0.1 SARP REVISION STATUS

Title	SAFKEG-LS 3979A Docket No. 71-9337	**Number**	CTR 2008/10
		Issue	Revision 7
		File Reference	[CTR2008-10-R7-Sc0-v2-Status and Contents.docx]
Compiled		**Checked**	
	S Bryson		R A Vaughan
Approved		**Date**	17 December 15
	R A Vaughan		
Croft Associates Ltd F4 Culham Science Centre Abingdon Oxon OX14 3DB UK Tel 44 (0)1865 407740			

0.2 PAGE AND SUPPORTING DOCUMENT REVISION STATUS

Page/Document Reference	Issue Status	Title
Section 0 – Page and Supporting Document Revision Status		
Page 0-1	Rev 5	
Page 0-2	Rev 7	
Page 0-3	Rev 7	
Page 0-3a	Rev 7	
Page 0-4	Rev 5	
Page 0-5	Rev 6	
Page 0-6	Rev 7	
Page 0-7	Rev 7	
Page 0-8	Rev 7	
Page 0-9	Rev 7	
Page 0-9a	Rev 7	
Page 0-10	Rev 5	
Page 0-10a	Rev 7	
Page 0-11	Rev 6	
Page 0-12	Rev 6	
Page 0-13	Rev 6	
Section 1 - GENERAL INFORMATION		
Page 1-1	Rev 6	
Page 1-2	Rev 4	
Page 1-3	Rev 4	
Page 1-4	Rev 4	
Page 1-5	Rev 4	
Page 1-6	Rev 4	

Page/Document Reference	Issue Status	Title
Section 0 – Page and Supporting Document Revision Status		
Page 1-7	Rev 4	
Page 1-8	Rev 4	
Page 1-9	Rev 4	

Page/Document Reference	Issue Status	Title
2C-6171	Issue C	LS-12x65-Tu insert design no. 3984 (licensing drawing)
2C-6172	Issue C	LS-31x73-Tu insert design no. 3983 (licensing drawing)
2C-6175	Issue D	LS-50x103-SS insert design no. 3986 (licensing drawing)
Documents in Section 1.3.4 Supporting Documents		
PCS 036	Issue D	Package Contents Specification for Safkeg-LS - Package Design No 3979A
Section 2 - STRUCTURAL EVALUATION		
Page 2-1	Rev 4	
Page 2-2	Rev 4	
Page 2-3	Rev 7	
Page 2-3a	Rev 7	
Page 2-4	Rev 4	
Page 2-5	Rev 4	
Page 2-6	Rev 4	
Page 2-7	Rev 4	
Page 2-8	Rev 4	
Page 2-9	Rev 4	
Page 2-10	Rev 4	
Page 2-11	Rev 4	
Page 2-12	Rev 4	
Page 2-13	Rev 4	
Page 2-14	Rev 4	
Page 2-15	Rev 4	
Page 2-16	Rev 4	

Page/Document Reference	Issue Status	Title
Page 2-17	Rev 4	
Page 2-18	Rev 4	
Page 2-19	Rev 7	
Page 2-20	Rev 4	
Page 2-21	Rev 4	
Page 2-22	Rev 4	
Page 2-23	Rev 4	
Page 2-24	Rev 4	
Page 2-25	Rev 4	
Page 2-26	Rev 4	
Page 2-27	Rev 4	
Page 2-28	Rev 4	
Page 2-29	Rev 4	
Page 2-30	Rev 4	
Page 2-31	Rev 4	
Page 2-32	Rev 4	
Page 2-33	Rev 4	
Page 2-34	Rev 4	
Page 2-35	Rev 4	
Page 2-36	Rev 4	
Page 2-37	Rev 4	
Page 2-38	Rev 4	
Page 2-39	Rev 7	
Page 2-40	Rev 4	
Page 2-41	Rev 4	
Page 2-42	Rev 4	

Page/Document Reference	Issue Status	Title
Page 2-43	Rev 4	
Page 2-45	Rev 4	
Page 2-46	Rev 4	
Page 2-47	Rev 4	
Page 2-48	Rev 4	
Page 2-49	Rev 4	
Page 2-50	Rev 4	
Page 2-51	Rev 4	
Page 2-52	Rev 4	
Page 2-53	Rev 7	
Page 2-54	Rev 4	
Page 2-55	Rev 4	
Page 2-56	Rev 4	
Page 2-57	Rev 4	
Page 2-58	Rev 4	
Page 2-59	Rev 4	
Page 2-60	Rev 4	
Page 2-61	Rev 4	
Page 2-62	Rev 4	
Page 2-63	Rev 7	
Page 2-63a	Rev 7	
Page 2-64	Rev 4	
Page 2-65	Rev 7	
Page 2-66	Rev 7	
Documents in Section 2.12.2, Appendix		
CTR 2009/21	Issue D	Prototype Safkeg-LS 3979A/0002 NCT and HAC Regulatory Test Report

Page/Document Reference	Issue Status	Title
CTR 2009/27	Issue A	Prototype SAFKEG LS 3979A/0002 NCT and HAC Regulatory Test Report
SERCO/TAS/002762/01	Issue 1	Compression Testing of Cork
Vectra, 925-3272/R1	Rev 6	Stress Analysis of Safkeg LS 3979A Containment Vessel
CS 2009/08	Issue A	SAFKEG LS 3979A – Maximum Pressure in CV
CS 2010/11	Issue B	Calculation of the Density of the 3977A Package
Vectra, 925-3274/R1	Rev 1	Safkeg LS 3979A – Additional HAC Case
Vectra, 925-3272/M2	15/03/10	Safkeg LS 3979A – Mesh Sensitivity Analysis
Section 3 - THERMAL EVALUATION		
Page 3-1	Rev 4	
Page 3-2	Rev 4	
Page 3-3	Rev 4	
Page 3-4	Rev 4	
Page 3-5	Rev 4	
Page 3-6	Rev 4	
Page 3-7	Rev 4	
Page 3-8	Rev 4	
Page 3-9	Rev 4	
Page 3-10	Rev 4	
Page 3-11	Rev 4	
Page 3-12	Rev 7	
Page 3-12a	Rev 7	
Page 3-13	Rev 4	

Page/Document Reference	Issue Status	Title
Page 3-14	Rev 4	
Page 3-15	Rev 4	
Page 3-16	Rev 4	

Page/Document Reference	Issue Status	Title
Page 3-17	Rev 4	
Page 3-18	Rev 4	
Page 3-19	Rev 4	
Page 3-20	Rev 4	
Page 3-21	Rev 4	
Page 3-22	Rev 4	
Page 3-23	Rev 4	
Page 3-24	Rev 4	
Page 3-25	Rev 4	
Page 3-26	Rev 4	
Page 3-27	Rev 4	
Page 3-28	Rev 4	
Page 3-29	Rev 4	
Documents in Section 3.5.2, Appendix		
SERCO/TAS/5388/001	Issue 2	Thermal Analysis of the Safkeg LS Design
SERCO CJF10302	31 Mar 10	Response to comments on thermal performance of SAFKEG LS raised by NRC assessor
CS 2010/16	Issue A	SAFKEG LS 3979A – Maximum Temperature of CV Inserts
Section 4 - CONTAINMENT		
Page 4-1	Rev 4	
Page 4-2	Rev 4	
Page 4-3	Rev 4	
Page 4-4	Rev 4	
Page 4-5	Rev 4	
Page 4-6	Rev 4	

Page/Document Reference	Issue Status	Title
Page 4-7	Rev 4	

The inner cavity wall/flange and the bolted flange for the containment vessel closure form the cavity into which the radioactive contents are placed. The flange is machined with 8 closure holes into which CV closure screws (occasionally referred to as bolts) are fitted.

The containment vessel lid is comprised of two pieces a lid top and a stainless steel clad lead plug. The CV lid top is a circular plate machined from a stock billet of 304L stainless steel. Eight equally spaced counter bored holes are machined to accommodate the closure bolts. Four further holes are machined in the lid, the first accommodates the test port in order to leak test the closure system. The second is a blind hole in the centre of the lid and is fitted with a threaded insert. This allows a lifting eye to be fitted for the handling of the containment vessel. The last two allow jacking screws to be fitted which assist in the removal of the lid. Two grooves are machined onto the underside of the lid top into which the O-rings are fitted.

The lead is cast into a machined stainless steel casing forming the shielding plug. The plug is welded to the lid top with a circumferential weld which is liquid penetrant and visually tested.

The containment vessel lid is attached to the body with eight L43 alloy steel screws/bolts which are tightened to a torque of 10 ± 5 Nm.

The design pressure for the containment vessel is 10 bar (1,000 kPa) gauge which envelopes the MNOP of 7 bar (700 kPa) gauge. The containment boundary is formed by the inner cavity wall/flange, lid and containment O-ring. This containment boundary is leak tested on manufacture, during annual maintenance and on loading.

Insert

Any one of the three inserts specified in Section 1.3.2 shall be used to provide further shielding and confinement for the contents. Two of the inserts, LS-12x65-Tu Design No 3984 and LS-31x73-Tu Design No 3983, are machined from tungsten with one, LS-50x103-SS Design No 3986, machined from stainless steel. All of the inserts consist of a body and a lid which are machined from a solid. The lid screws onto the body with an O-ring seal. The three types of inserts each have different cavity sizes and provide varying levels of shielding.

2.1.2 Design Criteria

In order to evaluate the containment design, an FEA was performed on the containment vessel under NCT and HAC using the software code Abaqus: as discussed in Vectra Report 925-3272 and report 925-3273 M2 (Section 2.12.2).

The initial load combinations used during the evaluation are discussed in Section 2.1.2.1. The resultant calculated stresses are compared against the allowable stresses presented in Section 2.1.2.2. Further evaluation is carried out to determine buckling, fatigue and brittle fracture as discussed in Sections 2.1.2.3, 2.1.2.4 and 2.1.2.5 respectively.

With regards to the model's boundary conditions the plane of symmetry was the plane Z=0. The boundary conditions on this plane were:

UZ=0
URX=0
URY=0
Where U is the displacement and UR is a rotation. As both the geometry and loading was symmetric about the plane Z=0, the use of a half-symmetry model has no effect on the results.

For the non-impact cases (NCT1-6), the flask was fixed at a single point at the centre of the bottom of the flask in the X-direction. The outer edge of the bottom of the flask was fixed in the Y-direction. These boundary conditions prevent any rigid body movement but do not affect the overall behaviour of the model. No stress concentrations were observed at these locations.

For impact cases NCT7, NCT8, HAC1 and HAC2 (drop on lid), the X and Y boundary conditions were maintained during the pre-loading steps. During the impact loading step, the Y boundary conditions were removed. Excessive movement in the Y direction and rotation about the Z axis was prevented by contact between the flask and the cork. Rigid body motion of the cork was prevented.

For impact cases NCT9, NCT10, HAC3 and HAC4 (drop on side), the X and Y boundary conditions were maintained during the pre-loading steps. During the impact loading step, the X boundary condition was removed. The Y boundary condition was changed so that it just applied to the centre of the bottom of the flask. This prevented rigid body motion in the Y direction but about allowed rotation about the Z axis. Excessive movement in the X direction was prevented by contact between the flask and the cork. Rigid body motion of the cork was prevented.

For impact cases NCT11, NCT12, HAC5 and HAC6 (drop on top corner), the X and Y boundary conditions were maintained during the pre-loading steps. During the impact loading step, the X and Y boundary conditions were removed. Excessive movement in the X and Y directions was prevented by contact between the flask and the cork. Rigid body motion of the cork was prevented.

The effectiveness of the packaging components under all the conditions of the regulatory requirements (both NCT and HAC) has been verified by physical tests. As the structural materials of the package are all austenitic stainless steel, the package is not susceptible to

2.2.1.2 Shielding Material

The shielding is formed from lead cast within the stainless steel cladding. The lead is alloyed with 4% antimony to provide greater hardness and strength and therefore is less susceptible to lead slumping [2.19]. The mechanical properties of lead used in the structural evaluation are presented in Table 2-13.

2.2.1.3 Cork Packing

The inner and outer cork is machined from resin bonded cork. The cork may be formed from one piece or from several pieces glued with a contact adhesive.

The mechanical properties of the cork have been determined by testing. Loads were applied by a piston at a rate of 4.5 mm/minute to 45 mm thick racially constrained cork samples. The displacement of the cork was then recorded continuously at a rate of 20 readings/second. In order to cover the full range of service temperatures tests were carried out with corks at -29°C, 20°C and 100°C. The test details and results are discussed in the Serco Report SERCO/TAS/002762/01 [Section 2.12.2].

Table 2.14 presents the mechanical properties of the cork determined from testing. The test results show that cork is harder at low temperatures and softer at high temperatures. At an applied stress of 8 MPa, the cork at 100°C showed most deformation: which would indicate the containment vessel will travel a further distance into the cork before it is resisted by the same forces it would be resisted with at room temperature.

2.2.2 Chemical, Galvanic or Other Reactions [71.43(d)]

The package has been evaluated to determine all the material interactions of chemically or galvanic dissimilar materials. These interactions are identified in Table 2-15.

There is no potential for chemical, galvanic or other reactions between the components of the package which are stainless steel and cork in dry conditions, and stainless steel and encapsulated lead which is sealed and therefore dry. The only contents which could cause reactions or generate gases are liquids carried in product containers within the tungsten or steel inserts which are fitted with an EP O-ring seal. Under NCT, the liquids are contained within the product containers and inserts and therefore no liquid comes into contact with the containment system. Under HAC, the liquids are assumed to leak from the product containers and inserts and therefore the liquid may come into contact with the containment system but this would be only for a short time. The containment system is stainless steel and EP which would be only slightly affected by even acidic contents (limited to HCL and, HNO_3 of maximum concentration 0.1N) during the short period that the package would be in the public domain following an accident (HAC).

The effect of a free drop test on the package was determined with a series of physical drop tests on a prototype package and a finite element analysis of the containment vessel.

The NCT free drop tests were carried out on a prototype package within the series of NCT and HAC tests, as described in the Croft Reports CTR 2009/21 and CTR 2009/27, appended in Section 2.12.2. The test package of 61.8 kg mass was dropped 1.2 meters onto a steel target with a mass of 500 kg, which was located on a thick concrete base. The NCT free drop tests were all carried out at an ambient temperature of 14°C.

In order to determine the effect of testing on the package several modifications were made to the containment vessel, cork and keg. To accommodate the wiring for the test equipment small holes of up to 25 mm were drilled though the center of the containment vessel lid, top cork and keg lid. A drain hole on the side of the keg was enlarged to allow the test equipment wiring to pass through it. Finally two cavities and threaded holes were machined into the containment vessel lid to allow the attachment of the accelerometers. The changes are discussed in more detail in the Croft Reports CTR 2009/21 and CTR 2009/27(Section 2.12.2). These changes are would not affect the structural integrity of the package or the test results: if anything they would slightly weaken the integrity causing the tests to have a greater effect on the test package than the actual package.

The total mass of the tested package was 61.72 kg which is 5% lighter than the design weight of 64.8 kg given in section 2.1.3. The design weight is greater than the tested package weight to allow for variations due to manufacturing tolerances. In order to account for the lower weight of the test package it was dropped from 10.2 m under the HAC tests, this is a 13% increase in the drop height and energy of the package at impact.

Aside from minor weight differences and the modifications discussed for testing, the prototype package was identical to the manufactured package.

The drop tests caused minor denting to the bottom and top rim of the 3979 keg. No visible damage or deformation was present on the body of the keg after each of the drop tests. This indicates there would be no significant change in the radiation level. Helium leakage testing was carried out prior to and after the entire test series. The leakage testing demonstrated the containment vessel remained leak tight throughout the test series. The containment vessel bolts did not loosen during the test series.

A detailed analysis of the stress present in the containment vessel during the free drop test was carried out using a finite element model of the containment vessel as described in Vectra Report 925-3272/R1 appended in Section 2.12.2.

The three drop orientations illustrated in Figure 2-2 were modeled under 'hot' and 'cold' conditions as required by Regulatory Guide 7.8 [2.2]. The hot conditions assumed the package experienced the maximum ambient temperature of 38°C, in still air with maximum insolation and decay heat. With these conditions it was assumed that the containment vessel was at a uniform temperature of 110°C. Along with the hot temperature it was assumed that

Package Test

As described in Section 2.7.1, the prototype test package was cooled to -40°C and dropped onto its side, top corner and then the top end with damage from each drop accumulating for the next test. The side drop is described in the appended reports CTR 2009/21 and CTR 2009/27 (Section 2.12.2). The package was slung in the correct orientation and dropped onto the test target. The package impacted the target with the bottom rim first and then rocked over for the secondary impact to occur on the top rim and came to rest on the side.

The maximum g values recorded during the end drop are given in Table 2-29. The accelerations were measured by accelerometers attached to the lid of the containment vessel. The accelerometers logged at 100,000 samples per second. The raw data was filtered using a low pass digital 4th order Butterworth filter [2.18] with a cut off frequency of 500 Hz. The maximum radial acceleration is 430 g and the maximum axial acceleration is 298 g.

The keg received some minor denting which is discussed in Section 2.7.1.5.

Containment Vessel Evaluation

A detailed analysis of the stress present in the containment vessel during the free drop test was carried out using a finite element model of the containment vessel as described in the Vectra Group report 925-3272/R1 (Section 2.12]. The commercial finite element code Abaqus/Standard v 6.8 was used for the analysis. A half symmetry model was generated because the geometry and load cases were all symmetrical about a vertical plane through the centre of the vessel. The model is described in detail in the Vectra report.

The side drop was modelled under 'hot' and 'cold' conditions as required by Regulatory Guide 7.8. The hot conditions assumed the package experienced the maximum ambient temperature of 38°C, in still air with maximum insolation and decay heat. With these conditions it was assumed that the containment vessel was at a uniform temperature of 150°C. Along with the hot temperature it was assumed that the containment vessel had an internal pressure of 800 kPa. The external pressure was taken as 100 kPa, so the internal gauge pressure was 700 kPa

The cold conditions assumed an ambient temperature of -29°C, in still air with no insolation or decay heat. It has been assumed that the internal pressure is 0 kPa with an external pressure of 100 kPa, so the internal gauge pressure is -100 kPa. The load combinations modelled for the HAC drop tests are outlined in Table 2-1.

A body force was applied to the model which was equivalent to the radial value measured during the test. The measured g values are shown in Table 2-29 with the value of g applied to the model shown in Table 2-30.

Table 2-43 Containment Vessel Stress Summary for Immersion						
.NCT Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
4	Increased External Pressure	P_m	44.9	C2	115	1.56
		P_m+P_b	86.8	C2	173	0.99
		P_m+P_b+Q	82.1	C4	345	3.2
		Bearing	68.7	Under bolts	172	1.50

2.7.7 Deep Water Immersion Test (for Type B Packages Containing More than 10^5 A2) [71.61]

Not applicable as the contents are < $10^5 A_2$.

2.7.8 Summary of Damage

The mechanical damage sustained by the package during the NCT and HAC test series is reported in CTR 2009/21 [Section 2.12.2]. The testing was carried out in series with the NCT drop testing, followed by the HAC puncture tests, HAC drop tests and the HAC thermal test.

The NCT drop tests caused minimal denting to the rim of the keg at the points of impact. The puncture tests also caused minimal damage to the keg rim however the side puncture test did cause an indent of 14.6 mm on the side of the keg. The 10.2 meter drop tests caused more severe denting to the top and bottom rims with the drop test over the top rim causing a 12 mm dent and the side drop causing a dent to the bottom rim.

The thermal test was carried out on completion of the HAC drop and puncture tests, to determine if the damaged package was able to withstand the rigors of this test. During the test the package skin reached 800°C however the containment vessel was insulated by the design and to some extent by the damage and only reached a temperature of 110°C which is within the operational range of the containment seal. On completion of the test series the keg and the components were inspected and revealed that the outer cork was charred with the inner and top cork partially charred.

On completion of the test series, examination of the containment vessel found no damage and no change in the measured dimensions. Leak tests carried out prior to and on completion of testing detected no signs of leaks, indicating that the containment vessel remained leak tight throughout the NCT and HAC tests. Additionally the force required to maintain compression of the containment O-ring is 9.9 kN, Table 2-44 below demonstrates that the total bolt force for all eight bolts at the end of each analysis in the FEA. As shown in the table all are well in excess of the 9.9 kN required and therefore will maintain compression in the containment O-ring.

The examination of the containment vessel (as detailed in report CTR 2009/21, Table 9, page 46, under the table section headed Containment Vessel in rows 12 -15), showed the outside diameter of the CV body at lower and mid height of the body at reference and 90° to reference – all are seen to be close to the nominal diameter of 118.5 mm and there are no significant changes following the drop test program. This demonstrates that there was no distortion of the CV shell due to lead slumping.

Table 2-44 - Total Bolt Force After Analysis

Case ID	Total Bolt force (for all eight Bolts) (kN)
NCT1	84.7
NCT2	52.4
NCT3	84.7
NCT4	54.6
NCT5	84.7
NCT6	54.5
NCT7	84.9
NCT8	55.1
NCT9	84.9
NCT10	55.2
NCT11	85.1
NCT12	55.3
HAC1	95.1
HAC2	55.5
HAC3	95.2
HAC4	54.9
HAC5	95.3
HAC6	55.6

[2.7] Regulatory Guide 7.11, *Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inch (0.1 m)*, U.S. Nuclear Regulatory Commission, Office of Standards Development, June 1991.

[2.8] NUREG/CR-3854, *Fabrication Criteria for Shipping Containers,* U.S. Nuclear Regulatory Commission, Washington D.C., April 1984.

[2.9] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB, *Class 1 Components,* 2001 Edition with Addenda through July 1, 2003.

[2.10] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NF, *Supports*, 2001 Edition with Addenda through July 1, 2003.

[2.11] NUREG/CR-6407, INEL-95/0551, Classification of Transportation Packaging and Dry Spent Fuel Storage System Components According to Importance to Safety, February 1996

[2.12] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, *Ferrous Material Specification, 2007 Edition with Addenda through July 1, 2009*

[2.13] American National Standards Institute, for Radioactive Material*, Leakage Tests on Packages for Shipment*, ANSI N14.5-1997

[2.14] NUREG CR/3019, UCRL-53044 Recommended Welding Criteria for Use in the Fabrication of Shipping Containers for Radioactive Materials, March 1984

[2.15] Parker Hannifin Corporation, *Parker O-ring Handbook*, ORD 5700/USA, 2001.

[2.16] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section II, Part D, *Materials*, 2001 Edition with Addenda through July 1, 2003.

[2.17] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section V, *Non Destructive Examination*, 2001 Edition, with Addenda through July 1, 2001

[2.18] Vibration, Measurement and Analysis, JD Smith, Butterworth-Heinemann

[2.19] Zeitstachuntersuchungen an Blei und Bleilegierungen (Investigations on Long Term Behaviour of lead and Lead-Alloys) K. Gerischer und CM Meyenbug

2.12.2 Supporting Documents

Document Reference	Title
SERCO/TAS/002762/01	Compression Testing of Cork
Vectra, 925-3272/R1	Stress Analysis of Safkeg LS 3979A Containment Vessel
Vectra, 925-3272/M2	Safkeg LS 3979A Mesh Sensitivity Analysis
CTR 2009/21	Prototype SAFKEG LS 3979A/0002 NCT and HAC Regulatory Test Report
CTR 2009/27	Prototype SAFKEG LS 3979A/0002 NCT and HAC Regulatory Test Report
CS 2009/08	SAFKEG-LS 3979A – Maximum Pressure in CV
CS 2010/10	Calculation of the Density of the 3977A Package
Vectra, 925-3274/R1	Safkeg LS 3979A – Additional HAC Case

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 sensitivity of the air gaps were discussed in the SERCO letter CJF10302 for NCT and HAC conditions. This letter demonstrated that the air gaps are relatively unimportant to the thermal performance of the package.

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

3.5.2 Supporting Documents

Document Reference	Title
SERCO/TAS/5388/001	Thermal Analysis of the SAFKEG LS Design
SERCO CJF10302	Response to comments on thermal performance of SAFKEG LS raised by NRC assessor
CS 2010-16	SAFKEG-LS # 3979A – Maximum temperature of CV inserts