Thermal Analysis of the R7021 Radioactive Materials Transport Container at 3074W Internal Heat Load

Report R7410/1.1

July 2010

Thermal Analysis of the R7021 Radioactive Materials Transport Container at 3074W Internal Heat Load

prepared for

REVISS Services (UK) Ltd

Dr M. Beiler
FTT Technology CC

Summary

This report extends a previous study of the R7021 transport container [2]*. It presents a thermal analysis of the container under IAEA normal and accident conditions of transport with an internal heat load of 3074W. Normal conditions was modelled as an ambient temperature of 38^{o}C and solar radiation from the top and sides. Accident conditions modelled an environment simulating an 800^{o}C furnace test with a forced updraft around the container. This heating phase lasted for thirty minutes and was followed by natural cooling in the normal conditions environment. The container was modelled upright for normal conditions and then inverted, with drop test damage, for accident conditions as that had previously been shown to generate the highest shielding temperature. The radioactive contents were modelled separately in each instance using the maximum cavity wall temperature.*

Contents

1 Purpose and Scope

The purpose of this report is to demonstrate the thermal performance of the R7021 container under IAEA normal and accident conditions of transport with an internal heat load of 3074W.

2 R7021 Description and Specification

The R7021 transport container comprises an upright, cylindrical stainless steel flask mounted on a carbon steel pallet [1]. The flask has a central cavity holding the source capsules and a removable closure plug at the top. Lead surrounds the cavity. Voids in the flask corners and at the base are filled with ceramic fibre insulation. Vertical fins are fitted to the cylindrical flask surface. A cylindrical shield, the jacket, surrounds the flask. A second shield is mounted on top of the flask. The jacket and parts of the top shield are filled with ceramic fibre insulation. A simple screen is mounted between the jacket and the top shield.

3 Modelling

The CFD code Ansys CFD was used to model the heat transfer and gas flow processes involved. Ansys CFD is a leading, general purpose CFD code suitable to solve fluid flow, thermal radiation and heat transfer problems.

The model comprises different types of zones. The flask and shields comprise solid heat conducting regions and solid heat conducting and heat generating regions. Regions surrounding the transport container were modelled as gas flow regions with thermal radiation. The voids of the top shield were modelled as gas regions with radiation heat transfer. Natural convection inside the voids was neglected. The screen was modelled as an isotropic porous region with similar pressure loss characteristics. The energy equation was solved for solid regions. Continuity, momentum, turbulence and energy equations were solved for the fluid flow domain. A Monte Carlo radiation model was used to calculate thermal radiation between free surfaces emitting, absorbing and reflecting long wavelength radiation.

Steady state temperatures depend mainly on natural convection therefore a flow domain enclosed the container. The container was modelled on a solid floor and exposed to natural convection at the required ambient air temperature. A heat flux was applied to simulate insolation. Free air flow was allowed across the flow domain so that the floor was free to dissipate heat from insolation. For accident conditions the container was modelled in an 800^{o}C furnace with an 800^{o}C forced updraught to simulate the air movement associated with a fire. All salient modelling parameters are presented in Appendix 2.

Continuous heat production was modelled in the cavity wall and lead shielding. Heat from the container contents was modelled as a heat flux applied to the cavity wall. The rate of heat production in each component or region is shown in the following table, with Q_t the total heat production.

A thermal contact resistance was specified between lead and stainless steel surfaces. The appropriate value was obtained from benchmarking simulations. The pallet is in thermal contact with the flask. The top shield rests on the flask, but to model the intermittent contact between the adjacent surfaces of the top shield and flask, a contact resistance equivalent to a 0.1mm gap was modelled. The thin volume between the side and base of the closure and the flask was specified as a non-convective air layer.

Table 1: Internal Heat Load Distribution.

Location	Energy deposition [W]
Cavity wall heat flux	$0.258Q_t$
Cavity wall	$0.11Q_t$
First 12mm radial lead	$0.397Q_t$
Remaining radial lead	$0.235Q_t$
Total	$1.0Q_t$

The container model does not include the cavity contents; a separate model was used to model the transport processes inside the cavity. The container model provided the cavity wall temperature, which is required to define the cavity model. The cavity model comprises the sources and basket.

Source temperatures at accident conditions were calculated using the peak cavity wall temperature.

3.1 Benchmarking

This study revisited benchmarking as the previously predicted flask surface temperatures were generally higher than the measured values. The benchmark model incorporated a 3mm gap between closure and flask to model the gap provided for the thermocouple leads to exit. The total heat load of Q_t =2362W was applied as shown in Table 1.

The following parameter changes were found to give improved results and were adopted:

1. The emissivity of flask external surfaces was increased from 0.45 to 0.55
2. The two-equation k-ω based shear stress transport turbulence model was replaced with the standard two-equation k-ω based turbulence model.

The reduction in flask surface temperatures resulted in the contact coefficient at lead-stainless steel interfaces having to be reduced from 400W/m^{2}K to 330W/m^{2}K to provide the required mid-height cavity wall temperature.

3.2 Normal Conditions Analysis

The normal conditions analyses determine equilibrium temperature distribution throughout the container and contents under IAEA normal conditions of transport. The model described in section 3.1 was employed to predict temperatures at normal conditions, but the emissivity of external painted carbon steel surfaces and the insulation conductivity were adjusted to the values from a previous sensitivity study, which resulted in the highest temperatures[2]. Container temperatures were calculated with and without solar insolation. An ambient air temperature of 38^{o}C was specified.

The basket was loaded with fourteen capsules, increased from twelve in the previous study in proportion to the increased heat load. The capsules were evenly distributed around the basket (positions 1, 3, 4, 6, 8, 10, 11, 13, 15, 16, 18, 20, 22 & 23) which was then enclosed in an air filled, cylindrical domain representing the cavity wall.

3.3 Accident Conditions Analysis

The model was used to predict container temperatures during the transient period simulating a fire under IAEA accident conditions of transport. The container was modelled in a furnace at a temperature of 800^{o}C for thirty minutes. An upward air flow, which resulted in peak flow velocity surrounding the container of not less than 10m/s, was applied to the enclosing flow domain. The temperature of both inflow and surrounding vertical walls was 800^{o}C. The emissivity of external surfaces was changed to a value of 0.8 to represent blackened surfaces. The wall emissivity was specified as 0.9. Insolation heat fluxes were excluded. The steady state solution for normal transport conditions provided the initial condition temperatures of the container. A cooling period at normal conditions followed the heating phase. The container was modelled in air, allowing for free convection cooling at an ambient air temperature of 38°C. The normal conditions insolation heat fluxes were re-applied during the cooling phase.

The container was modelled inverted throughout and included a representation of the drop test damage from the inverted drop tests as this had been determined by the previous report to generate the highest shielding temperature. Damage, as before, was modelled as a 150mm x 150mm hole in the center of the top shield outer plate and with the cones completely removed.

The basket and contents were modelled inverted in an air filled, cylindrical domain representing the cavity at its peak temperature.

4 Results

4.1 Benchmarking

Table 2 shows the measured temperatures, the previously predicted temperatures and the temperatures of the revised benchmark model. It can be seen that the revised model provides a better correlation. In most locations temperature variance is reduced and nowhere has it increased. The deviation at flask surface mid-height between the fins (L) decreased from 8°C to 4°C. The deviation at the lifting fin (H) decreased from 5°C to 0°C.

Table 2: Measured and Calculated Container Temperatures.

Identity	Location	Temperature [°C]		
		Measurements [3]	Previous Results [2]	New Results
A1	Cavity wall (50mm below top)	151 / 196*	153	152
B1	Cavity wall (mid-height)	155 / 155 / 154 / 270*	156	155
C1	Cavity wall (50mm above base)	149	152	150
F	Closure and vent seal	112 / 116	114	111
G	Lifting fin (100mm from top edge, 75mm from outer edge)	49	67	64
H	Lifting fin (40mm from top edge, 55mm from outer edge)	55	60	55
I	Lifting fin (135mm from top edge, 35mm from outer edge)	61 / 59	68	65
L	Flask wall (mid-height, midway between fins)	112 / 111 / 112 / 113	120	116
N1	Drain point (centre of cylinder, outer surface)	83	101	97
P	Flask foot (top surface, 30mm from outer edge)	27 / 27	33	32
R	Jacket (top edge)	36 / 36	39	39
S	Jacket (inner surface, 40mm from top edge)	43 / 40	46	46
T	Top shield (mid height vertical face)	35 / 36	39	38
U	Top shield (half way across horizontal face)	35 / 35	38	38
V	Top shield (top surface centre)	40	37	39
T_a	Ambient	21	21	21

*The highest measurement in both A1 and B1 were ignored as they were inconsistent with the other measurements.

4.2 Normal Conditions

Table 3 presents steady state temperatures for normal conditions without and with insolation. The temperature distribution on a vertical section is shown in Figure A1.2, and Figure A1.3. illustrates the source temperature distribution.

Table 3: Normal Conditions Temperatures [^oC].

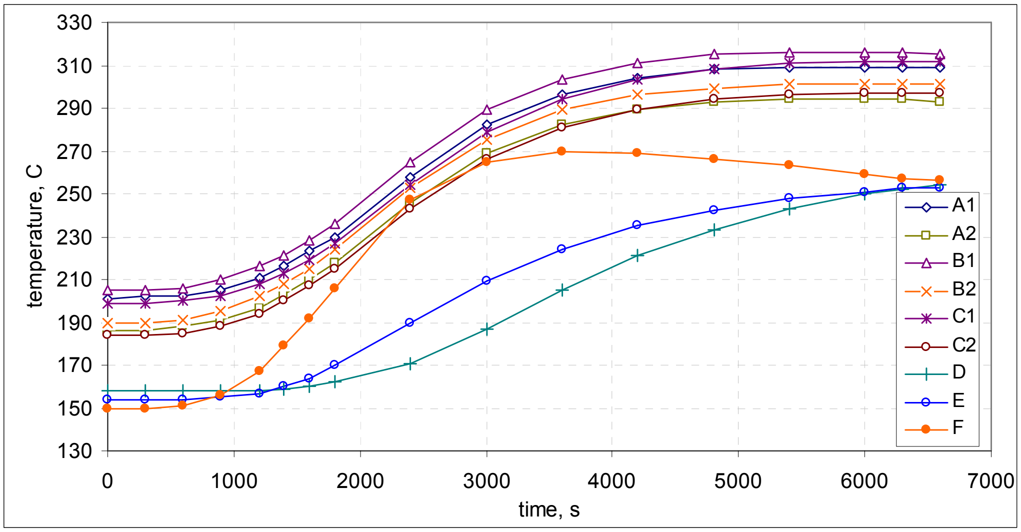
Location	Location	Without insolation	With insolation
Tc_{max}	Capsule wall	409	411
A1	Cavity wall (50mm below top)	196	201
A2	Lead adjacent to A1	181	186
B1	Cavity wall (mid-height)	201	205
B2	Lead adjacent to B1	185	190
C1	Cavity wall (50mm above base)	194	199
C2	Lead adjacent to C1	179	184
D	Lead (closure base centre)	151	158
E	Lead (closure top centre)	146	154
F	Closure and vent seal	141	150
H	Lifting fin (40mm from top edge, 55mm from outer edge)	79	93
J	Lead (top chamfer top corner)	150	157
K	Lead (top chamfer bottom corner)	153	158
L	Flask wall (mid-height, midway between fins)	149	153
M	Lead (bottom chamfer top corner)	150	154
N2	Drain seal	148	152
O	Lead (bottom chamfer bottom corner)	157	161
P	Flask foot (top surface, 30mm from outer edge)	50	67
Q	Jacket (mid height outer surface)	51	64
V	Top shield (top surface centre)	57	100
W	Maximum lead temperature	186	191
T_a	Ambient	38	38

4.3 Accident Conditions

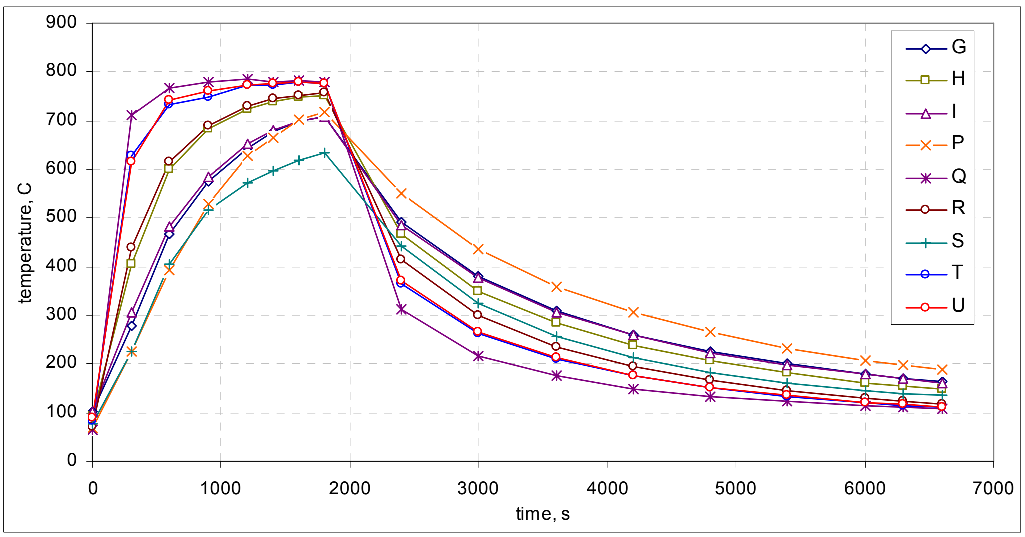
Table 5 shows the calculated peak temperatures for the damaged inverted container. The temperatures histories during heating and subsequent cooling at various locations are shown in Graph 4 to 6. The peak lead temperature is reached at t=5400s at the vertical cavity wall. Typical temperature distributions at 1800s and 6600s after the start of the accident are shown in Figures A1.6 and A1.7. Steady state capsule temperatures were calculated for the contents exposed to the peak cavity wall temperature. Figure A1.8 illustrates the capsule temperature distribution at peak accident conditions.

Table 5: Peak Accident Conditions Temperatures

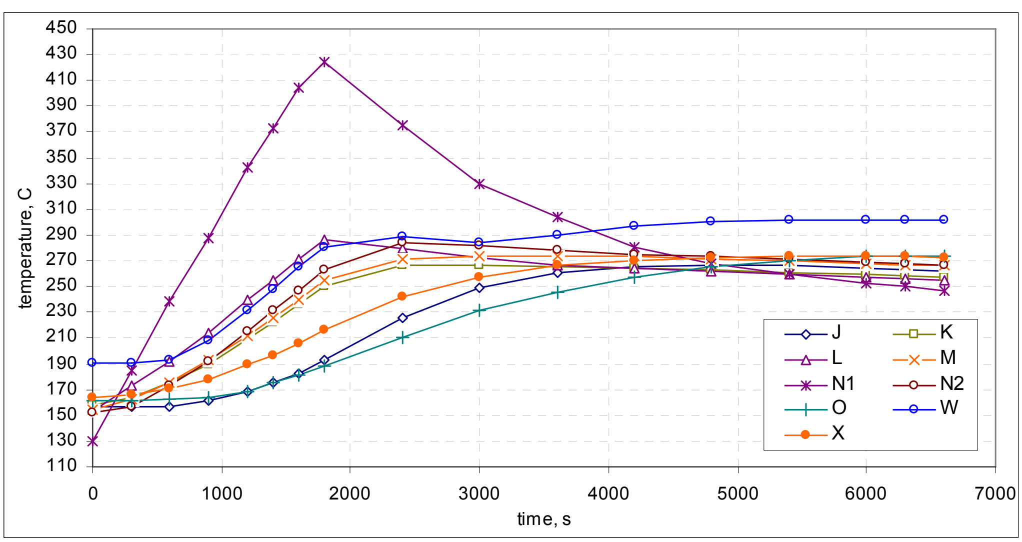
	Location	Temperature [C]
Tc_{max}	Capsule wall	471
A1	Cavity wall (50mm below top)	309
A2	Lead adjacent to A1	294
B1	Cavity wall (mid-height)	316
B2	Lead adjacent to B1	301
C1	Cavity wall (50mm above base)	312
C2	Lead adjacent to C1	297
D	Lead (closure base centre)	254
E	Lead (closure top centre)	253
F	Closure and vent seal	270
H	Lifting fin (40mm from top edge, 55mm from outer edge)	753
J	Lead (top chamfer top corner)	267
K	Lead (top chamfer bottom corner)	266
L	Flask wall (mid-height, midway between fins)	287
M	Lead (bottom chamfer top corner)	274
N2	Drain point seal	284
O	Lead (bottom chamfer bottom corner)	274
p	Flask foot (top surface, 30mm from outer edge)	718
Q	Jacket (mid height outer surface)	787
V	Top shield (top surface centre)	800
W	Maximum lead temperature	302



Graph 1: Accident temperatures for inverted container orientation, damaged [^{o}C]



Graph 2: Accident temperatures for inverted container orientation, damaged [^{o}C]



Graph 3: Accident temperatures for inverted container orientation, damaged [^{o}C]

5 Conclusions

5.1 Benchmarking

The correlation between predicted and measured temperatures is improved when:

- the emissivity of external flask surfaces is increased from 0.45 to 0.55,
- the two-equation *k-ω* based shear stress transport model is replaced with the standard two-equation *k-ω* based turbulence model,
- the contact coefficient is reduced from 400W/m^{2}K to 330W/m^{2}K.

5.2 Results

The R7021 transport container temperatures, under IAEA TS-R-1 normal and accident conditions of transport with an internal heat load equivalent to 3074W, are summarized in the following table.

Location	Temperature [^{o}C]		
	Normal conditions		Peak accident conditions with damage
	Without insolation	With insolation	
Capsule wall	409	411	471
Cavity wall	201	205	316
Closure and vent seal	141	150	270
Lifting fin	79	93	753
Drain plug seal	148	152	284
Flask wall at mid-height	149	153	287
Flask foot	50	67	718
Top shield top surface	57	100	800
Lead shielding (max)	186	191	302

6 References

[1] QS7021 issue 4: R7021 Transport Container Drawings List and associated drawings, Reviss Services (UK) Ltd.

[2] R7110/1.1: Thermal Analysis of the R7021 Radioactive Materials Transport Container, FTT Technology, July 2010.

[3] RTR 225: R7021 Thermal Survey Record on 3981/01, Reviss Services (UK) Ltd.

Appendix 1: Figures

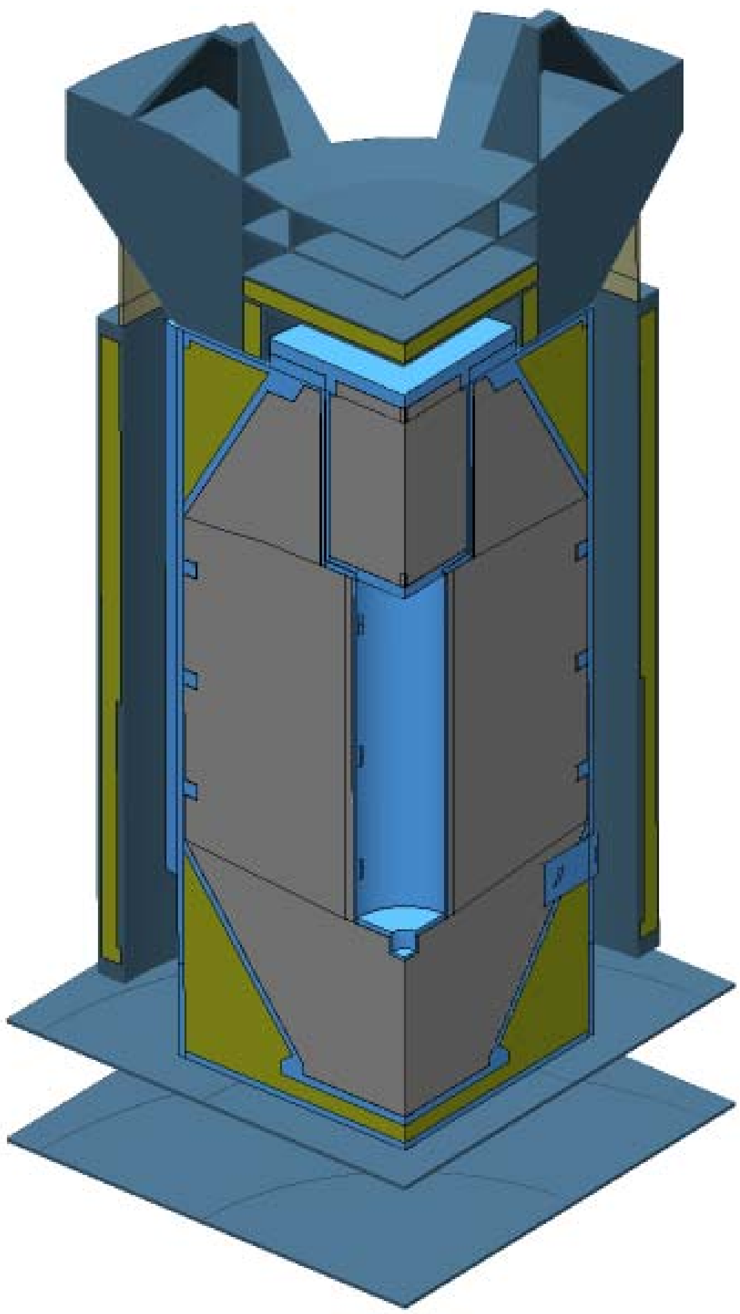


Figure A1.1: Sectional view of the transport container assembly.

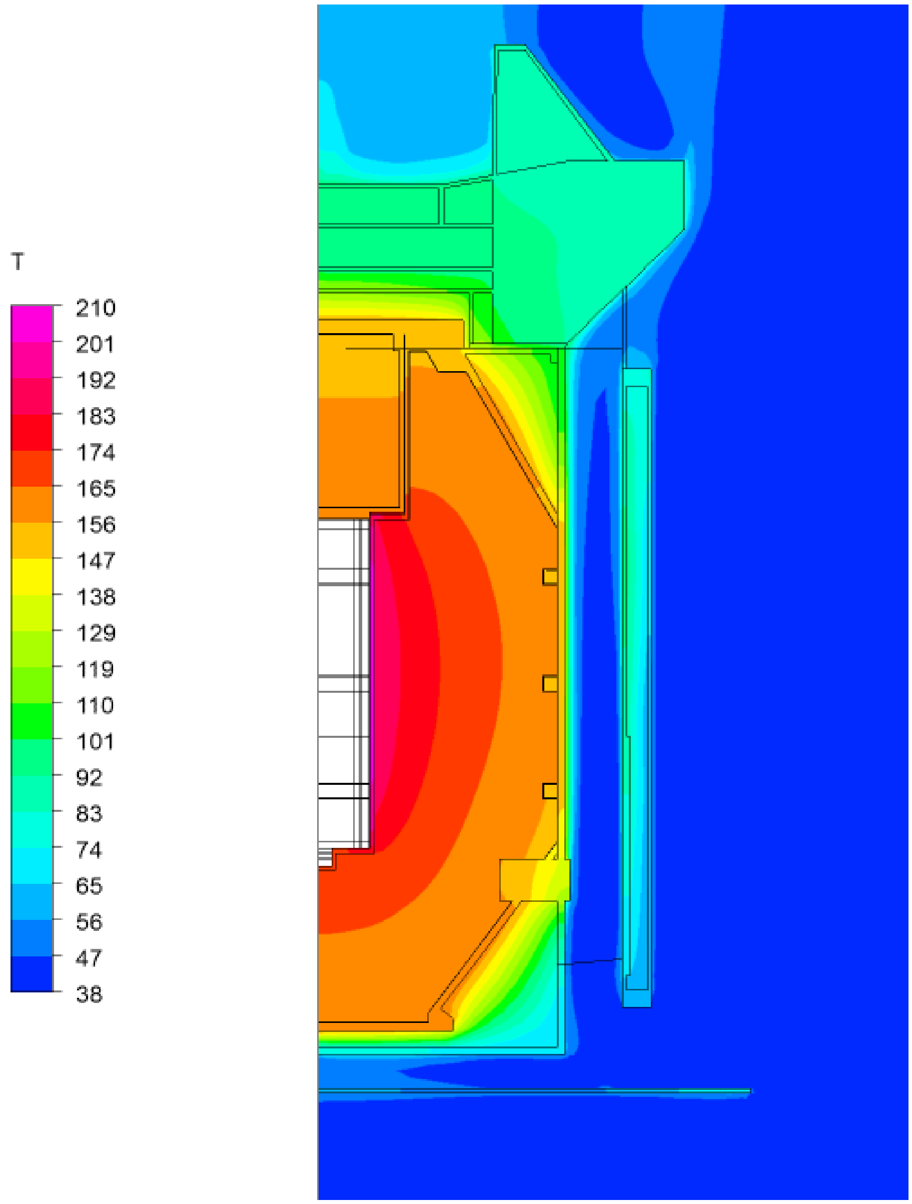


Figure A1.2: Temperature distribution at normal conditions with insolation [^{o}C]

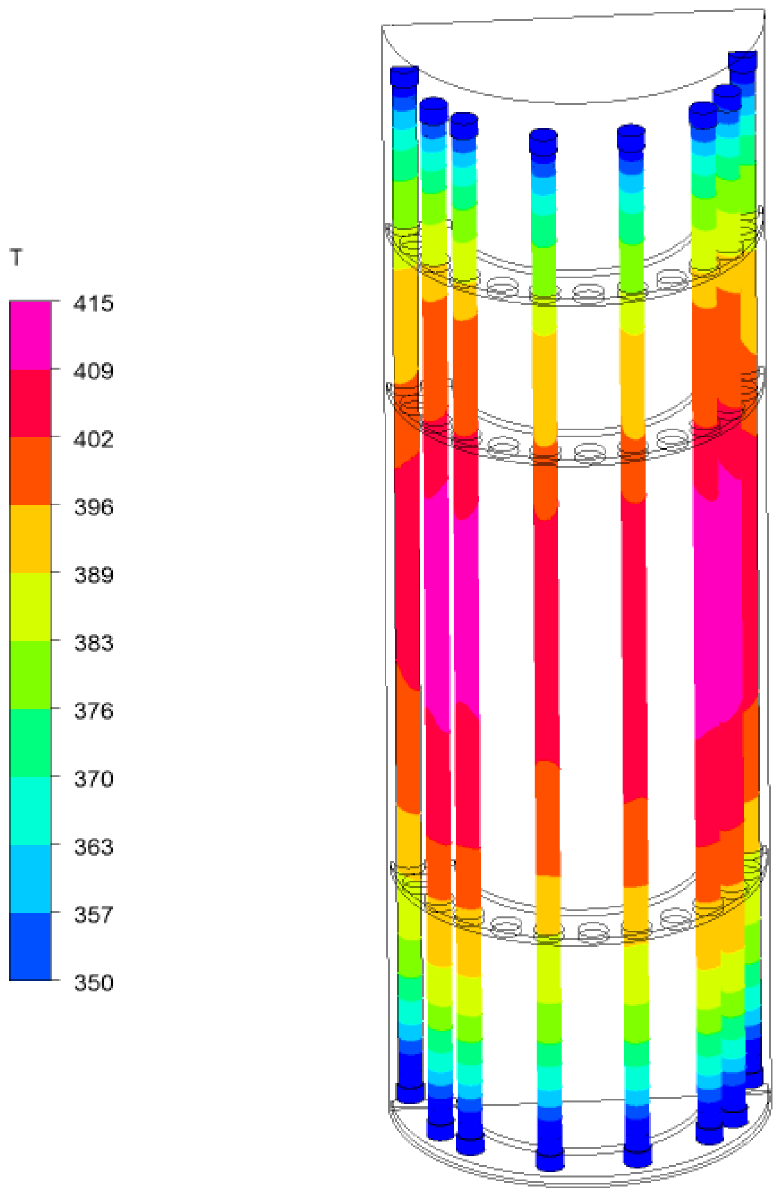


Figure A1.3: Capsule temperatures at normal conditions with insolation [^{o}C]

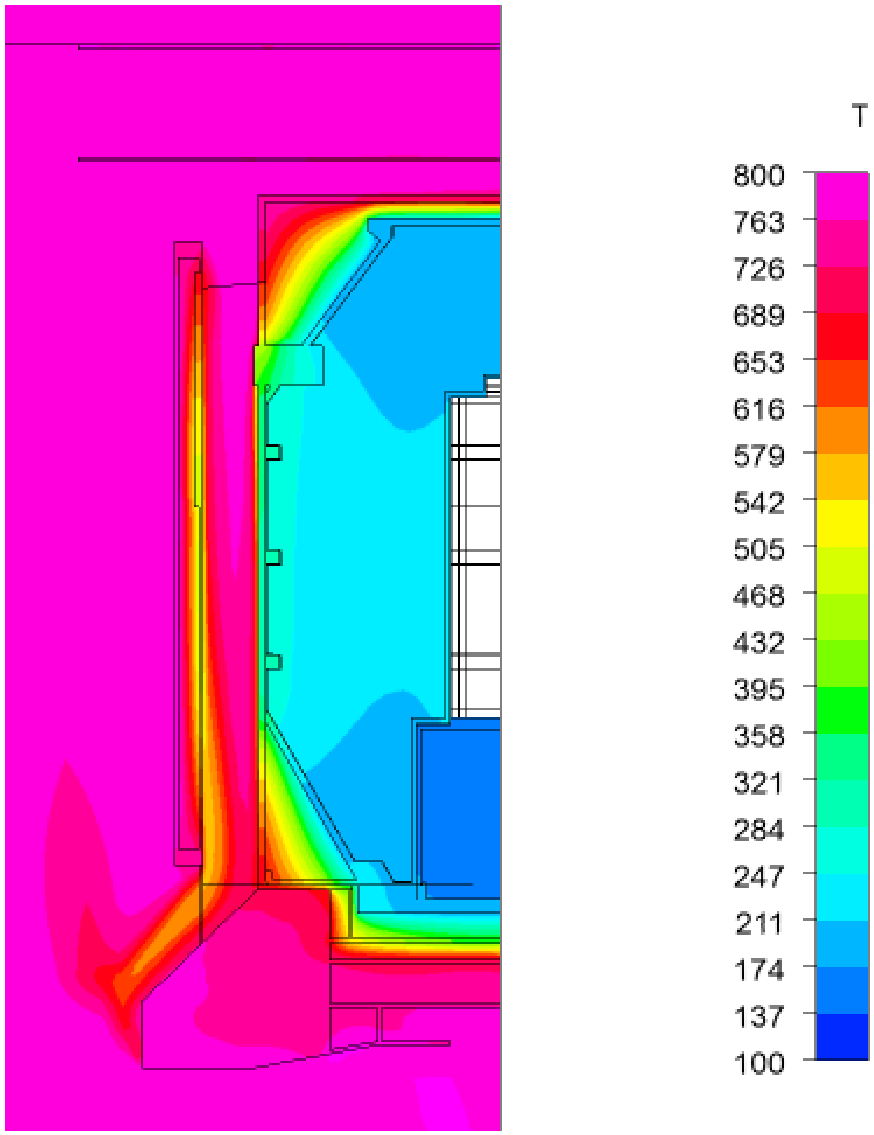


Figure A1.4: Accident conditions temperature distribution at 1800s [^{o}C]

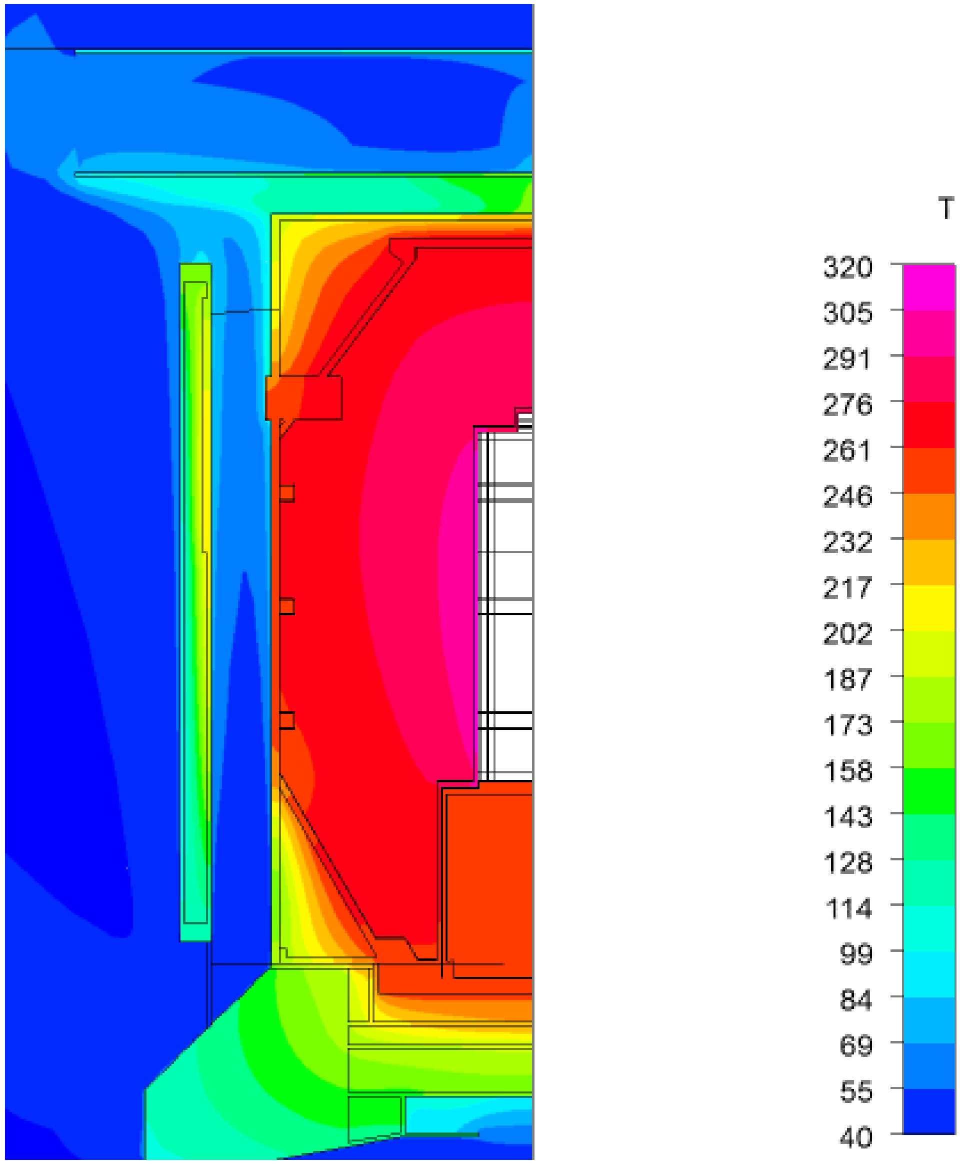


Figure A1.5: Accident conditions temperature distribution at 6600s [^oC]

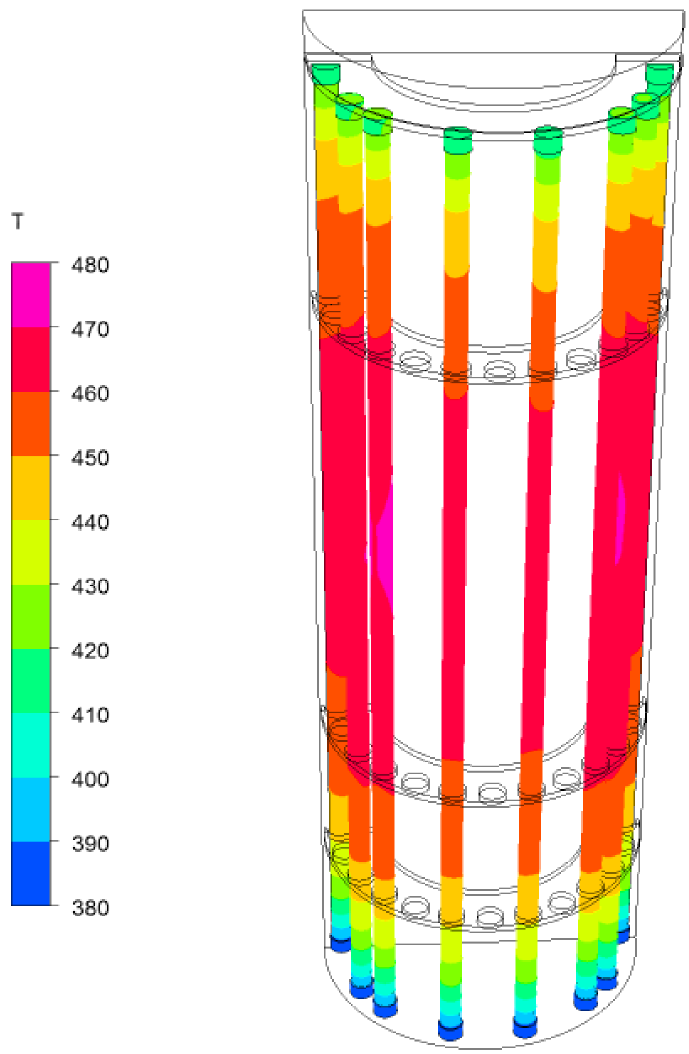


Figure A1.6: Peak accident conditions source temperature distribution [^{o}C]

Appendix 2: Specifications

General

Domain overall height	6m
Domain height above pallet base	3.5m
Domain width / depth (complete model)	5.5m
Heat load at benchmark conditions	2362W
Heat load at transport conditions	3074W
Emissivities:	
Benchmark:	
External flask surfaces emissivity	0.55
Unpainted carbon steel surfaces emissivity	0.90
Painted carbon steel surfaces emissivity	0.90
Cavity wall emissivity	0.40
Normal conditions:	
External flask surfaces emissivity	0.55
Unpainted carbon steel surfaces emissivity	0.98
Painted carbon steel surfaces emissivity	0.98
Cavity wall emissivity	0.40
Thermal test and cooling period:	
Flask surface covered by top shield emissivity	0.55
Unpainted carbon steel surfaces emissivity	0.98
Blackened external surfaces emissivity	0.80
Furnace walls emissivity	0.90
Cavity wall emissivity	0.40

Domain conditions

Insolation:

Downward heat flux (-y direction):	$800W/m^2$
Horizontal direction (-x direction):	$200W/m^2$
Horizontal direction (+x direction):	$200W/m^2$
Horizontal direction (-z direction):	$200W/m^2$
Horizontal direction (+z direction):	$200W/m^2$

Normal conditions:

Ambient air temperature:	38^oC
Sides and top:	Open flow boundaries
Floor:	Solid base
Flow:	Turbulent, free convection flow

Thermal test:

Ambient air temperature:	800^oC
Base:	8m/s inflow at domain base (container suspended)
Sides:	Wall
Top:	Opening
Flow:	Turbulent, free and forced convection flow

Cooling period:

Ambient air temperature:	38^oC
Base:	Wall (container suspended)
Sides and top:	Open flow boundaries
Flow:	Turbulent, free convection flow