CONTENTS

3 THERMAL EVALUATION

This section identifies the key thermal design features for the Safkeg-HS 3977A 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 were validated using the results of a steady state thermal test of a prototype Safkeg-HS 3977A package and the results of a 800ºC fire test carried out on a similar design the SAFKEG-LS 3979A. The test procedures, results and the FEA model are presented and discussed within this section.

From this work maximum operational temperatures of the package have been determined for the maximum heat load of the contents. These temperatures have been shown to be lower than the maximum design temperatures of the package components.

3.1 Description of Thermal Design

The Safkeg-HS 3977A is designed to transport a range of nuclides, with a maximum allowable heat output of 30 W for solids and gases and 5 W for liquids. 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-HS 3977A 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 depleted uranium 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^{o}C the fuse plug melts allowing pressure relief of the keg cavity.

The package does not have any mechanical cooling.

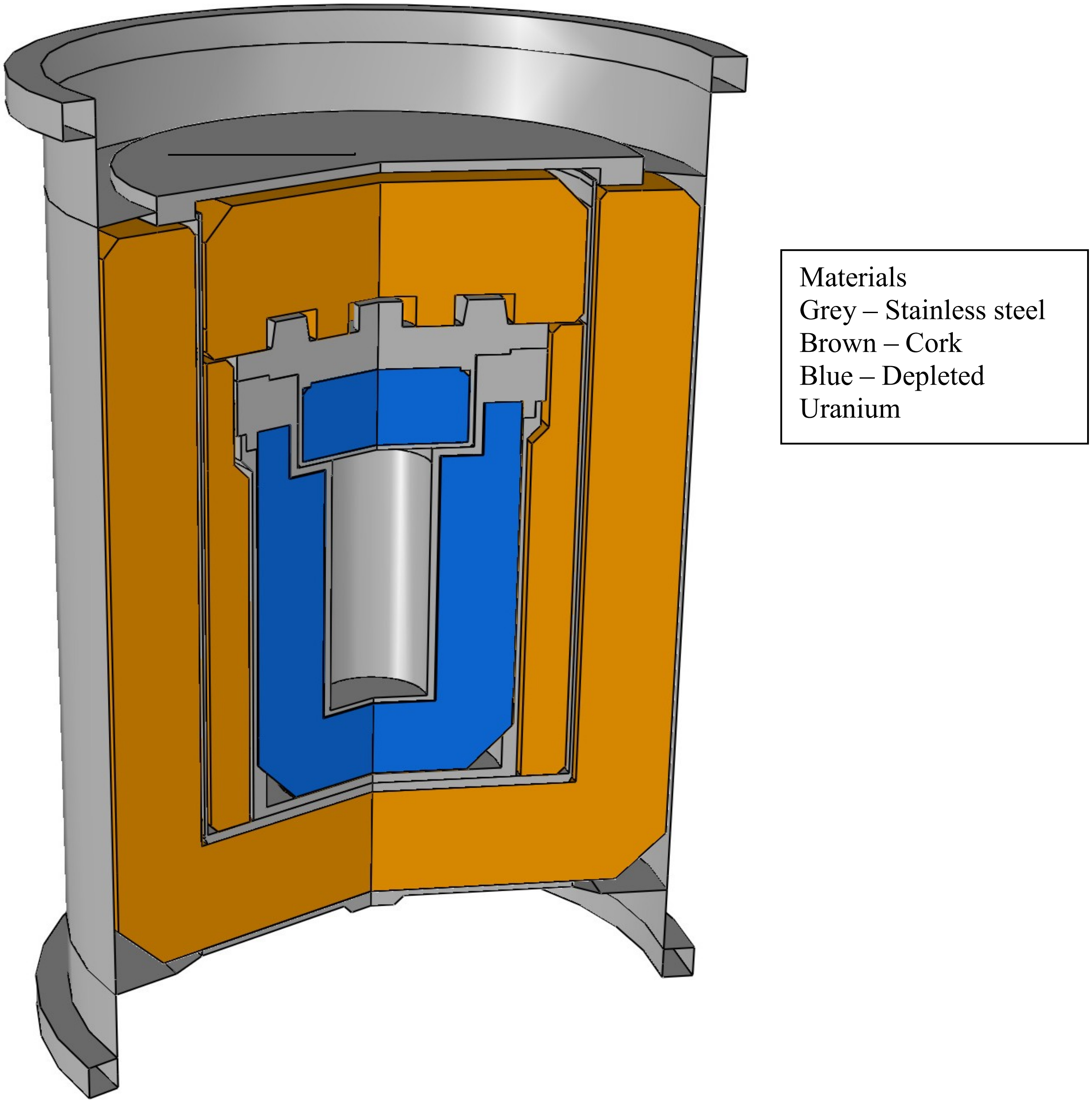

Figure 3-1 Thermal Design Properties

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

The contents decay heat is limited to a maximum of 30 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 AMEC/6335/001 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 30 Watts under NCT and HAC thermal conditions.

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

	Maximum Temperature under heat load (°C)		
Heat load (W)	0	5	30
NCT – no insolation	38.0	58.9	148.4
NCT – with insolation	58.8	78.1	163.2
HAC – with insolation	115.4	132.0	208.0

The maximum temperatures within the containment vessel are generated at 30W; therefore the temperatures reached at critical locations with this heat load were calculated in the AMEC 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 0 W, 5 W and 30 W has been determined in Calculation Sheet CS 2012-01 [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.

The package temperatures for Contents Type CT-6 (thorium target located at mid height of the CV cavity) would be bounded by those calculated for the higher maximum heat output of 30 W, as determined for the Inserts.

Table 3-2 Summary of Package Temperatures under NCT
(Ambient 38°C, with and without insolation)

Location	Maximum Temperature (°C)						Temperature Limit of component (°C)
	No insolation			With Insolation			
Internal Heat Load W	0	5	30	0	5	30	
Shielding Insert	38	60.9	158.4	58.8	80.1	173.2	427 (1)
Shielding Insert Liner	38	60.9	158.4	58.8	80.1	173.2	1650
Shielding Insert seal for 12x95 Tu, 31x114 Tu and 55x138 SS Inserts	38	60.9	158.4	58.8	80.1	173.2	204 (5)
Shielding Insert seal for 50x85 SS Insert	38	60.9	NA	58.8	80.1	NA	150 (7)
Containment vessel cavity	38	58.9	148.4	58.8	78.1	163.2	427 (1)
Silicone Sponge Rubber Disc	38	58.9	148.4	58.8	78.1	163.2	200 (6)
Containment vessel lid seal	38	56.2	135.0	59.5	76.4	151.1	205 (4)
Cork (2)	38	56.2	135.0	59.5	76.4	151.1	160 (3)
Keg lid	38	39.7	46.5	97.5	98.4	102.4	427 (1)
Keg bottom	38	41.5	56.8	69.9	72.0	84.5	427 (1)
Mid height on keg surface	38	39.8	46.8	65.4	66.4	71.2	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]
4. Viton GLT O-ring temperature limit for continuous operation
5. Silicon O-ring temperature limit for continuous operation

6. Manufacturers temperature limit for continuous operation

7. EPM/EPDM 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 AMEC 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 38ºC, with insolation)

Internal Heat Load W	0W		5W		30W		**Temperature Limit of component (ºC)**
Location	Max T (ºC)	Time After Fire Start (mins)	Max T (ºC)	Time After Fire Start (mins)	Max T (ºC)	Time After Fire Start (mins)	
Shielding Insert	115.4	210	134.0	210	218.0	180 (2)	427
Shielding Insert Liner	115.4	210	134.0	210	218.0	180 (2)	1650
Shielding Insert seal	115.4	210	134.0	210	218.0	180 (2)	250
Containment vessel cavity	115.4	210	132.0	210	208.0	180	1427
Silicone Sponge Rubber Disc	115.4	210	132.0	210	208.0	180	300
Containment vessel lid seal	115.3	254	130.1	244	196.3	210	205
Cork	787.4	30	787.6	30	788.2	30	N/A (1)
Depleted Uranium Shielding	115.3	210	130.3	210	198.2	180	1120
Keg lid	784.3	30	784.4	30	785.0	30	1427
Keg bottom	788.6	30	788.7	30	789.3	30	1427
Mid height on keg surface	786.6	30	786.6	30	786.1	30	1427

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

2 The inserts would reach a maximum temperature nominally at the same time as the peak in the CV temperature with possibly a small 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 kPa (bar) abs
MNOP	7 bar (700 kPa) gauge 8 bar (800 kPa) abs
HAC	10 bar (1,000 kPa) gauge 11 bar (1,100 kPa) 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, depleted uranium 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	

Table 3-5: Thermal Properties of Packaging Materials

Material	Property	Temperature (°C)	Value	Reference
		816	26.5 W/m/K	
	Density	-	7900 kg/m^3	[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	
		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	
Depleted Uranium	Conductivity	0	23.1 W/m/K	[3.3]
		400	32.5 W/m/K	[3.3]
	Density	-	18,650 kg/m^3	[3.4]
	Specific Heat	0	117.5 J/kg/K	[3.3]
		300	142.0 J/kg/K	
Cork	Conductivity	-	See Figure 3-2	[3.7]
	Density	-	290 kg/m3	[3.7]
	Specific Heat	-	1650 J/kg/K	[3.7]e

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, this package uses the same cork specification as the HS design. The test has then been simulated using the LS model in order to validate the model 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-HS 3977A package has also been simulated using the model. As with the LS design 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.

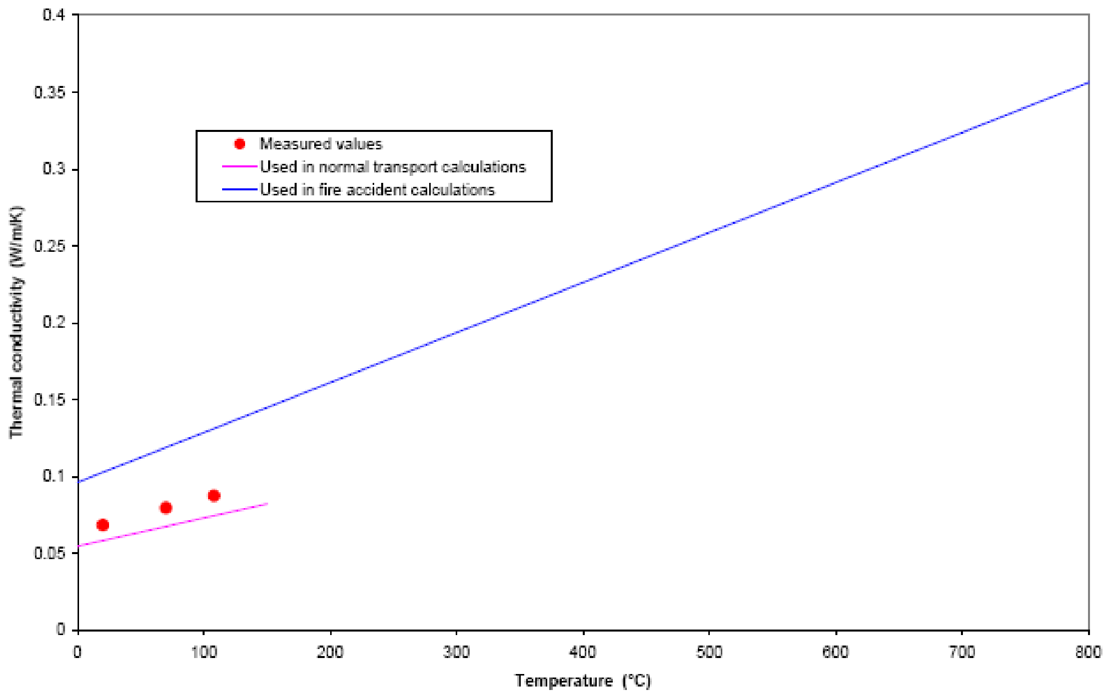

Figure 3-2 Thermal Conductivity of Cork

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 2010/02 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	[3.8]
	External surface – Heating test and NCT	0.25	[3.8]
	External surface – fire test	0.8	[3.9]
Cork	All conditions	0.95	[3.10]
Depleted Uranium	Internal surfaces (un-oxidised)	0.31	

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 Viton GLT.

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 102ºC for continuous operations and 788ºC for short term operations. The upper temperature reached by the stainless steel in the containment vessel is < 163ºC for continuous operations and 210ºC 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 depleted uranium shielding reaches a maximum temperature of 198ºC during HAC conditions. The depleted uranium does not provide any structural function therefore it is limited by its melting point of 1130ºC.

The cork is unaffected by temperatures up to 160ºC which is higher than the maximum temperature for the cork packing under NCT where cork temperatures may reach 151ºC for athin layer of the cork adjacent to the CV. Under HAC conditions the cork reaches a

maximum temperature of 788ºC. 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 151°C for continuous operation (NCT conditions), and 196°C for short term operation (HAC conditions). These temperatures are within the allowable range of the O-ring material properties.

3.3 Thermal Evaluation under Normal Conditions of Transport

The Safkeg-HS 3977A 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 carried out on the 3977A package with a standard containment vessel lid (simulating normal conditions of transport) and a furnace test (simulating the fire accident), carried out on a similar package 3979A.

NCT Thermal Test

A 30 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 three thermocouples on the containment vessel surface, one on the top cork, 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 thermocouples attached to the surface of the package and a hand held digital thermometer. 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 thermocouples attached to the surface of the package and a hand held digital thermometer.

Thermal Model

The analytical model is described in detail the Report AMEC/6335/001 (Section 3.5.2). The model used was that of the standard lid containment vessel. This bounds that of the split lid because the 0.5 mm air gap added in the lid of the CV would reduce the temperature of the O-rings and the CV closure. The temperature of the CV plug would increase however the thermal model assumed 5W would be applied over the whole cavity of the CV, in reality the Mo-99 contents would be at the bottom of the insert therefore the top of the insert and the plug would be cooler that determined in the thermal model, plus the DU and stainless steel have melting points that far exceed the possible temperature of the plug.

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 AMEC/6335/001 (Section 3.5.2).

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 42ºC which is reached on the keg lid, the base of the keg reaches 45ºC however this surface is not accessible and therefore not considered. This demonstrates that the package is capable of fulfilling the requirements of 71.43 (g) as the accessible surface temperature is less than 50ºC with maximum contents heat load of 30W.

The package temperatures have also been modeled under normal conditions of transport and subject to solar insolation as described in the report AMEC/6335/001 (Section 3.5.2).

Figure 3-3 shows the transient temperature at various locations on the outer surface of the keg with a 30W 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 102°C. Figure 3-4 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 151°C. Figure 3-5 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 thermal margin with the smallest being the containment seal with a thermal margin at 4ºC.

For the NCT cold evaluation the package is assumed to be in an ambient of -40ºC, 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 -40ºC. This temperature is within the allowable service limits for all the components.

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

NCT Operating Condition	CV
Assumed Max. Temperature	ºC
Max. Pressure	7 bar (700kPa) gauge 8.0 bar (800kPa) abs
Min. Temperature	-40ºC
Min. Pressure	-1 bar (-100kPa) gauge 0 kPa (0 bar) abs

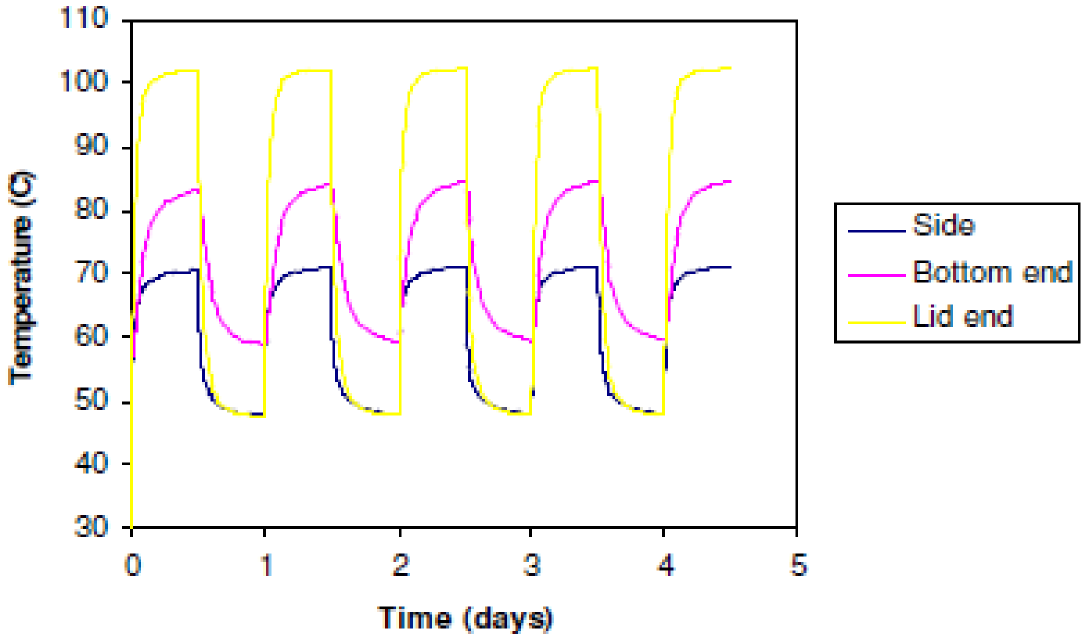

Figure 3-3 Predicted temperature on the Outside of the Keg During Normal Transport with Insolation

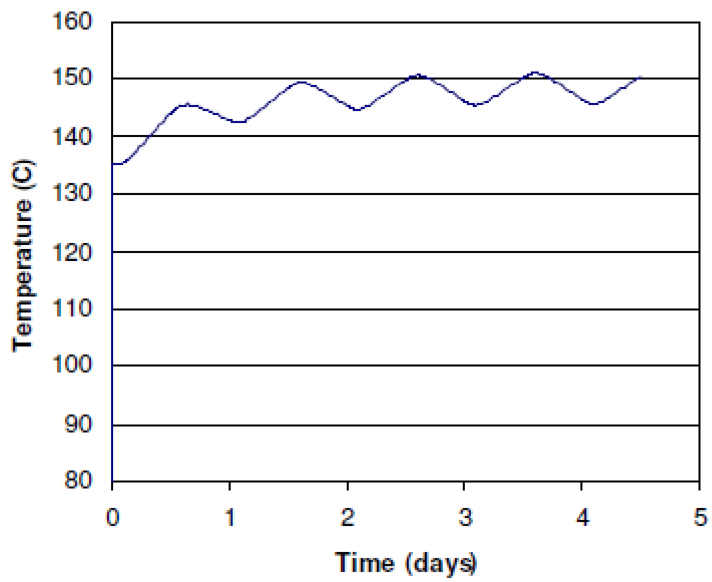

Figure 3-4 Predicted Temperature at the Containment vessel lid Seal During Normal Conditions of Transport with Insolation

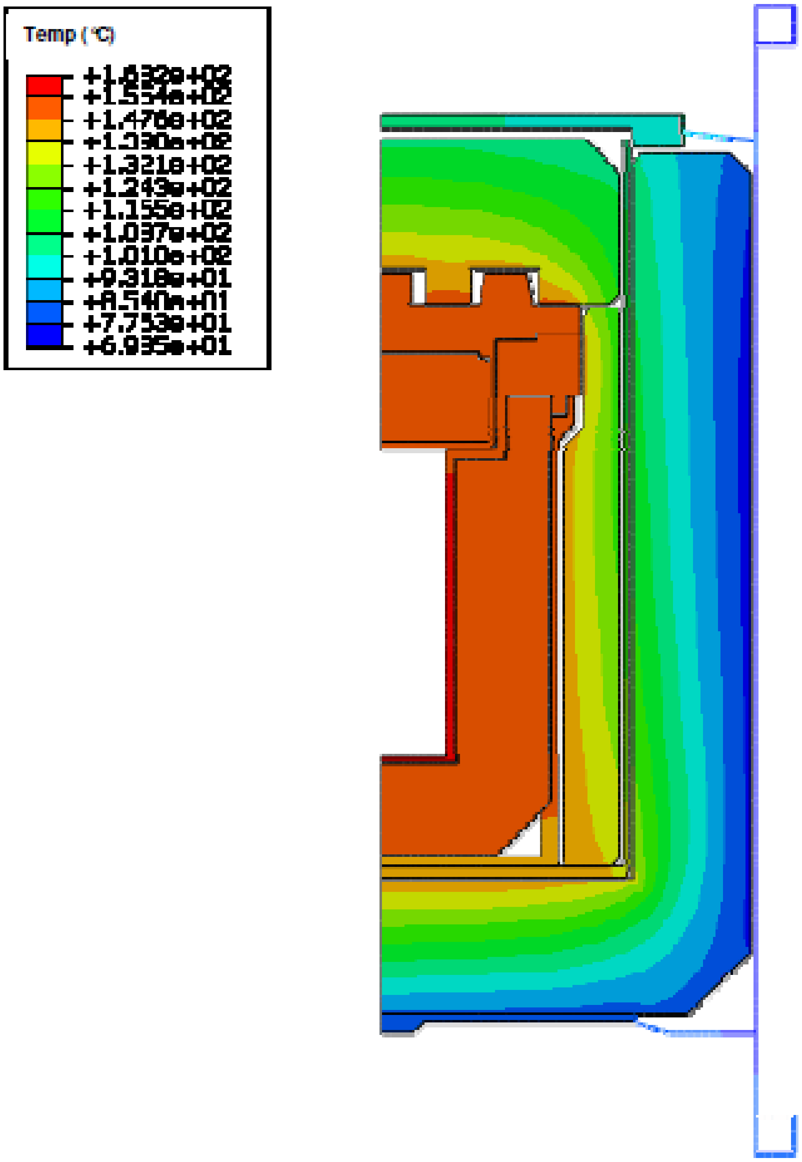

Figure 3-5 Predicted Temperature Profile under Normal Conditions of Transport with Solar Insolation and 30W heat load

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

The MNOP is 7 bar (700 kPa) gauge.

For solid contents emitting 30W, under NCT the maximum temperature of the CV is 163°C and the maximum temperature of the Shielding Insert and air within the CV is 173°C. Assuming the content were loaded at 20°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, would be 1.63 bar (163 kPa) gauge (see Calculation Sheet CS 2012/02),which is well within the design envelope.

With regards to the liquid content the maximum normal operating pressure is calculated using the maximum temperature during NCT, the free volume of the containment vessel cavity and product containers, and all possible sources of gas generation and gases that are present on loading the containment vessel.

For I-131 the maximum temperature of the contents is 80°C (Section 3.1.3, Table 3-1). The maximum free volume is 216 cm^3 when 2 glass vials containing a maximum of 10 ml each of solution are loaded into the 3987 insert. Pressure will build up in the CV due to heating of the air present in the CV on loading, Xe-131 generation, saturated vapour pressure and radiolytic decomposition over a 10 day period for the liquid. Using the free volume, temperature and considering all the pressure rise mechanisms, calculations were performed and are presented in CS 2017/02 (section 3.5.2). These calculations demonstrate that a maximum pressure of 2.61 barg is reached for the I-131 contents. This pressure is below the bounding design pressure of 7 barg (8 bara).

For Mo-99 the maximum temperature of the contents within the insert is 84.56°C as calculated in CS 2016/28 (section 3.5.2). This temperature assumes a constant 5W heating over the course of a year, however in reality the thermal power of the contents decreases over time. The maximum free volume of the containment vessel is 233 cm^3. This corresponds to the free volume inside the insert, product bottle, the free volume that surrounds the insert and the volume around the containment vessel lid up to the seals.

Pressure will build up in the CV via radiolysis, heating of the air in the CV and saturated vapour pressure. The Mo-99 contents generate hydrogen due to radiolysis. The Mo-99 producer has carried out experiments, to determine the radiolytic gas generation of the Mo-99 solution contained in the stainless steel bottles described in section 1 of this SAR. Using this information and taking into account all these mechanisms the highest pressure was calculated in CS 2016/31 (section 3.5.2), this was 5.97 barg for a solution with an activity of 60 Ci/ml and a dispensed product volume of 16.667 ml. This pressure is below the bounding maximum pressure for NCT operating conditions.

For CT-6 (Thorium Target) Calculation CS 2019/02 shows that the pressure increase that could arise from gas production due to radiolysis of moisture in the CV would be 0.021 bar which is insignificant.The bounding temperatures and pressures for the package are as follows.

NCT Operating Condition	CV
Assumed Max. Temperature	160°C
Max. Pressure	800kPa (8.0 bar) abs
Min. Temperature	-40°C
Min. Pressure	0 kPa (0 bar) abs

The producer of the Mo-99 performed mass spectrometer measurements of the gas samples obtained during the radiolytic gas generation calculations. Of the 2 samples tested the results were 1.8% and 0.8% hydrogen by volume of the pure evolved gas. This is an average of 1.3%, with a 2σ uncertainty of 1.4%. So the concentration of hydrogen in the pure evolved radiolysis product is conservatively estimated to be 2.7% by volume. This is well below 5% by volume and therefore does not constitute a risk of flammability or ignition.

The hydrogen generation calculations for the I-131 contents for a shipment time of 10 days indicate the hydrogen concentration is 26%. Under normal conditions of transport (NCT) all hydrogen will be trapped in the product container within the insert, and no source for ignition exists. If somehow the product container fails, and the hydrogen escaped into the insert, and then the insert were to leak as well, into the containment vessel, and somehow ignition were to occur, the total energy release would be less than 966 Joules (231 calories).

The energy content of combustion of evolved hydrogen is negligible compared to the heating of the cask from the decay of I-131. For example, the decay heating rate of 200 Ci of I-131 was previously calculated to be 0.656 watts or 0.656 J/sec which would release 966 Joules of energy in less than one-half hour. Thus, the heating created by ignition of all of the hydrogen generated over 10 days would be negligible compared to the heating of the package by the decay of I-131.

These calculations and experiments indicate that hydrogen ignition in the case of I-131 liquid contents is not a credible source of risk to the public, see section 3.5.2.

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 30 W. All components are at their maximum temperatures as shown in Table 3-2. 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.

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 and validated against a fire test carried out on a prototype Safkeg-LS 3979A package. The model and analysis used is described in detail in section 5 of the Report SERCO/TAS/5388/002 (Section 3.5.2).

3.4.3 Maximum Temperatures and Pressure

The maximum temperatures experienced by the components of the Safkeg-HS 3977A 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 3-6 shows the predicted temperature on the exterior surface of the keg. 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

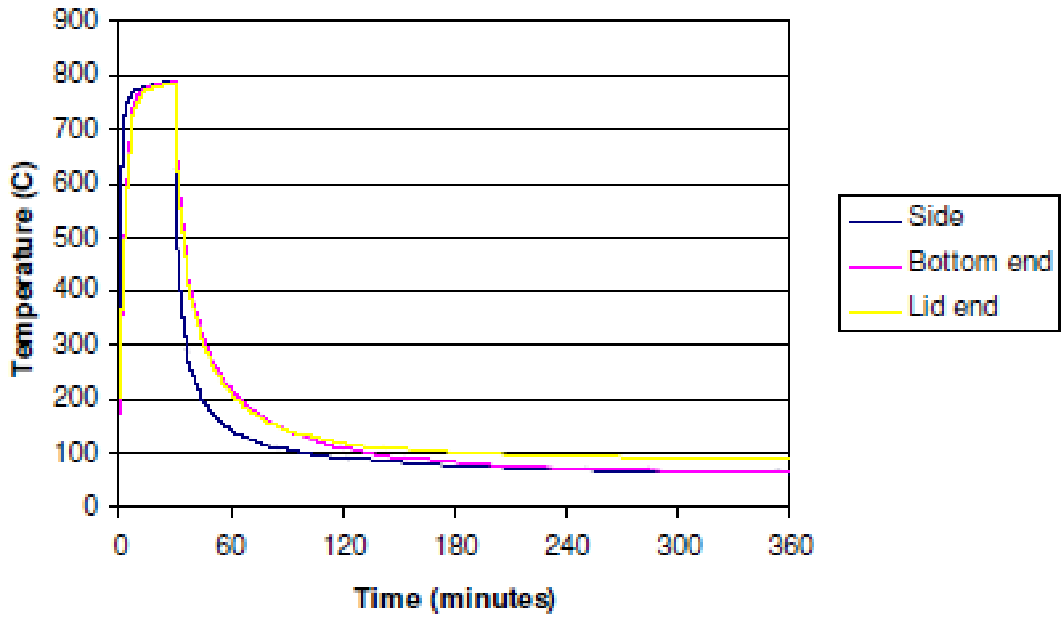

Figure 20 – Predicted Temperature on the Outside of the Keg during the Fire Accident – Internal Heat Load of 30W

Figure 3-6 Predicted Temperature of the Outside of the Keg during the Fire Test and 30W heat load

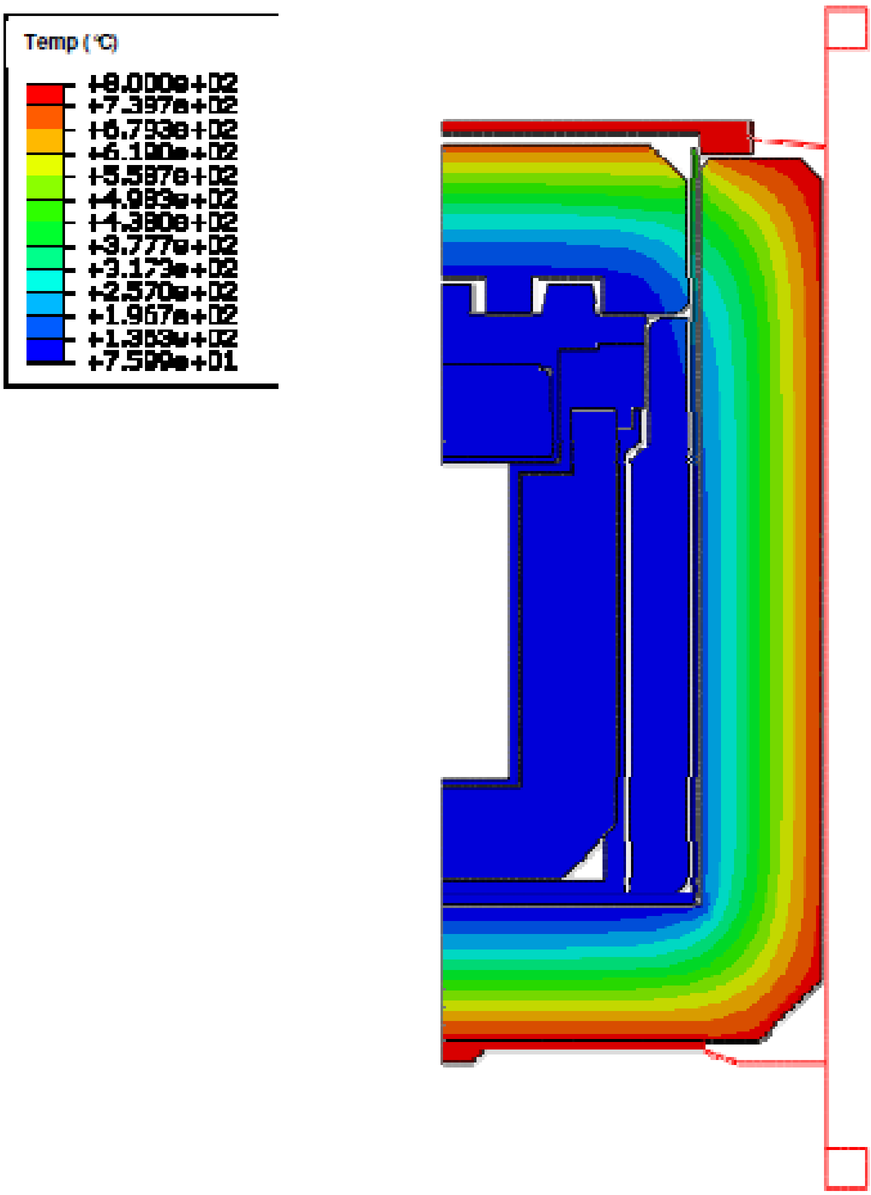

Figure 3-7 Predicted Temperature Profile at the end of the Heating Phase of the Fire Accident and a 30 W heat load

Figure 3-8 shows the predicted temperature of the inner containment vessel seal during and after the thermal test. The lid seal reaches a maximum temperature of 192°C after 3 ½ hours. A similar maximum temperature is experienced by the depleted uranium shielding this temperature is well below its melting point of 1130ºC.

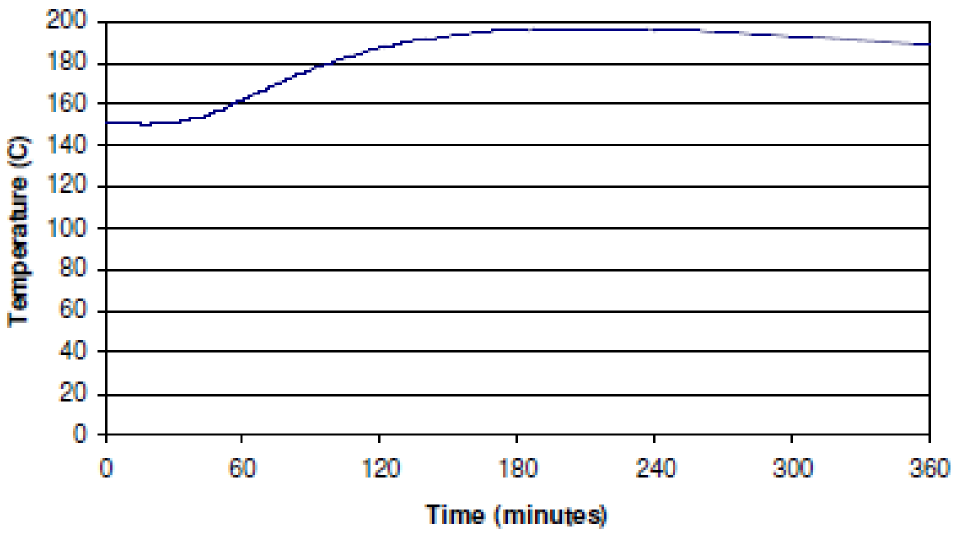

Figure 21 – Predicted Temperature of the Containment Vessel Lid Seal during the Fire Accident – Internal Heat Load of 30W

Figure 3-8 Predicted Temperature of the Containment Vessel Lid Seal during the Fire Test with a 30 W source

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

For solid contents emitting 30W, under HAC the maximum temperature of the CV is 208ºC and the maximum temperature of the Shielding Insert and air within the CV is 218ºC. Assuming the content were loaded at 20ºC 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, would be 1.8 bar (180 kPa) gauge (see Calculation Sheet CS 2012/02 in section 2.12.2), which is well within the design envelope.

For I-131 liquid contents emitting 5W, under HAC the maximum temperature of the CV is 132ºC and the maximum temperature of the insert is 134 ºC (Section 3.1.3, Table 3-1). Assuming the pressure at NCT is calculated as the maximum of 2.61 barg, the pressure at the maximum temperature of the CV, calculated according to Boyle's and Charles' Laws, would be 3.01 bar gauge. However, the vapour pressure of the liquid contents (the liquid contents are aqueous) would be 2 bar gauge (from steam tables). Therefore the maximum pressure within the CV would be 5.01 bar gauge which is well within the design envelope (CS 2017/02, Section 3.5.2).

For Mo-99 liquid contents emitting 5W, under HAC the maximum temperature of the CV is 132ºC and the maximum temperature of the contents is 143.82ºC (CS 2016/28 section 3.5.2). Assuming the pressure at NCT is calculated as the maximum of 5.37 barg, the pressure at the maximum temperature of the contents, calculated according to Boyle's and Charles' Laws, would be 6.26 bar gauge. However, the vapour pressure of the liquid contents (the liquid contents are aqueous) would be 3.2 bar gauge (from steam tables). Therefore the maximum pressure within the CV would be 9.46 bar gauge (CS 2016/31, section 3.5.2) which is within the design envelope provided below. The temperatures reached are within the bounding conditions for the package which are as follows:

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

[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] Croft Associates Ltd, Effects of Temperature on Resin Bonded Cork, TR 97/03/01.

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

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

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

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

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

[3.13] 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
AMEC/6335/001	Thermal Analysis of the SAFKEG HS Design
CS 2012/01	SAFKEG-HS 3977A – Maximum temperature of CV inserts
CS 2016/27	Temperature of Mo-99 Contents in the HS Package
CS 2016/31	Maximum Pressure in Containment Vessel 3978 Under NCT and HAC
CS 2017/02	Maximum Pressure in Containment Vessel 3978 Under NCT and HAC for I-131 Contents
CS 2019-02	Safkeg-HS - Gas generated by radiolysis of moisture in the air
ETR 426	Hydrogen Generation Analysis – MURR Technical Note
ETR 427	Analysis Of The Possibility Of, And Consequences From, Hydrogen Deflagration And Detonation Resulting From Radiolysis-Produced Hydrogen In An Iodine-131 Radiopharmaceutical Solution, MURR Technical Note
ETR 428	Additional Contents Request for Croft Packaging, MURR, 19th July 2016, MURR Technical Note
ETR 429	Radiolytic Gas Formation in Mallinckrodt Produced Mo-99 Solutions, Mallinckrodt Technical Report