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 800ºC 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.

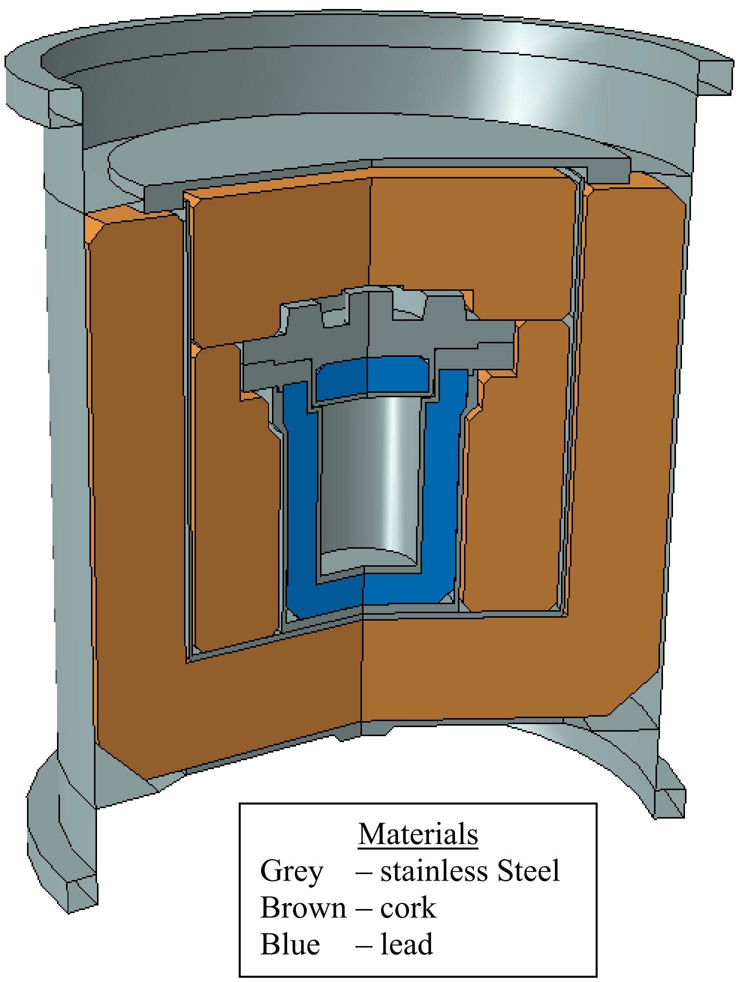

Figure 3-1 Thermal Design Properties

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.

The temperature of the Shielding Inserts under NCT and HAC conditions with contents emitting 10W has been determined in Calculation Sheet CS 2010-16 [appended in Section 3.5.2] as 12°C above that of the CV body: this is based on the worst case assumption that all the heat from the contents, which is emitted as radiation, is absorbed within the Shielding Insert. The maximum resulting temperatures of the Shielding Inserts calculated are presented in Table 3-2 and Table 3-3: these temperatures are within the acceptable temperature limits for the all the components of the inserts.

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 38ºC, with and without insolation)

Location	**Maximum Temperature (ºC)**		**Temperature Limit (ºC)**
	No insolation	**With Insolation**	
Shielding Insert	106.2	128.4	427 (1)
Shielding Insert seal	106.2	128.4	150 (4)
Containment vessel cavity	94.2	116.4	427 (1)
Containment vessel lid seal	94	116	150(4)
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 427ºC 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]

4 EP O-ring temperature limit for continuous operation

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

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)
Shielding Insert	196	225 (3)	427
Shielding Insert seal	196	225 (3)	200 (1)
Containment vessel cavity	184	225	1427
Containment vessel lid seal	183	225	200 (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 150°C for 8 ¼ hours. Batch testing of the seals prior to use, as detailed in section 8.1.5.2, assures that the O-ring will perform satisfactorily after a period of 24 hours at 200°C.

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

3 The Inserts would reach maximum temperature nominally at the same time as the peak in CV temperature with possibly a small time lag.

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 (°C)	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.

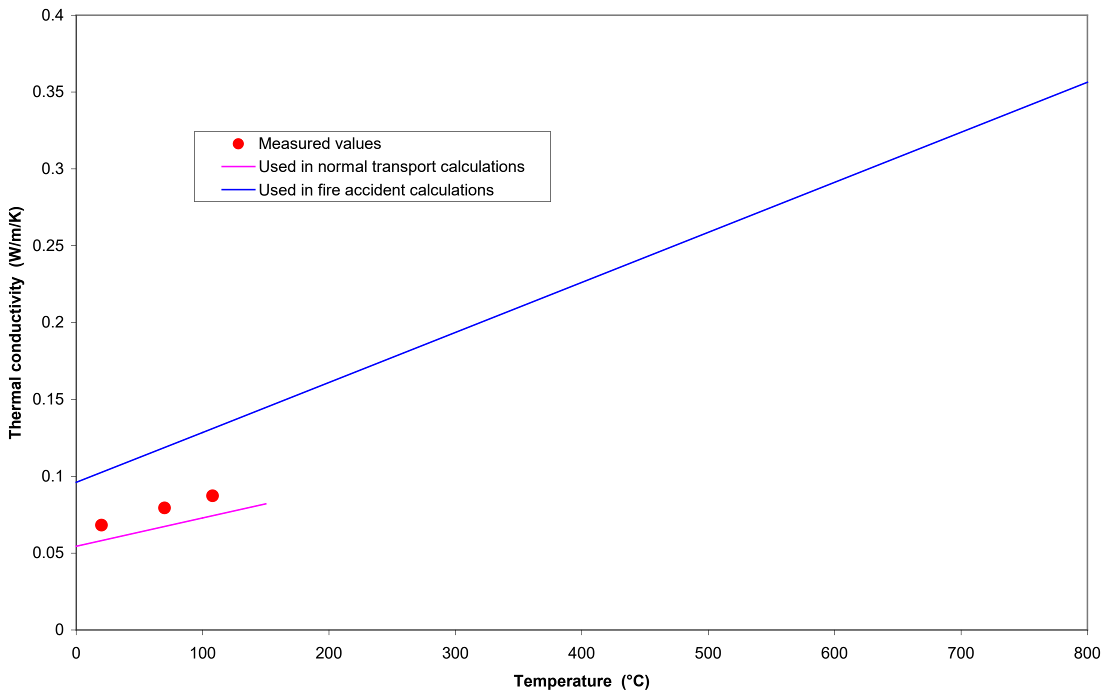

Figure 3-2 Thermal Conductivity of Cork

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 rubber.

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 -40ºC. 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 104ºC for continuous operations and 780ºC for short term operations. The upper temperature reached by the stainless steel in the containment vessel is 116ºC for continuous operations and 184ºC for short term operations under HAC conditions.

The allowable temperature limit for steel when relied upon for structural support is 427ºC 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 1427ºC, which is the melting point of steel.

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

The cork is unaffected by temperatures up to at least 140ºC 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 775ºC. 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 rubber to ASTM D2000 M3 BA 810 A14 B13 F17 Z1, where Z1 stands for hardness of 75±5 IRHD (or Shore A) (see drawings in Section 1.3.3). EP has a recommended temperature range of -57°C (-70°F) to 150°C (302°F) for continuous static and dynamic use with a maximum temperature of up to 204°C (400°F) for 2 hours duration as specified in the Parker O-Ring Handbook [3.12]. The ASTM D2000 standard F17 ensures that the O-ring material is suitable for use at -40ºC. The critical characteristic tests specified section 8.3.2 provides assurance that the material supplied for use in packages, provides the required degree of sealing at 130ºC for 1000 hours and at 200ºC for 24 hours.

Note. The NCT 1000 hour temperature test mentioned above was reduced from 150ºC to 130ºC for Revision 8 of this SARP, as justified in CTR 2021/22 [3.5.2], with confirmatory testing reported in CTR 2021/24 [3.5.2].

Under HAC conditions the O-ring remains above 149ºC for 8 ¼ hours reaching a maximum temperature of 183ºC. Therefore the O-rings operate outside of the 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 200ºC - the test is specified in the drawings in section 1.3.3.

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 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.

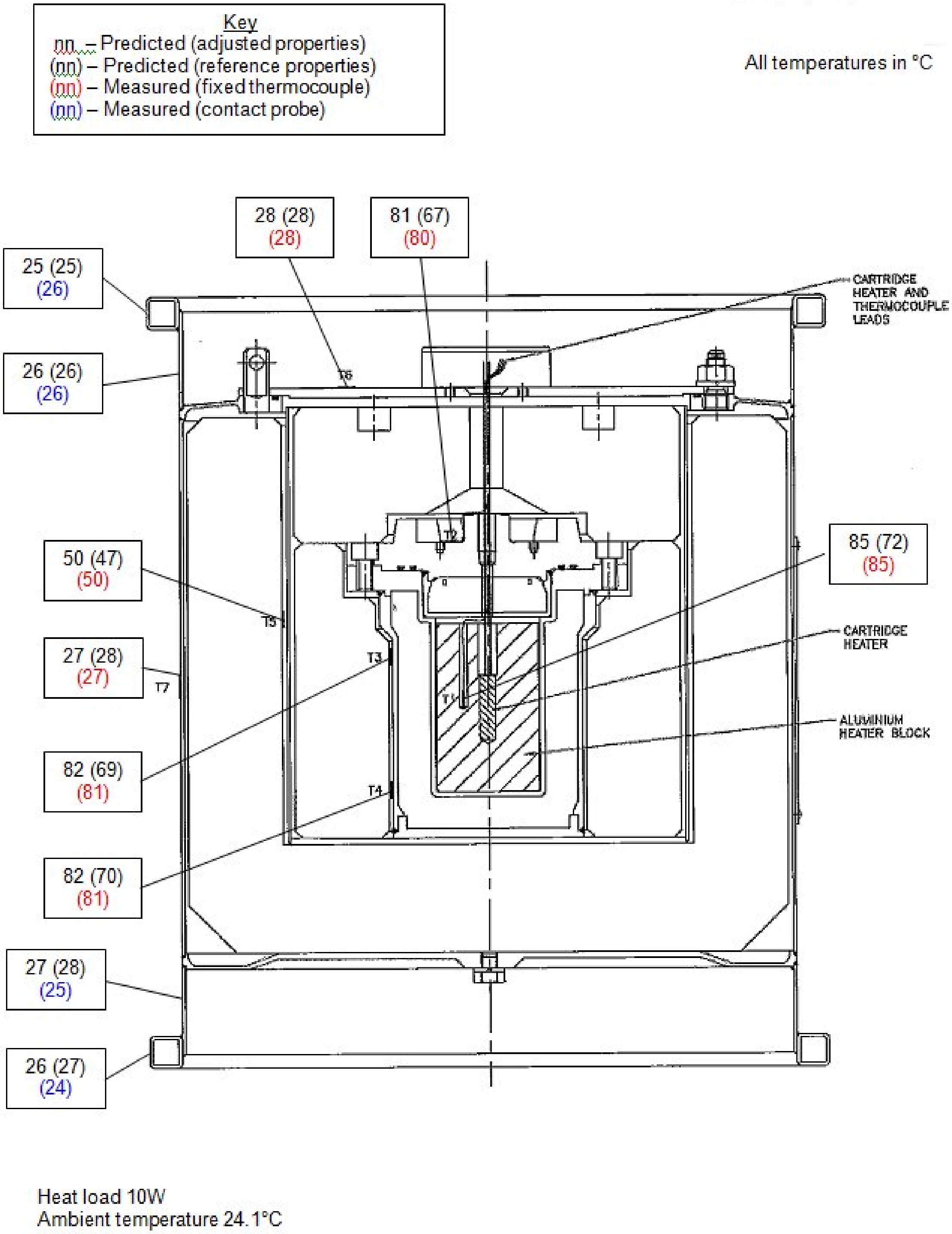

Figure 3-3 Comparison of Measured and Predicted Temperatures in the Steady-State Heating Test

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 38ºC, 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 43ºC which is reached on the keg lid, the base of the keg reaches 46ºC 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 50ºC 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 38ºC. 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

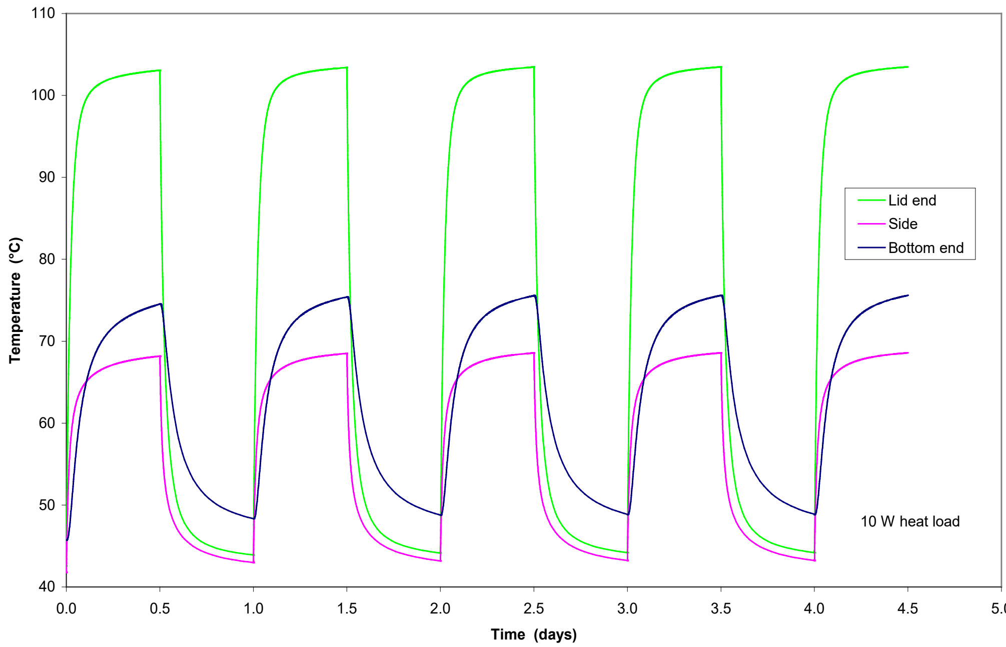

Figure 3-4 Predicted temperature on the Outside of the Keg During Normal Transport with Insolation

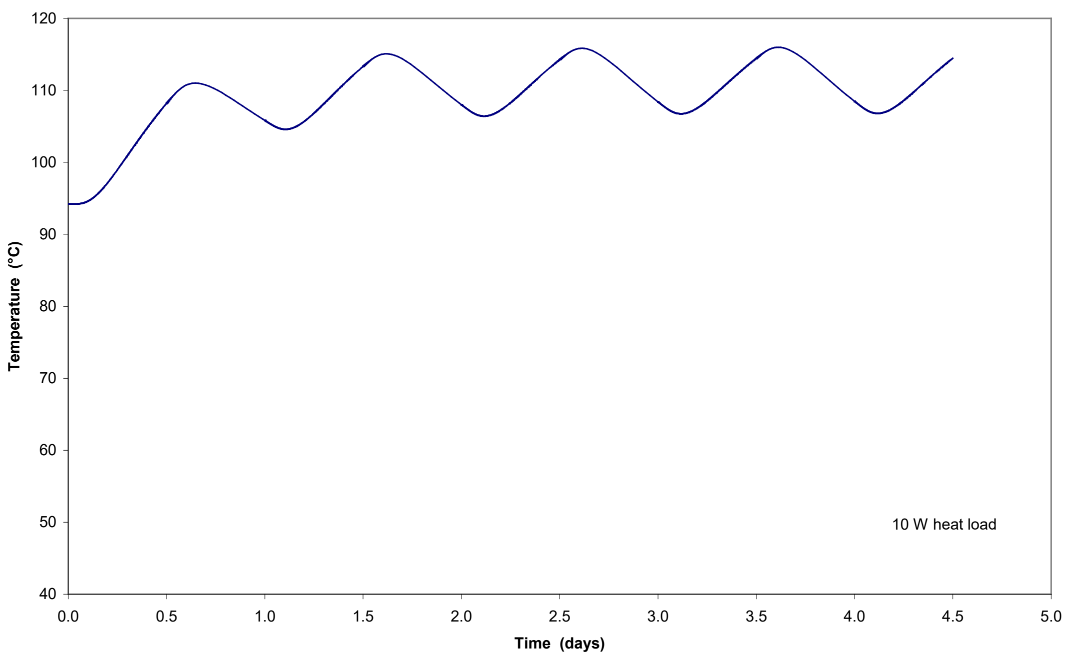

Figure 3-5 Predicted Temperature at the Containment vessel lid Seal During Normal Conditions of Transport with Insolation

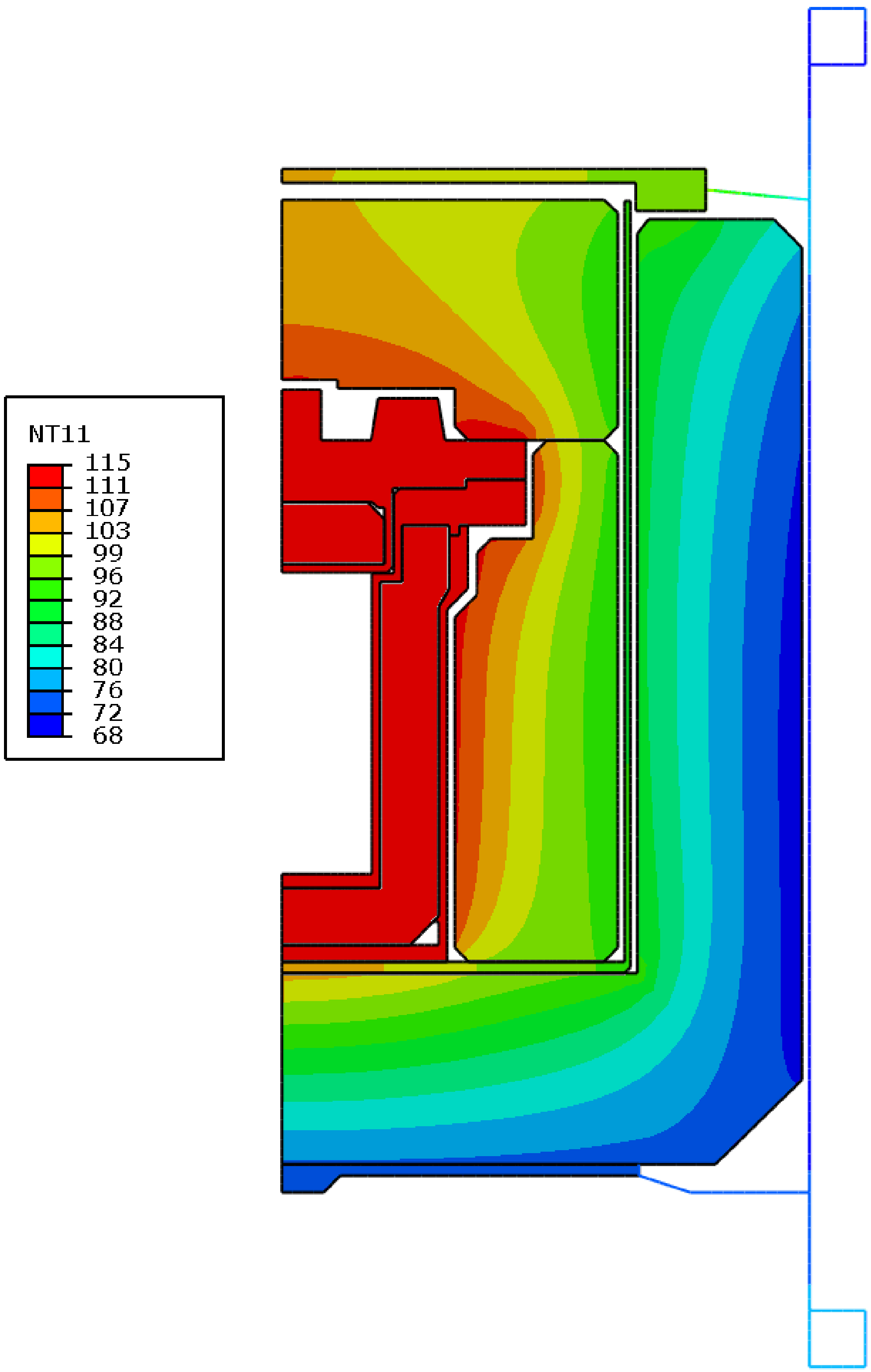

Figure 3-6 Predicted Temperature Profile under Normal Conditions of Transport With Solar Insolation

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 and the maximum temperature of the Shielding Insert and air within the CV is 128°C. Assuming the content were loaded at -40°C and a pressure of 1 bar abs, the pressure at the maximum temperature of the Shielding Insert, calculated according to Boyle's and Charles' Laws of 128°C, would be 1.72 bar (172kPa) gauge (see Calculation s Sheet CS 2009/08), 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 800ºC. Once the package reached 800ºC 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 800ºC. 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.

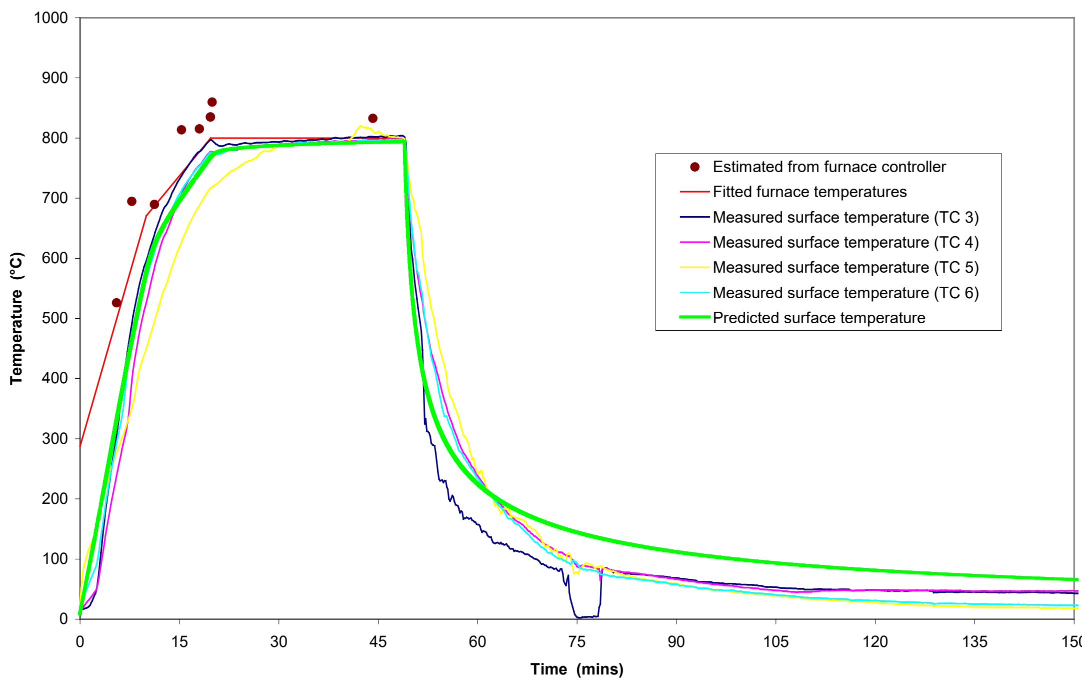

Figure 3-7 Furnace Temperature and External Surface Temperature in the Fire Test

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.

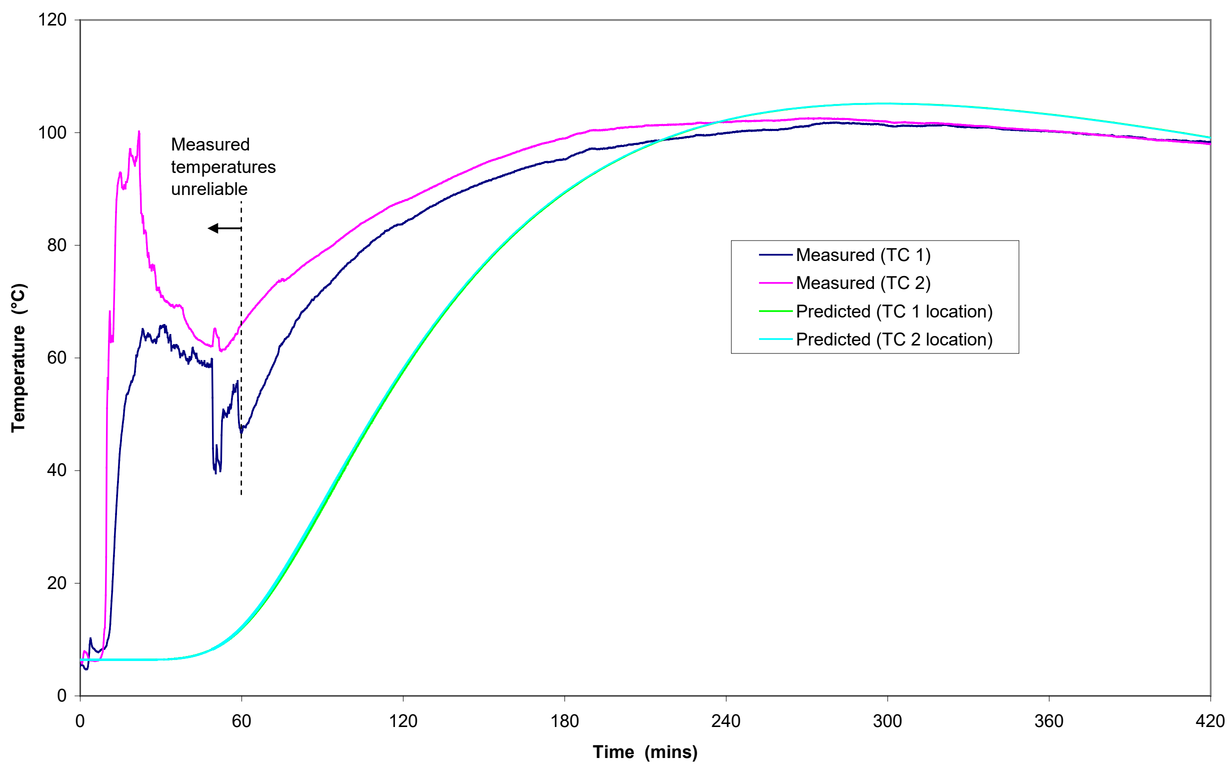

Figure 3-8 Comparison of Predicted and Measured Temperature of the Containment Vessel Lid in the Fire Test

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 38ºC 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.

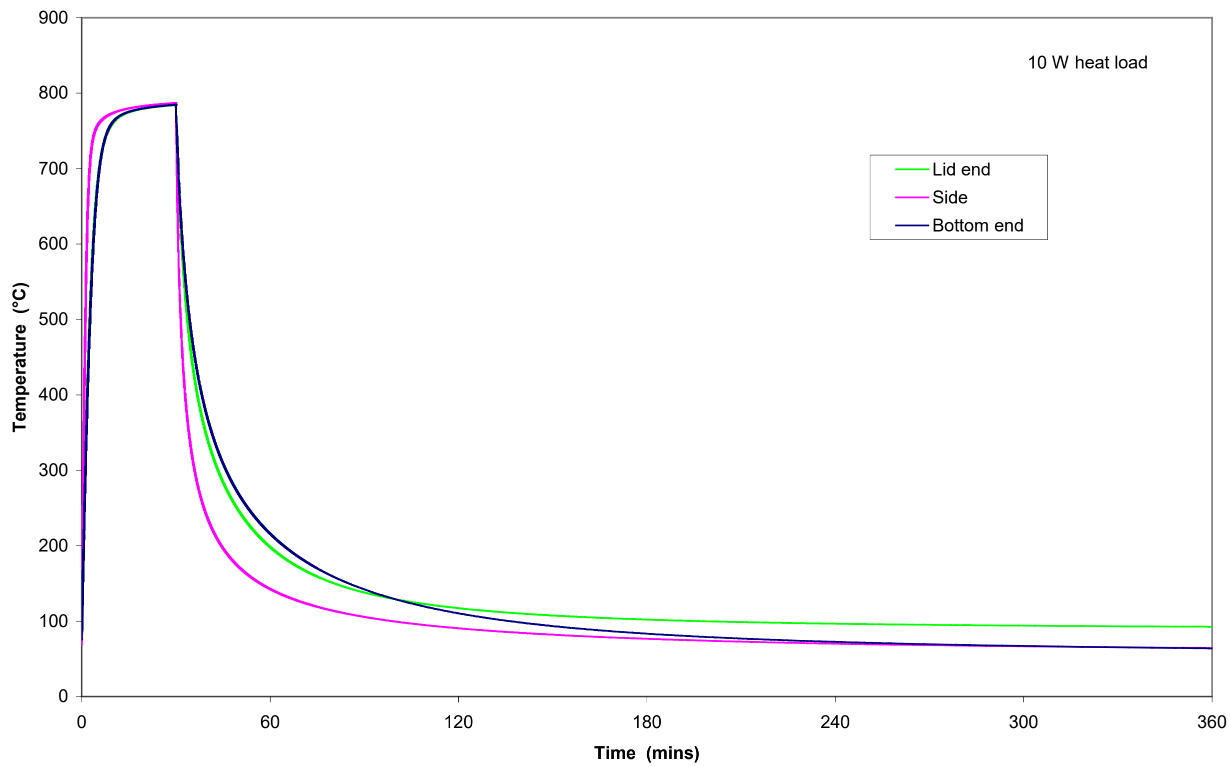

Figure 3-9 Predicted Temperature of the Outside of the Keg during the Fire Test

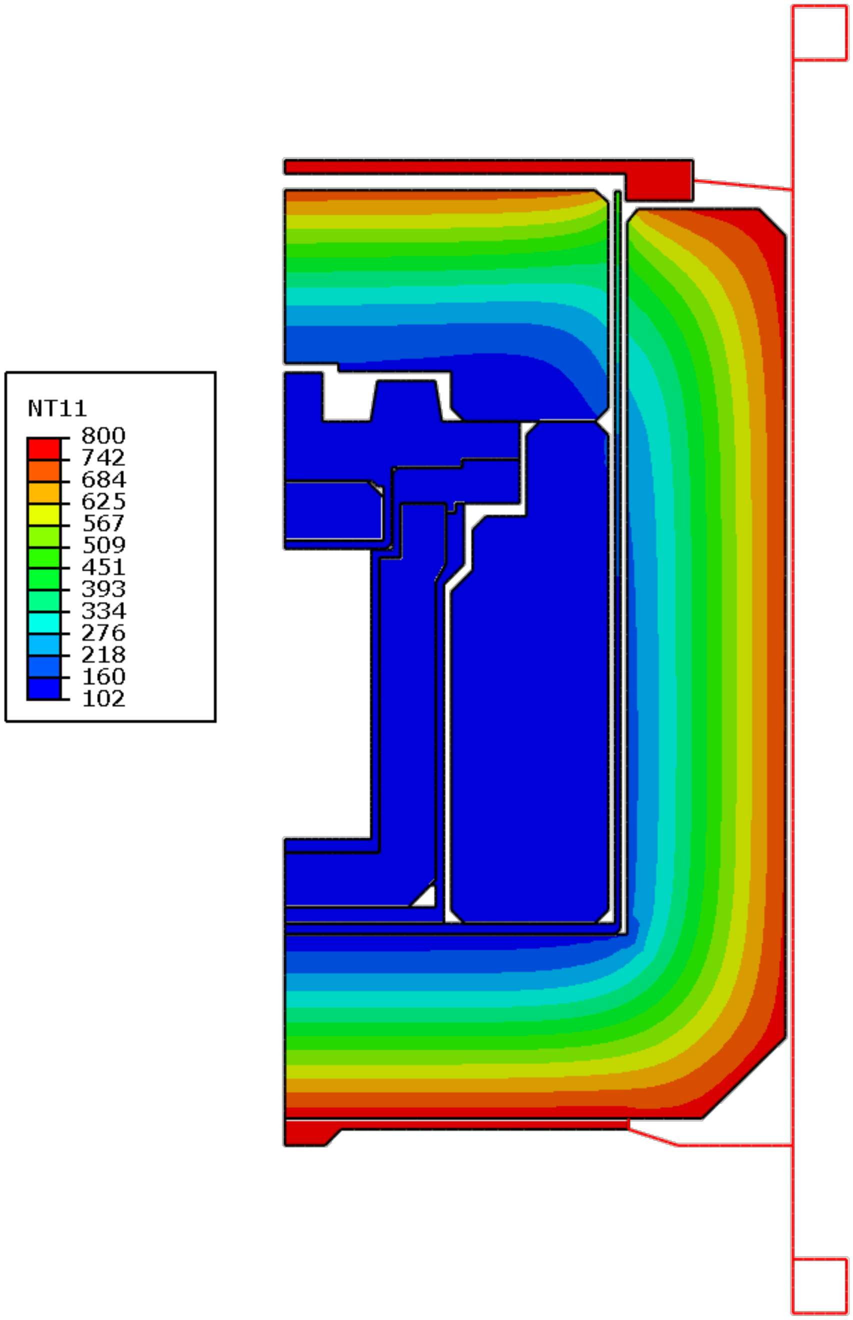

Figure 3-10 Predicted Temperature Profile at the end of the Heating Phase of the Fire Accident

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 252ºC. Figure 3-6 shows the maximum temperatures throughout the package under HAC.

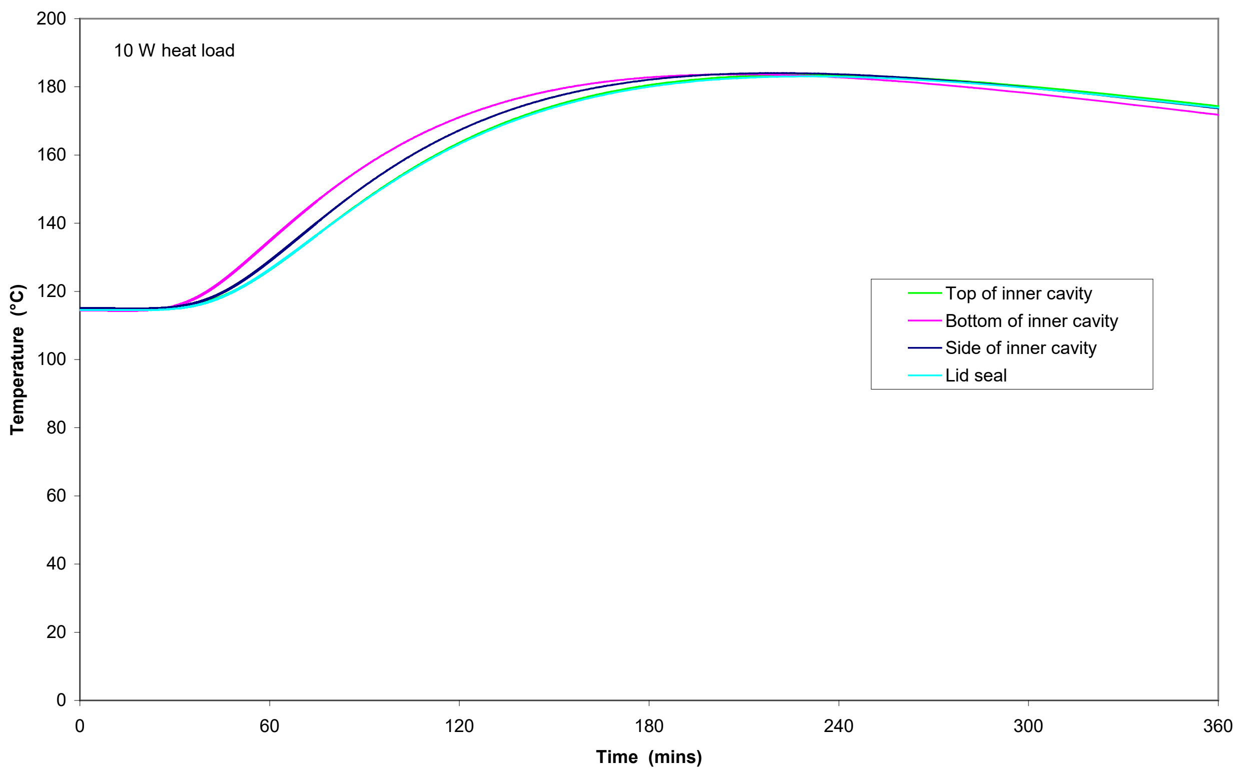

Figure 3-11 Predicted Temperature of the Containment Vessel during the Fire Test

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 184ºC and the maximum temperature of the Shielding Insert and air within the CV is 196ºC. Assuming the content were loaded at -40ºC and a pressure of 1 bar abs, the pressure at the maximum temperature of the Shielding Insert, calculated according to Boyle's and Charles' Laws of 196ºC, would be 2 bar (200 kPa) gauge (see Calculation Sheet CS 2009/08 in section 2.12.2), which is well within the design envelope.

For liquid contents emitting 5W, under HAC the maximum temperature of the CV is 162ºC (Section 3.1.3, Table 3-1). Assuming the content were loaded at -40ºC 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 162ºC 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. i

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

[3.1] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section II, Part D, 2001 Edition

[3.2] Design Manual for Structural Stainless Steel (Second edition), The Steel Construction Institute, Building series, Vol 3

[3.3] Edwards A.L, ‘For Computer Heat-Conduction Calculations a Compilation of Thermal Properties Data’, UCRL-50589, 1969

[3.4] Goodfellows data sheet, http://www.goodfellow.com/AntimonialLead.html

[3.5] The Equilibrium Diagram of the System Lead-Tin, London Institute of Metals, 1951

[3.6] CRC, Handbook of Chemistry and Physics, 75th Edition, 1994-1995 CRC Press

[3.7] Summary of the Physical Properties and Composition of Resin Bonded Cork, CTR 2001/11, Issue D, 2002

[3.8] Atomic Energy Technical Data Sheets – Properties of Substances in SI units, UDC 53.

[3.9] Touloukian & DeWitt, Thermal Radiative Properties – Metallic elements and alloys, Thermophysical properties of matter, Vol 7, Pub IFI/PLENUM, 1970

[3.10] Title 10, Code of Federal Regulations, Part 71, Office of the Federal Register, Washington, DC, 2009

[3.11] The Emissivity of Various Materials Commonly Encountered in Industry’, Land pyrometers Technical Note 101

[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
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
CTR 2021/22	3979A O-ring NCT Test Temperature Reduction - SARP Impact
CTR 2021/24	LS 3979A (3980) O-ring Seal Thermal Tests