Thermal Analysis of the R7021 Radioactive Materials Transport Container at 2460W and 3074W Internal Heat Load

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prepared for

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Summary

This report updates previous studies of the R7021 transport container [1] & [2] by incorporating subsequent design modifications made to the flask body [3]. It presents a thermal analysis of the container under IAEA normal and accident conditions of transport with internal heat loads of 2460W and 3074W. Normal conditions was modelled as an ambient temperature of 38ºC and solar radiation from the top and sides. Accident conditions modelled an environment simulating an 800ºC 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 seal and shielding temperatures. The radioactive contents were modelled separately for the higher heat load 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 2460W and 3074W.

2 R7021 Description and Specification

The R7021 transport container [4] comprises an upright, cylindrical stainless steel flask mounted on a carbon steel pallet. 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.

Issue E of the flask body drawing incorporates four 20mm stainless steel plates around its lower cone and an 8mm stainless steel disc on the underside of the flask base. The cone plates are welded to the webs between the cone and the outer wall. One of the cone plates has a lead plate set into it which is secured by a cap sheet.

3 Modelling

The CFD code Ansys CFX [5] was used to model the heat transfer and gas flow processes involved. Ansys CFX 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.

The flask model used for this study includes the stainless steel disk welded to the base, as well as four additional plates around the lower flask cone [3]. The four plates were modelled as solid stainless steel in thermal contact with the four webs. A contact resistance equivalent to a 0.5mm gap was modelled between the plates and the flask cone.

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 Normal Conditions Analysis

The normal conditions analyses determine equilibrium temperature distribution throughout the container and contents under IAEA normal conditions of transport.

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 [1]. Container temperatures were calculated with and without solar insolation. An ambient air temperature of 38ºC was specified. Key variables were taken from previous benchmarking [2]. The emissivity of flask external surfaces was 0.55, the contact coefficient at lead-stainless steel interfaces was 330W/m^{2}K and the standard two-equation k-ω based turbulence model was used.

The basket was loaded with fourteen capsules. 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.

3.2 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 800ºC 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 800ºC. 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 Normal Conditions

Table 2 presents steady state temperatures for normal conditions without and with insolation. Temperature distributions on a vertical section with and without insolation are shown in Figure A1.2 to A1.5, while Figure A1.6 illustrates the source temperature distribution at the load of 3074W.

Table 2: Normal Conditions Temperatures [ºC].

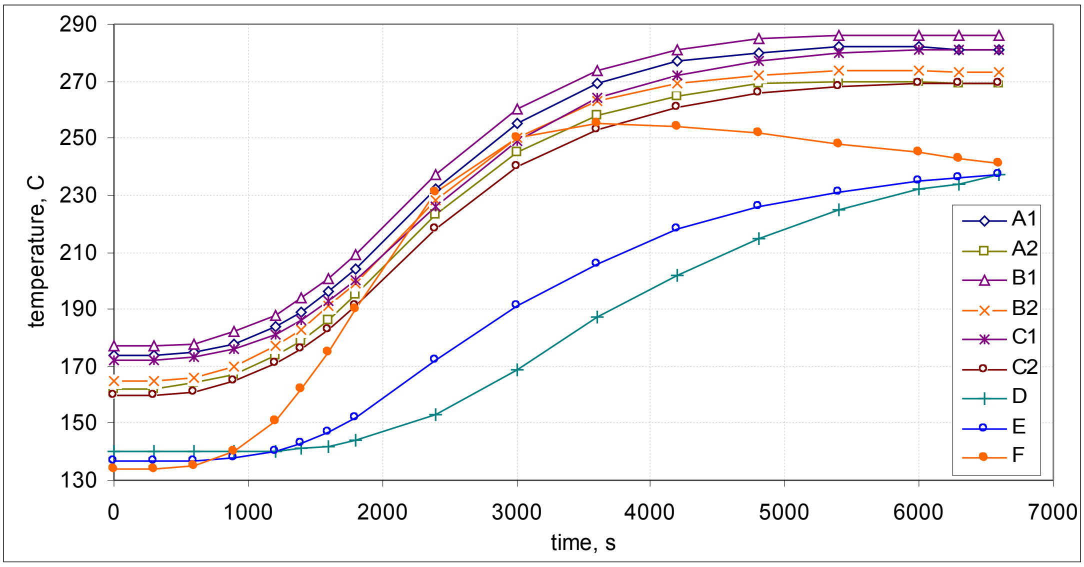
	Location	Load 2460W		Load 3074W	
		Without insolation	With insolation	Without insolation	With insolation
$T_{c,max}$	Capsule wall	-	-	409	411
A1	Cavity wall (50mm below top)	168	174	197	203
A2	Lead adjacent to A1	156	162	182	187
B1	Cavity wall (mid-height)	172	177	201	207
B2	Lead adjacent to B1	159	165	186	191
C1	Cavity wall (50mm above base)	167	172	195	200
C2	Lead adjacent to C1	155	160	180	185
D	Lead (closure base centre)	132	140	151	159
E	Lead (closure top centre)	128	137	147	155
F	Closure and vent seal	124	134	142	151
H	Lifting fin (40mm from top edge, 55mm from outer edge)	72	88	78	92
J	Lead (top chamfer top corner)	131	139	150	157
K	Lead (top chamfer bottom corner)	133	140	153	159
L	Flask wall (mid-height, midway between fins)	131	136	149	154
M	Lead (bottom chamfer top corner)	131	136	150	155
N2	Drain seal	130	135	148	153
O	Lead (bottom chamfer bottom corner)	137	142	157	163
P	Flask foot (top surface, 30mm from outer edge)	47	65	49	65
Q	Jacket (mid height outer surface)	45	65	48	67
V	Top shield (top surface centre)	53	97	58	101
W	Maximum lead temperature	160	166	187	192
T_a	Ambient	38	38	38	38

4.3 Accident Conditions

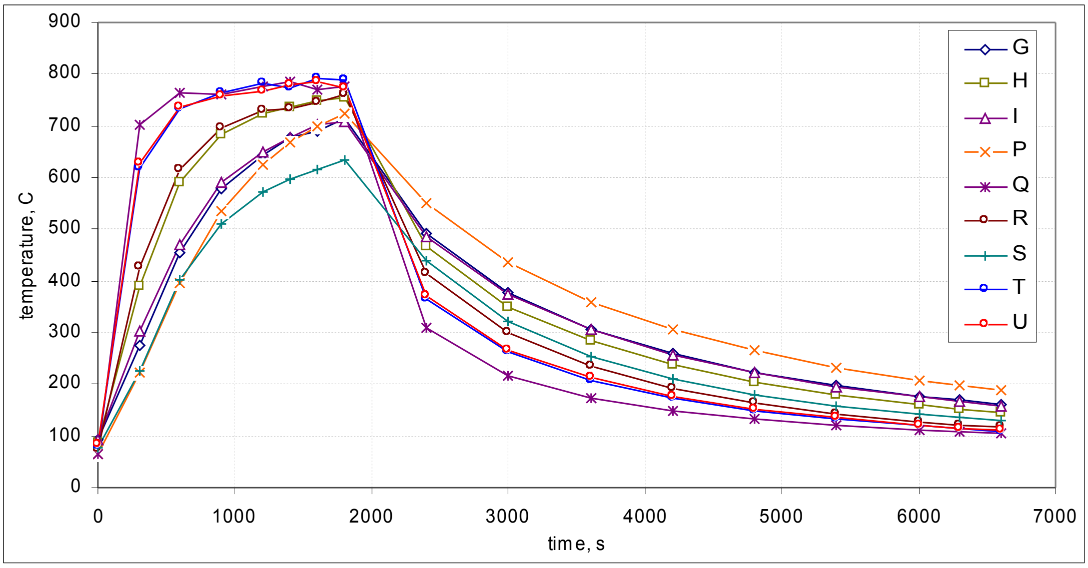
Table 3 shows the calculated peak temperatures for the damaged inverted container. The temperatures histories during heating and subsequent cooling at various locations are shown in Graph 1 to 6. The peak lead temperature is reached at t=5400s at the vertical cavity wall. Typical temperature distributions at 1800s and 6600s after the start of the accident are shown in Figures A1.7 and A1.8. Steady state capsule temperatures were calculated for the contents exposed to the peak cavity wall temperature. Figure A1.9 illustrates the capsule temperature distribution at peak accident conditions.

Table 3: Peak Accident Conditions Temperatures [^{o}C]

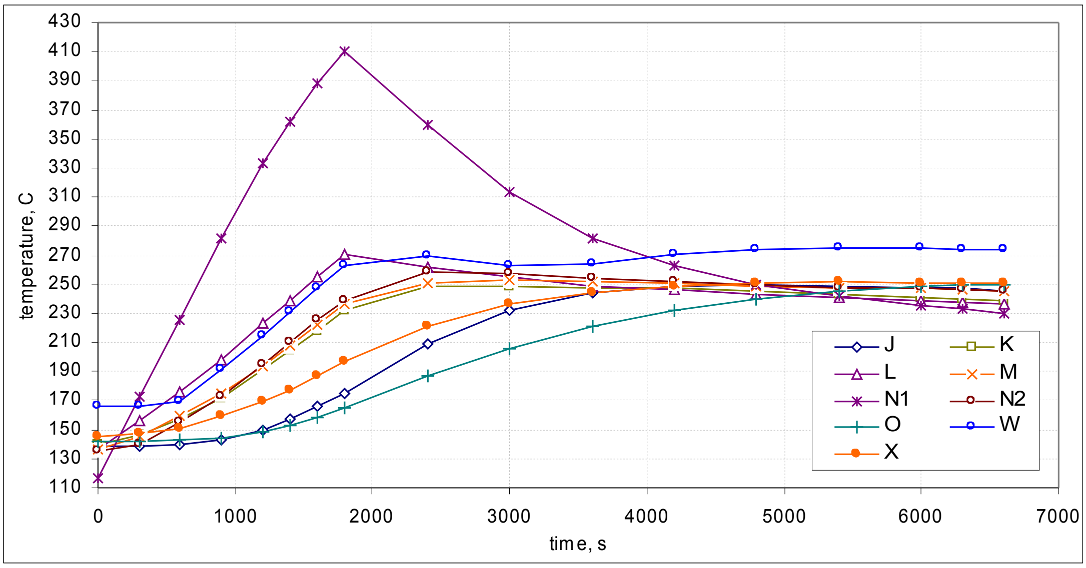
	Location	Load 2460W	Load 3074W
$T_{c,max}$	Capsule wall	-	471
A1	Cavity wall (50mm below top)	282	309
A2	Lead adjacent to A1	270	294
B1	Cavity wall (mid-height)	286	315
B2	Lead adjacent to B1	274	299
C1	Cavity wall (50mm above base)	281	309
C2	Lead adjacent to C1	269	294
D	Lead (closure base centre)	237	255
E	Lead (closure top centre)	237	254
F	Closure and vent seal	255	271
H	Lifting fin (40mm from top edge, 55mm from outer edge)	756	760
J	Lead (top chamfer top corner)	250	267
K	Lead (top chamfer bottom corner)	249	267
L	Flask wall (mid-height, midway between fins)	271	289
M	Lead (bottom chamfer top corner)	253	271
N2	Drain point seal	259	277
O	Lead (bottom chamfer bottom corner)	250	270
p	Flask foot (top surface, 30mm from outer edge)	724	718
Q	Jacket (mid height outer surface)	785	794
V	Top shield (top surface centre)	800	800
W	Maximum lead temperature	275	301



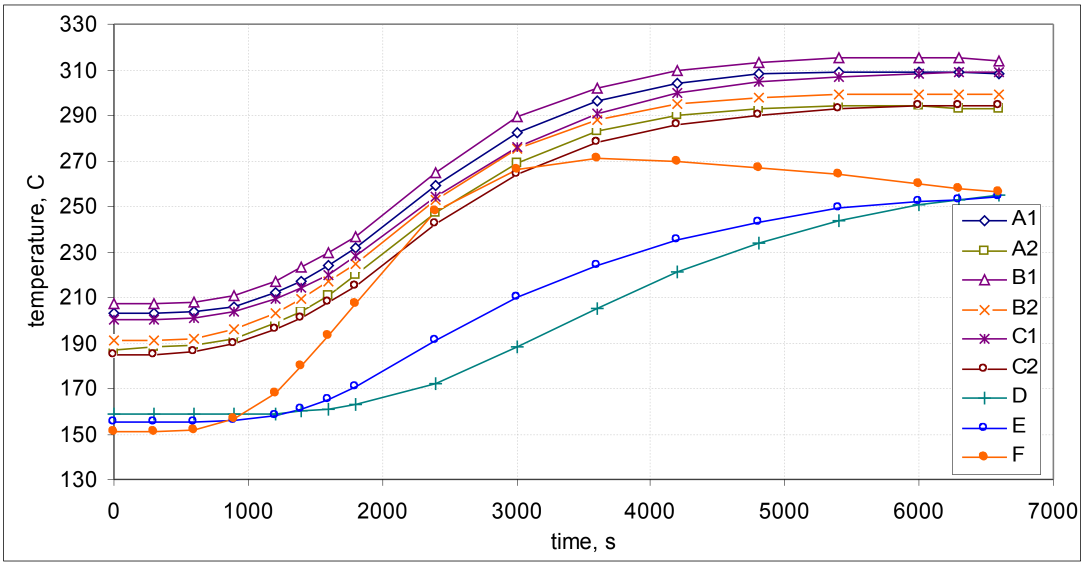
Graph 1: Accident temperatures for inverted container orientation, damaged, 2460W load [ºC].



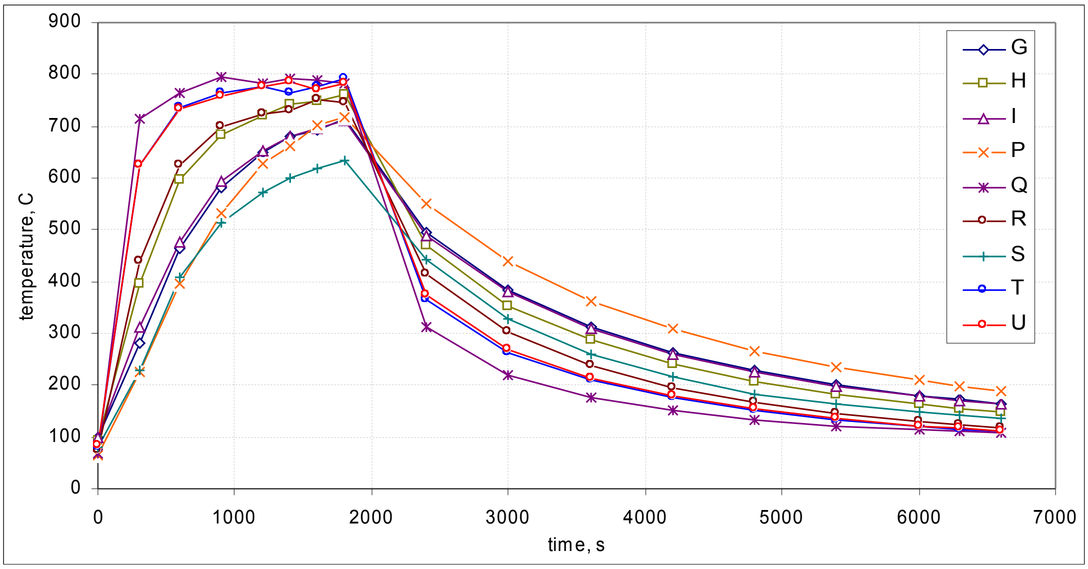
Graph 2: Accident temperatures for inverted container orientation, damaged, 2460W load [ºC].



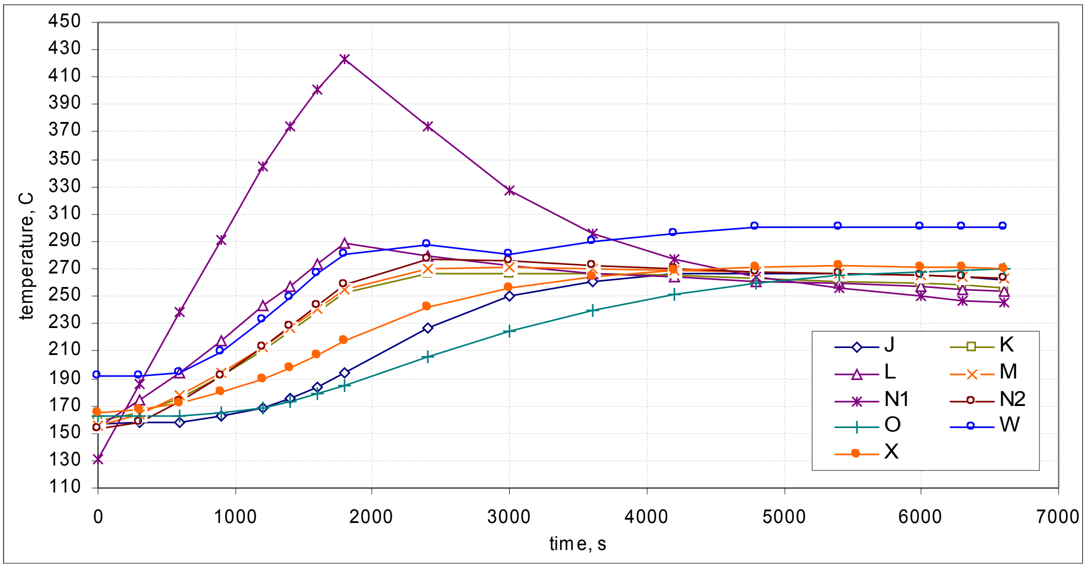
Graph 3: Accident temperatures for inverted container orientation, damaged, 2460W load [ºC].



Graph 4: Accident temperatures for inverted container orientation, damaged, 3074W load [ºC].



Graph 5: Accident temperatures for inverted container orientation, damaged, 3074W load [ºC].



Graph 6: Accident temperatures for inverted container orientation, damaged, 3074W load [ºC].

5 Conclusions

The R7021 transport container temperatures, under IAEA TS-R-1 normal and accident conditions of transport with an internal heat load equivalent to 2460W and 3074W, are summarized in the following tables.

2460W load

Location	Temperature [ºC]		
	Normal conditions		Peak accident conditions with damage
	Without insolation	With insolation	
Cavity wall	172	177	286
Closure and vent seal	124	134	255
Lifting fin	72	88	756
Drain plug seal	130	135	259
Flask wall at mid-height	131	136	271
Flask foot	47	65	724
Top shield top surface	53	97	800
Lead shielding (max)	160	166	275

3074W load

Location	Temperature [ºC]		
	Normal conditions		Peak accident conditions with damage
	Without insolation	With insolation	
Capsule wall	409	411	471
Cavity wall	201	207	315
Closure and vent seal	142	151	271
Lifting fin	78	92	760
Drain plug seal	148	153	277
Flask wall at mid-height	149	154	289
Flask foot	49	65	718
Top shield top surface	58	101	800
Lead shielding (max)	187	192	301

6 References

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

[2] R7410/1.1: Thermal Analysis of the R7021 Radioactive Materials Transport Container, Report, FTT Technology, May 2010.

[3] R7021/002 issue E: R7021 Flask Body Drawing, Reviss Services (UK) Ltd.

[4] QS7021 issue 5: R7021 Transport Container Drawings List, Reviss Services (UK) Ltd.

[5] ANSYS CFX 12.0, Ansys, Inc., Canonsburg, USA.

Appendix 1: Figures

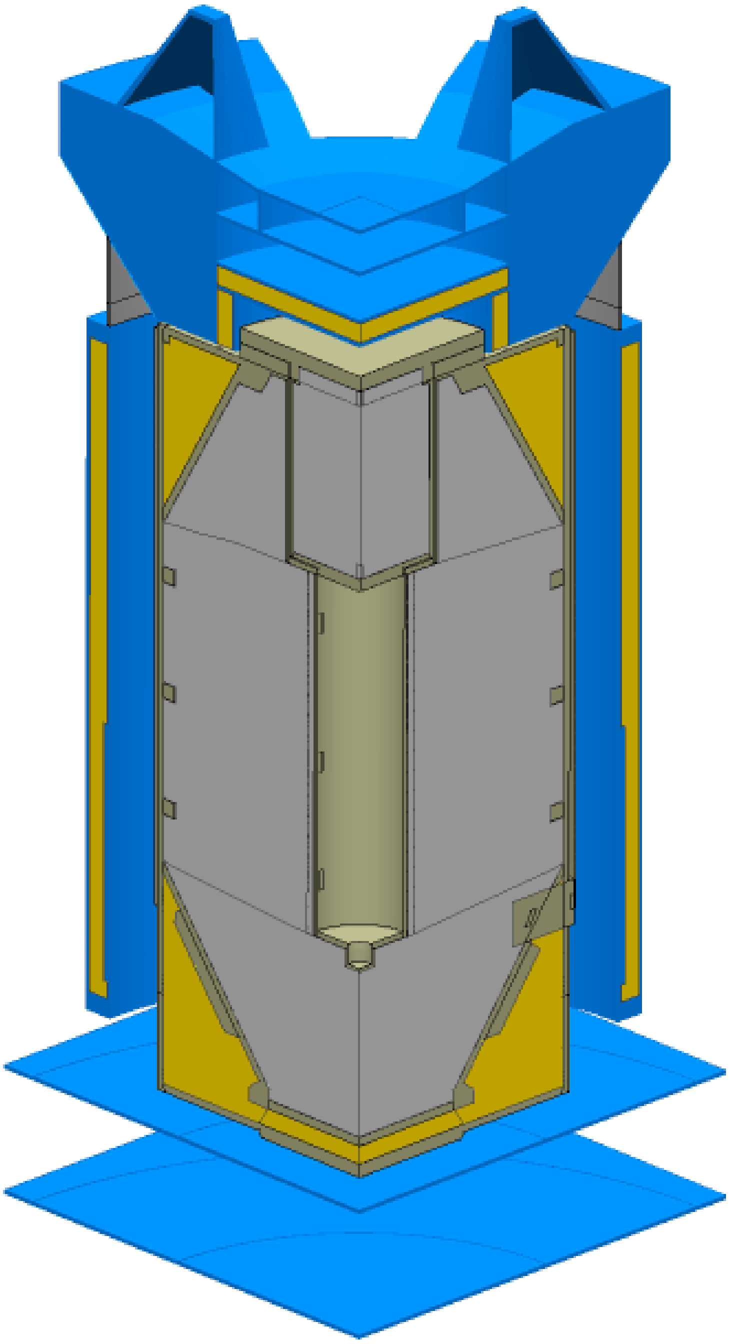


Figure A1.1: Sectional view of the transport container assembly.

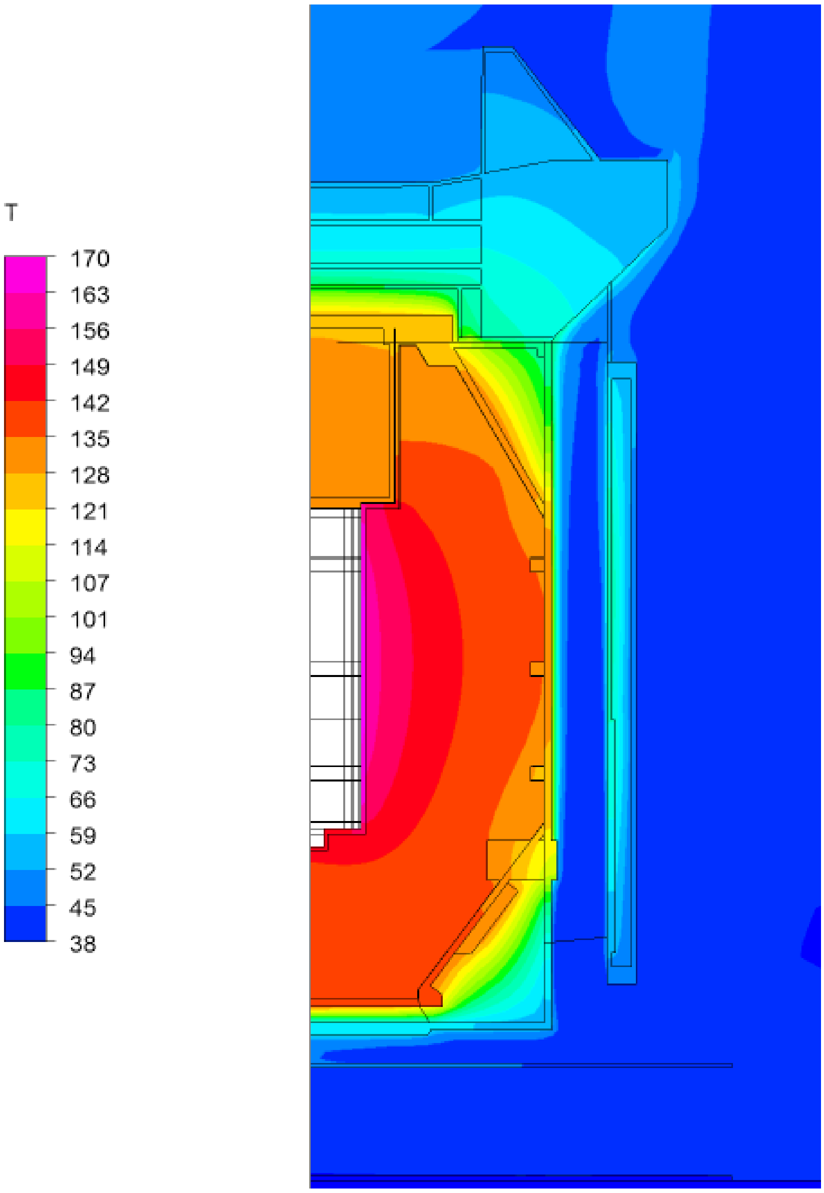


Figure A1.2: Temperature distribution at normal conditions without insolation, 2460W load [ºC]

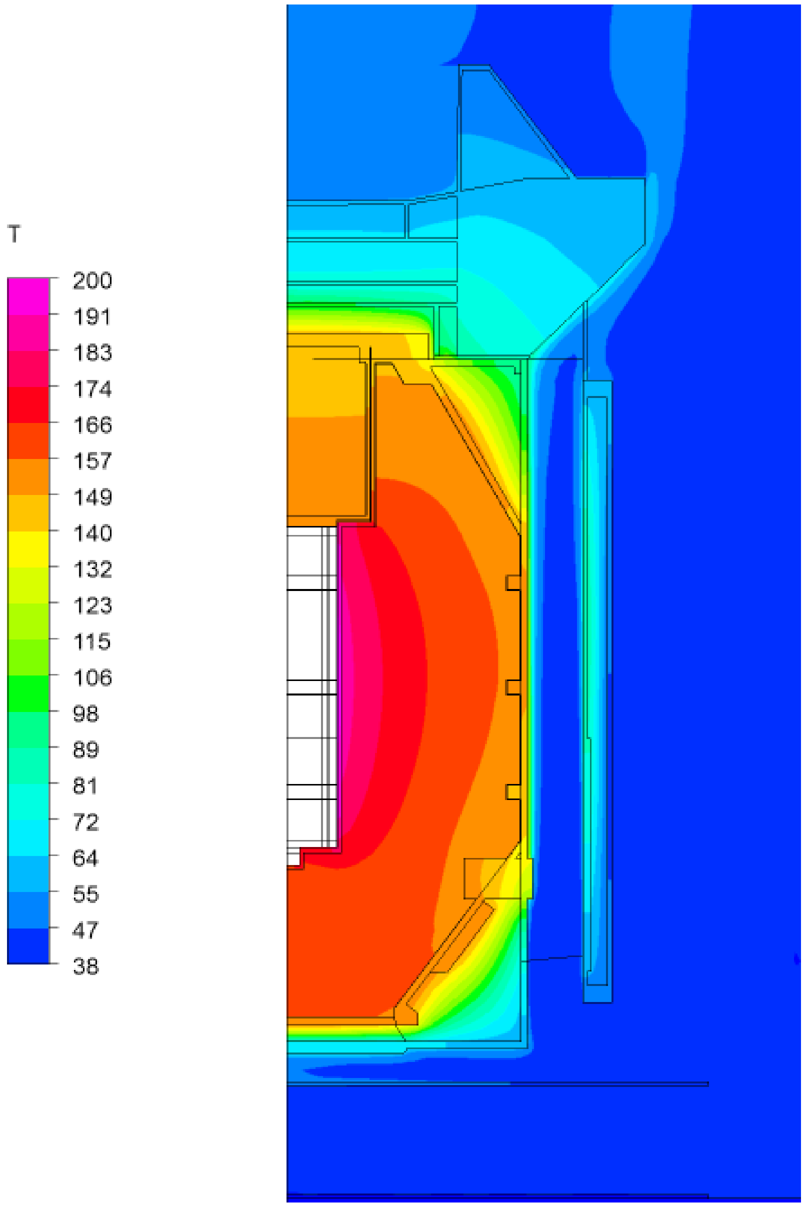


Figure A1.3: Temperature distribution at normal conditions without insolation, 3074W load [ºC]

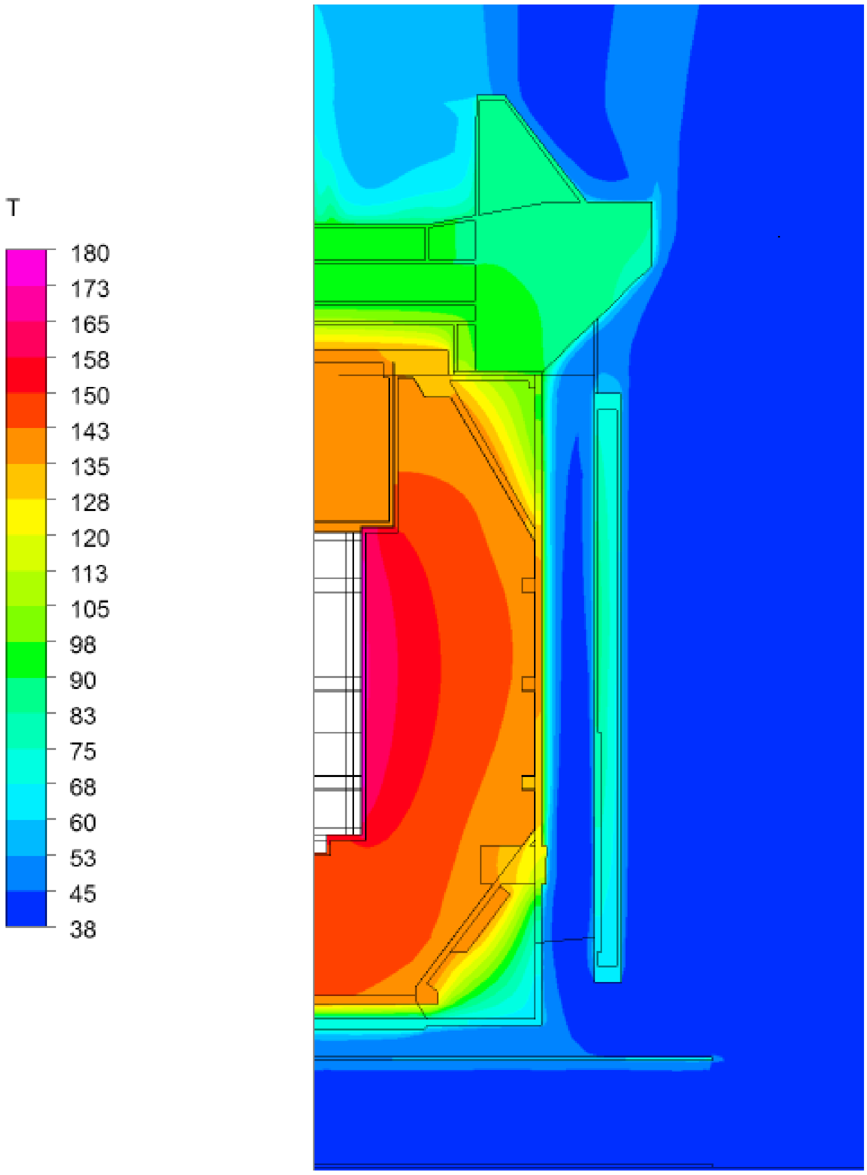


Figure A1.4: Temperature distribution at normal conditions with insolation, 2460W load [ºC]

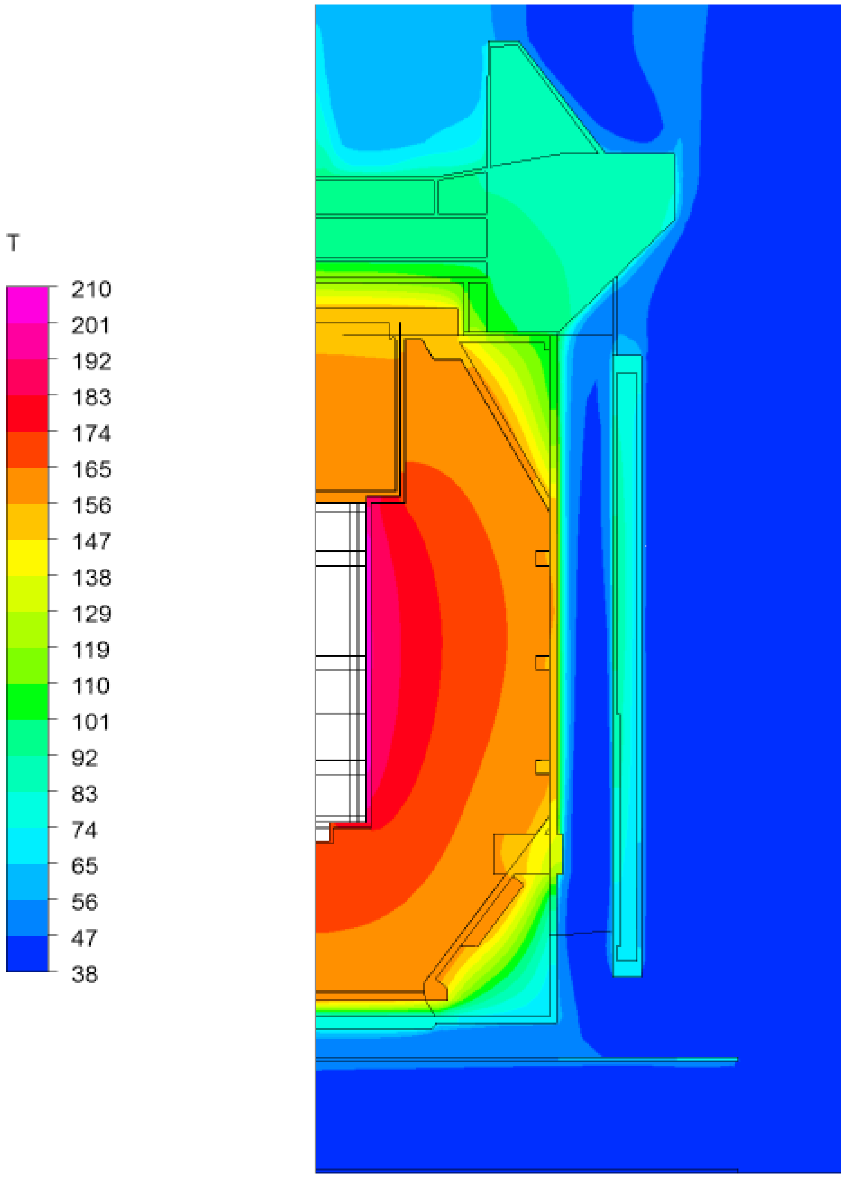


Figure A1.5: Temperature distribution at normal conditions with insolation, 3074W load [ºC]

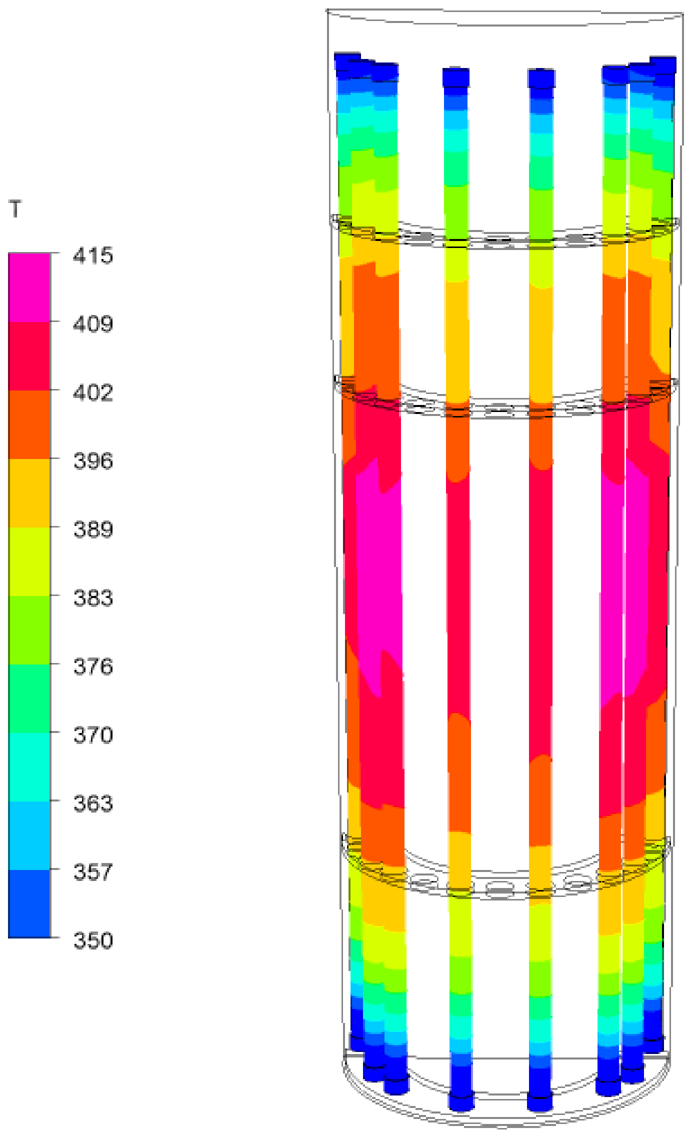


Figure A1.6: Capsule temperatures at normal conditions with insolation, 3074W load [^{o}C]

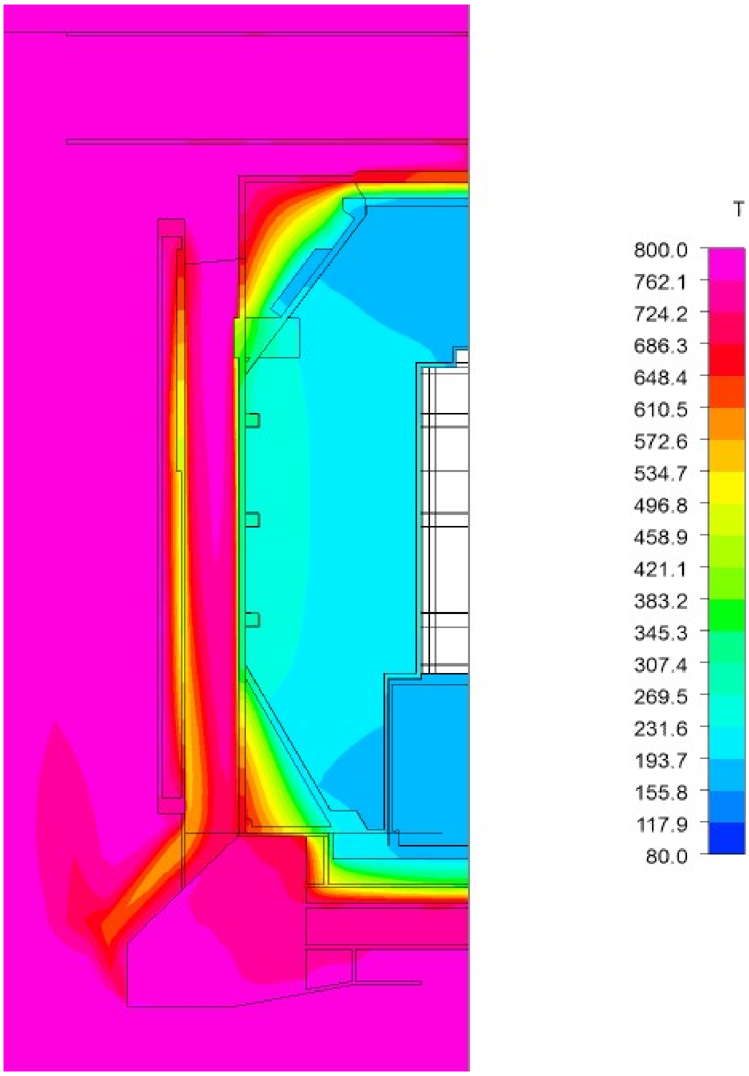


Figure A1.7: Accident conditions temperature distribution at 1800s [ºC]

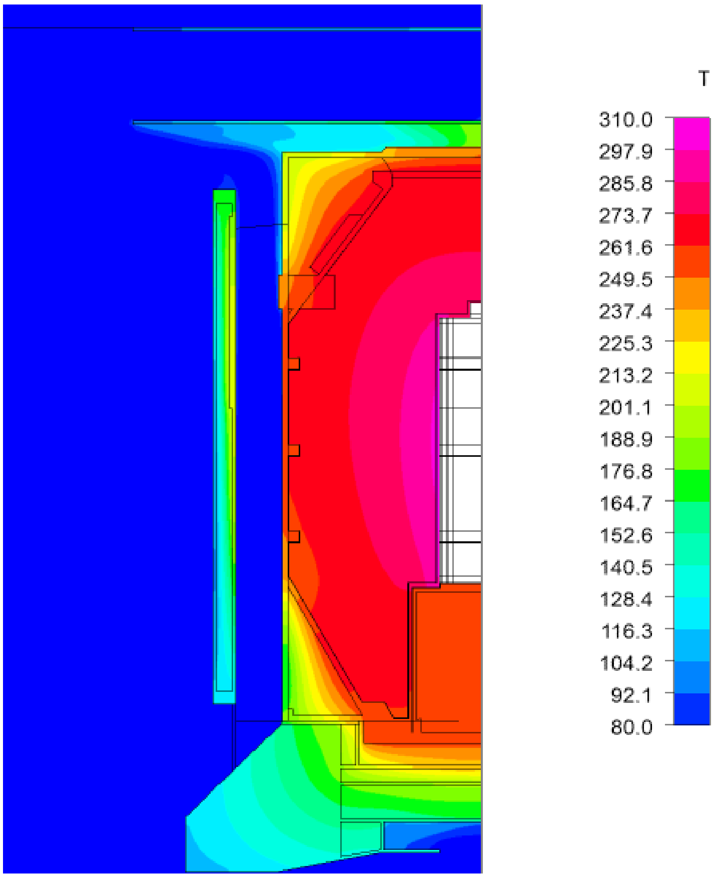


Figure A1.8: Accident conditions temperature distribution at 6600s [ºC]

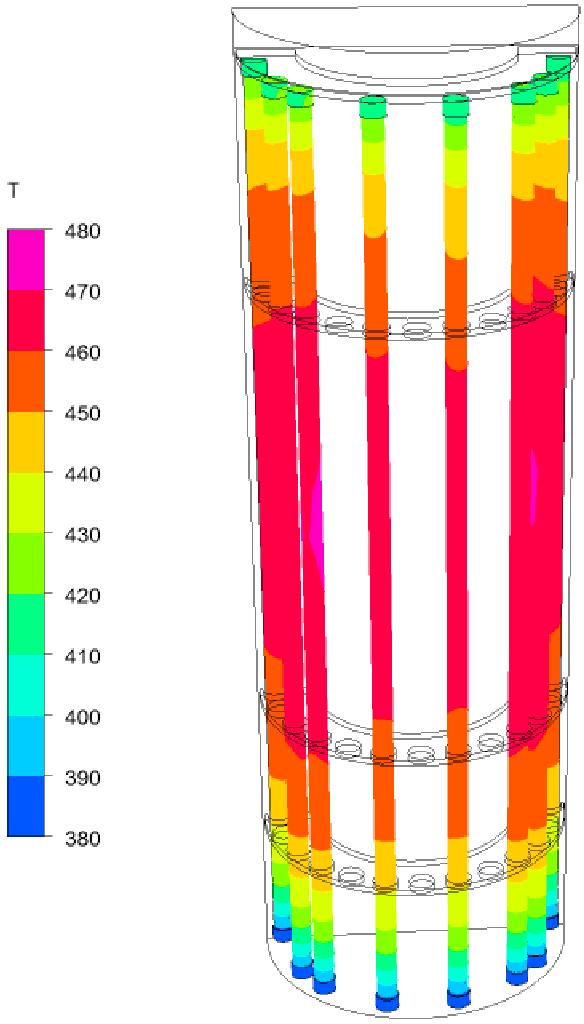


Figure A1.9: Peak accident conditions source temperature distribution [ºC]

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^{o}C
Sides and top:	Open flow boundaries
Floor:	Solid base
Flow:	Turbulent, free convection flow

Thermal test:

Ambient air temperature:	800^{o}C
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^{o}C
Base:	Wall (container suspended)
Sides and top:	Open flow boundaries
Flow:	Turbulent, free convection flow