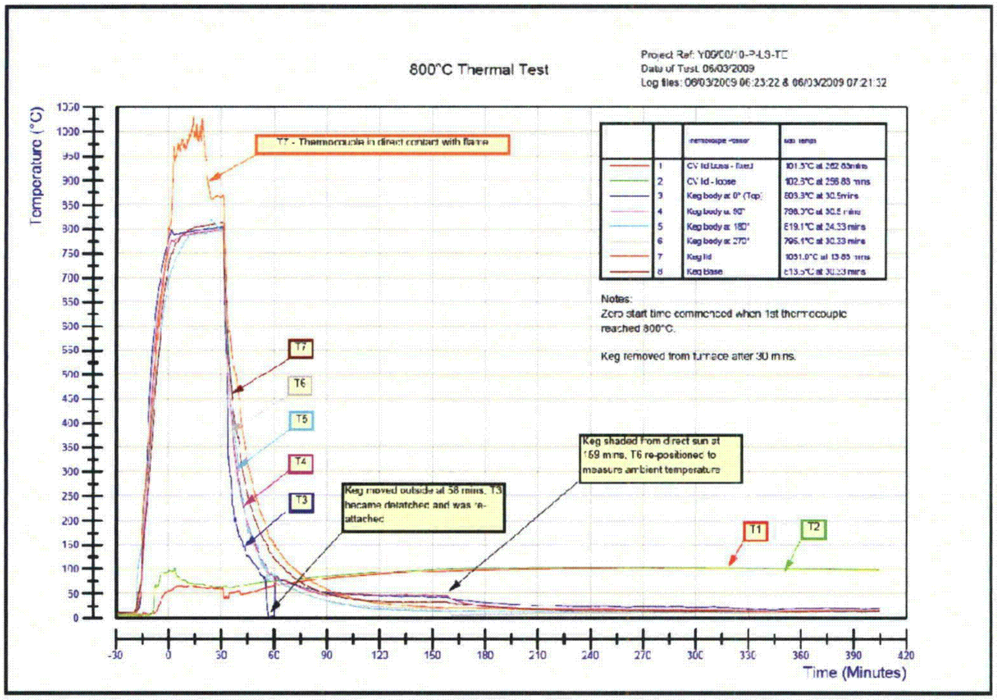


Figure 17 – Temperature Trace Recorded During the 800°C Thermal Test

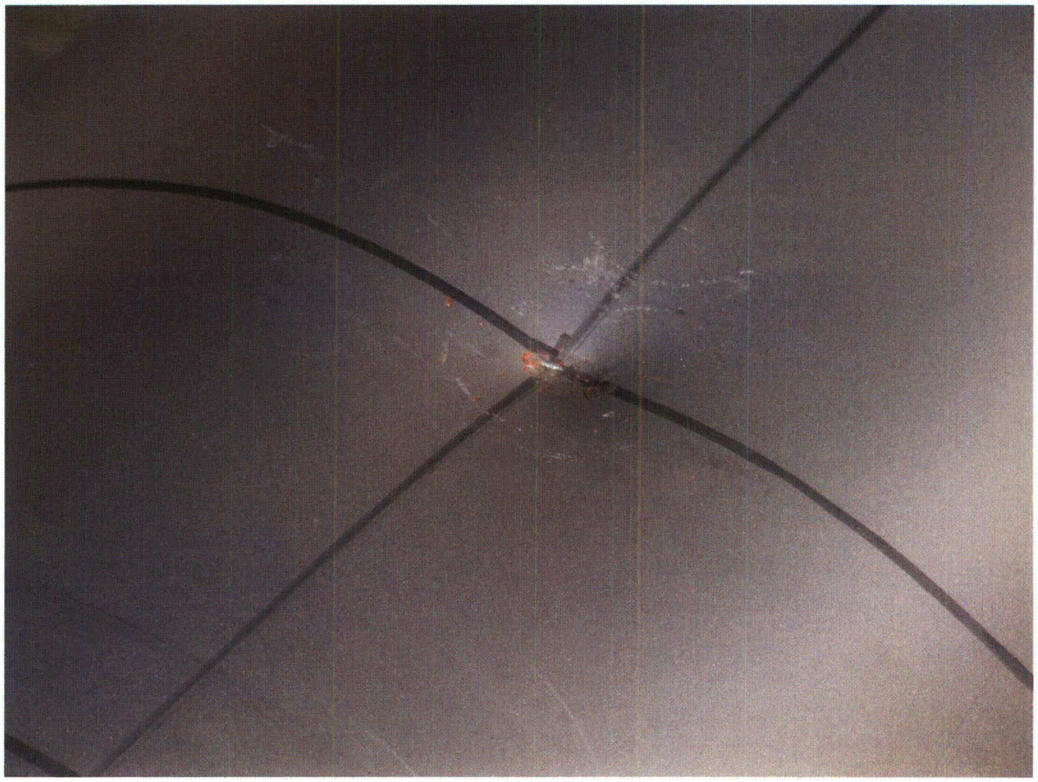
Component	Ref Position	Pre-test Dimension (mm)	Post-test Dimension (mm)	Diff (mm)
Insert Assembly				
Insert height	A-A	107.11	107.09	-0.02
Body lower dia.	B-B @ 0°-180°	62.00	62.00	0
Body lower dia.	B-B @ 90°-270°	62.00	61.99	-0.01
Body mid dia	C-C @ 0°-180°	62.00	62.00	0
Body mid dia	C-C @ 90°-270°	62.00	61.99	-0.01
Lid dia	D-D @ 0°-180°	62.04	62.03	-0.01
Lid dia	D-D @ 90°-270°	62.04	62.03	-0.01
Containment Vessel				
CV height	A-A	203.40	203.40	0
CV lower diameter	B-B @ 0°-180°	117.82	117.82	0
CV lower diameter	B-B @ 90°-270°	118.00	117.98	-0.02
CV mid diameter	C-C @ 0°-180°	118.57	118.57	0
CV mid diameter	C-C @ 90°-270°	118.43	118.42	-0.01
CV upper diameter	D-D @ 0°-180°	134.72	134.71	-0.01
CV upper diameter	D-D @ 90°-270°	134.50	134.50	0
CV lid diameter	E-E @ 0°-180°	174.97	174.97	0
CV lid diameter	E-E @ 90°-270°	174.98	174.98	0
CV lid inner O-ring groove	F-F @ 0°-180°	89.56/57	89.58	-0.015
CV lid inner O-ring groove	F-F @ 90°-270°	89.56/57	89.59	-0.015
Top Cork				
Cork top diameter	A-A @ 0°-180°	239.54	Not possible to measure due to charring of the cork which occurred during the 800°C furnace test	
Cork top diameter	A-A @ 90°-270°	239.58		
Cork top height	B-B @ 0°	86.10		
Cork top height	B-B @ 90°	86.75		
Cork top height	B-B @ 180°	86.65		
Cork top height	B-B @ 270°	86.89		
Keg Liner				
Liner height	A-A @ 0°	275.53	Not possible to measure because the inner cork stuck to the keg liner.	
Liner height	A-A @ 90°	275.79		
Liner height	A-A @ 180°	275.83		
Liner height	A-A @ 270°	275.06		
Liner lower dia.	B-B @ 0°-180°	247.73		
Liner lower dia.	B-B @ 90°-270°	249.51		
Liner mid dia	C-C @ 0°-180°	246.51		
Liner mid dia	C-C @ 90°-270°	248.77		
Liner top dia	D-D @ 0°-180°	245.30		
Liner top dia	D-D @ 90°-270°	249.71		
Keg Assembly				
Keg height	A-A @ 0°	480.76/78	466.29	-14.48
Keg height	A-A @ 90°	481.29/26	478.03	-3.24
Keg height	A-A @ 270°	479.66/60	466.30	-13.33
Keg height	A-A @ 360°	481.16/08	480.33	-0.79
Keg rim diameter	B-B @ 0°-180°	419.84	419.85	+0.01
Keg rim diameter	B-B @ 90°-270°	419.76	412.00	-7.76
Keg rim diameter	D-D @ 0°-180°	421.13	412.37	-8.76
Keg rim diameter	D-D @ 90°-270°	419.30	418.76	-0.54
Keg outside diameter	C-C @ 0°-180°	382.22	375.45	-6.77
Keg outside diameter	C-C @ 90°-270°	382.28	382.51	+0.23
Stud & Nut 1 closed	Angle from perpendicular	0.2°	5.5°	+5.3
Stud & Nut 2 closed	Angle from	0.3°	4.4°	+4.1

	perpendicular			
Stud & Nut 3 closed	Angle from perpendicular	0.2°	4.4°	+4.2
Stud & Nut 4 closed	Angle from perpendicular	0.1°	4.4°	+4.3
Stud & Nut 5 closed	Angle from perpendicular	0.3°	3.4°	+3.1
Stud & Nut 6 closed	Angle from perpendicular	0.6°	3.8°	+3.2
Stud & Nut 7 closed	Angle from perpendicular	0.3°	3.8°	+3.5
Stud & Nut 8 closed	Angle from perpendicular	0.0°	3.7°	+3.7

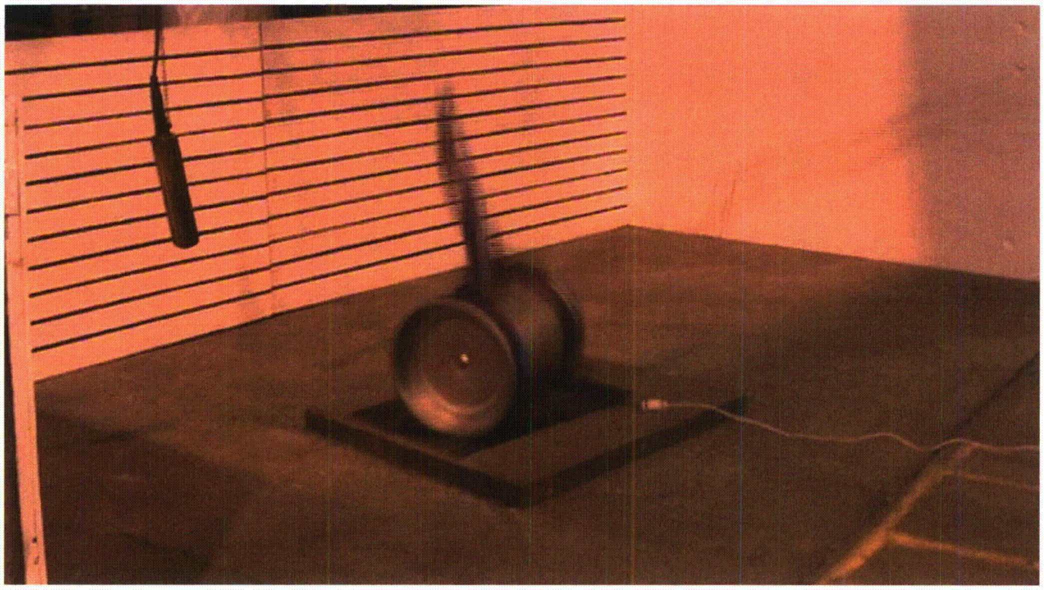
Table 9 – Dimensions taken before and after NCT and HAC tests

Component	Pre test weight (g)	Post test weight (g)	Diff (g)
Package assembly	61876.5	58437	-3439.5
Keg Body	32625	Not possible to weigh in isolation	
Keg lid			
Keg liner			
Keg nuts and washers			
Keg O-ring	11.3	Disintegrated	
Top cork	10.36	Not retrievable	
Inner cork body	1519	Not retrievable	
CV body	20965	20965	0
CV lid			
CV screws			
CV O-rings	4.9	4.9	0
Insert body	4400.0	4400.5	+0.5
Insert lid	1121.0	1120.5	-0.5
Insert O-ring	0.3	0.3	0
Dummy contents	42.0	41.5	-0.5

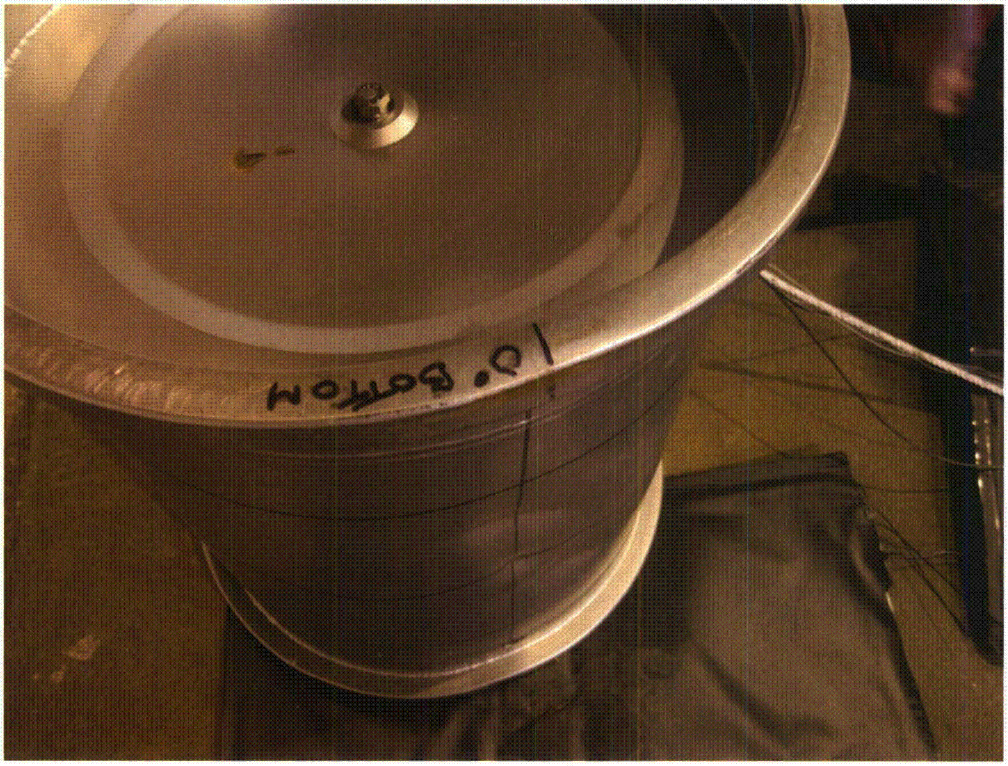
Table 10 – Weights measured before and after NCT and HAC tests



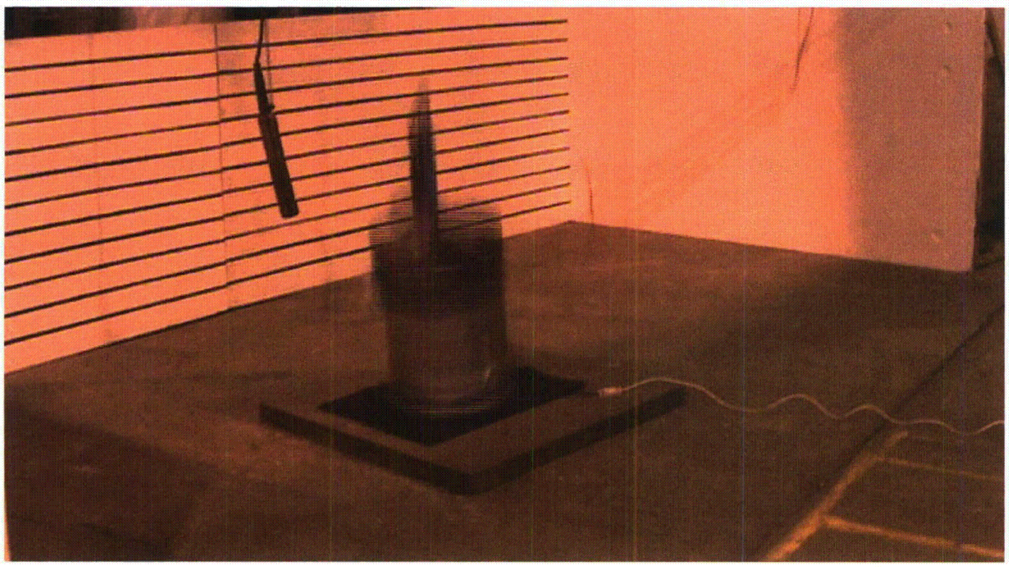
Photograph 24 – Indent resulting from penetration test



Photograph 25 – Test 4 point of impact

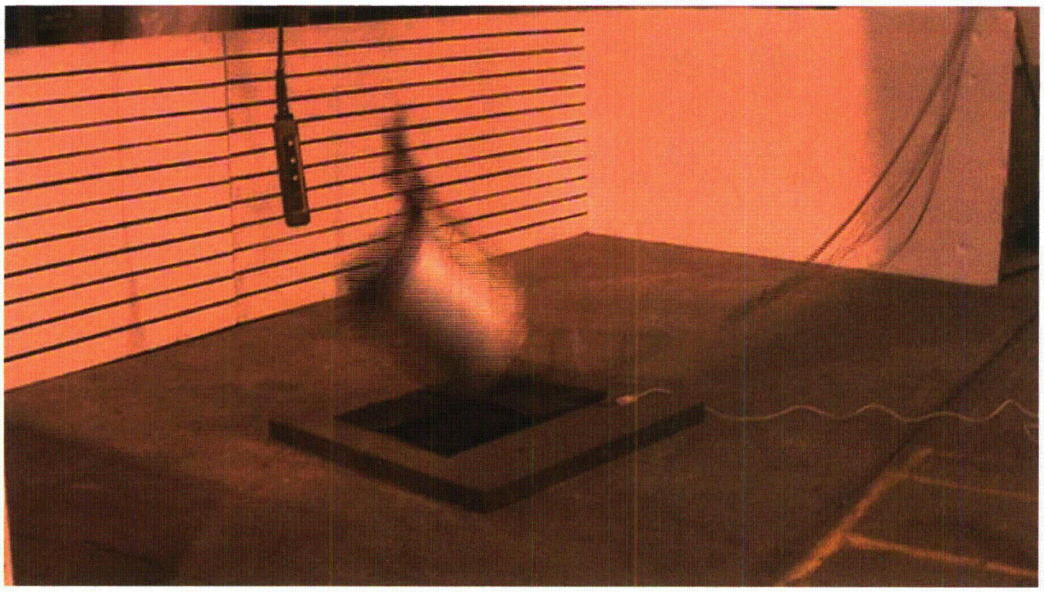


Photograph 26 – Test 4 Damage caused to keg

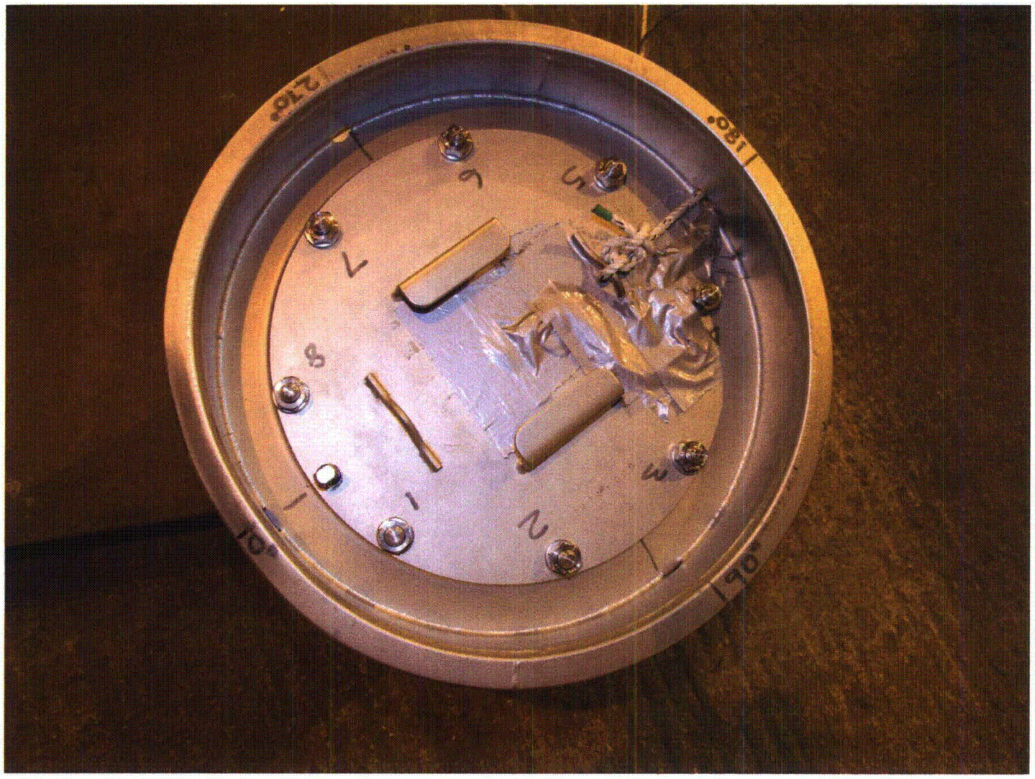


Photograph 27 – Test 5 point of impact

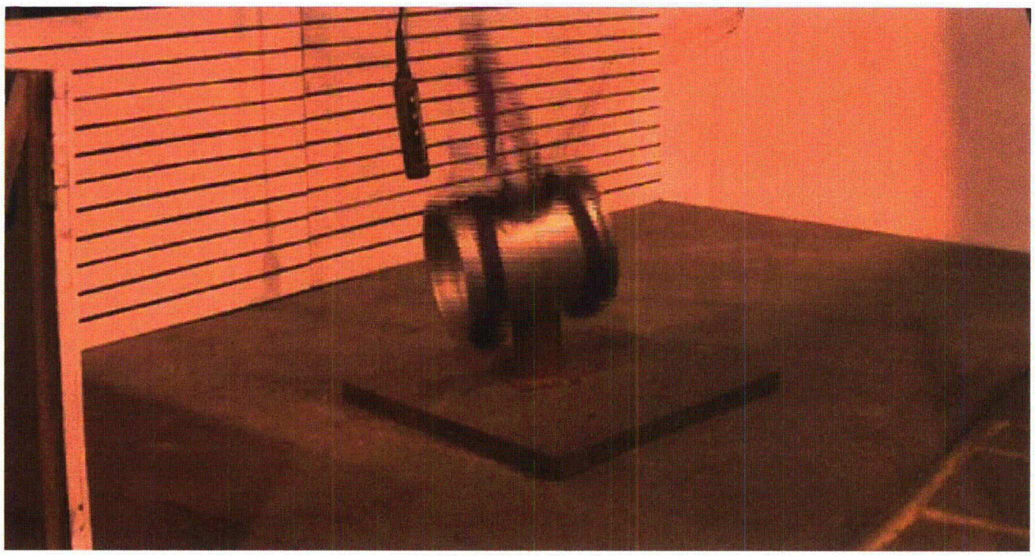
Photograph 28 – Test 5 damage caused to keg



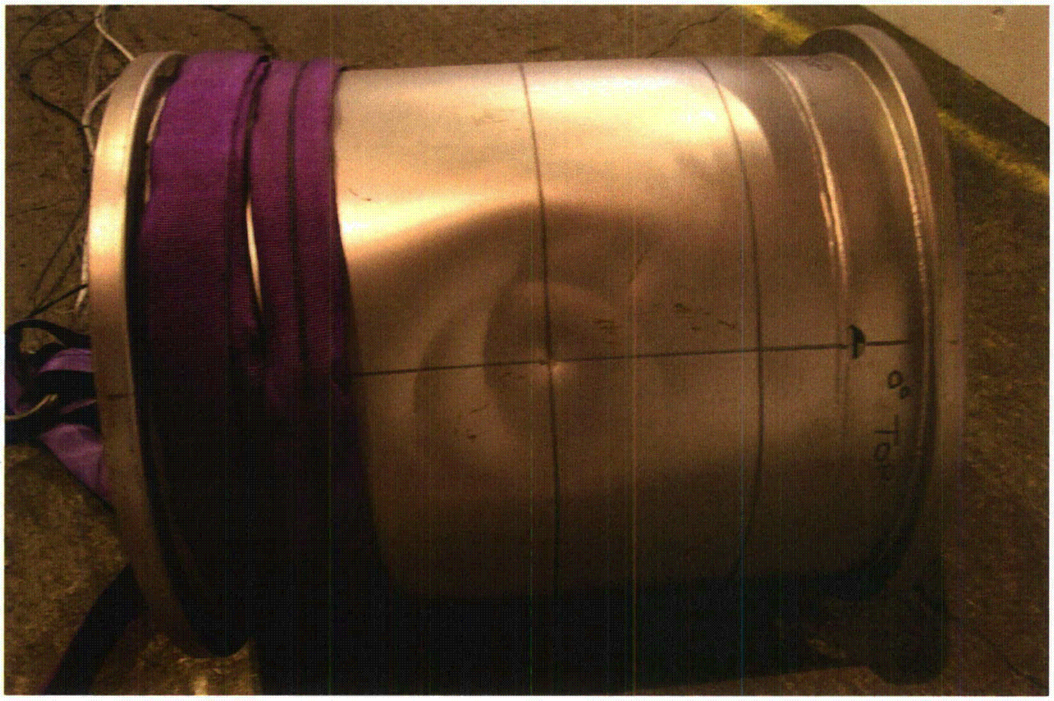
Photograph 29 – Test 6 point of impact



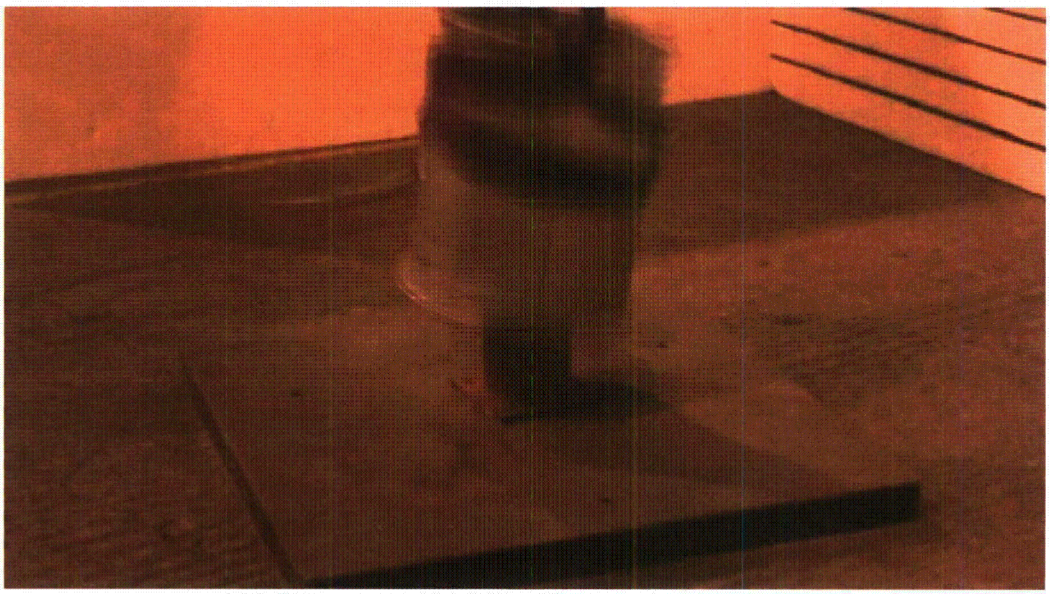
Photograph 30 – Test 6 damage caused to keg



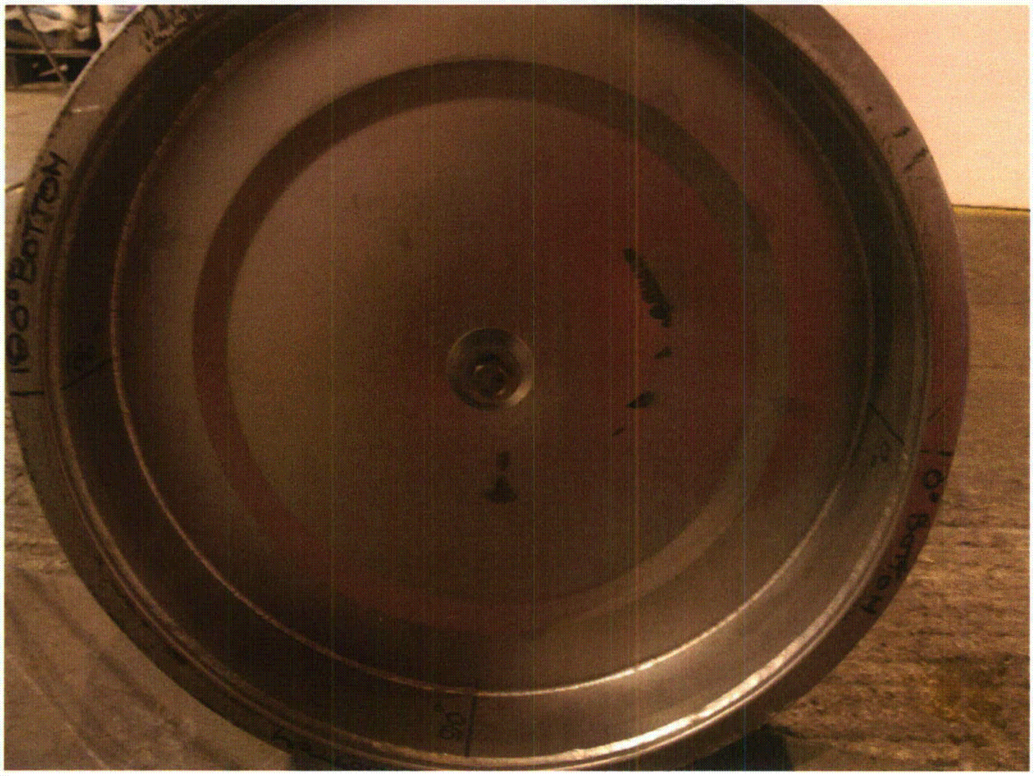
Photograph 31 – Test 7 point of impact



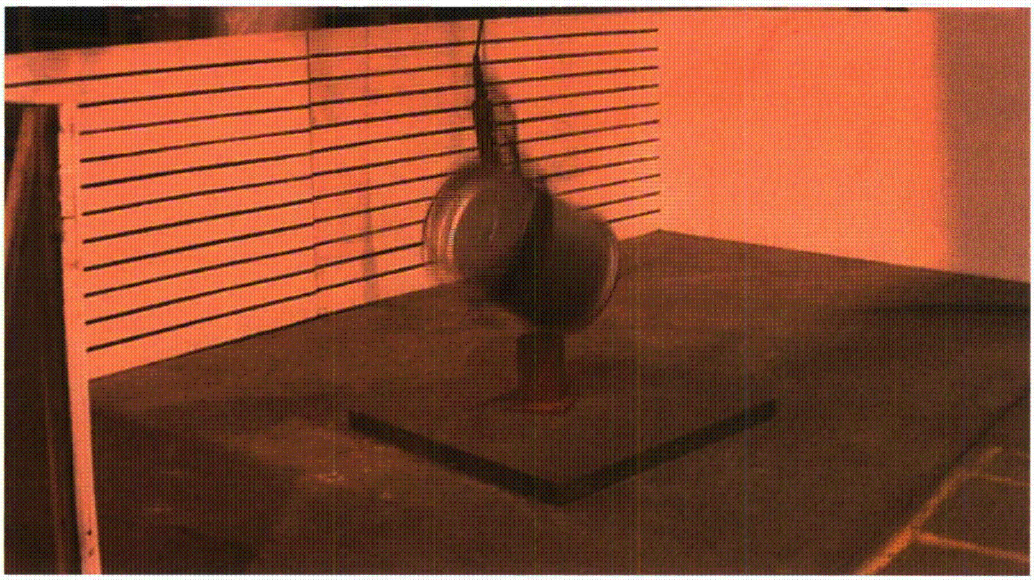
Photograph 32 – Test 7 damage caused to keg



Photograph 33 – Test 8 point of impact



Photograph 34 – Test 8 damage caused to keg



Photograph 35 – Test 9 point of impact

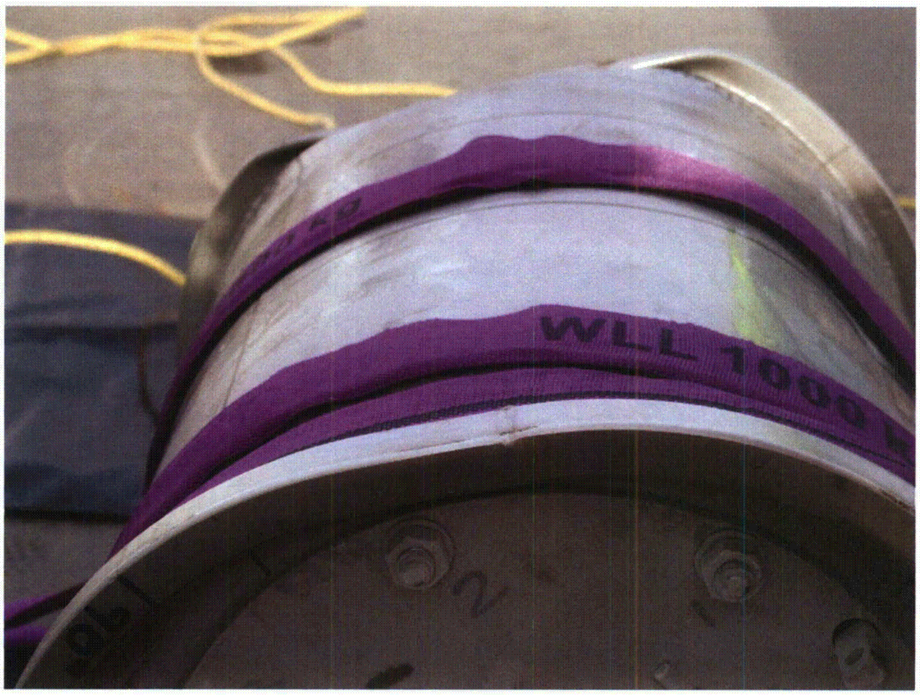
Photograph 36 – Test 9 damage caused to package

Photograph 37 – Test 10 point of impact

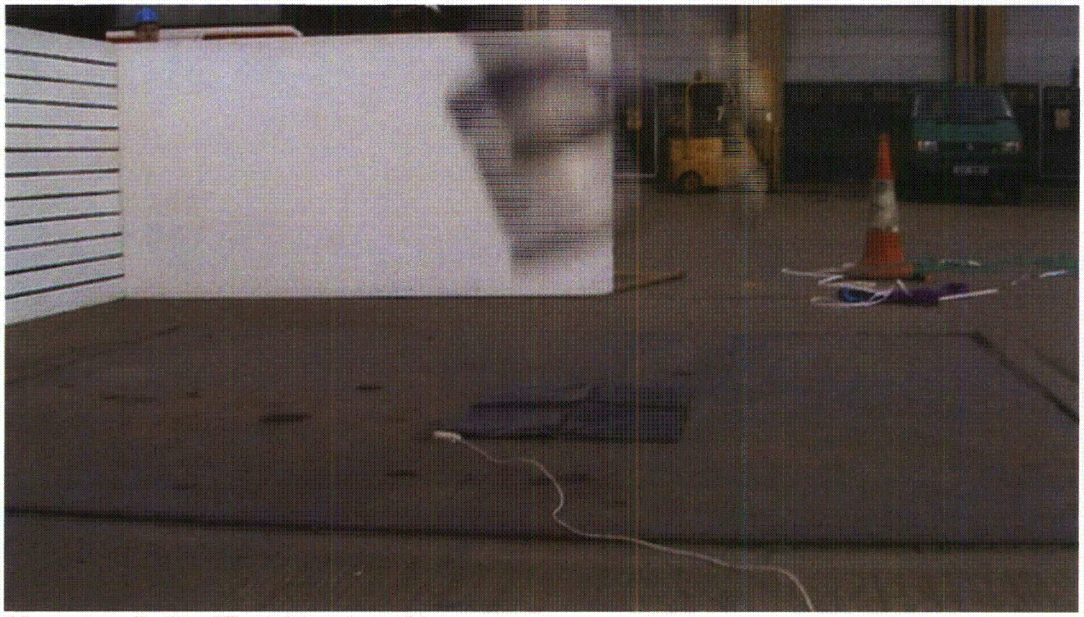
Photograph 38 – Test 10 secondary impact

Photograph 39 – Test 10 pre test damage

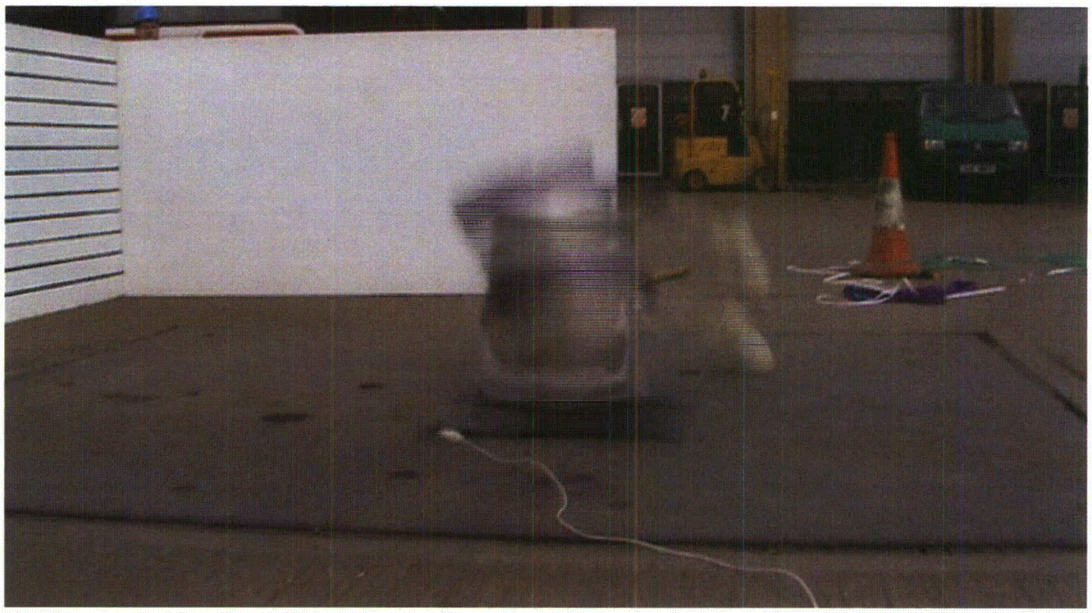
Photograph 40 – Test 10 damaged caused to keg



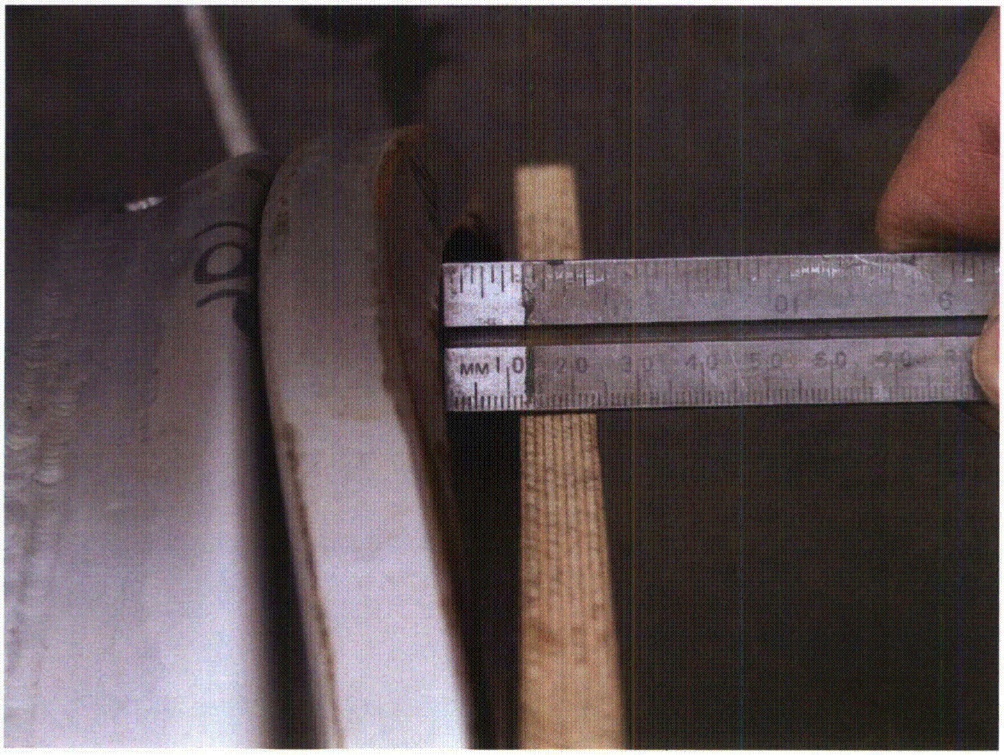
Photograph 41 – Test 10 damage caused to keg by secondary impact



Photograph 42 – Test 11 point of impact



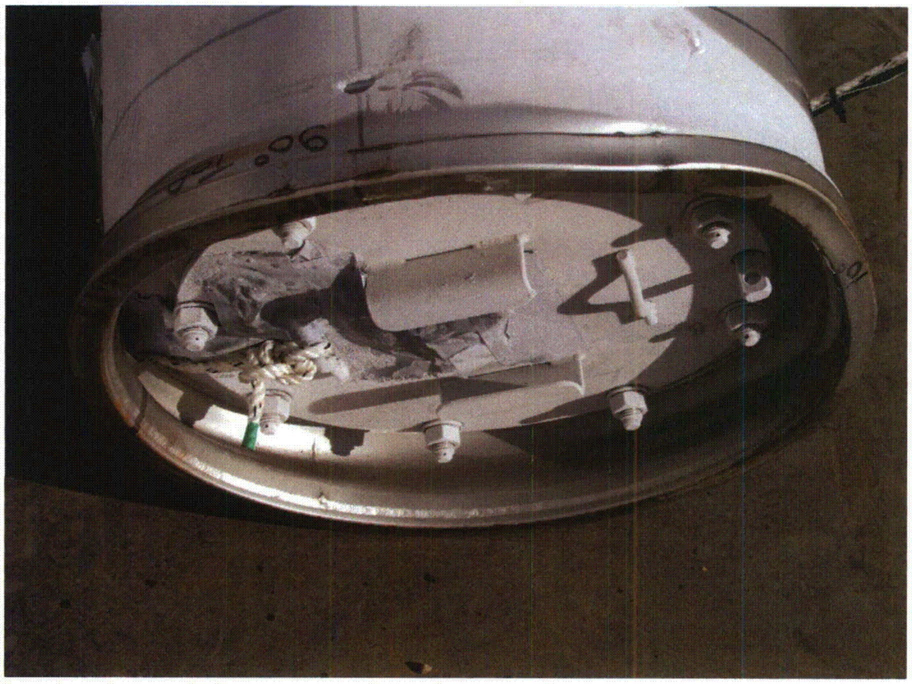
Photograph 43 – Test 11 secondary impact



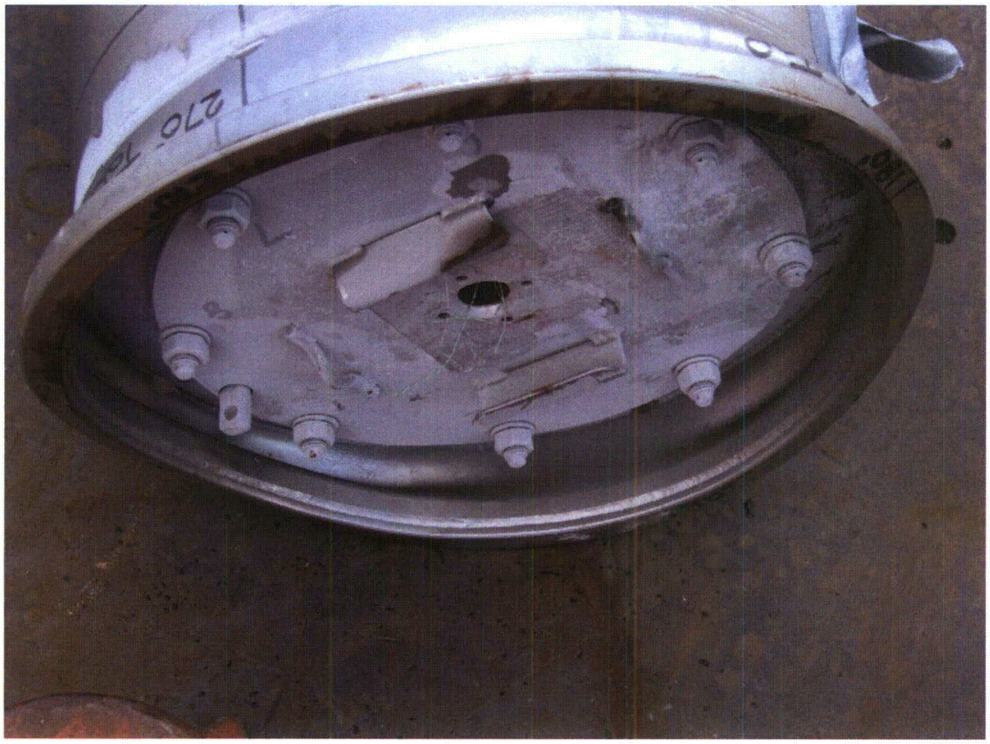
Photograph 44 – Test 11 Damage Caused to Keg

Photograph 45 – Test 12 point of impact

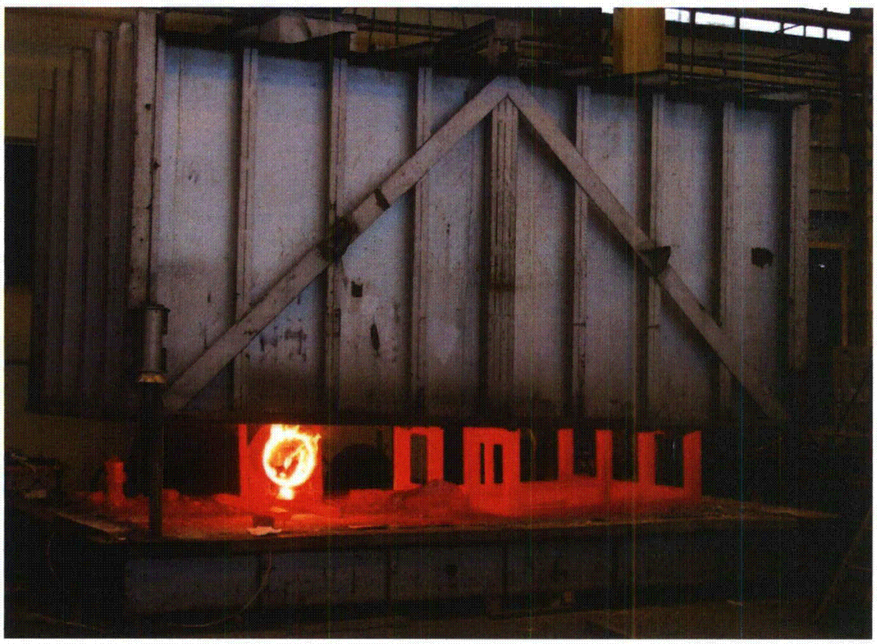
Photograph 46 – Test 12 damage caused to keg



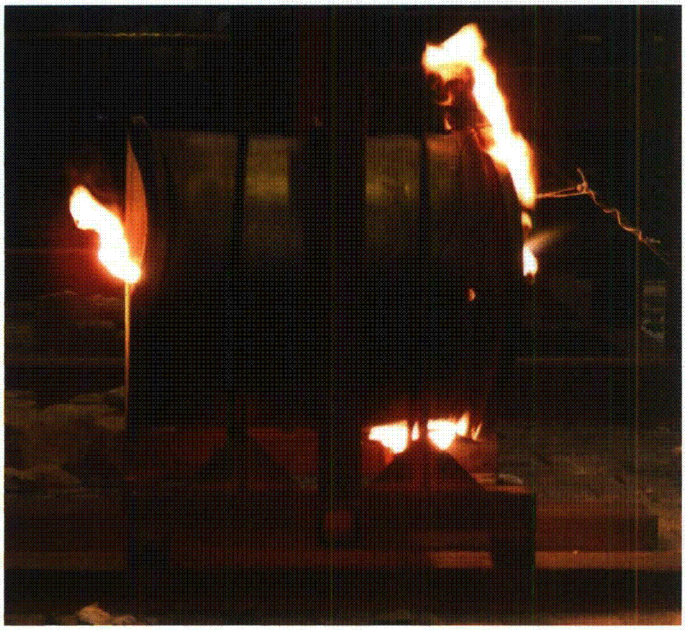
Photograph 47 – Test 12 damage caused to keg



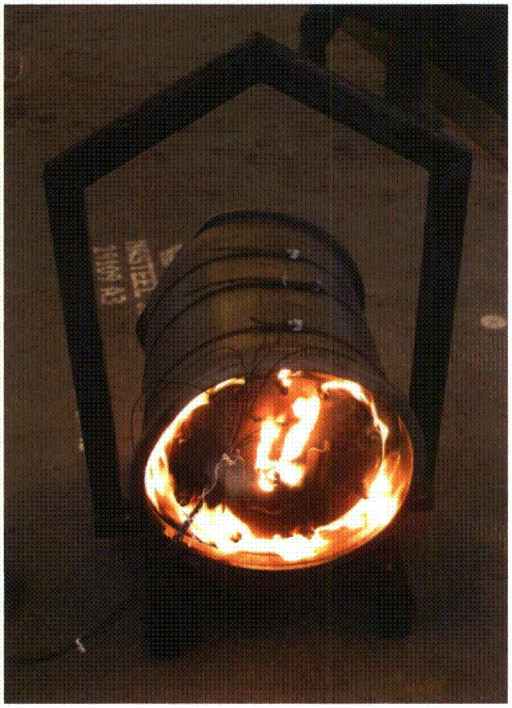
Photograph 48 – Test 12a damage caused to keg



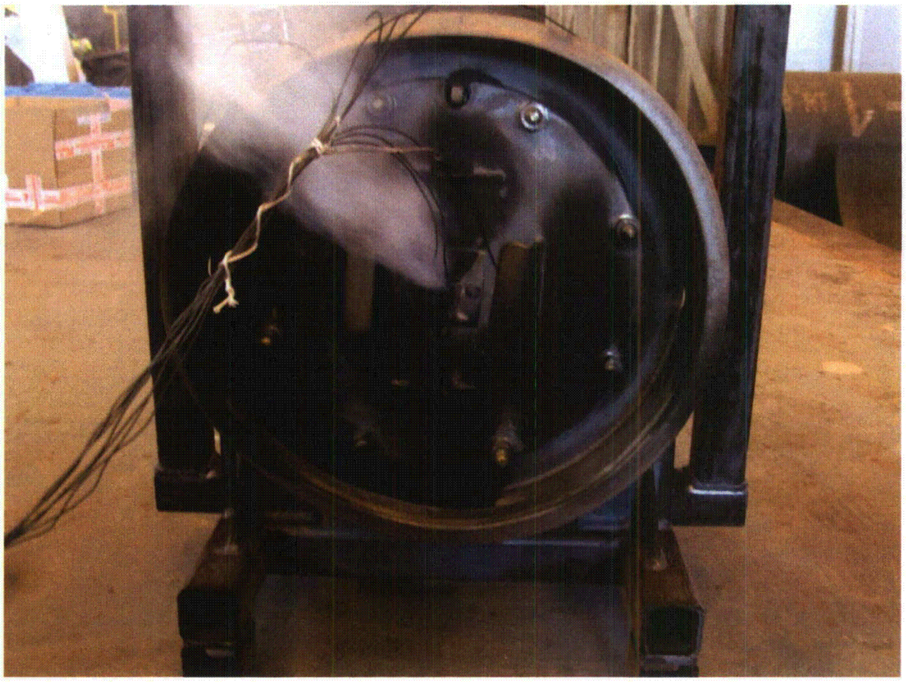
Photograph 49 – Test 13 Removal of Package from Furnace



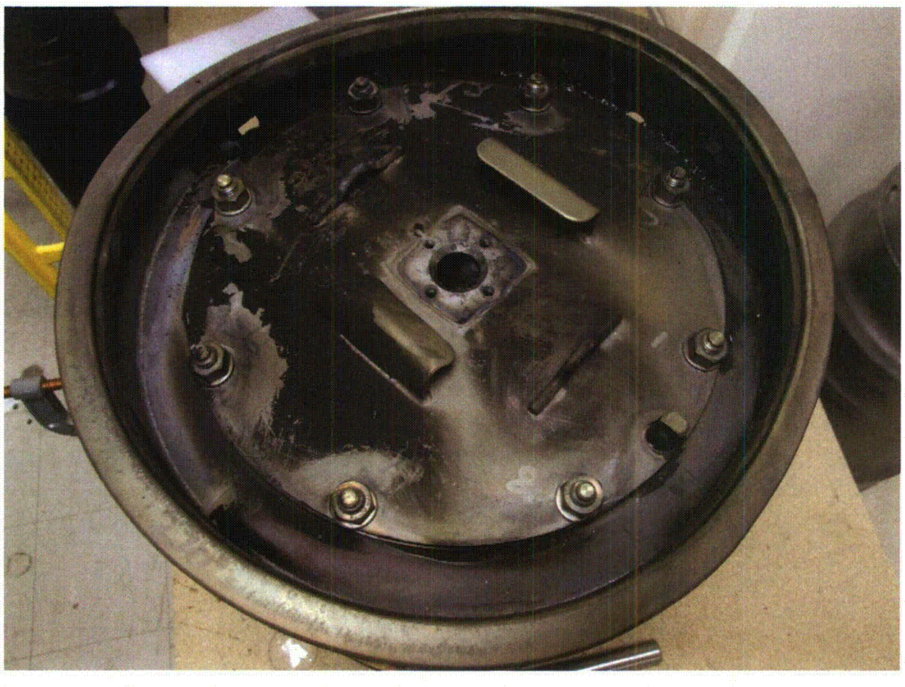
Photograph 50 – Test 13 Removal of Package from Furnace



Photograph 51 – Test 13 package approximately 10 minutes after removal from furnace

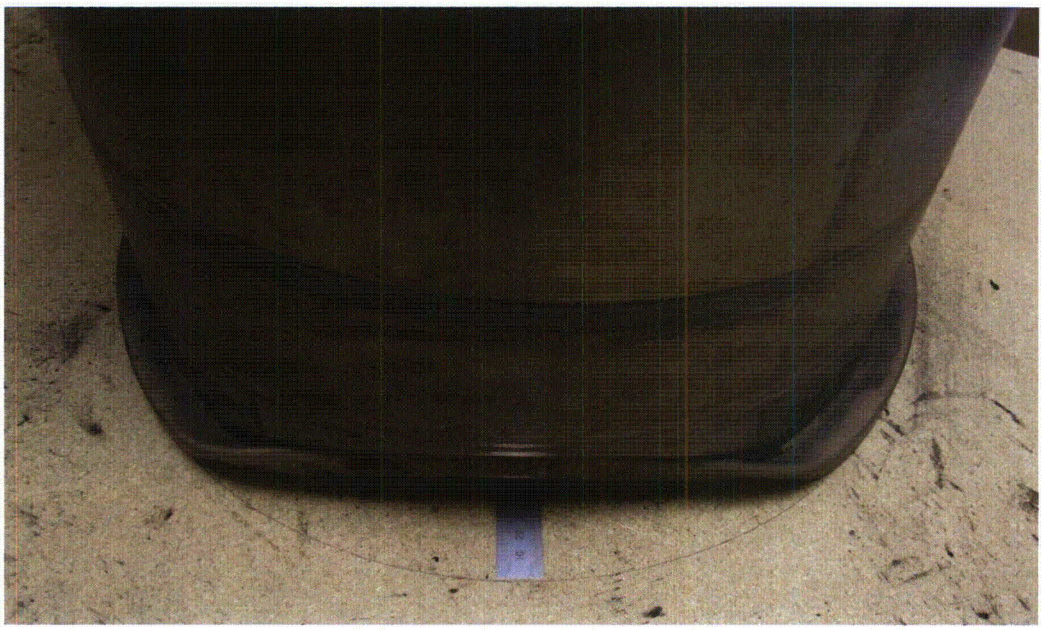


Photograph 52 – Test 13 package after flames self extinguished

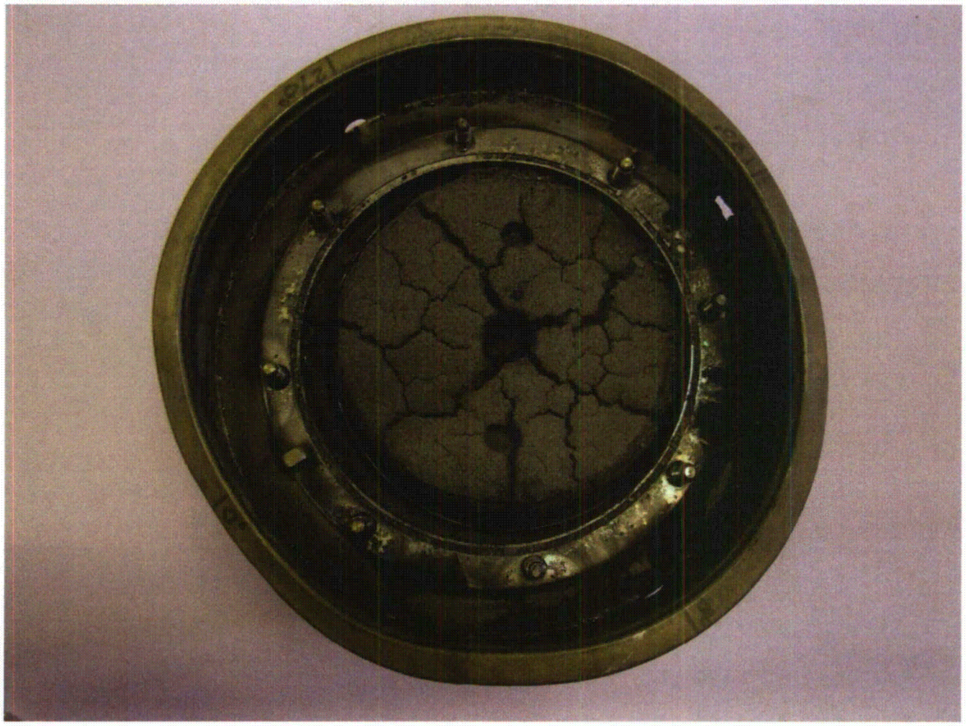


Photograph 53 – Package after completion of testing

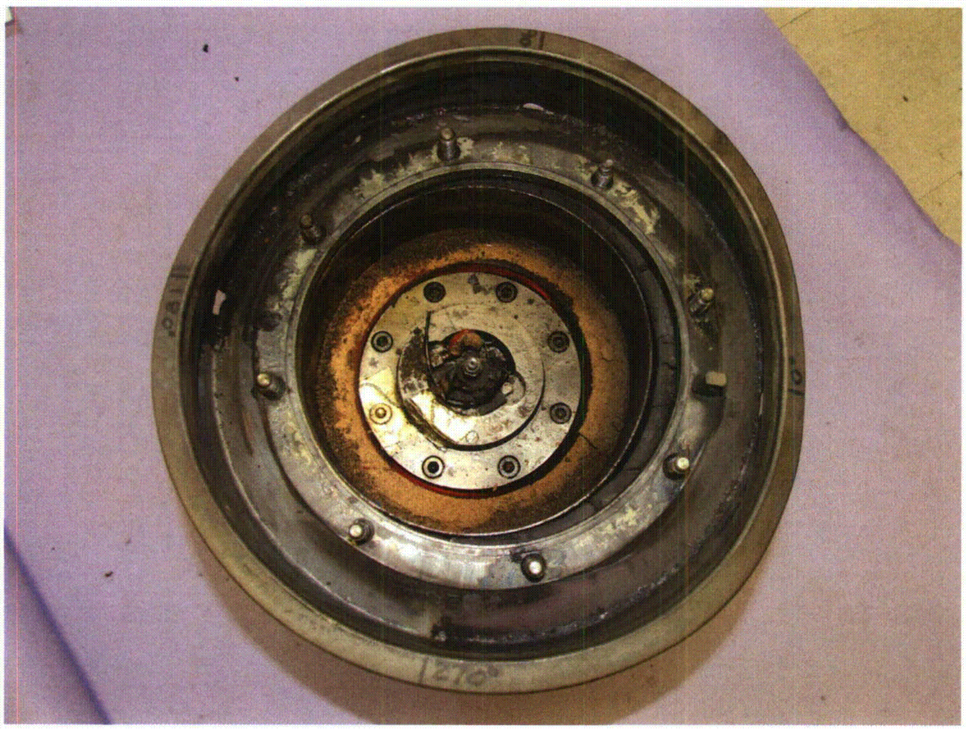
Photograph 54 – Damage caused to top rim



Photograph 55 - Damage caused to bottom rim



Photograph 56 – Charred upper cork

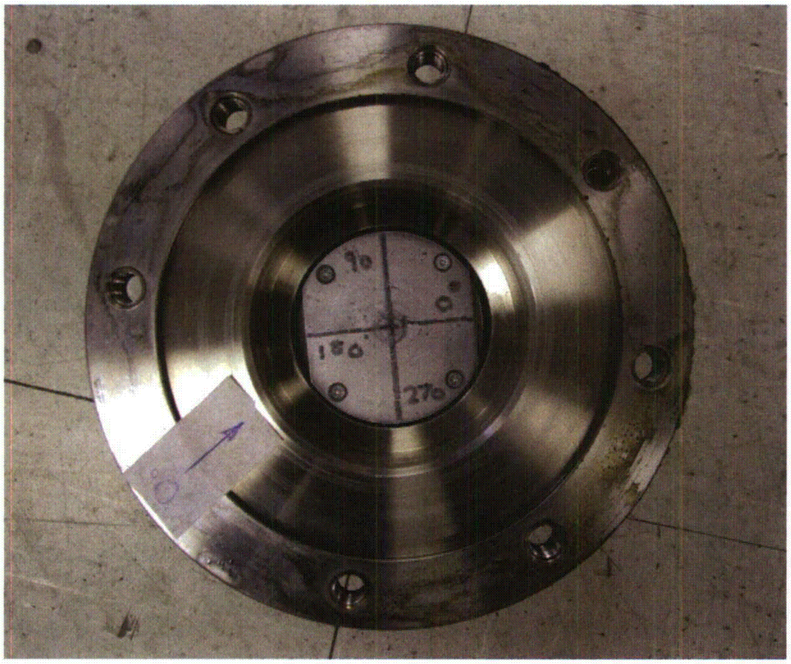


Photograph 57 – Containment vessel and inner cork after testing

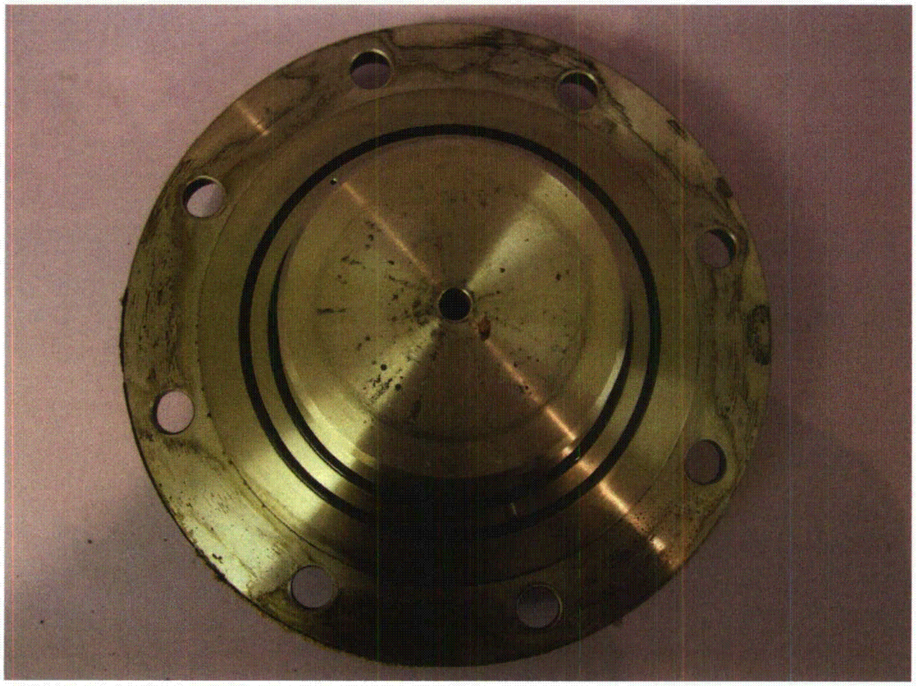
Photograph 58 – Removal of CV from package

Photograph 59 – Top cork

Photograph 60 – Containment vessel after testing



Photograph 61 – Insert inside containment vessel after testing



Photograph 62 – Containment lid underside after testing

Photograph 63 – Insert after testing

Photograph 64 – Insert body after testing

6 CONCLUSIONS

On examination of the packaging components on disassembly after the test series the following can be concluded:

- The containment vessel remained leaktight.
- The dimension and the weights of the containment vessel did not alter.
- The cork was charred to a limited extent.
- The keg remained intact with the keg lid in place.
- The keg skin suffered from minor denting however it was not penetrated and the welds were not torn.
- The majority of the damage was caused to the rims of the keg with minor damage caused to the body by the penetration test. The drop tests only caused damage to the keg rims.

This test series has also established the maximum temperature of the packaging components under both steady state and HAC thermal tests.

7 REFERENCES

1. Croft Associates Ltd, Certificate of Conformity number QAC 1382
2. Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), Packaging and Transportation of Radioactive Material. 23 Feb 2009
3. Croft Associates Ltd, Drawing 0C-6042, Keg Design No 3979
4. Croft Associates Ltd, Drawing 0C-6043, Cork Set for Safkeg LS
5. Croft Associates Ltd, Drawing 1C-6046 Containment Vessel Design No 3980
6. Croft Associates Ltd, Drawing 1C-6046 Containment Vessel Body
7. International Atomic Energy Authority, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, Safety Guide No TS-G-1.1 (Rev 1)
8. Croft Associates Ltd Document No TR 09/03/13, Steady State Thermal Test, Issue A
9. Croft Associates Ltd Document No TR 09/03/15, Inspection Details Before and after NCT and HAC testing, Issue A
10. Croft Associates Ltd Document No TR 09/03/16, Compression test of keg at ambient temperature, Issue A

11. Croft Associates Ltd Document No TR 09/03/18, Penetration Test at Ambient, Issue A

12. Croft Associates Ltd Document No TR 09/03/32, Report of Invalid 1.2 m and Puncture tests. Issue A

13. Croft Associates Ltd Document No TR 09/03/17, Helium Leakage Test Prior to Regulatory Test Series, Issue A

14. Croft Associates Ltd Document No TR 09/03/19, Repeat 1.2 m Drop Test 1 at Ambient, C of G over Side, Issue A

15. Croft Associates Ltd Document No TR09/03/20, Repeat 1.2m drop test 2 at ambient, C of G over top end, Issue A

16. Croft Associates Ltd Document No TR 09/03/21, Repeat 1.2m drop test 3 at ambient, C of G over top rim edge, Issue A

17. Croft Associates Ltd Document No TR 09/03/22, Repeat 1m puncture test on side impact point at ambient temperature, Issue A

18. Croft Associates Ltd Document No TR 09/03/23, Repeat 1m puncture test on bottom end impact point at ambient temperature, Issue A

19. Croft Associates Ltd Document No TR 09/03/24, Repeat 1m puncture test on top rim edge impact point at ambient, Issue A

20. Croft Associates Ltd Document No TR 09/03/33, 10.2 m drop test 1 at -40°C, C of G over side, Issue A

21. Croft Associates Ltd Document No TR 09/03/25, Repeat 10.2m drop test 1 at -40°C, C of G over side, Issue A

22. Croft Associates Ltd Document No TR 09/03/26, 10.2m drop test 2 at -40°C, C of G over top rim edge, Issue A

23. Croft Associates Ltd Document No TR 09/03/27, 10.2m drop test 3 at -40°C, C of G over top end, Issue A

24. Croft Associates Ltd Document No TR 09/03/28, 1m puncture test on top impact point at -40°C temperature, Issue A

25. Croft Associates Ltd Document No TR 09/03/29, 800°C thermal test, Issue A

26. Croft Associates Ltd Document No TR 09/03/30, Helium leakage test of containment vessel after testing, Issue A

Project No Y06/08/10	**Design/Drawing No 3977A**
Calculation of the Density of the 3977A Package	

1 Objective

Demonstrate that the package density is > 1,000 kg/m^3 - that is, the package would not float in water.

2 Assumptions

The principle external dimensions of the package are given in Figure 1. For this calculation, a simplified model is assumed which pessimistically represents the package, for this model the rolled tubes are assumed to be absent, and the package overall dimensions are therefore 382.5 mm diameter x 464 mm height (the model can be seen from the dimensions as specified below).

Body overall dimensions (excluding tubes)	= 382.5 mm diameter x 464 mm height	= 0.0533 m^3
Top skirt air volume	= 378.5 mm diameter x 48.5 mm height	= 0.00546 m^3
Bottom skirt air volume	= 378.5 mm diameter x 53.5 mm height	= 0.00601 m^3
Net volume of package		= 0.0418 m^3
Weight of the package		= 67.2 kg
Weight of rolled tubes		= 2.87 kg
Net weight of package without rolled tubes		= 64.33 kg

Results

Density of the package body = 64.33/0.0418 = 1,540 kg/m^3

Comments

The package meets the criteria of density is > 1,000 kg/m^3 by a large margin.

The calculation ignores the rolled tubes: including these would increase the overall density as the tubes (even sealed) have a density > 1,000 kg/m^3.

Prepared	Checked
S Marshall	R A Vaughan
Approved	**Date**
R A Vaughan	23 March 2010

See CAP 3-01 for guidance

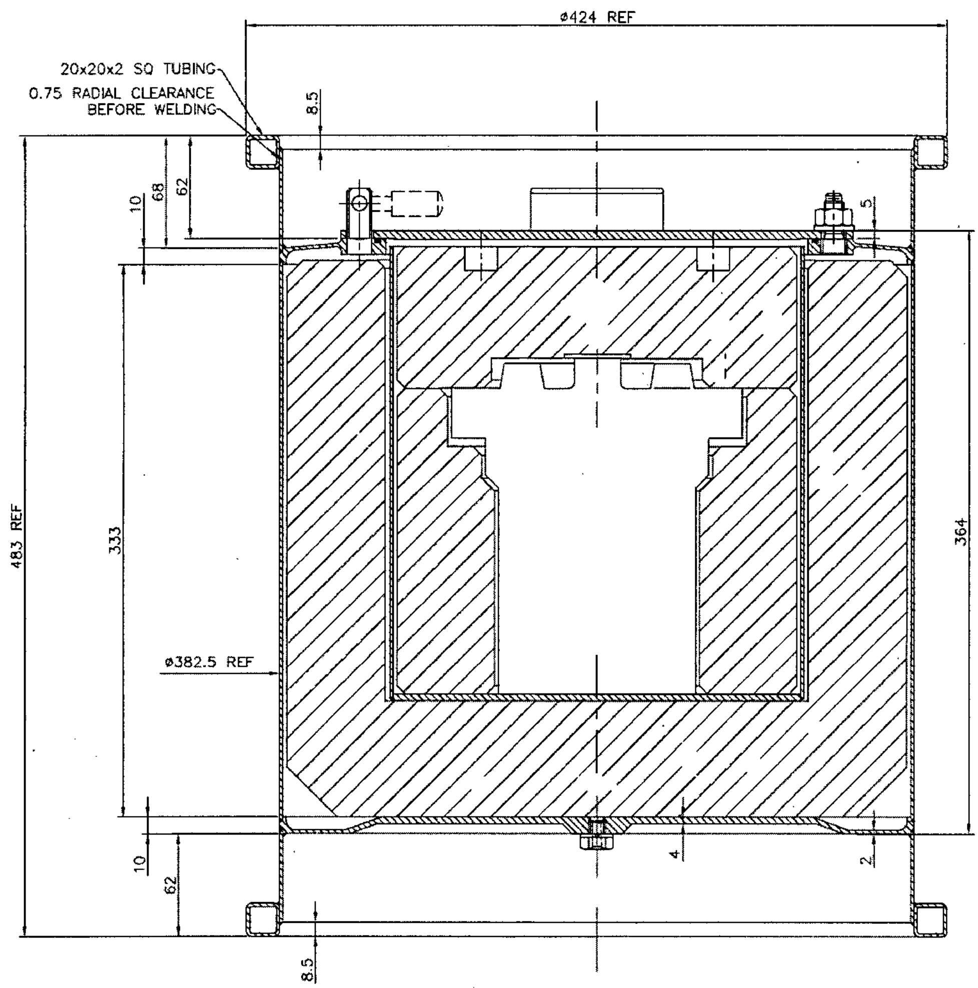


Figure 1 - SAFKEG LS 3977A External Dimensions

CONTENTS

3 THERMAL EVALUATION

This section identifies the key thermal design features for the Safkeg-LS 3979A package. The maximum temperatures at both NCT and HAC conditions have been calculated for these features by a Finite Element Analysis (FEA) and a thermal model of the package. The FEA and the thermal model of the package were validated against testing of a prototype Safkeg-LS 3979A package under both steady state internal heating and an 800°C fire test. The test procedure and results of the tests and the FEA are presented and discussed.

The maximum operational temperatures determined for the maximum contents heating have been listed and shown to be lower than the maximum design temperatures of the package.

3.1 Description of Thermal Design

The Safkeg-LS 3979A is designed to transport a range of nuclides, with a maximum allowable heat output of 10 W. The following sections detail the design features affecting the thermal performance of the package.

3.1.1 Design Features

The only design features that are significant with respect to heat transfer in the Safkeg-LS 3979A are:

- The stainless steel keg outer skin
- The stainless steel keg inner liner
- The cork liner
- Top cork and side cork
- The stainless steel containment vessel
- The lead shielding in the containment vessel

These features are all axi-symmetric and are illustrated in Figure 3-1.

The keg and the cork provide the containment vessel with protection from impact and fire. Under HAC fire conditions the keg skin is designed to heat up very quickly with the cork providing insulation to the containment vessel, as a result of its low thermal conductivity and ablation properties. Since heating of the cork during the HAC fire causes gas evolution within the keg cavity, a fuse plug is provided in the bottom of the keg. On heating above 98°C the fuse plug melts allowing pressure relief of the keg cavity.

The package does not have any mechanical cooling.

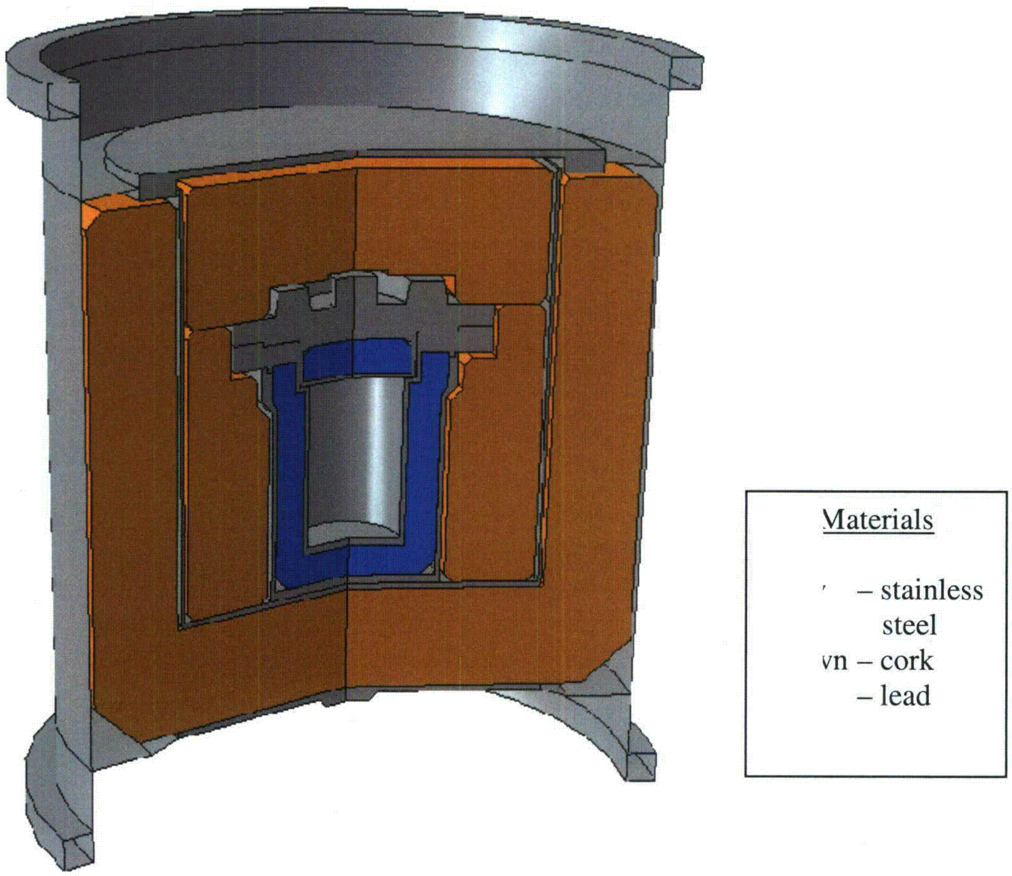


Figure 3-1 Thermal Design Properties

3.1.2 Content's Decay Heat [71.33 (b)(7)]

The contents decay heat is limited to a maximum of 10 W for solids and gases and 5 W for liquids.

3.1.3 Summary Tables of Temperatures

The maximum temperatures reached under NCT and HAC conditions have been determined using an FEA thermal model detailed in the report SERCO/TAS/5388/001 appended in Section 3.5.2. Table 3-1 summarizes the results of this report and presents the maximum temperatures reached in the containment vessel cavity with internal heat loads from 0 to 10 Watts under NCT and HAC thermal conditions.

The maximum temperatures within the containment vessel are generated at 10 W, therefore the temperatures reached at critical locations with this heat load were calculated in the SERCO report under NCT and are summarized here in Table 3-2. The maximum temperatures calculated are all within the acceptable temperature limits for the package components.

Table 3-1 Calculated Maximum Containment Vessel Temperature under NCT and HAC
(Ambient 38°C, with and without insolation)

	Maximum Temperature under heat load (°C)				
Heat load (W)	0	3	5	6	10
NCT – no insolation	38	55.8		72.8	94.2
NCT – with insolation	63.7	80.4	91.1 (1)	96.4	116.4
HAC – with insolation	139.6	153.5	162.41 (1)	166.9	184

1 Interpolated

Table 3-2 Summary of Calculated Package Temperatures with 10 W Internal Heat Load under NCT (Ambient 38°C, with and without insolation)			
Location	**Maximum Temperature (°C)**		**Temperature Limit (°C)**
	No insolation	**With Insolation**	
Containment vessel cavity	94.2	116.4	427 (1)
Containment vessel lid seal	94	116	150
Cork (2)	94	116	180 (3)
Keg lid	43	104	427 (1)
Keg bottom	46	75	427 (1)
Mid height on keg surface	42	68	427 (1)

1 The allowable temperature limit for steel when relied upon for structural support is 427°C as specified in ASME Section II Part D [3.1].

2 Maximum cork temperature is same as the CV which it carries.

3 [3.7]

The minimum package temperature is limited by the ambient conditions, therefore the minimum temperature of the package is assumed to be -40°C.

Table 3-3 summarizes the data obtained from the SERCO report (section 3.5.2) for the peak temperatures in the package resulting from the HAC thermal test and the period of post test heating of the internal parts of the package. As can be seen, all the CV components remain within acceptable temperature limits.

Table 3-3 Summary of Package Temperatures for HAC Thermal Test (Ambient 38°C, with and without insolation)			
Location	**Maximum Temperature (°C)**	**Time after Fire initiation (mins)**	**Temperature Limit (°C)**
Containment vessel cavity	184	225	1427
Containment vessel lid seal	183	225	204 (1)

Cork	775	30	NA (2)
Lead Shielding	182	225	252
Keg lid	775	30	1427
Keg bottom	775	30	1427
Mid height on keg surface	780	30	1427

1 The containment lid seal remains above the continuous operation temperature of the O-ring of 149°C for 8 ¼ hours

2 Cork ablates under high temperatures and leaves a low density carbonaceous layer which provides insulation equivalent to still CO_2.

3.1.4 Summary Tables of Maximum Pressures

Table 3-4 shows the maximum design pressure under NCT and HAC.

Table 3-4 Summary Table of Maximum Pressures in the Containment Vessel

Case	Maximum Pressure
MNOP	7 bar (700kPa) gauge 8 bar (800kPa abs)
HAC	10 bar (1,000kPa) gauge 11 bar (1,100kPa abs)

3.2 Material Properties and Component Specifications

3.2.1 Material Properties

The materials affecting heat transfer within and from the package are cork, lead and stainless steel type 304L. The thermal properties for each material are summarized in Table 3-5.

Table 3-5: Thermal Properties of Packaging Materials

Material	Property	Temperature (℃)	Value	Reference
304 Stainless Steel	Conductivity	21	14.9 W/m/K	[3.1]
		38	15.0 W/m/K	
		93	16.1 W/m/K	
		149	16.9 W/m/K	
		205	18.0 W/m/K	
		260	18.9 W/m/K	
		316	19.5 W/m/K	
		371	20.4 W/m/K	
		427	21.1 W/m/K	
		482	22.0 W/m/K	
		538	22.8 W/m/K	
		593	23.5 W/m/K	
		649	24.2 W/m/K	
		705	25.1 W/m/K	
		760	25.8 W/m/K	
		816	26.5 W/m/K	
	Density	-	7900 kg/m3	[3.2]
	Specific Heat	21	483 J/kg/K	[3.1]
		38	486 J/kg/K	
		93	506 J/kg/K	
		149	520 J/kg/K	
		205	535 J/kg/K	
		260	544 J/kg/K	
		316	551 J/kg/K	
		371	559 J/kg/K	
		427	562 J/kg/K	
		482	570 J/kg/K	

Table 3-5: Thermal Properties of Packaging Materials

Material	Property	Temperature (°C)	Value	Reference
		538	577 J/kg/K	
		593	583 J/kg/K	
		649	585 J/kg/K	
		705	591 J/kg/K	
		760	596 J/kg/K	
		816	601 J/kg/K	
Lead	Conductivity	-	29.7 W/m/K	[3.3]
	Density	-	11040 kg/m3	[3.4]
	Specific Heat	-	133.9 J/kg/K	[3.3]
	Melting Point		Solidus 252°C Liquidus 290°C	[3.5] [3.6]
Cork	Conductivity	-	See Figure 3-4	[3.7]
	Density	-	290 kg/m3	[3.7]
	Specific Heat	-	1650 J/kg/K	[3.7]e
Air (1)	Conductivity	0	0.0243 W/m/K	[3.1][3.8]
		100	0.0314 W/m/K	
		200	0.0386 W/m/K	
		400	0.0515 W/m/K	
		800	0.0709 W/m/K	

1 The thermal conductivity was used to represent heat transfer across the air gaps in the model. The model did not include the thermal capacity of air. No data was therefore required for the density or specific head of air

During a fire the cork experiences temperatures up to ~800°C. No measurements of cork properties at high temperatures are available. However, the HAC thermal test has been performed on the Safkeg-LS 3979A package as detailed in report CTR 2009/21 (Section 2.12.2). The test has then been simulated in order to validate the model against the measured data and, to demonstrate the acceptability of the thermal properties assumed for the cork. It was found that, in order to obtain agreement with the measured temperatures, the thermal conductivity of the cork needed to be increased by 50%. It should be noted that these thermal properties, validated against the furnace test, are 'effective' properties that include any effects of charring and shrinkage of the cork.

The NCT thermal test performed on the Safkeg-LS 3979A package has also been simulated using the model. It was found that, to produce the best agreement with the measured temperatures, the thermal conductivity of the cork needed to be reduced by 15%. Because cork is a natural material, this degree of variation in conductivity may well be possible. To ensure that all the calculations performed with the model are pessimistic, the lower, fitted conductivity has been assumed for the calculations of temperature during normal transport and the higher, measured thermal conductivity assumed for the calculations of temperature during the fire accident. Values used for the thermal conductivity of the cork are shown in Figure 3-2.

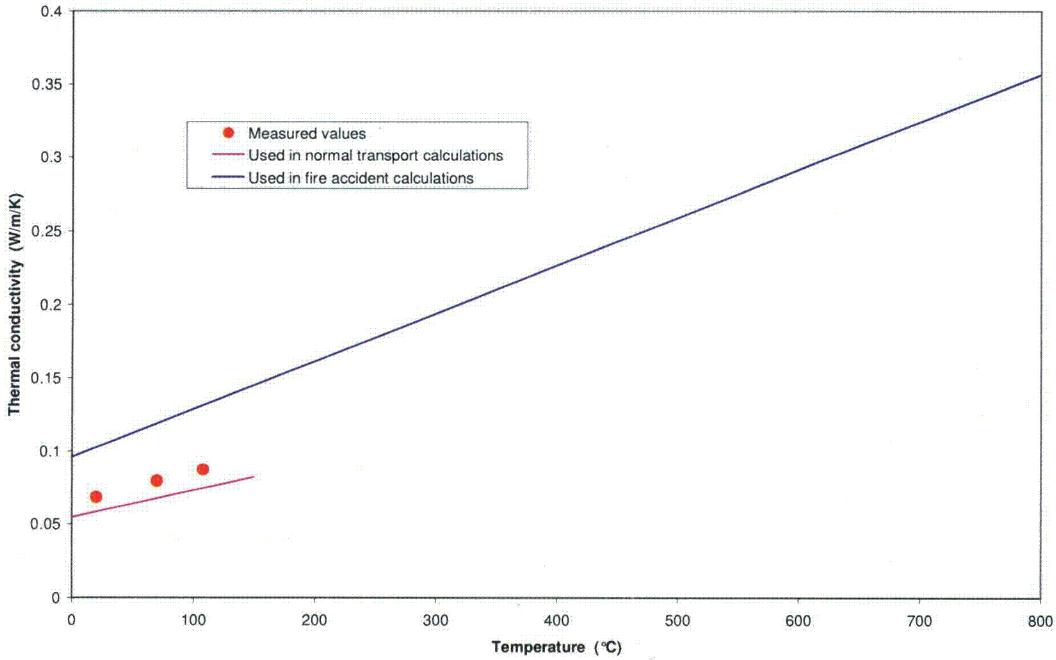


Figure 3-2 Thermal Conductivity of Cork

The package surface and internal emissivity values used in the thermal evaluation are given in Table 3-6. The emissivity of stainless steel can vary significantly depending upon the surface finish and level of oxidation. The values presented in Table 3-6 are shown to produce good agreement with the measured temperatures in the steady state heating test carried out in report CTR 2009/21 (Section 2.12.2) and are discussed in depth in Sections 3.3 and 3.4.2.

Table 3-6: Emissivities used in the Thermal Model

Material	Condition	Value	Reference
304 Stainless Steel	Internal surfaces	0.2	[3.9]
	External surface – heating test	0.4	Fitted to measured surface temperature in heating test.
	External surface - NCT	0.25	[3.9]

	External surface – fire test	0.8	[3.10]
Cork	All conditions	0.95	[3.11]

3.2.2 Component Specifications

The components that are important to thermal performance are the outer keg, the cork packing material, the containment vessel and the containment seal. The outer keg and the containment vessel are manufactured from stainless steel 304L with the containment seal manufactured from Ethylene Propylene (EPM).

The allowable service temperatures for all the components cover the maximum and minimum temperatures anticipated during NCT and HAC conditions of transport. The minimum allowable service temperature for all components is less than or equal to -40°C. The maximum service temperature for each component is determined from the temperatures calculated from the thermal model.

The upper temperature reached by the stainless steel in the keg is 104°C for continuous operations and 780°C for short term operations. The upper temperature reached by the stainless steel in the containment vessel is 116°C for continuous operations and 184°C for short term operations under HAC conditions.

The allowable temperature limit for steel when relied upon for structural support is 427°C as specified in ASME Section II Part D [3.1]. During the HAC test the temperature of the keg skin exceeds this temperature for a short period of time. During a fire the steel is providing shielding to the cork from the direct exposure of the flames, its main function is not providing structural support therefore the maximum allowable temperature it can reach is 1427°C, which is the melting point of steel.

The lead shielding reaches a maximum temperature of 116°C for continuous operations and 183°C during HAC conditions. The lead does not provide any structural function therefore it is limited by its solidus which is 252°C.

The cork is unaffected by temperatures up to at least 140°C which is higher than the maximum temperature for any position in the cork packing under NCT. Under HAC conditions the cork reaches a maximum temperature of 775°C. Cork ablates under high temperatures and leaves a low density carbonaceous layer which provides insulation equivalent to still CO_2.

The upper temperature reached by the containment seal is 116°C for continuous operation (NCT conditions), and 183°C for short term operation (HAC conditions). The temperatures under NCT conditions are within the allowable range of the O-ring material properties. The O-rings are specified as Ethylene Propylene (EPM) to ASTM D2000 M3 BA 710 F17 Z1 (see drawings in Section 1.3.3). EPM has a recommended temperature range of -54°C (-65°F) to 149°C (300°F) for continuous static and dynamic use with a maximum temperature of up to 205°C (401°F) for 2 hours duration as specified in the Parker O-Ring Handbook [3.12]. Under HAC conditions the O-ring remains above 149°C for 8 ¼ hours reaching a maximum temperature of 183°C. Therefore the O-rings operate outside of the Parker temperature ranges specified. In order to validate the O rings for use, each batch of O-rings will be tested to ensure they meet the critical requirement of remaining leak tight after 24 hours at 200°C - the test is specified in the drawings in section 1.3.3.

The O-rings have been shown, by the tests (report CTR 2009/21, Section 2.12.2) carried out on the prototype Safkeg-LS 3979A package to remain leaktight at the lower operating temperature of the package of -40°C.

3.3 Thermal Evaluation under Normal Conditions of Transport

The Safkeg-LS 3979A package has been evaluated for compliance with 10 CFR 71 by thermally modeling the package. The thermal model has been validated by comparison against both an experimental self heating test (simulating normal conditions of transport) and a furnace test (simulating the fire accident), both carried out by Croft and documented in report CTR 2009/21 (Section 2.12.2).

NCT Thermal Test

A 10 W cartridge heater located inside an aluminum block was placed in the cavity of the containment vessel. The package was orientated in the vertical position on a wooden board covered with aluminum foil. The temperature of the package was monitored using thermocouples located in seven positions on and in the package. One thermocouple was located in the aluminum block, three thermocouples on the containment vessel surface, one on the keg liner and two on the keg surface. Temperatures were logged every minute until the package temperature reached equilibrium. The surface temperature of the package was then mapped using a temperature probe. The package was repositioned in the horizontal orientation and the temperatures logged until the package reached thermal equilibrium. The surface temperature of the keg was mapped using a temperature probe.

Thermal Model

The analytical model is described in detail the Report SERCO/TAS/5388/001 (Section 3.5.2). An axi-symmetrical model was generated with 5159 nodes and 2538 elements using the Abaqus code [3.13]. Each of the components was generated separately and joined, thermally, using tied constraints or interactions (representing narrow air gaps). The thin outer skin of the keg was modelled using 'shell' elements while all the other components were modelled using solid elements.

It was assumed that heat was lost from the package through natural convection and radiation from external surfaces. The convection coefficients used are described in detail in report SERCO/TAS/5388/001 (Section 3.5.2). The heat generated by the package contents was represented in the model as a uniform heat flux applied over the side, top and bottom of the cavity inside the containment vessel. The package contents themselves were not represented in the model.

Narrow gaps present were represented as air gaps, heat transfer across these gaps was assumed via conduction and thermal radiation. The package design also creates a number of small cavities across which radiation heat transfer will occur (in such small cavities heat transfer by conduction and convection is expected to be negligible). In these cavities radiation exchange between all the surfaces is modelled. The view factor from each element to each other element in the cavity is determined and radiation heat transfer, including the effect of reflection, then calculated.

The predicted temperatures from the model were compared against the actual values obtained. This comparison showed that the temperature of the containment vessel was initially underestimated. The calculation showed that, as expected, the majority of the temperature difference between the containment vessel and the outer surface of the keg results from heat transfer through the cork. It was therefore concluded that the low predicted containment vessel temperature was probably due to the thermal conductivity of the cork being lower than assumed in the model. The calculation was therefore repeated with the thermal conductivity of the cork reduced by 15%. Such a variation in thermal conductivity is considered possible in a natural material such as cork.

The external surface temperature was also initially moderately overestimated. The assumed value of the surface emissivity was therefore increased from the reference value of 0.25 to 0.4. The emissivity of stainless steel can vary significantly depending upon the surface condition (e.g. level of oxidation) and a value of 0.4 is well within the range of possible values.

The predicted temperatures in the repeat calculation are in good agreement with those measured in the test. The predicted temperature profile is shown in report SERCO/TAS/5388/001 Figure 5 (Section 3.5.2) and it can be seen that, as expected, the highest temperatures occur in the heater block and inner containment vessel and high temperature gradients are generated in the cork. The temperatures measured in the steady state test and the predicted temperatures are summarised in Figure 3-3 (report SERCO/TAS/5388/001 (Section 3.5.2)). The temperatures initially predicted by the model are also shown on this Figure. The predicted temperatures agree with the temperatures measured by the fixed thermocouples to within 1.2°C. The predicted temperature on the outside of the keg, at the bottom, is around 2°C higher than the measured values. This is probably due to the board on which the container was sitting being modelled as perfectly insulating whereas, in practice, there was some heat loss through the board.

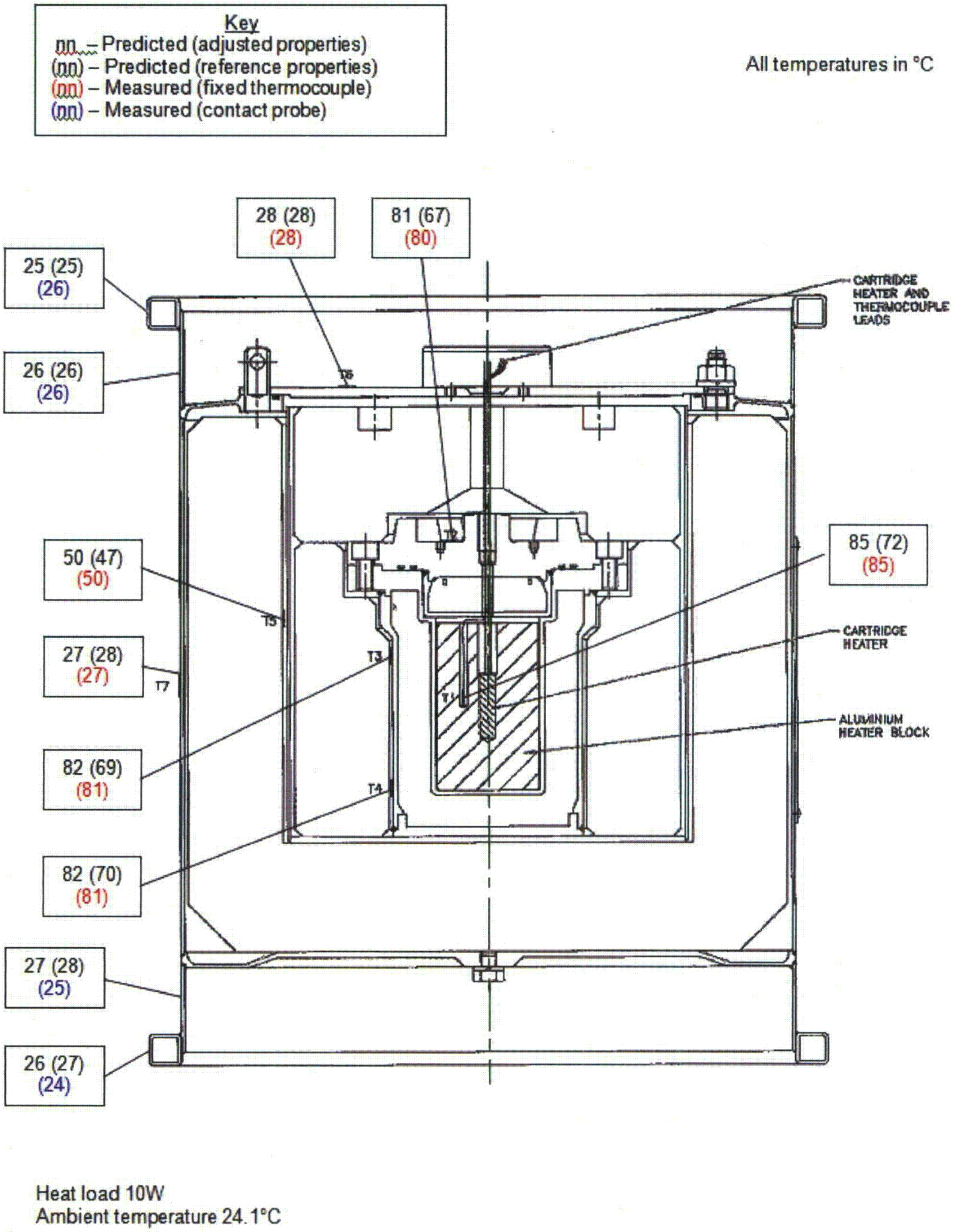


Figure 3-3 Comparison of Measured and Predicted Temperatures in the Steady-State Heating Test

3.3.1 Heat and Cold

The finite element model has been used to determine the temperature of the container under normal conditions of transport in the absence of solar insolation as described in the report SERCO/TAS/5388/001 (Section 3.5.2). A steady state calculation was performed which represented the container, stood vertically on an insulating surface, with heat loads of 0W, 3W, 6W and 10W and an ambient temperature of 38°C.

Heat losses to ambient by radiation and natural convection from the sides and top of the keg were simulated. In the validation of the model against the self heating test it was found that the best agreement was obtained with the thermal conductivity of the cork reduced by 15% compared to the measured values. To ensure that the temperatures predicted under normal conditions of transport are pessimistic, the lower, adjusted, thermal conductivity value has been used.

When modelling the heat test the surface emissivity was increased to 0.4 in order to improve the agreement between predicted and measured temperatures. To ensure that the temperatures predicted under normal conditions of transport are pessimistic, the lower, reference, emissivity value of 0.25 has been used.

The maximum temperatures reached, under NCT with no insolation and ambient of 38°C, at the containment seal and on the keg surface are given in Table 3-2. As shown the maximum temperature of the accessible surface is 43°C which is reached on the keg lid, the base of the keg reaches 46°C however this surface is not accessible and therefore not considered. This demonstrates that the package is capable of fulfilling the requirements of 71.73 (g) as the accessible surface temperature is less than 50°C with maximum contents heat load of 10W.

The package temperatures have also been modeled under normal conditions of transport and subject to solar insolation as described in the report SERCO/TAS/5388/001 (Section 3.5.2). Heat loads of 0, 3, 6 and 10 W were applied with an ambient temperature of 38°C. Transient calculations were performed covering a period of 4½ days with solar insolation incident upon the container for 12 hours each day.

Calculations were performed corresponding to both the horizontal and vertical orientation of the container. It was found that, at the end of each insolation period, the temperature of the inner container was around 1°C hotter in the vertical orientation than in the horizontal orientation due to the greater insolation heat flux onto the top of the container. The temperatures corresponding to vertical orientation of the container are therefore presented and also used as the starting point for the fire test calculation.

Figure 3-4 shows the transient temperature at various locations on the outer surface of the keg with a 10W heat load. The highest temperatures occur on the top of the container because the insolation flux is greater on the top than on the side. The maximum predicted temperature, which occurs on the top, is 104°C. Figure 3-5 shows the transient temperature at the inner containment vessel lid seal. It can be seen that the maximum temperature has effectively been reached after 1½ days. The maximum seal temperature is predicted to be 116°C. Figure 3-6 shows the maximum temperatures throughout the package under NCT.

The peak temperatures experienced during NCT conditions with insolation are shown in Table 3-2 along with the allowable maximum temperatures for each component listed. Each component has a large thermal margin with the smallest being the containment seal with a thermal margin at 34°C.

For the NCT cold evaluation the package is assumed to be in an ambient of -40°C, with zero insolation and zero heat decay. No analysis has been carried out because it has pessimistically been assumed that the package and all the components will eventually reach thermal equilibrium at -40°C. This temperature is within the allowable service limits for all the components.

The temperatures reached are within the NCT bounding conditions for the package which are as follows:

NCT Operating Condition	CV
Assumed Max. Temperature	120°C
Max. Pressure (MNOP)	7 bar (700kPa) gauge 8 bar (800kPa) abs
Min. Temperature	-40°C
Min. Pressure	-1 bar (-100 kPa) gauge 0 bar (0 kPa) abs

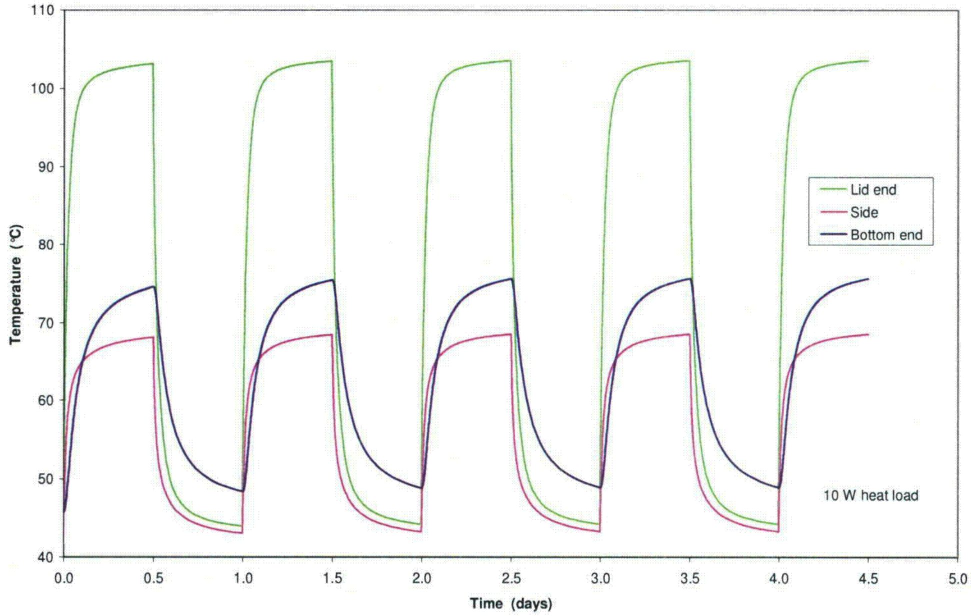


Figure 3-4 Predicted temperature on the Outside of the Keg During Normal Transport with Insolation

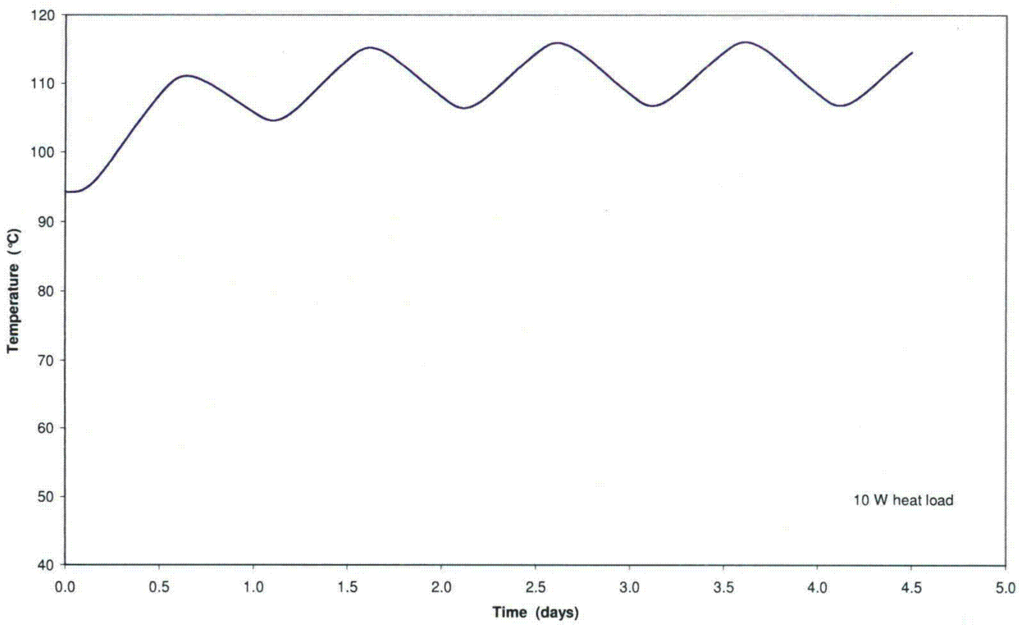


Figure 3-5 Predicted Temperature at the Containment vessel lid Seal During Normal Conditions of Transport with Insolation

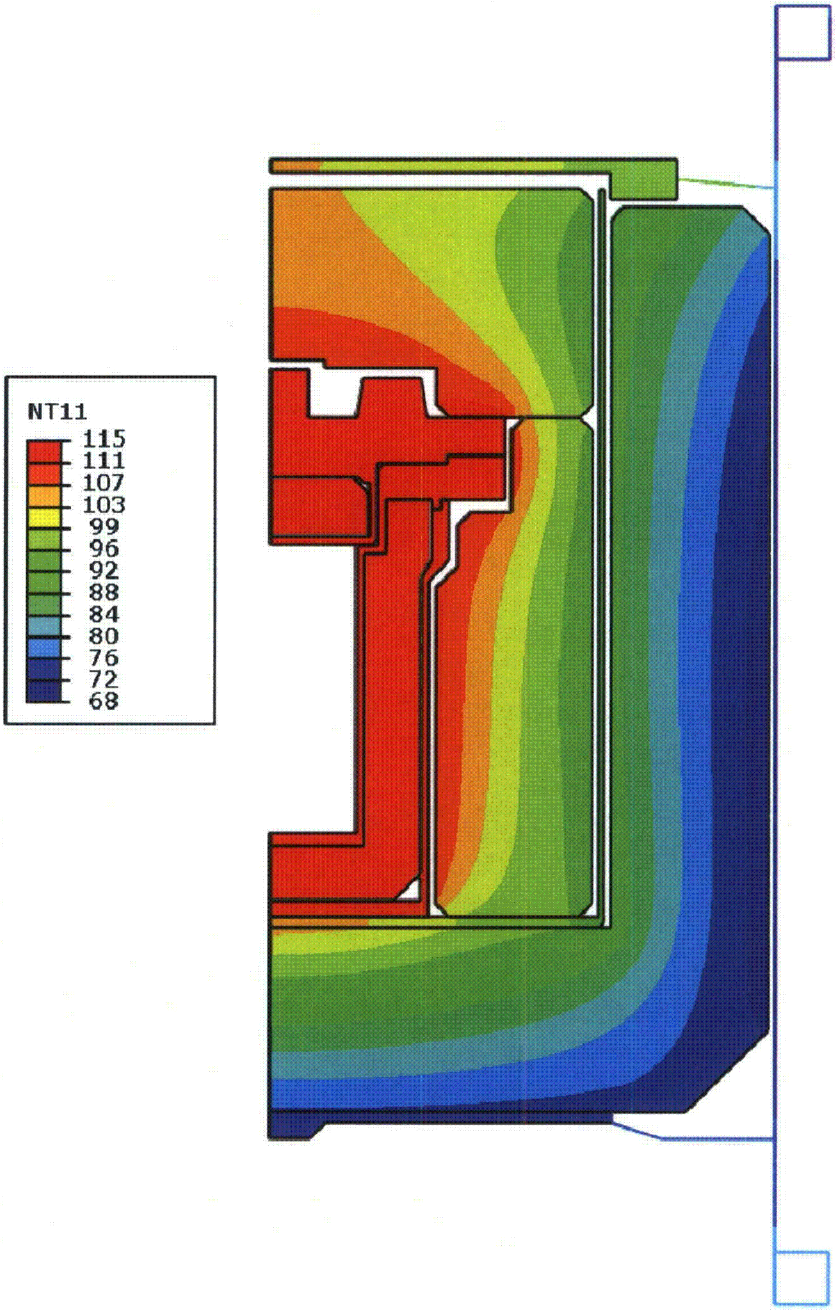


Figure 3-6 Predicted Temperature Profile under Normal Conditions of Transport With Solar Insolation

3.3.2 Maximum Normal Operating Pressure [71.33 (b)(5)]

The MNOP is 7 bar (700 kPa) gauge.

For solid contents emitting 10W, under NCT the maximum temperature of the CV is 116°C. Assuming the content were loaded at -40°C and a pressure of 1 bar abs, the pressure at the maximum temperature of the CV, calculated according to Boyle's and Charles' Laws of 116°C, would be 1.7 bar (170kPa) gauge, which is well within the design envelope.

For liquid contents emitting 5W, under NCT maximum temperature of the CV is 91°C (Section 3.1.3, Table 3-1). Assuming the content were loaded at -40°C and a pressure of 1 bar abs, the pressure at the maximum temperature of the CV, calculated according to Boyle's and Charles' Laws of 91°C, would be 1.6 bar (160kPa) gauge, which is well within the design envelope. There is no pressure increase due to the vapour pressure of the liquid contents (the liquid contents are aqueous with a boiling point of 100°C) as the temperature is < 100°C.

The bounding temperatures and pressures for the package are as follows.

NCT Operating Condition	CV
Assumed Max. Temperature	120°C
Max. Pressure	7 bar (700kPa) gauge 8 bar (800kPa) abs
Min. Temperature	-40°C
Min. Pressure	-1 bar (-100 kPa) gauge 0 bar (0 kPa) abs

Data is to be added here re pressures from liquids within the CV due to gas generation and steam pressure being <10 bar (1,000kPa) gauge, together with determination of production of H_2 such that concentration is < 5%.

3.4 Thermal Evaluation under Hypothetical Accident Conditions

3.4.1 Initial Conditions

The initial conditions used for the thermal model of the fire test are taken at the end of a 12 hour period of insolation under Normal Conditions of Transport with a content decay heat of 10 W. All components are at their maximum temperatures as shown in Table 3-2.

3.4.2 Fire Test Conditions [71.73 (c)(4)]

The thermal assessment of the package under fire conditions has been carried out using a finite element model. The model was validated against a fire test carried out on a prototype Safkeg-LS 3979A package and then used to calculate the temperatures experienced during a fire with the initial conditions specified in section 3.4.1.

Fire Test

The fire test was carried out within a series of regulatory tests described in the report CTR 2009/21 (Section 2.12.2). A prototype package that had undergone the NCT and HAC drop and penetrations tests was placed into a furnace which was heated to 800°C. Once the package reached 800°C the thermal test was started and the package remained in the furnace for 30 minutes. During the fire test the temperature of the package was logged with eight thermocouples. Two were on the containment vessel lid, four were attached to the keg body, one was attached to the keg lid and one was attached to the keg base. The thermocouples logged the temperature of the package every 10 seconds until the termination of the test. The containment vessel and insert were also instrumented with temperature sensitive strips.

The temperatures recorded during the furnace test are shown in Figure 3-7; the data shows that the thermocouple output during the time that the package was in the furnace are false: it is understood that this is due to small thermocouples being used which are affected by the case of the thermocouple being at nominally 800°C. Once the package was removed from the furnace, the thermocouples provided valid temperature data.

On completion of the 30 minutes test period, the package was removed from the furnace. The package was allowed to cool naturally with temperatures logged until the temperature of the package peaked and began to decrease.

Validation of the Thermal Model

The thermal model described in Section 3.3 was modified with the addition of a tungsten insert containing lead shot and changing the boundary conditions in order to model the fire test carried out during the regulatory testing.

The lead shot was represented as a solid material filling the cavity inside the tungsten insert. There was assumed to be good heat transfer between the sides, top and bottom of the containment vessel and the tungsten insert and between the tungsten insert and the lead shot. These are pessimistic assumptions since they will tend to minimise the temperature increase predicted by the model (and hence reduce the level of conservatism compared to the measured data). The density of the lead shot material was adjusted to give a total mass of 42g.

During the heating phase of the furnace test all exterior surfaces of the keg were assumed to receive heat by forced convection and radiation from the furnace. A convection coefficient of $10W/m^2/K$ was assumed (the value suggested in the Advisory Material for the IAEA Regulations [3.14]). The absorptivity of the surface of the keg was assumed to be 0.8 (the value specified in the IAEA Regulations [3.14]). It was recognised that the predicted temperature of the inner containment vessel would be insensitive to these heat transfer boundary conditions because the exterior skin of the keg, which has very little thermal capacity, will rapidly rise to near the temperature of the furnace.

The prototype Safkeg-LS 3979A package was placed inside the furnace by removing its lid and this resulted in the furnace being significantly cooler than 800°C when the package is first placed inside. This is why the package was inside the furnace for longer than the Regulatory

30 minutes. The temperature of the furnace increased back to 800°C over the first 19 minutes of the test. Unfortunately, the temperature provided from the furnace controller, as a function of time, was not sufficiently accurate for modelling purposes and the thermocouple attached to the support frame also gave false readings. However, the temperature of the exterior skin of the keg is expected to rapidly reach the furnace temperature. In the model, therefore, the temperature provided from the furnace controller was used as a guide but the modelled furnace temperature was adjusted in order to give good agreement between the predicted outer keg skin temperature and the maximum measured skin temperature, as a function of time. These temperatures are shown in Figure 3-7.

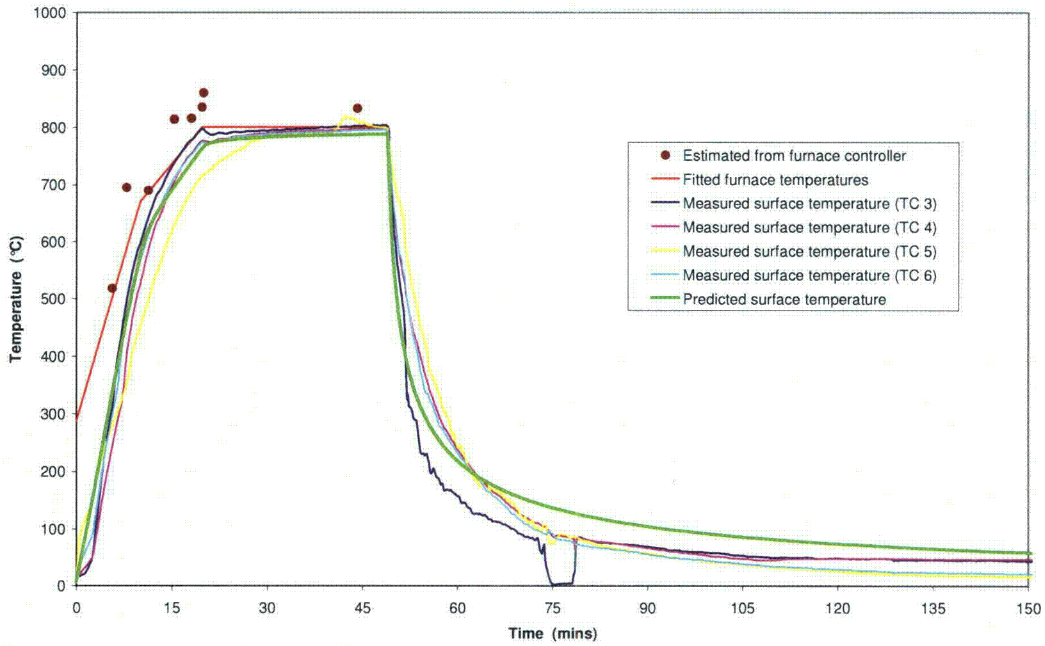


Figure 3-7 Furnace Temperature and External Surface Temperature in the Fire Test

During the cooling phase, heat was modelled as being lost from all exterior surfaces of the keg by radiation and natural convection. The emissivity of the surface of the keg was assumed to remain at 0.8, the value assumed during the heating phase (pictures of the container show the surface to be blackened and oxidised by the furnace). Established correlations for natural convection were again used to derive the appropriate convection coefficient (see Appendix 2 of report SERCO/TAS/5388/001 (Section 3.5.2)).

The predicted temperature of the containment vessel was initially much lower than the measured value. It was therefore concluded that the effective thermal conductivity of the cork was higher than had been assumed. The thermal conductivity of the cork (which was initially based on a linear extrapolation of the measured values) was therefore increased by 50%. It should be noted that this thermal conductivity in the model is an effective conductivity which includes possible additional heat transfer mechanisms such as evaporation and condensation of water or waxes.

The resulting predicted temperature at the location of the thermocouples on the containment vessel lid is compared against the measured values in Figure 3-8. The temperatures measured while the container was inside the furnace are believed to have been influenced by the flames inside the furnace and are hence unreliable. The temperatures measured during the cooling phase, however, are reliable and the maximum measured temperature agrees well with the temperature sensitive strip in this location. The general trend in measured temperature is predicted correctly but the predicted temperature lags behind the measured value but the maximum temperature is predicted reasonably well. The maximum temperature is overestimated by 2.5°C.

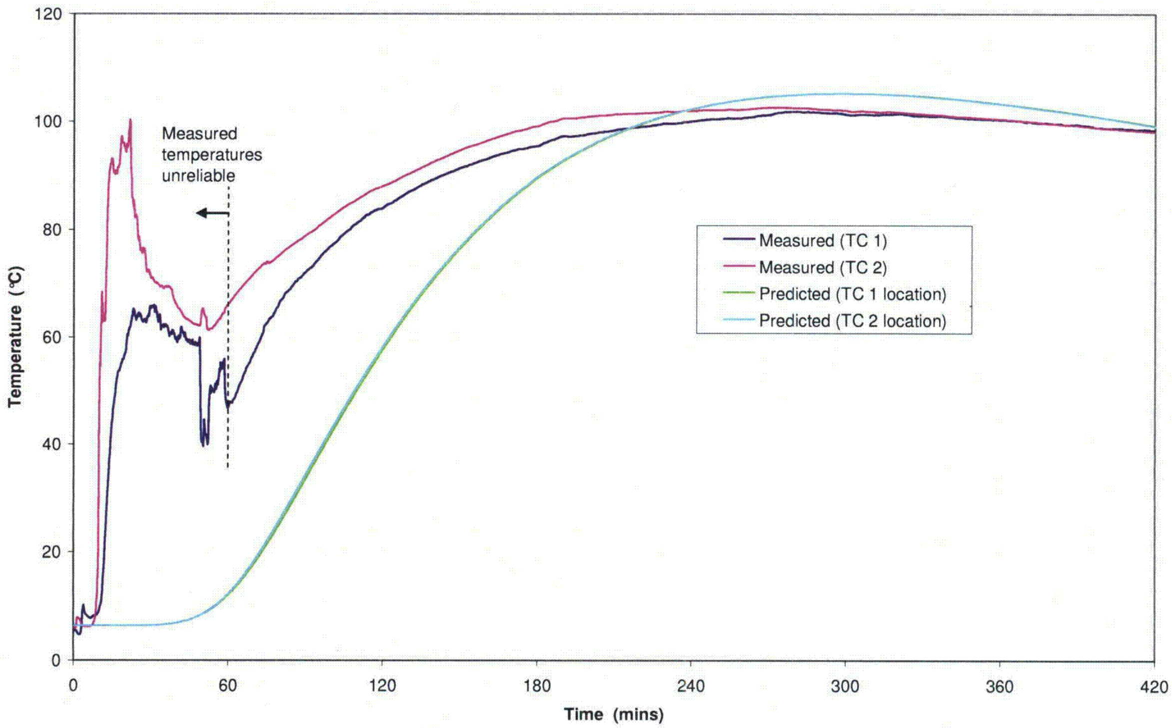


Figure 3-8 Comparison of Predicted and Measured Temperature of the Containment Vessel Lid in the Fire Test

It is therefore concluded that, with the adjusted cork conductivity, the finite element model is slightly pessimistic with respect to the peak inner containment seal temperature predicted during the fire test.

Thermal Model Used During the Fire Accident

The finite element analysis was used to determine the temperature of the container during the HAC fire test. A 30 minute, 800°C fire was simulated followed by a 12 hour cooling period.

During the heating phase, the model was the same as that used to validate the furnace test except:

- The tungsten insert and lead shot inside the inner containment vessel were removed.
- A heat load of 10W was applied to the inner surface of the containment vessel.
- The fire temperature was fixed at a constant value of 800°C.
- The convection heat transfer coefficient was increased from $10W/m^2/K$ to $15\ W/m^2/k$ to ensure that the value was pessimistic.
- The duration of the fire was reduced to 30 minutes.
- The calculation started from the temperature profile obtained for normal conditions of transport with insolation.

10 CFR 71.73 requires the thermal test to be performed upon a container which has already been subjected to the regulatory impact tests. A series of NCT and HAC drop and penetration tests was carried out on a prototype package (see Section 2.12.2). These tests caused denting of the top and bottom skirts of the package with minimal damage to the keg body.

These 'skirts' are not significant to the thermal performance and it is judged that the damaged 'skirt' would provide greater protection in a fire than an undamaged 'skirt' (since, when bent over, it will provide shielding of the top and bottom of the keg from the fire). The finite element model used to model the fire accident was therefore unchanged from that used to model Normal Conditions of Transport.

Although the temperature profile at the start of the fire test calculation corresponded to that at the end of a 12 hour period of solar insolation, solar insolation was (pessimistically) also applied during the 12 hour cooling phase of the fire accident calculation.

During the cooling phase, the boundary conditions were the same as those used to model normal conditions of transport (with the container vertical) except that the emissivity of the keg outer surface was assumed to be 0.8. The results of the HAC thermal evaluation are discussed in section 3.4.3.

3.4.3 Maximum Temperatures and Pressure

The maximum temperatures experienced by the components of the Safkeg-LS 3979A package calculated under a HAC fire test, with an ambient temperature of 38°C and insolation, are given in Table 3-3. The temperature each component reaches during the HAC thermal test is within it maximum allowable service temperature.

At the end of the heating phase the external surface of the keg is close to the temperature of the fire (800°C). Figure 3-9 shows the predicted temperature on the exterior surface of the keg. As measured in the furnace test detailed in report CTR 2009/21 (Section 2.12.2), the outer skin of the keg heats up and cools down rapidly because it is insulated from the inner containment vessel by the cork. The temperature of the keg lid changes more slowly than that of the side or base because the lid is thicker than the outer shell and therefore has a greater thermal capacity.

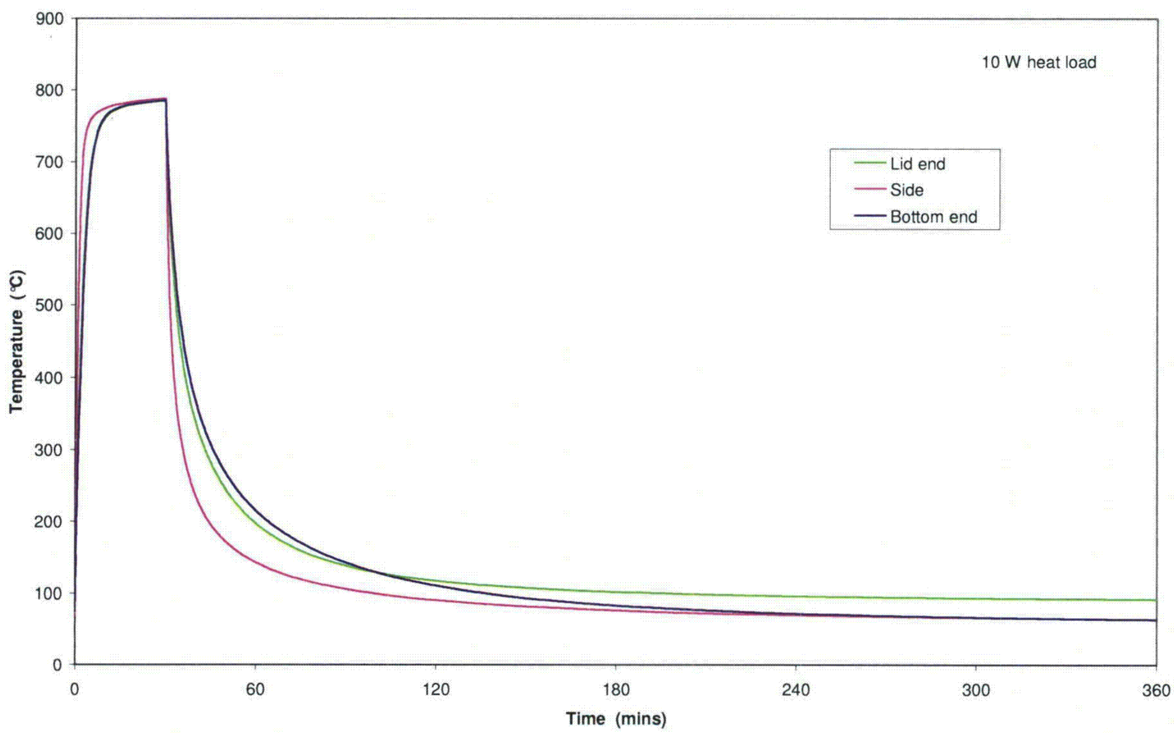


Figure 3-9 Predicted Temperature of the Outside of the Keg during the Fire Test

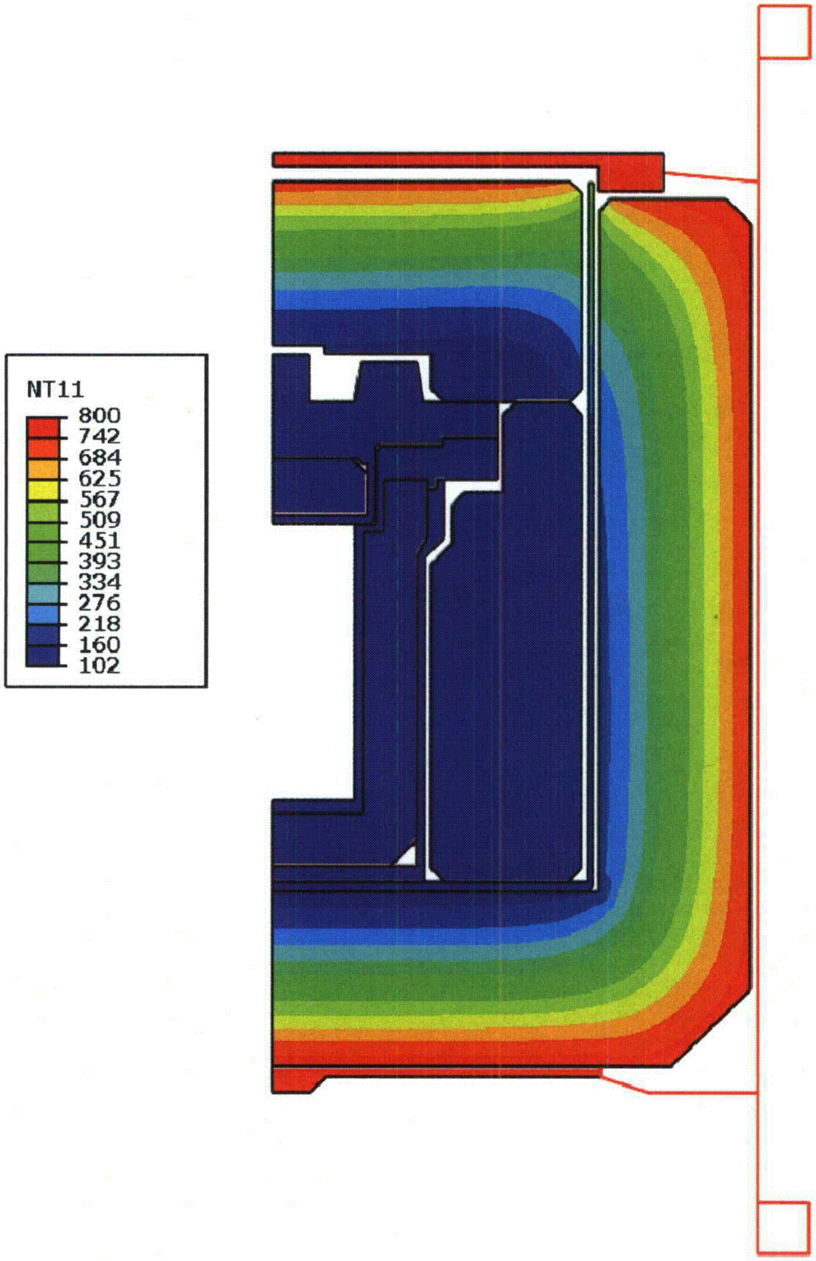


Figure 3-10 Predicted Temperature Profile at the end of the Heating Phase of the Fire Accident

Figure 3-10 and Figure 3-11 show the predicted temperature of the inner containment vessel. The lid seal reaches a maximum temperature of 183°C after 3¾ hours. A similar maximum temperature is experienced by the lead shielding. The lead therefore remains well below its solidus of 252°C. Figure 3-6 shows the maximum temperatures throughout the package under HAC.

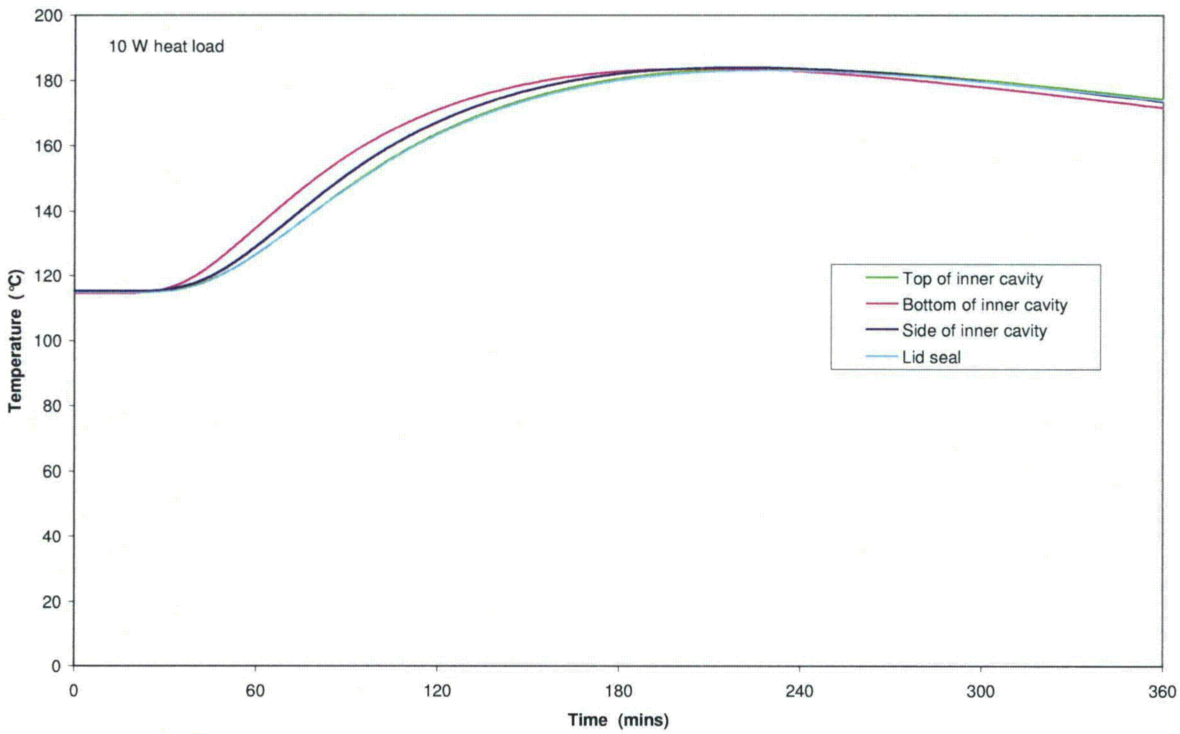


Figure 3-11 Predicted Temperature of the Containment Vessel during the Fire Test

The Design Pressure of the CV is 10 bar (1,000 kPa) gauge.

For solid contents emitting 10W, under HAC the maximum temperature of the CV is 184°C. Assuming the content were loaded at -40°C and a pressure of 1 bar abs, the pressure at the maximum temperature of the CV, calculated according to Boyle's and Charles' Laws of 184°C, would be 2 bar (200 kPa) gauge, which is well within the design envelope.

For liquid contents emitting 5W, under HAC the maximum temperature of the CV is 162°C (Section 3.1.3, Table 3-1). Assuming the content were loaded at -40°C and a pressure of 1 bar abs, the pressure at the maximum temperature of the CV, calculated according to Boyle's and Charles' Laws is 162°C would be <1.9 bar (190 kPa) gauge. However, the vapour pressure of the liquid contents (the liquid contents are aqueous) would be 5.5 bar gauge (from steam tables). Therefore the maximum pressure within the CV would be 5.5 bar gauge which is well within the design envelope.

The temperatures reached are within the bounding conditions for the package which are as follows:

HAC Operating Condition	CV
Assumed Max. Temperature	200°C
Max. Pressure	10 bar (1,000kPa) gauge 11 bar (1,100kPa) abs
Min. Temperature	-40°C
Min. Pressure	-1 bar (-100 kPa) gauge 0 bar (0 kPa) abs

3.4.4 Maximum Thermal Stress

As discussed in section 2.7.4.3 the NCT heat calculations bound the HAC test results. The resulting stresses from the NCT heat results are discussed in section 2.6.1.3 and 2.6.1.4. All the stresses calculated are within the allowable limits for the containment vessel.

3.4.5 Accident Conditions for Fissile Material Packages for Air Transport [71.55(f)]

Not applicable – air shipment of fissile material is not specified.

3.5 Appendix

3.5.1 References

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[3.12] Parker Hannifin Corporation, Parker O-ring Handbook, ORD 5700/USA, 2001

[3.13] Abaqus version 6.8-1, Dassault Systemes Simulia Corp

[3.14] Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material', 2005 Edition, IAEA Safety Guide No. TS-G-1.1 (Rev. 1), 2008.

3.5.2 Supporting Documents

Document Reference	Title
SERCO/TAS/5388/001	Thermal Analysis of the SAFKEG LS Design