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Revisions history

Rev.	Date	Purpose and record of changes	Prepared by / Checked by
0		First issue	

1. Introduction

The purpose of this analysis is to evaluate, using numerical calculations, the temperature of the FCC packaging under Normal Conditions of Transport (NCT)

2. Calculations - approach and methods

2.1. Software

The calculations are carried out using the I-DEAS software interfaced with the thermal module TMG <1>.

2.2. Model mesh & geometry

The model used in this study is a 2D thermal model, representing a section of the uninterrupted section of the FCC4 packaging shell and internal fittings. The model details the plates, the resin of the frame and the doors, the fuel rod claddings, the guide tubes and the pellets, as per the models presented in Appendix 2.2-1.

As in Appendix 2.2-1, the sizes of the air inlet openings in the cavity of the internal fittings are, respectively, 7mm in the upper section and 5 mm in the lower.

The 17x17 rod array is represented in the calculation model. The geometry and meshing of the internal fittings and17x17 fuel rod array is presented in figure 1.

The geometry of the shell is modelled in accordance with drawing <2> in Appendix 1.4-1 of Chapter 1.4. As per this drawing, the outer radius of the upper shell is [redacted] mm, the outer radius of the lower shell is [redacted] mm. The calculation model also represents the air between the internal fittings and the packaging shell.

2.3. Materials

The characteristics of the materials used for the packaging, and the air, are given in tableau 1.

2.4. Power levels

The fresh UO2 pellets do not emit any power.

2.5. Heat exchanges

2.5.1. Conduction

The conductive exchanges within the materials are calculated directly by the code <1>, using the thermal conductivity of each material, given in Table tableau 1.

The gap between the claddings and the pellets is calculated using the geometric characteristics of the 17x17 array, taken from Chapter 2.2-1, and listed in the table below:

d_C: External rod diameter (mm)	[redacted]
e: Thickness of claddings (mm)	[redacted]
d_P: Pellet diameter (mm)	[redacted]
Array pitch (mm)	12.6

The radial gap (noted j) between the claddings and the pellets is calculated using the following equation:

$j = \frac{1}{2}\left(d_c - 2e - d_p\right) =$ [redacted] $=$ [redacted] mm for the 17x17 array.

The Contact Resistance value (R_c) is deduced using the equation:

$$R_c = \frac{j}{\lambda_{helium}}$$

Where λ_{helium} = [redacted] W.m^{-1}.K^{-1}. from tableau 1

Therefore, the contact resistance for a 17x17 array is as follows:

$$R_c = \text{[redacted]} = \text{[redacted]}\ m^2.K/W$$

2.5.2. Convection

The air surrounding the packaging shell is not represented. The heat exchanges, by convection, are modelled, using a coefficient of exchange: h = 1.4$\Delta T^{1/3}$ W.m^{-2}.K^{-1}. The calculation is based upon correlations taken from <3>.

2.5.3. Radiation

[redacted]

The radiative exchanges between the claddings and the plates of the internal fittings, and between the outer surface of the internal fittings and the shell of the packaging, are directly calculated using the code <1>. They are modelled using radiative boxes. The emissivity levels of the various materials are given in Table 1.

Radiative exchanges between the outer surfaces of the shell and the ambient air are modelled using a view factor of 1. The shell is covered, inside and out, with a paint coating, the emissivity of which ε is [redacted] (conservative value from Appendix 2.2-1).

2.5.4. Ambient

The temperature of the ambient air is assumed to be 38°C.

2.5.5. Exposure to sunlight

The calculation is carried out for transient operating conditions with 12 hours of sunlight exposure per 24 hour period. (regulatory exposure over 12 hours followed by zero exposure for the next 12 hours). The exposure is defined below, as per Table 13 of <4>:

- The solar flux received by the upper (curved) section of the packaging shell is 400 W/m².
- The solar flux received by the vertical walls and lower (curved) section of the packaging shell is 200 W/m².

The density of the solar flux received by a given surface is $\varphi = \alpha \times E$, where α is the surface absorptivity and E the regulatory sunlight.

The absorptivity α is conservatively considered as being equal to 1 (See tableau 1)

3. Results

The following table gives the maximum temperatures reached by the shell and packaging in steady state transient operating conditions.

Structure	Temperature	Time
Shell	T_{max} = [redacted] °C	43,200 s
External plates	T_{max} = [redacted] °C	43,210 s
Resin	T_{max} = [redacted] °C $T_{avg\ max}$ = [redacted] °C	43,230 s 43,500 s
Internal plates	T_{max} = [redacted] °C	44,100 s
Claddings	T_{max} = [redacted] °C	44,100 s

The figure below shows the changes in the maximum temperatures of the various components making up the packaging.

Proprietary drawing

The figure below shows the range of packaging temperatures at the moment the temperature of the external plates of the doors on the internal fittings is maximum.

Proprietary drawing

4. Conclusion

The maximum temperatures reached by the main components making up the FCC packaging under Normal Conditions of Transport and regulatory sunlight exposure are as follows:

- External shell of the packaging, Tmax = [redacted]°C,
- External plates of the internal fittings, Tmax = [redacted] °C,
- Resin within the internal fittings, Tmax = [redacted]°C,
- Fuel rod claddings, Tmax = [redacted]°C.

5. References

<1> Finite element calculation software NX I-DEAS 6.1 M1 interfaced with the thermal model TMG 6.0.1181 distributed by Siemens PLM software.

<2> Drawing of the FCC4 packaging with its shell, entitled: “Container for two UO_2 fuel assemblies, 14-foot model – 17 x 17 (Type XL and EPR)” and reference 229 K 0602.

<3> Handbook of Transfer Fundamentals – W.M. ROHSENOW, J.P. HARTNETT, E.N. GANIC, Mc Graw Hill – 2nd Edition

<4> Regulations for the Safe Transport of Radioactive Materials - Requirements N° SSR 6 - at the revision indicated in Chapter 1.2.

<5> Archiving

CDE3040600 / Thermique / CAL-13-00078918-002-00			
Model: FCC4_coque.			
Part	**FE model**	**FE study**	**Description**
2D model	Basic configuration	TRANSIENT	2D model of the FCC4 packaging in the shell, for thermal calculations under transient operating conditions

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FIGURE 1

GEOMETRY OF THE INTERNAL FITTINGS AND ARRAY OF FUEL RODS (17X17) FOR THE FCC4 PACKAGING

GEOMETRY OF THE INTERNAL FITTINGS:	GEOMETRY OF THE FUEL ROD ARRAY (17X17)
Proprietary drawing	Proprietary drawing

FIGURE 2

MESHING OF THE INTERNAL FITTINGS AND ARRAY OF FUEL RODS (17X17) FOR THE FCC4 PACKAGING

Proprietary drawing

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TABLEAU 1

THERMAL PROPERTIES OF THE MATERIALS USED IN THE FCC4 PACKAGING

Material	**Thermal conductivity λ (W m^{-1} K^{-1})**		**Specific heat Cp (J/kg K)**		**Den sity ρ (kg/m^3)**	**Emissivity ε**	**Solar absorptivity α**
Stainless steel	20°C	14.71	500		7800	[redacted]	1
	200°C	17.30					
Resin	[redacted]		[redacted]		[redacted]	-	-
Zy-4 claddings	20°C	[redacted]	20°C	[redacted]	[redacted]	[redacted]	-
	200°C	[redacted]	200°C	[redacted]			
UO_2	20°C	9.9	20°C	234.6	10.410	-	-
	200°C	7.1	200°C	277.8			
Air	20°C	0.0256	1,150		-*	-	-
	200°C	0.0385					
Helium	0.33		5.190		3.28	-	-

* The thermal inertia of air is ignored.