framatome

No of Pages: 113

Document Type:
AC - DESIGN CALCULATION

Document Title:

Justification by CFD simulation of the thermal behavior of the FCC container

NON-PROPRIETARY VERSION

Subject:

FCC thermal justification

This document is validated through an electronic workflow. Validation dates are stored inside the Electronic Documentation Management system.

Ind.: **A** Status: **FIN** Date: **2022-04-29** Modif./Obs.: **First Issue**

Issuer [redacted]
Technical Reviewer
Primary Author

EDM classification: **ADV-AUT**

Safety Related: **YES**

	Responsible: **DTIPL-F**	Issuing entity: **FFP**

Export Control: **AL: 0E001** **ECCN: N**

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DOCUMENT NUMBER

D02-ARV-01-198-455

PUBLIC

Info.Control: [redacted] EDM Accessibility: [redacted]

[redacted]

VALID

REVISIONS

IND REV	RELEASE DATE	PARAGRAPH	SCOPE OF THE REVISION
A	See Cover Page		Original issue, replacing former chapters 2.2-1 (PVED DC 04 055) and 2.2-2 (NEPL-F 2018 DC 152)

SUMMARY

This document presents all the thermal analyses related to the thermal justification for the FCC transport containers in the regulatory thermal test. In this respect, CFD simulations are performed in order to assess the thermal behavior of the container under accident conditions. Thermal performance is assessed using the version 2019.2 of the three-dimensional thermal and fluid mechanics code STAR-CCM+.

This document details the study conditions as well as the results of the simulations performed in the frame of the regulatory thermal criteria defined by the IAEA. With the aim of determining the worst-case scenario, twenty-five simulations were carried out related to sensitivities to numerical parameters, the transported kind of assembly, the material properties, the three-dimensional effects, the plenum zone, the deformation of the assembly and transport in a rod box. The two worst-case configurations are identified for a transport of a 17x17 assembly without deformation in the plenum zone of the top end of the assembly with pre-oxidized M5® and Zircaloy-4 claddings. The maximum computed cladding temperatures are respectively equal [redacted] for Zircaloy-4 and [redacted] for pre-oxidized M5®.

KEY WORDS

FCC, fire test, CFD

ABBREVIATIONS

IAEA	International Atomic Energy Agency
ACT	Accident Conditions of Transport
CFD	Computational Fluid Dynamics

[redacted]

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AL: 0E001 ECCN: N

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0. REFERENCES

[1] Regulations for the Safe Transport of Radioactive Materials
2018 edition of Requirements No. SSR-6 – IAEA Safety Standards Series.

[2] D02-ARV-01-155-263 B FIN
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1. INTRODUCTION

The FCC transport container for UO_2 new fuel assemblies (FCC3 and FCC4) developed by Framatome must meet the transport regulatory requirements defined by the AIEA. This report therefore provides elements for the justification of the thermal resistance of the container with regard to the fire test. This fire test consists of a heating phase at $800°C$ for thirty minutes followed by a cooling phase, the procedure is defined according to the Regulations for the Safe Transport of Radioactive Materials issued by the AIEA, see reference [1].

The demonstration is based on CFD simulations (Computational Fluid Dynamics) allowing to simultaneously solve equations governing fluid dynamics and the thermal behavior of the fluid and solids. The calculations are performed using STAR-CCM+ version 2019.2 which has been subject to a physical validation process, see references [2] and [3].

The numerical approach developed is based on penalizing hypotheses for the computational domain and for the boundary and initial conditions on one hand, and on many sensitivities with the aim of determining the worst-case configuration on the other hand. The latter aim to examine the impact of the cladding properties (Zy-4 or M5®), the kind of transported assembly (rods array), the potential deformation of the assembly, three-dimensional effects, the impact of plenum zones or transport of rods in a dedicated box. For all the simulated cases, the analysis focuses the temporal evolution of the cladding temperature, and the aim is to find the configuration that yields the highest cladding temperatures.

The first part of this document provides a description of the involved physical phenomena in the context of the fire test, the applied hypotheses, and the selected configurations. In the second part, the used modelling is detailed, and the results of dedicated sensitivities for model verification are provided. Lastly, the final part is dedicated to sensitivities to the kind of transported assembly, material properties, three-dimensional effects, plenum zone, assembly deformation and transport of unassembled rods in a rod box.

2. PHENOMENOLOGY AND ASSUMPTIONS

2.1. Description of the regulatory fire test

The regulatory fire test is described in the Regulations for the Safe Transport of Radioactive Materials (see Article 727 in the reference [1] and the transposition in Appendix A) with the following details:

- The specimen needs to be initially in thermal equilibrium for an ambient temperature of $38°C$, for sunlight exposure conditions with a solar radiation of $400\ W/m^2$ for 12 hours per day.
- The fire phase lasts 30 minutes, *i.e.* 1,800 seconds. During this period the specimen is exposed to flames with a temperature of $800°C$ and an emissivity of [redacted]. The absorptivity of the walls, taking account of the potential presence of soots deposits on the surfaces, is equal to [redacted]. The heat transfer coefficient between the flames and the walls is specified as [redacted] $W \cdot K^{-1} \cdot m^{-2}$.
- The cooling phase starts after 30 minutes of the fire phase, the external conditions are then the same as the initial conditions. The cooling phase continues as long as there is no significant decrease of the temperatures at all points on the specimen.

2.2. Dominant physical phenomena

The diagram below illustrates the internal equipment of the container without its shell, under conditions of the transport of two fuel assemblies. In transport configuration, the assembly is placed in the internal equipment consisting of a frame and is protected by the doors attached to the frame. The right half of the internal equipment represents a reference zone outside the grids or the nozzles while the left half shows the holddown system using two pads that presses a fuel assembly grid against the frame. All the physical phenomena involved in the fire test and impacting the thermal resistance of the claddings are outlined below.

PROPRIETARY FIGURE

Figure 1: Diagram of heat transfers

The main physical phenomena are the followings,

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assembly and for any type of cladding material, except for cladding with chromium coating, which is inert to oxidation.

Lastly, the transported fuel assemblies have not yet been irradiated, and the thermal output of the pellets is assumed to be negligible.

2.3. Selection of the envelope array

A comparative analysis is carried out on the different arrays likely to be transported within FCC containers, and the comparison is aimed at determining the array that would be the most severe in terms of thermal loading (fire) under Accident Conditions of Transport (ACT). The following six arrays are examined:

- For the FCC3 container, 14x14, 15x15 and 17x17.
- For the FCC4 container, 16x16, 17x17 and 18x18.

This entails performing a comparative analysis of the various arrays. The comparison is essentially based on geometric considerations with a direct impact on the predominant physical phenomena discussed above. The comparative analysis concerns:

- The geometry of the different arrays (contents).
- The geometry of the different cavities (containers).
- Resulting gaps (container/content, between rods, etc.).
- Relationships between thermal loading (heated surface – skins of doors and frame) and thermal inertia (proportional to the mass of fuel transported).

Table 1 summarizes all the parameters concerning six types of array. From a macroscopic standpoint, the geometrical parameters of the arrays are close. However, three criteria (highlighted in Table 1) indicate that the 16x16, 17x17 or 18x18 arrays (FCC4) would be slightly more severe from a thermal point of view:

- The available space between rods is large for the 16x16 array ([redacted] mm), and this array makes it easier for hot gas to penetrate into the cavity, this space is slightly smaller than that of the 15x15 array ([redacted] mm), but the latter has less severe values for other parameters such as the driving pressure provided by the equation Eq. 1 or the space between cavity and rods,
- The top space between the internal skin of the cavity and the top row of rods is [redacted] mm for the 16x16 array. This space is slightly smaller than that of the 18x18 array ([redacted] mm), but the latter has less severe values for other parameters such as the space between rods,
- The driving pressure is maximum for the 16x16 and 18x18 arrays ($\Delta H =$ [redacted] mm).

The comparison of relationships L/D_h corresponding to the channel of the space between the door and top part of the assembly (top space between cavity and assembly) also highlights the 16x16 and 18x18 assemblies as the most critical. These relationships are minimal in particular for arrays with a maximum driving term $\Delta P =$ [redacted] (16x16 and 18x18 arrays), the combination of these two effects taking the form of a more severe convective flowrate for the heating of the rods.

It can thus be stated that, considering the plenum zone of the rods, the most critical case is the one with the smallest rod thickness, *i.e* [redacted] mm (envelope value) for 17x17, to be compared with [redacted] mm or [redacted] mm respectively for the 18x18 or 16x16 arrays. The rod corresponding to the 17x17 or 18x18 array has a minimum diameter ([redacted] mm) that minimises thermal inertia.

The weighting of each of these criteria, however, remains difficult to assess, so the decision was made to examine the 16x16, 17x17 and 18x18 arrays (type FCC4) in the reference section in order to refine the comparison and confirm the most severe configuration. FCC3 type arrays covered by those of the FCC4 type are not studied.

2.4. Structural hypotheses

2.4.1. Results from drop tests

The thermal test as defined by the regulations needs to be consecutive to the mechanical tests to ensure that these tests are combined in the most damaging way for the package. At the end of the mechanical tests, there was no cladding failure. However, these mechanical tests performed on a full-scale specimen container caused:

- opening or closing of some gaps between the doors and the frame,
- piercing of the external shell, see Section 2.4.2, and
- deflection and reduction of spaces between fuel assembly rods (compacting), see Section 2.4.3.

Figure 2 shows the changes in the frame/door gaps reported on the FCC specimen following the mechanical test. The nominal frame/door gaps are equal to [redacted] mm. The recorded data shows a maximum increase in gaps of [redacted] mm observed on sections of [redacted] m. The increase appears on one of the frame/door gaps (gap "C" in Figure 2), as the diagonally opposite gap (gap "D") tends to close up slightly. For conservative purposes, the frame/door gaps considered are the followings:

- Frame/door gap for zone "C" of [redacted] mm (nominal [redacted] mm plus an increase of [redacted] mm due to deformations during the container drop).
- Nominal/maximum frame/door gap "D" of [redacted] mm.

These gaps are assumed to extend over the whole length of the internal equipment, which constitutes a conservative representation of the reality.

2.4.2. Represented solid structures

The following solid structures are taken into account for the simulations,

- The frame and doors of the internal equipment (steel and resin structures).
- The assembly composed of an array of fuel rods containing fissile material (UO_2). Three arrays are examined: 17x17, 16x16 and 18x18. In addition, the transport of rods contained in a fuel rod box is analyzed, with several filling configurations for the box.

The external shell is not modelled explicitly. In fact, after the drop test onto a bar, examination of the container shows a small hole pierced through the shell. A hole of this type could lead to flames entering and reaching the equipment. Also, for conservative purposes, the shell is not considered during the fire phase (application of fire conditions directly to the whole of the external skin of the internal equipment). This assumption is severe for the following reasons:

- The shell, even when pierced, effectively protects the internal equipment from flames radiation.
- The presence of a single hole on the shell significantly limits the quantity of hot air likely to get into the equipment, as conservation of mass ensures that the incoming and outgoing air flows go through the same orifice.

However, in the cooling phase, in order to minimize heat losses, the presence of the shell is taken into account (equivalent thermal resistance producing a slowdown of the cooling phase), but its inertia is not considered during the cooling.

2.4.3. Deformation of the assembly

The mechanical drop tests showed a change in the external dimensions of the fuel assembly. Figure 3 shows axial changes in grid widths and heights after drop tests on FCC3 and FCC4 containers. At the end of the drop test, there is a compacting of the assembly, *i.e.* reduction in grid height and slight increase in width, observed for both containers. The points with the shortest height and the greatest width are used to obtain the most compacted array, *i.e.* grid [redacted] for the FCC3 and grid [redacted] for the FCC4. The greatest deformation is obtained for grid [redacted] and this situation will be examined later.

2.4.4. Container position considered after drop

The container is assumed to be tilted at [redacted] degrees to the vertical, as represented below.

PROPRIETARY FIGURE

The horizontal flat lying container position is the most unfavorable position because a tilting of the axis would cause hot air to accumulate in the top part of the package. Under these conditions, the heat flow is no longer distributed over the rods closest to the door/frame gaps but over a larger number of rods, which limits the maximum cladding temperature. In addition, a tilting of the axis would not heat the whole length of the rod.
Rotation to [redacted]° leads to the most unfavorable position because convection is produced by the difference in density due to air temperatures. Gravity determines the direction in which the convective flows spread. Tilting at [redacted]°, as illustrated above, is used to maximize the difference in driving pressure.
This position implies that top-down flow is established, which empties out the denser cold air contained in the cavity. With regard to the orientation chosen, the largest space "C", later referred to as the top space, [redacted] allows hot air to come into the container, and the smallest space "D" of [redacted] (bottom space) allows it to escape.

2.4.5. Initial state

The initial conditions are specified in the regulatory requirements, see Section 2.1. The equilibrium temperature of the container shell surface is evaluated on the basis of the following elements:

- in steady-state operating conditions,
- with the assumption of an incidental solar flux of [redacted] with the external shell surface cooled by natural convection and radiation with an infinite medium considered [redacted] (ambient air surrounding the package),
- with the internal shell surface assumed adiabatic.

The equilibrium temperature obtained is [redacted]$°C$. This value is applied conservatively and applied as the initial temperature for all structures representing the internal equipment. [redacted]

3. MODEL

3.1. Organization of the cases

All the cases analyzed are listed in Table 2, they are organized as follows:

- Case 1 is a two-dimensional reference case for which all sensitivities are implemented. Its modelling is described in the following sections, the other cases implemented maintain the same basis for modelling, and only the modifications made to the reference case will be described in Parts 4 and 5.
- [redacted]
- Sensitivity to the type of assembly is implemented via Cases 9 (16x16 array) and 10 (18x18), see Section 5.1
- Cases 11 to 14 examine the impact of material properties on cladding performance, see Section 5.2. Case 11 therefore examines M5® cladding, Case 12 pre-oxidized M5® cladding, Case 13 rods with thickened pellets and Case 14 chromium-coated M5® cladding.
- The three-dimensional and thermal bridge effects are examined by Case 15 (bottom area of assembly) and by Cases 16 and 17 (top area of assembly), see Section 5.3 and Appendix D.
- Cases 18 to 22 study the impact of a deformation of the assembly, see Section 5.4. Cases 18, 19 and 20 examine theoretical deformations leading to, respectively, a uniform enlargement of the bundle, a diagonal separation, and blocking by rods of the door/frame gaps. Lastly, compacting of the bundle is examined by Cases 21 and 22.
- The situation with transport of rods in a rod box is analyzed with Cases 23, 24 and 25 with two opposite rod box filling situations (23 vs. 24) and a variant of the modelling of the rod box (24 vs. 25), see Section 5.5.

3.2. Computational domain

Figure 4 shows the whole computational domain and because of the geometry symmetry only half of the equipment is represented. The fluid domain concerns the air circulating inside (in red on Figure 4-a) and outside the internal equipment (in blue on Figure 4-a). The fluid domain outside of the internal equipment provides a connection between the entry point and exit point of the internal cavity of the container. It is sufficiently large to limit air velocities and allow unbiased application of modelling of a piezometric pressure type condition on one hand, and to avoid generating pressure losses that would be favorable to the flowrate in the cavity, on the other hand.

The solid domain, represented in Figure 4-b, incorporates the following elements:

- fuel rod cladding,
- stainless steel plating around the frame and doors,
- resin included in the frame and in the doors, and,
- UO_2 pellets in the rods and air contained in the guide tubes.

The two-dimensional geometry is extruded in the axial direction on a single cell layer for the purpose of solving balance equations using the STAR-CCM+ code.

3.3. Boundary and initial conditions

3.3.1. Fluid domain

The boundary conditions relative to the fluid domain are detailed in Figure 5-a and listed below:

- A piezometric pressure (green surface in Figure 5-a) is imposed on the top part of the fluid domain.
- The walls of the fluid domain outside of the cavity (orange surfaces in Figure 5-a) are slip so that the air flow outside of the cavity does not entail a pressure loss. In this area, an enthalpy source term is applied in order to sustain air temperature at $800°C$ during the fire phase and then [redacted]$°C$ during the cooling phase. The walls are adiabatic, and the conjugate heat transfer with the steel plating is deactivated.
- The walls of the fluid domain inside the cavity (black surfaces in Figure 5-a) are no-slip and hydraulically smooth. The conjugate heat transfer with the rod cladding and with the steel plating is activated.

The emissivity values applied for the various boundary conditions are described in Section 3.4.2. The transverse surfaces on both sides of the extruded two-dimensional geometry are defined as symmetries. Under the initial conditions, the air is still, at a fixed temperature of [redacted]$°C$ inside the cavity and $800°C$ outside, see Section 2.4.5.

3.3.2. Solid domain

The boundary conditions for the solid domain are illustrated in Figure 5-b and listed below:

- The surfaces of the steel plating outside of the cavity (represented in green and blue on Figure 5-b) do not have a conjugate heat transfer with the adjacent air as mentioned above. A penalizing thermal flux is nonetheless prescribed on these surfaces. Appendix C describes the modelling used for the fire and cooling phases. The key points in this modelling are listed below:
  - During the fire phase, the heat transfer coefficient is fixed at [redacted] $W \cdot K^{-1} \cdot m^{-2}$ and the associated temperature is $800°C$ in accordance with the regulatory requirements.
  - During the cooling phase, a more realistic approach is adopted, and the presence of the external shell (not accounted for during the fire phase) is taken into account in order to slow down the cooling of the container. The associated temperature is the initial temperature of [redacted]$°C$. For conservative purposes, only the top surface contributes to cooling (green surfaces on Figure 5-b), whilst the heat transfer coefficient on the bottom surface (blue surfaces) is nil during this phase.
- The surface separating the internal equipment into two sides (represented in red on Figure 5-b) is defined as a symmetry.
- The interfaces between solids (steel/resin, cladding/UO_2) are in conjugate heat transfer by conduction. It should be noted that a thermal resistance representative of the helium gap is defined in the interface between the cladding and the UO_2 pellets, see Section 0.
- The interfaces between the claddings and air are defined in conjugate heat transfer, taking account of the oxidation power defined in Section 3.4.4.

The emissivity values applied for the various boundary conditions are detailed in Section 3.4.2. The transverse surfaces on both sides of the extruded two-dimensional geometry are defined as symmetry. Under the initial conditions, the temperature of all the solid structures is fixed at [redacted] $°C$.

3.4. Modelling of the physical phenomena

3.4.1. Buoyancy

The driving force of the flow is gravity, which acts according to the orientation defined in Section 2.4.4, and the buoyancy effects are therefore considered.

The flow in the cavity of the internal equipment is generated by the difference in density between the inside and outside of the cavity, and the flowrate of movement inside the cavity is the result of:

[redacted]

3.4.2. Radiation

The domain relative to the air is assumed to be transparent and radiation is modelled using the [redacted]

PROPRIETARY TABLE

The table above describes all the emissivity values applied at the boundaries of the fluid and solid domains. In accordance with the regulations, the boundaries of the fluid domain outside of the cavity (green and orange surfaces on Figure 5-a) are related to an emissivity fixed at [redacted] in the fire phase. In the cooling phase, a standard emissivity of [redacted] for the steel is applied, in accordance with the external shell taken into account during this phase. The emissivity of the plating surfaces outside of the cavity is fixed at [redacted] during the fire phase in accordance with the regulatory requirements. For conservative purposes, a standard emissivity of [redacted] for the steel is applied during the cooling phase.

[redacted]

3.4.3. Helium gaps

The helium layer located between the fuel pellets and the cladding is modelled by an [redacted]. In Case 1, for which the gap is [redacted] mm, this thermal resistance is [redacted] Lastly, the radiation between the pellets and the internal surfaces of the cladding [redacted], which is conservative, since the radiation allows the [redacted]

3.4.4. Oxidation of the claddings

Oxidation of the claddings leads to an exothermic reaction between the oxygen in the air and the zirconium contained in the cladding alloy. The oxidation [redacted] Appendix C describes in detail the model implemented in STAR-CCM+ and based on the experimental results of Duriez *et al.*, see reference [4].

3.5. Grid

3.6. Material properties

The physical properties of the solids (thermal conductivities, densities, and heat capacities) vary according to temperature, except for the resin where the properties applied are those that correspond to the temperature of [redacted] $°C$. All the properties of the solids are reported in Table 3. Reference case 1 is dedicated to claddings with the Zircaloy-4 alloy. The properties of M5®, pre-oxidized M5® and Chromium coated cladding are used for specific cases reported in Section 5.2.

3.7. Numerical aspects

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4. VERIFICATION OF THE NUMERICAL MODEL

4.1. Reference case – Case 1

4.1.1. Qualitative aspects

Figure 7 shows velocity fields for different times. Given the container orientation in relation to gravity, see Section 2.4.4, the flow is established during the fire test in the direction of gravity. The hot air therefore goes into the top gap "C", and the cold air, initially contained in the cavity, is flushed by the bottom gap "D". The hydraulic path in the cavity around the cladding is distributed within the bundle, with the diagonal path between the inlet and outlet of the cavity being one of the hydraulic paths. As the transient progresses, the air in the cavity is progressively heated, and the difference of density between the inside and outside of the cavity is reduced. This leads to a decrease in the flowrate of the movement within the cavity. At the start of the cooling phase, the inversion of the temperatures outside of the cavity leads to an inversion of the driving term, which causes an inversion of the flow direction.

Figure 8 shows temperature fields at different times. In the fire phase, two hotter zones appear in the cavity; this concerns the cladding located close to the gaps. In the top gap “C”, the cladding is affected by the radiation emitted by the flames and by the hot air circulating nearby. In the bottom gap “D”, the cladding is heated mainly by the radiation. It should be noted that the hot front is moving in the cavity as the fire test progresses, and only fifteen rods located close to the top gap are significantly heated after thirty minutes of the fire test. Outside of these two hot zones close to the gaps, the other claddings are not very exposed. In particular, the claddings located in the center of the assembly remain at a temperature close to the initial state, at the end of the fire test.

4.1.2. Quantitative aspects

Figure 9 shows changes in mean and maximum temperatures of the five hottest claddings at the end of the fire test. Only three claddings have a maximum temperature exceeding [redacted] $°C$, *i.e.,* the claddings C1, C2 and C3, the closest claddings to the cavity inlet in the fire phase. The maximum temperatures of these claddings respectively reach [redacted] $°C$, [redacted] $°C$ and [redacted] $°C$, see Table 5. The period for which the cladding temperature of [redacted] $°C$ is exceeded lasts about [redacted] minutes.

The cladding close to the lower gap, much colder than that close to the top gap, does not exceed [redacted] $°C$ at the end of the fire phase. During the cooling phase, the hottest cladding cools down quickly, as these claddings give out more than [redacted] $°C$ in [redacted] minutes.

4.2. Sensitivity to the grid resolution – Cases 2 and 3

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4.3. Sensitivity to the temporal discretization – Cases 4 and 5

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4.4. Joint sensitivity to discretization in space and in time – Case 6

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4.5. Sensitivity to turbulence – Case 7

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4.6. Sensitivity to the emissivity of the internal walls – Case 8

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5. SENSITIVITIES

5.1. Sensitivity to the array – Case 9 and 10

The FCC containers are likely to transport different types of assembly. Section 2.3 provides a macroscopic analysis aiming to identify the most penalizing array. The 17x17, 16x16 and 18x18 arrays have thus been selected without any obvious hierarchy being established. One here proposes to assess the 16x16 and 18x18 arrays *via* Cases 9 and 10 respectively. The computational domains corresponding to the 16x16 and 18x18 arrays are displayed in Figure 11. The assumptions, numerical parameters, boundary and initial conditions, and selection of spatial and temporal discretizations are strictly identical for the three arrays.
The results obtained in terms of maximum cladding temperature are provided in Table 7. The temporal evolutions of cladding temperature, provided in Appendix E - Figures E9 and E10, show that the thermal dynamic of the cladding is similar for the three examined arrays. Only minimal differences appear in terms of maximum temperatures. More specifically, these cases show that the 17x17 array is the most conservative geometry. The maximum temperatures of the hottest cladding for the 17x17 (Case 1), 16x16 (Case 9), and 18x18 (Case 10) arrays are respectively [redacted] C, [redacted] C, and [redacted] C.

5.2. Sensitivity to material properties

5.2.1. M5® cladding – Case 11

Case 11 differs from reference case 1 by the change of the material forming the cladding, with the M5® material replacing the Zircaloy-4. The model modifications consist in changing the cladding properties and in specifying the values relative to M5® provided in Table 3. In addition, the characteristic parameters of the oxidation of the cladding material are also adapted to the M5® material, see Appendix B.

The results obtained in terms of maximum cladding temperature are reported in Table 8. The effect on the cladding temperatures induced by this material modification is almost insignificant as the maximum difference between the maximum temperatures of the ten hottest claddings does not exceed [redacted] $°C$. The Case 1 configuration remains nonetheless more conservative for the ten hottest claddings.

These results are consistent with the fact that the physical properties of Zircaloy-4 and the material M5® are similar for similar temperatures of [redacted] $°C$. The temporal evolutions of the cladding temperatures, provided in Appendix E - Figure E 11, show that the results are very similar for both cladding materials. From a thermal point of view, the results obtained with both cladding materials (Case 1 and Case 11) are equivalent.

5.2.2. Pre-oxidized M5® cladding – Case 12

This case is differentiated from the reference case (Case 1) by the replacement of the material forming the cladding, with the pre-oxidized M5® replacing Zircaloy-4, refer to the physical properties provided in Table 3.

In addition, the characteristic parameters of the oxidation of the cladding material are changed relative to Case 1. The values used for M5® material (Case 11) are also retained, for conservative purposes, in Case 12 with pre-oxidized M5® due to the lack of available data.

The effect on the cladding temperatures produced by this change of material is also insignificant here. The hottest cladding C1 increases by [redacted] $°C$ which, due to rounding, results in an increase of [redacted] $°C$ as shown in Table 8. The analysis of the other cladding shows a decrease to [redacted] $°C$. The temporal evolutions, available in Figure E 12 in Appendix E, show that the dynamic behavior is very similar to the reference case. In conclusion, both cases obtained with the [redacted] cladding materials (Case 1 and Case 12) are equivalent from the thermal point of view.

5.2.3. Zy-4 cladding with thickened pellets – Case 13

This case differs from the reference case by geometric modifications of the pellet and the cladding as listed in the table below:

	Case 1	Case 13
Rod diameter [mm]	PROPRIETARY TABLE	
Cladding thickness [mm]		
Pellet diameter [mm]		
Helium gap [mm]		

In addition to the geometrical modifications applied to the computational domain, the thermal resistance related to the helium gap between pellet and cladding is also reduced by a factor close to [redacted] due to the reduction of the helium gap thickness. This thermal resistance is equal to $R_{Helium} =$ [redacted] instead of [redacted] considered previously.

The differences obtained for the maximum cladding temperatures between both cases 1 and 13 are smaller than [redacted] $°C$ for the three hottest claddings, see Table 8 and Appendix E - Figure E 13. In particular, the maximum temperature of the hottest claddings varies from [redacted] $°C$ (Case 1) to [redacted] $°C$ (Case 13). [redacted]. From a thermal point of view, both effects compensate each other, and the results obtained are close to the reference case.

5.2.4. Chromium-coated M5® cladding – Case 14

Case 14 is differentiated from Case 1 by:

- Replacement of the properties of Zircaloy-4 by those of the material M5®.
- The addition of a chromium layer of 30 µm thickness around the cladding with the thermal properties described in Table 3.
- The removal of the thermal loading related to oxidation because of the reaction inhibition.

The results obtained are provided in Table 8 and it may be noted that the temperatures of the ten hottest claddings obtained for Case 13 are lower than the temperatures obtained for Case 1. In particular, the maximum temperature of the hottest cladding element (C1) changes from [redacted] $°C$ (Case 1) to [redacted] $°C$ (Case 14). The results obtained for Case 14 are less severe than for Case 1, as the chromium layer has a significant and beneficial influence on the maximum cladding temperatures.

Indeed, the chromium layer leads to the following beneficial effects:

- The chromium layer annihilates the oxidation by hot air of the cladding material. Consequently, the cladding is not subjected to additional thermal loading relative to the exothermic oxidation reaction.
- The chromium layer leads to an increase of the thermal inertia of the cladding. This is expressed in the form of the product $\rho \times V \times Cp$, with ρ , V and Cp respectively related to the density, volume and specific heat of the material considered. Based on cladding made of M5® in a 17x17 assembly and thermal properties in Table 3

taken at 800°C, the thermal inertia of the cladding together with its chromium coating with thickness of 30 μm increases by [redacted]% relative to standard cladding without coating. The increase in thermal inertia is favorable to the thermal resistance of the cladding as it slows down the increase in temperature during the fire phase. Nevertheless, the temporal evolutions of the cladding temperatures provided in Appendix E - Figure E 14 show that the slowdown of heating of the cladding due to the increase in inertia is limited.

- Lastly, the chromium layer acts as an insulation between the cladding and the surrounding hot air. The presence of the chromium layer is therefore favorable to the limitation of heat transfer by conduction, even if this effect is very limited due to the high conductivity of chromium (see Table 3) and the small thickness of the coating.

5.3. Investigation of three-dimensional effects

5.3.1. Investigated cases

Three-dimensional simulations are performed in addition to the two-dimensional simulations for FCC4 packaging in a 17X17 array. The purpose of these calculations is to investigate fuel assembly extremities where singularities can change the thermal behavior observed on the two-dimensional cases. Two particular areas of the packaging are examined:

- Case 15 corresponds to the bottom end area of the assembly. The computational domain includes the container end plate, the bottom nozzle, the first support grid with its holddown system using pads and stiffeners located in the frame and the door, and a downstream rod length corresponding to the distance between grids. This case is described exhaustively in Appendix D – Section D1 and the main results are provided in Section 5.3.2.
- Cases 16 and 17 aim to deal with the thermal behavior of the package on the top of the assembly. The computational domain concerns the container end plate, the top nozzle, the last support grid with its holddown system, a rod length upstream of the final grid corresponding to a span length. Case 17 differs from Case 16 in the cladding material, with pre-oxidized M5® for Case 17 as against Zircaloy-4 for Case 16. It is assumed that the computational domain for the cladding is related to the plenum zone where the UO_2 pellets are replaced by helium. This assumption is conservative as the plenum zone considered is longer than it is in reality. Appendix D – Section D2 describes the used modelling, with all results obtained. Section 5.3.3 provides the main results.

5.3.2. Bottom of the assembly – Case 15

Case 15 investigates the singularity relative to the rod plugs where large convective flux may develop due to the available space between the plugs and the nozzle, on one hand and the potential thermal bridges on the other hand. Two types of thermal bridges listed below are modelled:

- On the first support grid, the grid holddown system used with two pads, two locking screws carrying through the door as well as stiffeners within the frame and the door constitute potential thermal bridges from the outer surface of the container and the cavity.
- On the bottom nozzle, the four nozzle legs are in contact with the end plate and can transfer heat axially by conduction.

The main conclusions with regard to the phenomenological aspects are as follows,

- At the vicinity of the top gap, the presence of the grid is favorable to the thermal resistance of the cladding insofar as it constitutes a screen to the transverse convective flux of hot air.
- At the vicinity of the bottom gap, the thermal bridge relative to the holddown system leads to higher cladding temperatures in this area compared to the two-dimensional case.
- The thermal bridges related to the nozzle legs are negligible due to the high thermal inertia formed by the end plate and nozzle.
- The maximum cladding temperatures are reached on the farther section from the grid, the latter acts this favorably here on the thermal resistance of the claddings.
- The area related to the plugs is submitted to larger convective flux than in the reference section. The temperatures at the end of the fire phase are distributed far more uniformly than in the reference zone.

From a quantitative point of view, the main conclusions are as follows:

- The maximum cladding temperatures are smaller than for the reference case.
- The maximum temperatures provided in Table 9 show that the maximum temperature is equal to [redacted] $°C$ for Case 15 to be compared with [redacted] $°C$ for the two-dimensional Case 1.

5.3.3. Top of the assembly – Cases 16 and 17

Cases 16 and 17 aim to deal with the thermal behavior on the top of the assembly. Various effects, reported below, are examined:

- Replacement of UO_2 pellets with helium (reference zone vs. plenum zone)
- Two types of thermal bridges related to the holddown system of the grid and to the tightening screw between the end plate and the top nozzle.
- The singularity related to the rod plugs leading to space with minimal obstruction between the top nozzle and the plugs featured.
- The impact of the cladding material on the comparison of Case 16 (Zy-4) with case 17 (pre-oxidized M5®).

The main conclusions regarding Case 16 are as follows,

- Replacement of UO_2 with helium leads to a decrease of the thermal inertia which leads in larger cladding temperatures at the end of the fire phase.
- At the vicinity of the top gap, the grid acts favorably in terms of the thermal resistance of the cladding located in this zone.
- At the vicinity of the bottom gap, the thermal bridges associated with the holddown system of the grid lead to a severe thermal loading, with one cladding element ([redacted]) exceeding [redacted] $°C$.
- The tightening screw has a negligible impact with regard to the thermal behavior of the claddings.
- There are two critical zones from the point of view of the thermal loading on the claddings: firstly, the zone located close to the top gap for the section farther from the grid and secondly the zone within the grid close to the bottom gap.
- The space between the plugs in the cladding and the nozzle is subjected to larger convective fluxes. The cladding temperature field at the end of the fire phase is

distributed more uniformly than for other locations within the assembly but this zone is not one of the critical zones mentioned above.

- The cladding material has a low impact on the thermal resistance of the cladding, as mentioned in Section 5.2.2.

From a quantitative point of view, the main conclusions are as follows:

- The maximum cladding temperatures of Cases 16 and 17 are higher than for reference case 1.
- Four claddings, [redacted] and [redacted] exceed [redacted] at the end of the fire phase.
- The maximum temperatures provided in Table 9 for Case 16 show that the maximum temperature is equal to [redacted] $°C$ for Case 16 to be compared with [redacted] $°C$ for Case 1. For Case 17, the maximum temperature is equal to [redacted] $°C$.

5.4. Sensitivity to deformation of the assembly

5.4.1. Definition of geometry

The drop test results lead to the conclusion that the array is deformed in the event of a drop. This outcome is here dealt with from a thermal point of view, with consideration of various situations illustrated in Figures 12 and 13.

- Homogenous expansion: it is considered that the movement of the rods is identical in all directions, calculation Case 18, see Figure 12-a.
- Heterogeneous expansion: the displacement of the rods depends on rod positions (Case 19), as displayed in Figure 12-b. One here investigates the diagonal division of the array, which limits the head losses across the cavity.
- The obstruction of both gaps: Based on the array expanded homogenously, it is assumed that four rods almost completely block the inlet and outlet of the cavity. This is the purpose of Case 20, for which the solid computational domain is represented in Figure 12-c.
- Direct implementation of the compacting measured after the drop test. The largest displacement is retained, *i.e.,* the one for grid 9 of the FCC4 container, see Section 2.4.3. This deformation leads to compacting in one direction and slight elongation in the other. Two cases, 21 and 22, are examined, with a difference in the compacting direction, horizontal for Case 21, and vertical for Case 22. The computational domains are displayed in Figure 13.

5.4.2. Homogenous expansion – Case 18

Regarding the homogenous expansion of the array, see Figure 12-a, the rods displacement is chosen such that the rows located at the bottom and at the left are in contact with the wall of the frame/door. In this case, the pitch of the array is [redacted] instead of [redacted] for the non-expanded array. It should be noted that the rods located on the highest row and the rightmost column (see Figure 12-a) are not in contact with the wall. In fact, if they were, the bottom and top spaces would be blocked, and the fluid would no longer be able to enter into the cavity. The homogenous expansion considered here leads to exposure of the rods closest to the cavity inlet, but it also increases the head losses. The results obtained following a homogenous expansion of the array (see Table 10) are as follows:

- The maximum temperatures of the two hottest claddings [redacted] are smaller than the temperatures obtained for Case 1 by [redacted] $°C$ at [redacted] $°C$. In particular, the maximum temperature of the hottest cladding element [redacted] changes from [redacted] $°C$ (Case 1) to [redacted] $°C$ (Case 18).

- The temporal evolutions of the cladding temperatures see Appendix E - Figure E 18, do not show any significant changes in the thermal dynamics of the cladding compared to the reference case.

These results show that from the thermal point of view, Case 1 is more severe than the case with homogenous expansion.

5.4.3. Heterogeneous expansion of array – Case 19

This case is differentiated from the reference case by a change to the geometry represented in Figure 12-b. The obtained results following a heterogeneous deformation of the array (see Table 10) are as follows:

- The maximum temperatures of the five hottest claddings obtained for Case 19 are lower than the temperatures obtained for Case 1. In particular, the maximum temperature of the hottest cladding element ([redacted]) changes from [redacted] $°C$ (Case 1) to [redacted] $°C$ (Case 19), *i.e.,* a significant reduction by [redacted] $°C$.
- Figure E 19 in Appendix E shows that the hottest cladding is located at the diagonal of the assembly where the space between rods has been enlarged.
- Beyond the fifth hottest grid, the maximum cladding temperatures in Case 19 are higher than those in Case 1. The temperatures concerned are lower than [redacted] $°C$.

These results show that from the thermal point of view Case 1 is significantly more severe than the case with heterogeneous deformation.

5.4.4. Blocking of frame/door gaps – Case 20

This case differs from the reference case by a change to the geometry represented in Figure 12-c. The results obtained for a deformation of the array with blocking (see Table 10) are as follows:

- The temperatures of the three hottest claddings are lower by more than [redacted] $°C$ in relation to the temperatures obtained for Case 1.
- In particular, the maximum temperature of the hottest cladding element [redacted] for Case 1 *vs.* [redacted] for Case 20) changes from [redacted] $°C$ (Case 1) to [redacted] $°C$ (Case 20). The hottest claddings are located close to the bottom and top gaps, see Figure E 20 - Appendix E.
- Beyond the fifth cladding element the maximum cladding temperatures with blocking are lower by at least [redacted] $°C$ in relation to the temperatures obtained without blocking (Case 1).

The results obtained show that from the thermal point of view Case 1 is significantly more severe than the case with blocking of the inlet and outlet of the cavity (Case 20).

5.4.5. Compacting of the array – Case 21 and 22

Modifications of the geometry following crushing of the assembly are here studied. Two sensitivities are defined according to whether the compacting is horizontal (Case 21) or vertical (Case 22). These two cases incorporate the maximum deformation discussed in Section 2.4.3. For Case 21, therefore, the rod pitch is fixed at [redacted] in the horizontal direction and [redacted] in the vertical direction, and the directions are reversed for Case 22 as displayed in Figure 13.

The results obtained for lateral crushing are as follows (see Table 10 and Appendix E - Figure E 21):

- The maximum temperature of the hottest cladding element [redacted] changes from [redacted]$°C$ (Case 1) to [redacted]$°C$ (Case 21).
- Beyond the hottest cladding element [redacted]) the maximum cladding temperatures with lateral crushing are lower by at least [redacted]$°C$ than the temperatures obtained without deformation (Case 1).
- The comparison of the number of claddings exceeding [redacted]$°C$ is three for Case 1 and one for Case 21.

The results obtained for a vertical crushing (Case 22) are as follows:

- The temperatures of the ten hottest claddings are lower by more than [redacted]$°C$ in relation to the temperatures obtained for Case 1.
- The hottest cladding is cladding element [redacted] almost obstructing the bottom space (see Appendix E - Figure E 22). Nevertheless, this cladding has a maximum temperature of [redacted]$°C$ (Case 22) to be compared with [redacted]$°C$ for the hottest cladding element [redacted] of Case 1.

The analysis of cases 21 and 22 shows that compacting has on average a favorable effect on the thermal resistance of the cladding due to the increase in pressure drop and slowdown in flowrate of the hot air circulation. Nevertheless, local effects can lead to more severe results, as is the case for [redacted] cladding in case 21. Nevertheless, the effect remains confined to a single cladding element, as the temperatures of the rest of the cladding are much lower than for the reference case 1. Reference case 1 remains thus the most penalizing case.

5.5. Investigation of the transport of non-assembled rods in a rod box

5.5.1. Introduction

This section investigates the situation of transporting single rods placed in a rod box. There are three cases proposed that are related to sensitivities to the number of transported rods or to the modelling of the rod box:

- Case 23 examines the transport of 267 rods with diameter $9.5\ mm$ distributed over 13 rows. This situation leads to the filling up of the entire the rod box. This case is theoretical and is not a real transport situation as the total transportable mass is exceeded. The solid computational domain associated with this case is available in Figure 14-a.
- Case 24 is dedicated to a box with a single row of 21 rods, this case is conservative about the inertia of the contents of the box. The solid computational domain associated with this case is displayed in Figure 14-b
- Case 25 is a variant of Case 24 with a variant of the modelling of the rod box. The solid computational domain associated with this case is given in Figure 14-c.

The modelling of the box containing 13 rows of 267 rods assumes that the rods in the bottom row of *n* rods are held against the box due to the row above of *n-1* rods resting on the gaps between the rods. In the cases of a box containing a single row of [redacted] the rods are also considered to be held against the box.
With regard to the modelling of the rod boxes, steel plating of [redacted] of the rod box is represented. For Cases 24 and 25, the vertical walls of the rod box are as high as the stack of rods. For Case 25, the actual dimensions of the rod box are represented. The rods are held in

place by means of a system of spacers. They are not represented, given that the unfavorable effect associated with the potential thermal bridge is low in relation to the favorable effect concerning the thermal inertia contributed by these solid structures. Lastly, the air trapped between the rods is assumed to be static and is therefore modelled as solid.

5.5.2. Box of 267 rods – case 23

5.5.2.1. Qualitative aspects

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5.5.2.2. Quantitative aspects

Figure 17 shows the temporal evolutions of the temperature for the five hottest claddings. The thermal dynamics of the claddings here differs from the cases with transport fuel assembly because the temperature evolutions are almost linear.

The results in terms of maximum claddings temperatures are provided in Table 11. In the case of a filling with 267 rods distributed in 13 rows, the hottest cladding only reaches [redacted]. It should be noted that this maximum temperature is significantly smaller than the temperature of cladding [redacted] for the Case 1 *i.e.,* [redacted] This difference is mainly due to the presence of the plating which acts as a thermal shield.

The obtained results show that, from a thermal point of view, case 1 is much more severe than the case with rod boxes with a filling of 267 rods. The claddings located in a rod box are better protected from convection and radiation, due to the plating.

5.5.3. Box of 21 rods – case 24

The results obtained for a transport of 21 rods are provided in Table 11 and in Appendix E - Figure E 25. The hottest cladding here reaches [redacted] $°C$ which is more penalising than for case 23. In fact, the thermal inertia associated with the 21 rods is smaller than the transport of 267 rods. This situation is more severe than Case 23, but the reached maximum cladding temperature remains very significantly smaller than for the assembly transport (Case 1).

5.5.4. Box with 21 rods and metal structures – Case 25

Case 24 investigates the impact of the modelling of the rod box. The obtained results (see Table 11 and Appendix E - Figure E 25) are comparable to Case 24. The maximum cladding temperature is smaller than for Case 24, and the hottest cladding reaches [redacted] $°C$. This result shows that the simplified modelling of the rod box for Cases 23 and 24 is conservative.

6. CONCLUSIONS

CFD simulations have been performed using the STAR-CCM+ version 2019.2 code in order to verify the thermal behavior of the FCC container under Accident Conditions of Transport, in accordance with the regulatory safety requirements defined by the AIEA for transport. Under Accident Conditions of Transport, numerical models are established with the aim of assessing the temporal evolutions of the temperatures of the solid structures constituting the package.

The two-dimensional numerical model established for the 17X17 array in the FCC4 packaging has followed a verification process. Sensitivities to the grid and the time-step, influence of the emissivity of the cavity inner walls as well as the influence of turbulence have all been examined and they confirm the robustness of the conservative nature of the used numerical model.

The results of many sensitivities are described in this report. These sensitivities aim to examine the impact of the type of transported assembly, cladding properties, the potential deformation of the assembly, three-dimensional effects, plenum zone or even transport of rods in a dedicated box. The two worst-case configurations were identified for transport of a 17x17 assembly with no deformation in the plenum zone at the top end of the assembly with pre-oxidized M5® and Zircaloy-4 cladding. The maximum cladding temperatures are respectively [redacted] $°C$ for Zircaloy-4 and [redacted] $°C$ for pre-oxidized M5®.

Figure 2 Axial evolutions of the gaps after drop tests

PROPRIETARY FIGURE

Figure 3: Axial evolutions in grid heights and widths after drop tests of the FCC3 container (a) and FCC4 container (b)

PROPRIETARY FIGURE

[redacted]

Figure 4: Fluid computational domain (a) and solid computational domain (b) – Case 1

PROPRIETARY FIGURE

Figure 5: Boundary conditions of fluid domain (a) and solid domain (b) – Case 1

PROPRIETARY FIGURE

Figure 6: Grid – Case 1

PROPRIETARY FIGURE

Figure 7: Fluid velocity fields – Case 1

PROPRIETARY FIGURE

Figure 8: Temperature fields – Case 1

PROPRIETARY FIGURE

Figure 9: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 1

PROPRIETARY FIGURE

Figure 10: Sensitivity to the grid – Comparison of Cases 1, 2, 3 and 6

PROPRIETARY FIGURE

Figure 11: Fluid computational domain (a and b) and solid computational domain (c and d) for Cases 9 and 10

PROPRIETARY FIGURE

Figure 12: Solid computational domains for Cases 18 (a), 19 (b) and 20 (c)

PROPRIETARY FIGURE

Figure 13: Solid computational domains for Cases 21 (a) and 22 (b)

PROPRIETARY FIGURE

Figure 14: Solid computational domains for Cases 23 (a), 24 (b) and 25 (c)

PROPRIETARY FIGURE

Figure 15: Fluid velocity fields – Case 23

PROPRIETARY FIGURE

Figure 16: Temperature fields – Case 23

PROPRIETARY FIGURE

Figure 17: Temporal evolutions of the temperatures of the five hottest claddings – Case 23

PROPRIETARY FIGURE

Table 1: Comparison of arrays

<table>
<tr><th></th><th colspan="3">FCC3</th><th colspan="3">FCC4</th></tr>
<tr><th>Array</th><th>14x14</th><th>15x15</th><th>17x17</th><th>16x16</th><th>17x17</th><th>18x18</th></tr>
<tr><td>Rod length [mm]</td><td colspan="6" rowspan="25">PROPRIETARY TABLE</td></tr>
<tr><td>Number of rods</td></tr>
<tr><td>Rod length [feet]</td></tr>
<tr><td>Radius pitch [mm]</td></tr>
<tr><td>External rod diameter (mm)</td></tr>
<tr><td>Pitch / D</td></tr>
<tr><td>Space between rods [mm]</td></tr>
<tr><td>Cladding thickness [mm]</td></tr>
<tr><td>Pellet diameter [mm]</td></tr>
<tr><td>Assembly width [mm].</td></tr>
<tr><td>$\Delta P = \Delta\rho \cdot g \cdot \Delta H$ [Pa]</td></tr>
<tr><td>Number of guide tubes</td></tr>
<tr><td>External guide tube diameter [mm]</td></tr>
<tr><td>Internal guide tube diameter [mm]</td></tr>
<tr><td>Grid height [mm]</td></tr>
<tr><td>Grid thickness [mm]</td></tr>
<tr><td>Plenum length [mm]</td></tr>
<tr><td>Cavity/assembly top space [mm]</td></tr>
<tr><td>Cavity size [mm]</td></tr>
<tr><td>Cavity size / cavity/assembly top space [mm]</td></tr>
<tr><td>Cavity length [mm]</td></tr>
<tr><td>Door thickness [mm]</td></tr>
<tr><td>Door rib thickness [mm]</td></tr>
<tr><td>Frame rib thickness [mm]</td></tr>
<tr><td>Volume UO_2 [m^3]</td></tr>
</table>

Table 2: List of cases

Num.	Geometry	Cladding	$\varepsilon_{internal\ walls}$	Zone	Δx	Δt	Regime
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13			PROPRIETARY TABLE				
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							

Table 3: Physical properties for solids

Material	Temperature [°C]	Density [kg/m^3]	Thermal conductivity [W/(m.K)]	Specific heat [J/(kg.K)]
Zy-4				
M5®				
Cr				
Resin				
UO_2				
Steel				
Pre-ox. M5®				

PROPRIETARY TABLE

Table 4: Physical properties for fluids

Fluid	Temperature [°C]	Density [kg/m^3]	Thermal conductivity [W/(m.K)]	Specific heat [J/(kg.K)]	Dynamic viscosity [Pa.s]
Helium	PROPRIETARY TABLE				
Air					

Table 5: Maximum temperatures in °C of claddings for Cases 1 (reference), 2 & 3 (sensitivity to grid), 4 & 5 (sensitivity to time-step), 6 (combined sensitivity to grid and to time-step)

Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
PROPRIETARY TABLE					

Table 6: Maximum temperatures in °C of claddings for Cases 1 (reference), 7 (sensitivity to turbulence) and 8 (sensitivity to internal walls emissivity)

Case 1	Case 7	Case 8
PROPRIETARY TABLE		

Table 7: Maximum temperatures in °C of claddings for Cases 1 (17x17), 9 (16x16) and 10 (18x18)

Case 1	Case 9	Case 10
	PROPRIETARY TABLE	

Table 8: Maximum temperatures in °C of claddings for Cases 1 (reference Zy-4), 11 (M5®), 12 (pre-ox. M5®), 13 (thickened pellets) and 14 (chromium coated M5®)

Case 1	Case 11	Case 12	Case 13	Case 14
		PROPRIETARY TABLE		

Table 9: Maximum temperatures in °C of claddings for Cases 1 (reference), 15 (zone of the bottom of the assembly), 16 (plenum zone of the top of the assembly in Zy-4) and 17 (plenum zone of the top of the assembly in pre-ox. M5®)

Case 1	Case 15	Case 16	Case 17
	PROPRIETARY TABLE		

Table 10: Maximum temperatures in °C of claddings for Cases 1 (reference), 18 (homogenous expansion), 19 (heterogeneous expansion), 20 (blocking of gaps), 21 (horizontal compacting) and 22 (vertical compacting)

Case 1	Case 18	Case 19	Case 20	Case 21	Case 22
PROPRIETARY TABLE					

Table 11: Maximum temperatures in °C of claddings for cases 1 (reference), 23 (box of 267 rods), 24 (box of 21 rods) and 25 (box of 21 rods with sensitivity to the rod box modelling)

Case 1	Case 23	Case 24	Case 25
PROPRIETARY TABLE			

AL: 0E001 ECCN: N

Appendix A: Extract from IAEA guide SSR-6, 2018 edition

VALID

Article 727 of IAEA SSR-6, 2018 edition

728. Thermal test. The specimen shall be in thermal equilibrium under conditions of an ambient temperature of 38°C, subject to the solar insolation conditions specified in Table 12 and subject to the *design* maximum rate of internal heat generation within the *package* from the *radioactive contents*. Alternatively, any of these parameters are allowed to have different values prior to, and during, the test, provided due account is taken of them in the subsequent assessment of *package* response. The thermal test shall then consist of (a) followed by (b):

(a) Exposure of a specimen for a period of 30 min to a thermal environment that provides a heat flux at least equivalent to that of a hydrocarbon fuel–air fire in sufficiently quiescent ambient conditions to give a minimum average flame emissivity coefficient of 0.9 and an average temperature of at least 800°C, fully engulfing the specimen, with a surface absorptivity coefficient of 0.8 or that value that the *package* may be demonstrated to possess if exposed to the fire specified.

(b) Exposure of the specimen to an ambient temperature of 38°C, subject to the solar insolation conditions specified in Table 12 and subject to the *design* maximum rate of internal heat generation within the *package* by the *radioactive contents* for a sufficient period to ensure that temperatures in the specimen are decreasing in all parts of the specimen and/or are approaching initial steady state conditions. Alternatively, any of these parameters are allowed to have different values following cessation of heating, provided due account is taken of them in the subsequent assessment of *package* response. During and following the test, the specimen shall not be artificially cooled and any combustion of materials of the specimen shall be permitted to proceed naturally.

Appendix B: Determination of thermal power relative to the oxidation of the claddings

This Appendix is dedicated to modelling of the thermal power related to the exothermic reaction of oxidation of claddings by hot air. This document firstly reminds the related scientific literature. Secondly, the model derived for STAR-CCM+ is explained and its implementation is described.

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PROPRIETARY APPENDIX

Figure B 1: Temporal evolutions of the power flux density at constant temperature – Comparison of two formulations of the zirconia surface formation rate

PROPRIETARY FIGURE

Figure B 2: Temporal evolutions of the power flux density at constant temperature – Comparison between the analytical solutions and STAR-CCM+

PROPRIETARY FIGURE

Figure B 3: Temporal evolutions of the maximum cladding temperature

PROPRIETARY FIGURE

Figure B 4: Temporal evolutions of the power flux density with time-dependent temperature – Comparison of two formulations of the zirconia surface formation rate

PROPRIETARY FIGURE

Appendix C : Modelling of thermal flux applied to the external walls of the internal equipment

This section provides detailed description of the modelling applied for the heat flux prescribed on the external walls of the internal equipment. The modelling applied is direct during the fire phase as the regulatory values are applied. During the cooling phase, a more complex model is applied for conservative purposes. It incorporates the presence of the shell and includes an actual representation of the physical phenomena.

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PROPRIETARY APPENDIX

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PROPRIETARY APPENDIX

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Appendix D: Modelling and results of the three-dimensional cases 15, 16 and 17

This Appendix is supplementary to Section 5.3.2 and is intended to provide the details of the results and the three-dimensional modelling used to deal with the zones at the bottom of the assembly (Case 15) and at the top of the assembly (Cases 16 and 17). The Appendix provides the details of the used geometry, and the applied hypotheses. The results are comprehensively examined in order to understand the physical phenomena that are absent from the two-dimensional approach and their impact on the thermal resistance of the claddings.

D1. ZONE OF THE BOTTOM OF ASSEMBLY– CASE 15

D1.1. Selection of the conservative configuration

Case 15 aims to deal with the bottom assembly zone. The computational domain reaches from the container end plate to the mid-span between the first and second grid. The geometry is based on the 17x17 array. The geometry of the bottom nozzle and of the grid is based on the AFA3G assembly. The worst-case geometric configuration needs to be identified, and two characteristic dimensions, described below, are taken from an analysis of all transported assemblies:

- The distance between the top of the bottom nozzle and the plugs of the rods: The area between the bottom nozzle and the plugs of the rods is free apart from the guide tubes and offers little resistance to the cross flow. Consequently, the longest distance must be found in order to maximize convective effects. The distance of [redacted] relative to the 16x16 assembly is thus retained, see table below
- The rod length between the plugs extremity and the bottom surface of the first grid. The grid acts favorably with regard to convective effects insofar the outer straps of the grid act as a screen between the rods and the transverse flow. In order to ensure that the geometry is penalizing, the longest distance must be found. The retained value of [redacted] is relative to the EPR assembly.

	FCC3 15x15	FCC3 17x17	FCC4 17x17 1300MWe	FCC4 17x17 1450MWe	FCC3 14x14	FCC4 16x16	FCC4 18x18	17x17 EPR	Penalizing config.
Distance between plugs and the bottom nozzle	PROPRIETARY TABLE								
Rod length upstream of the first grid									

D1.2. Computational domain and grid

The fluid and solid computational domains are represented in Figure D 1. The following elements are represented:

- Rod cladding and guide tubes containing UO_2 and air respectively. The array studied is the 17x17 array. The guide tubes are in contact with the filter in the real geometry. The rod plugs have a simplified cylindrical shape and are located at a distance of [redacted] mm from the top of the nozzle as explained above. The rod length downstream the grid is [redacted] mm which corresponds to the half rod distance between two consecutive grids.
- The bottom nozzle, corresponding to a simplified geometry related to an AFA3G assembly. In particular, the nozzle filter is not represented in order to minimize the thermal inertia of the nozzle and to allow axial convective fluxes between the hot air contained under the bottom nozzle and the cladding located above.
- The doors and frame composed of resin protected by steel plating. The top gap of [redacted] mm and bottom gap of [redacted] mm between the door and frame are applied over the whole height of the computational domain.
- The grid corresponds to a simplified AFA3G grid. In particular, the dimples and springs are not represented, any associated thermal bridge is assumed to be negligible given the small cross-section and the small contact surface with the cladding. The mixing and guide vanes are not represented for conservative purposes insofar they constitute

obstacles to transverse flow. The guide tubes are in contact with the grid straps over a width of [redacted] mm.

- The holddown system composed of two pads with a total height of [redacted] mm and locking pins with diameter M12. This system is used to hold the grid in contact with the plating of the frame by tightening of the retaining screws.
- The end plate with thickness of [redacted] mm closing the internal equipment and supporting the nozzle legs.

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D1.3. Materials and boundary conditions

The material properties are identical to reference case 1, see Section 3.6. The grid is made of Zircaloy-4 and the metal structures related to the stiffeners, pads, and locking screws are made of stainless steel.

The definition of the boundary conditions is the same as for the reference case, the top wall in the reference section is defined as a symmetry.

The physical sub-models applied (floatability, oxidation…) are identical to the reference case, see Section 3.4.

D1.4. Qualitative results

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D1.5. Quantitative results

Figure D 6 shows the temperature field of the cladding and guide tubes at the end of the fire test with a view of the claddings located close to the top and bottom gaps. The purpose of this post-processing is to assess axial heterogeneity of the cladding temperatures at the end of the fire phase. These differ according to the examined cladding as explained below,

- With regard to claddings located close to the top gap, they are colder near the grid. In fact, the grid limits convection heat transfer as explained above, and the hot spot is obtained on the top surface of the computational domain, farthest from the grid.
- With regard to the claddings located close to the bottom gap, the bottom part including the grid and the area underneath the grid is hotter than the part located above the grid.

The temporal evolutions of maximum and mean temperatures of the ten hottest claddings are plotted in Appendix E- Figure E 15. The mean and maximum cladding temperatures are examined over the height of the computational domain. The maximum cladding temperature field available in Figure E 15 corresponds to the maximum temperatures of each cladding determined over the modelled height. From a quantitative point of view, the maximum claddings temperatures are smaller, see Table 9. The maximum temperature of the hottest claddings equals [redacted] $°C$ for Case 15 against [redacted] $°C$ for the reference case 1. The difference in terms of maximum temperatures between the two-dimensional Case 1 and three-dimensional Case 15 is explained by the favorable effect of the grid forming a cold spot within the assembly.

D2. ZONE OF THE TOP OF THE ASSEMBLY – CASES 16 AND 17

D2.1. Selection of the conservative configuration

Cases 16 and 17 aim to deal with the top of the assembly and the difference between both cases is related to the cladding material, Zircaloy-4 for Case 16 and pre-oxidized M5® for Case 17.

The computational domain extends from the mid-span between the penultimate and last grid up to the end plate of the container. The geometry is based on the 17x17 array and the geometries for the top nozzle and for the grid are based on the AFA3G assembly and simplified. The worst-case geometric configuration needs to be identified, and two characteristic dimensions, described below, are taken from an analysis of all transported assemblies:

- The distance between the extremity of the rod plugs and the bottom of the top nozzle. The longest distance must be found in order to maximize the convection effects. The distance applied is [redacted] mm and is relative to the EPR assembly.
- The rod length between the last grid and the plugs. As mentioned previously, the grid acts favorably with regard to convection effects and the longest distance must be found in order to ensure that the geometric configuration is penalizing. The value applied is [redacted] mm and is relative to the 16x16 assembly.

	FCC3 15x15	FCC3 17x17	FCC4 17x17 1300MWe	FCC4 17x17 1450MWe	FCC3 14x14	FCC4 16x16	FCC4 18x18	17x17 EPR	Penalizing config.
Distance between plugs and top nozzle	PROPRIETARY TABLE								
Rod length downstream of the first grid									

Lastly, it is assumed that the rod height represented is relative to the plenum zone. The thermal inertia attached to the cladding is significantly lower in the plenum zone than in the reference zone. Given that a condition of symmetry is applied to the bottom surface of the computational domain, the length of the plenum zone considered is longer than. The assumption concerning the length of plenum zone over the whole height of the computational domain is thus strongly penalizing.

D2.2. Computational domain and grid

The computational domain of Cases 16 and 17 is represented in Figure D 7, and includes the following elements

- The rod cladding and the guide tubes containing helium and air respectively. The array studied is the 17x17 array. The rod plugs have a simplified cylindrical shape as in Case 15 and are at a distance of [redacted] mm from the nozzle as discussed above. The rod length upstream of the last grid is equal to [redacted] mm.
- The top nozzle corresponds to a simplified geometry relative to an [redacted] assembly. The simplifications rely on the nozzle springs and on the filter, which has largely been recessed in order to allow axial convective fluxes through the nozzle. The end of the nozzle springs is located at [redacted] mm of the end plate.

- The doors and frame composed of resin protected by steel plating. The top gap of [redacted] and bottom gap of [redacted] between the door and frame are applied over the whole height of the computational domain.
- The end plate of a thickness of [redacted] enclosing the internal equipment and in which a locking screw of diameter M20 carried through the end plate is fixed to the nozzle.

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D2.3. Materials and boundary conditions

Regarding material properties, the nozzle, locking screw, end plate, doors, frame and the holddown system of the grid are made of stainless steel. The cladding is made of Zircaloy-4 for Case 16 and of pre-oxidized M5® for Case 17. The helium contained in the rods is modelled as a solid, its thermal properties are provided in Table 4. The radiation within the rod is not taken into account, this assumption is penalizing as the internal radiation leads to an internal redistribution of heat within the cladding which limits the azimuthal heterogeneities of temperature.

Regarding the boundary conditions, the bottom surface of the computational domain is defined as a symmetry, and the thermal flux relative to the fire is imposed on the external walls of the end plate.

The physical sub-models (floatability, oxidation…) applied are identical to reference case 1. The parameters related to the oxidation depend on the cladding material. For Case 17 relative to the pre-oxidized M5® cladding, the oxidation parameters are those of M5®. This is a conservative assumption, also applied for Case 12 (see Section 5.2.2).

D2.4. Qualitative results – Case 16

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D2.5. Quantitative results – Case 16

Figure D 12 shows cladding temperature field at the end of the fire test. The observations are similar to Case 15, i.e.

- Near the top gap, the maximum temperatures are reached on the plane of symmetry, *i.e.* on the mid-span section.
- Near the bottom gap, the maximum temperatures are reached within the grid.

The maximum temperatures recorded in Table 9 show that Case 16 is more severe than reference case 1 as a maximum temperature of [redacted]°C is reached, against [redacted]°C for Case 1. The temporal evolutions of claddings temperatures are available in Figure E 16 in Appendix E. The plotted evolutions correspond to the maximum and mean temperatures of each cladding over the whole of the modelled height. For the three hottest claddings ([redacted]), the mean temperatures for the sections where the maximum temperature is reached are also plotted. With regard to cases in the reference zone, the following two points are to be noted:

- Claddings [redacted] and [redacted], heated by convective heat transfer, show a much faster temperature increase dynamic than for cases in the reference zone. This difference is associated with the inertial effects lost with the absence of UO_2 pellets.
- The cladding element [redacted] heated mainly by convective and radiative effect shows a much more linear increase.

D2.6. Sensitivity to pre-oxidized M5® – Case 17

Case 17 corresponds to a sensitivity to pre-oxidized M5® replacing Zircaloy-4. The geometry is strictly identical between Cases 16 and 17.
From a qualitative point of view, the results are very similar to Case 16. The temperature field at the end of the fire phase, see Figure D 13 has the same characteristics as for Case 16. From a quantitative point of view, the temporal evolutions of temperature are also close to Case 16, see Figure E 17. Lastly, the maximum cladding temperatures reported in Table 9 prove to be slightly higher up to [redacted]°C compared with Case 16.

Figure D 1: Computational domain – Case 15

PROPRIETARY FIGURE

Figure D 2: Grid – Case 15

PROPRIETARY FIGURE

Figure D 3: Temperature fields for sections through the plugs (left), through the center of grid (center) and related to the symmetry plane (right) – Case 15

PROPRIETARY FIGURE

PROPRIETARY FIGURE

Figure D 4: Transverse section colored by temperature – Case 15

PROPRIETARY FIGURE

Figure D 5: Transverse section colored by velocity vectors – Case 15

PROPRIETARY FIGURE

Figure D 6: Rod claddings colored by temperature at the end of the fire phase – Case 15

PROPRIETARY FIGURE

Figure D 7: Computational domain – Case 16

PROPRIETARY FIGURE

Figure D 8: Grid – Case 16

PROPRIETARY FIGURE

Figure D 9: Temperature fields for sections through the plugs (left), through the center of grid (center) and related to the symmetry plane (right) – Case 16

PROPRIETARY FIGURE

PROPRIETARY FIGURE

Figure D 10: Transverse section colored by temperature – Case 16

PROPRIETARY FIGURE

Figure D 11: Transverse section colored by velocity vectors – Case 16

PROPRIETARY FIGURE

Figure D 12: Rod claddings colored by temperature at the end of the fire phase – Case 16

PROPRIETARY FIGURE

Figure D 13: Rod claddings colored by temperature at the end of the fire phase – Case 17

PROPRIETARY FIGURE

Appendix E: Temporal evolutions of the hottest claddings for all cases

Figure E 1: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 1

PROPRIETARY FIGURE

Figure E 2: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 2

PROPRIETARY FIGURE

Figure E 3: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 3

PROPRIETARY FIGURE

Figure E 4: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 4

PROPRIETARY FIGURE

Figure E 5: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 5

PROPRIETARY FIGURE

Figure E 6: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 6

PROPRIETARY FIGURE

Figure E 7: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 7

PROPRIETARY FIGURE

Figure E 8: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 8

PROPRIETARY FIGURE

Figure E 9: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 9

PROPRIETARY FIGURE

Figure E 10: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 10

PROPRIETARY FIGURE

Figure E 11: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 11

PROPRIETARY FIGURE

Figure E 12: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 12

PROPRIETARY FIGURE

Figure E 13: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 13

PROPRIETARY FIGURE

Figure E 14: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 14

PROPRIETARY FIGURE

Figure E 15: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 15

PROPRIETARY FIGURE

Figure E 16: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 16

PROPRIETARY FIGURE

Figure E 17: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 17

PROPRIETARY FIGURE

Figure E 18: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 18

PROPRIETARY FIGURE

Figure E 19: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 19

PROPRIETARY FIGURE

Figure E 20: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 20

PROPRIETARY FIGURE

Figure E 21: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 21

PROPRIETARY FIGURE

Figure E 22: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 22

PROPRIETARY FIGURE

Figure E 23: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 23

PROPRIETARY FIGURE

Figure E 24: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 24

PROPRIETARY FIGURE

Figure E 25: Temporal evolutions of the mean and maximum temperatures of the five hottest claddings – Case 25

PROPRIETARY FIGURE