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INFLUENCE OF THE CONVECTION COEFFICIENT ON THE NUMERICAL MODELING OF A FIRE TEST ON A NUCLEAR TRANSPORT PACKAGE

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ABSTRACT

To be approved, a package dedicated to the transport of radioactive material must withstand several tests required by the IAEA SSR-6 regulations, one of which is a 30-minute 800 °C fire test. To demonstrate the safety of the package, such a test may be performed on a package mock-up or numerically with boundary conditions representative of the fire. IAEA regulations specify values for flame emissivity and package surface absorptivity. However convection is addressed in the IAEA SSG-26 guidelines with a suggested coefficient of $10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ correlated with a range of flame velocity between 5 and $10 \text{ m}\cdot\text{s}^{-1}$. Recent research [REF 2] suggests that this value may not always be representative of such a fire and could be scaled up. What could be the influence of higher convection coefficients on the temperature of the package?

In order to answer that question, IRSN performed sensitivity calculations on transport packages models and studied the influence of the convection coefficient over a range from 0 (no convection) to $100 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ (very high convection, not necessarily representative of real fires). The temperatures in the package models during the fire and cooling phases were analyzed and put in perspective with safety issues.

INTRODUCTION

The thermal load that a package should sustain is specified by the IAEA regulations [REF 1] for each condition of transport. These regulations require that a type B or fissile package should be subjected to a specified thermal test (see figure 1) to demonstrate that its safety functions (containment, shielding, criticality, mechanical and thermal protection) are maintained in accident conditions of transport.

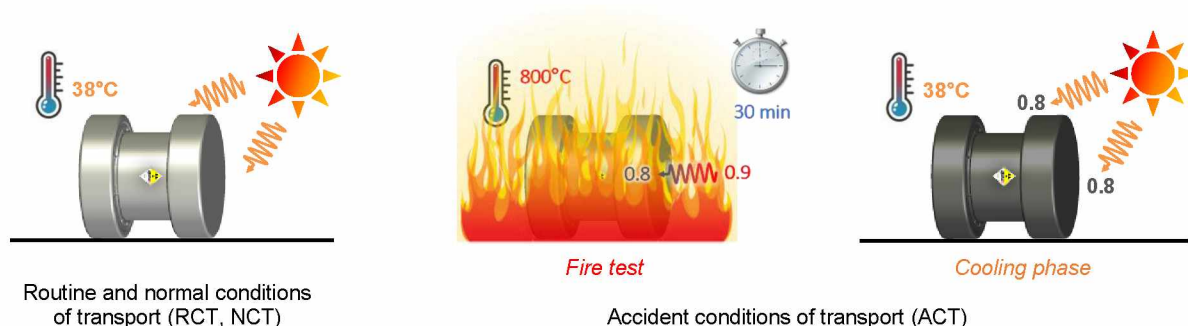


Figure 1. The three phases of the regulatory thermal test

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Recent research based on real fire tests [REF 2] suggests that the convection coefficient value may be higher than the one recommended by the IAEA guidelines No. SSG-26 [REF 3] for the regulatory fire test. Ultimately, are there any significant consequences on the safety of packages, i.e. does the value of the convection coefficient affect the temperature of the sensitive components of the package when it is subjected to the regulatory fire test? Previous calculations and analyses on that topic are provided in [REF 4]. As those calculations were limited, among other parameters, to convection coefficients between 5 and 10 $W.m^{-2}.K^{-1}$, IRSN performed numerical calculations to study the influence of the convection coefficient on two French type B package designs.

ENERGY CONVEYED BY THE CONVECTION AND THE RADIATION

To appreciate the proportion of energy brought by the main modes of heat transfer during the regulatory fire, IRSN compared the energy brought by convection for different coefficient values with the energy brought by radiation (considering the regulatory emissivity and absorptivity). The results are represented on the graphs of the figure 2. This study considers the difference between the temperature of the fire (800 °C) and that of a surface directly exposed to the flames (from 38 °C to 800 °C).

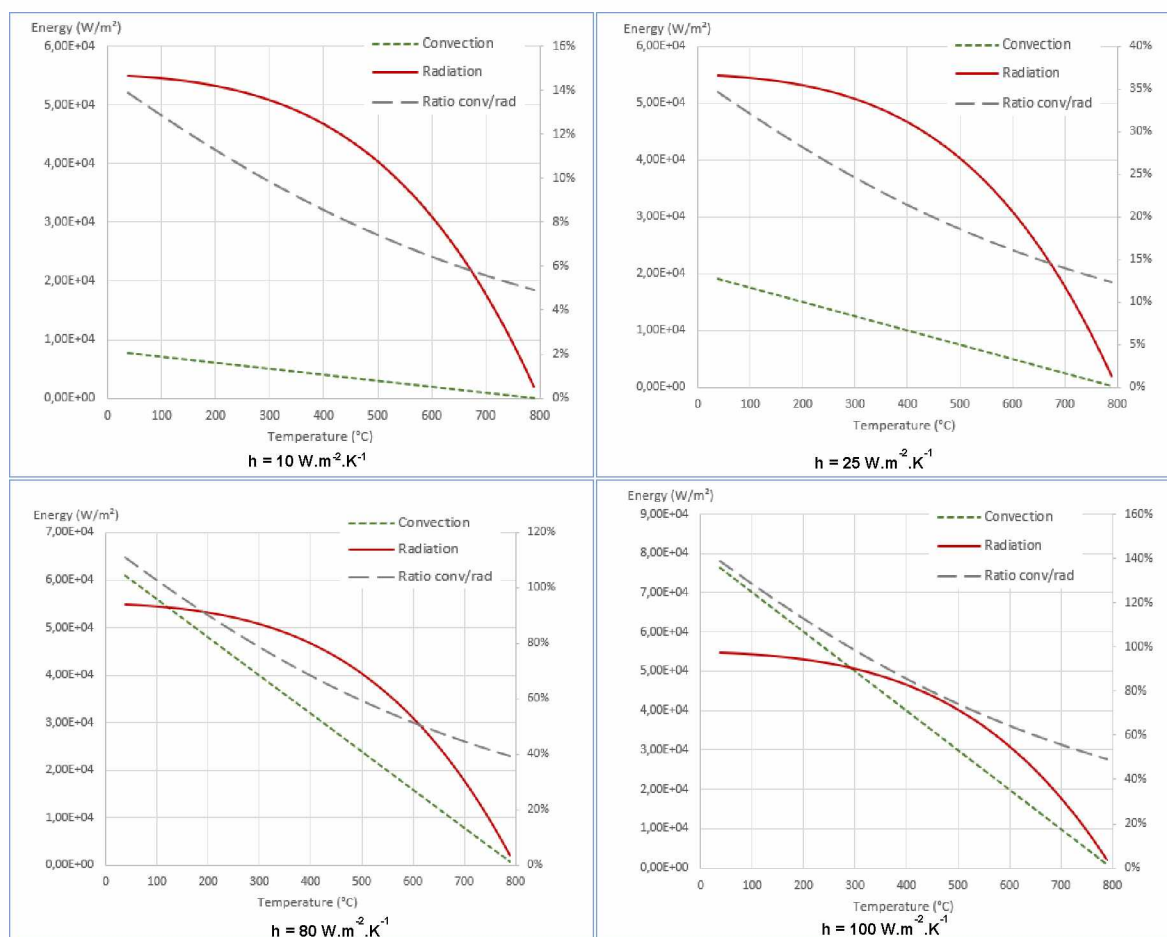


Figure 2. Energy brought by the convection for different values of the convection coefficient compared to the energy brought by the radiation.

For the SSG-26 recommended value of the convection coefficient during the fire test (first graph, $h = 10 W.m^{-2}.K^{-1}$), the energy conveyed by convection on the surface represents less than 14 % of the energy conveyed by the radiation at any time, that value being reached when the surface is at 38 °C (i.e. at the beginning of the fire).

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As seen on the graphs, when the convection coefficient increases, the energy conveyed by radiation increases until it can outweigh the energy conveyed by convection, starting at a coefficient of $80 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, though only for temperatures below $300 \text{ }^\circ\text{C}$.

HYPOTHESIS AND CALCULATION

IRSN performed calculations on two transport packages models in order to evaluate the temperature of the package models during the phases (see figure 1) of regulatory conditions of transport (RCT, NCT, fire test and cooling phase of ACT).

The thermal model is meshed and post-processed with the Cast3M 3D code [REF 5] and solved with the ThermX-Protee code [REF 6]. The latter considers the endothermic material behavior for classical materials used as thermal protection (here, resin and compound), based on fire tests on samples of such materials.

Model of the package with high thermal power

The package is 7 m high and 2.5 m in diameter, made of many layers, as detailed in figure 3. The cavity contains high thermal power radioactive material (spent fuel). The containment system is closed by a primary and a secondary lid, both equipped with an elastomer gasket. The design thermal power is around 50 kW.

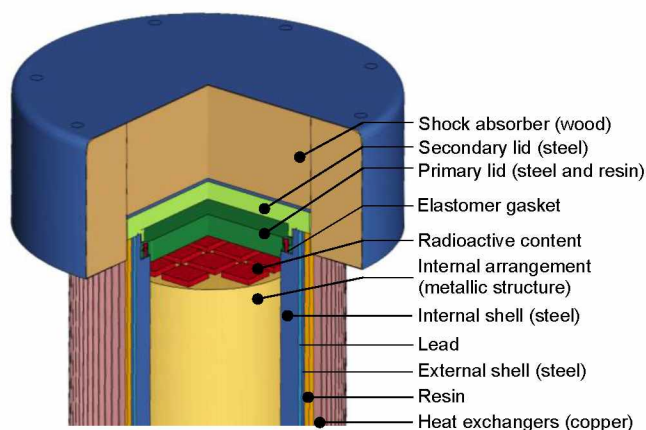


Figure 3. Simplified representation of the high thermal power package

Model of the package with low thermal power

The package is 1 m high and 0.9 m in diameter, made of three layers, as detailed in figure 4. The cavity contains low thermal power radioactive material (waste). The containment system is closed by a lid, equipped with an elastomer gasket. The design thermal power is around 100 W.

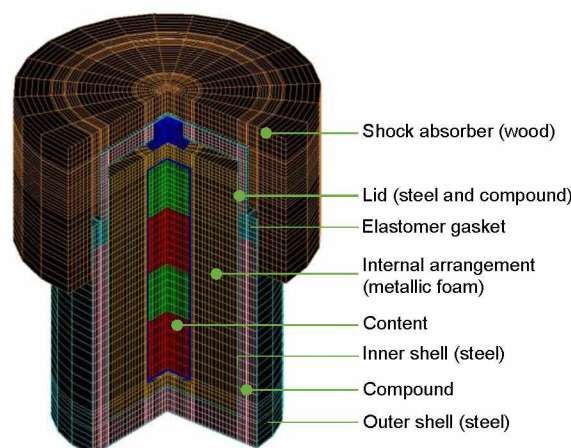


Figure 4. Numerical model of the low thermal power package

The numerical models represent simplified versions of existing French type B packages; due to the symmetry, only one fourth of the package is modelled. These simplifications also include the absence of fasteners. The internal arrangements, consisting of a metallic structure, are represented with an equivalent material, which considers the physical properties of the different metals and the air. The content is also modelled with an equivalent material and a volumetric heat flux is distributed over the height.

Moreover, the IAEA regulations require considering mechanical damages representative of the NCT and ACT mechanical tests. IRSN then performed additional calculations to study the influence of an overall reduced thickness of the compound or of the wood of the shock absorber, "numerically

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crushed”. The duration of each calculation was chosen according to two criteria. For the RCT and cooling phase of the ACT, the calculation ended when a temperature equilibrium was reached. For the fire test, the calculation lasted 30 minutes, as required by the IAEA regulations for type B packages.

For all calculations, during the ACT, the emissivity of the fire is taken at 0.9 and that of the external surfaces at 0.8. During the fire, the ambient temperature is taken at 800 °C. The convection coefficient varies from 0 (no convection) to 100 W.m⁻².K⁻¹ for the external flat surfaces, and a correction factor is applied on these values for external surfaces equipped with heat exchangers since it modifies the heat exchange surface. After the fire, the ambient temperature and insulation conditions are those of the RCT.

GENERAL OUTCOME

The temperature inside the low thermal power package at the end of each phase is shown in figure 5. In this first set of calculations, no damage to the package is considered.

At the end of the fire, the heat transfers are limited towards the inside of the package and the temperature is the highest on the external shells. The difference of temperatures between the outside and inside of the package is explained by the presence of the compound, an endothermic material, which delays the temperature increase of the inner components.

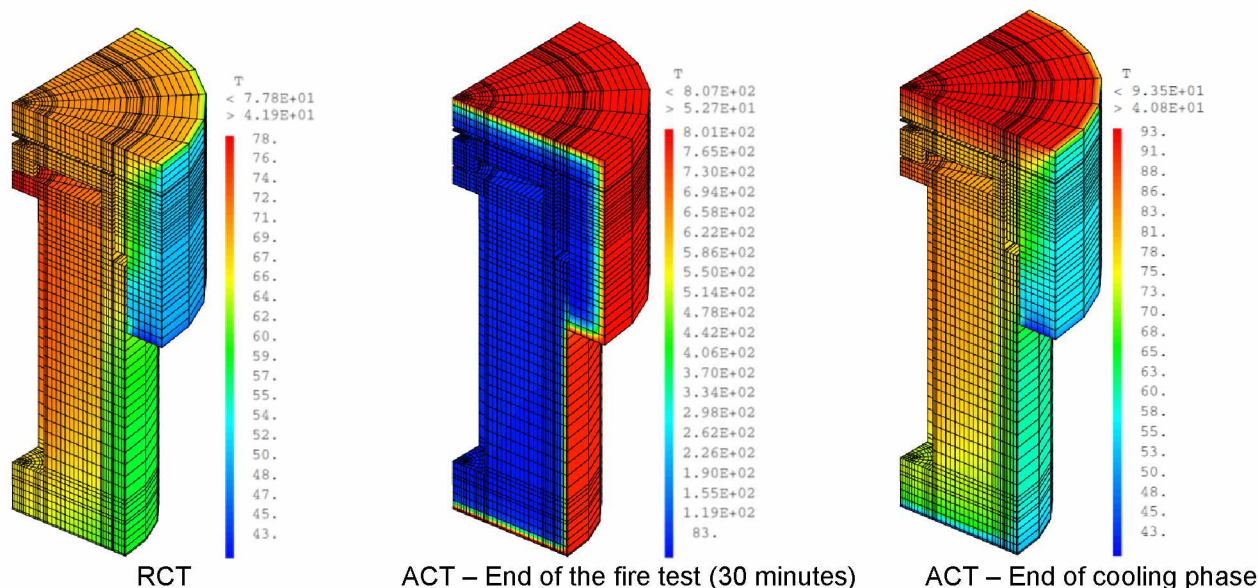


Figure 5. Temperature (°C) of the package during the three phases of the regulatory thermal test

These observations and conclusions are similar for the high thermal power package (not represented here).

The temperature evolution of the low thermal power package is detailed in figure 6 for the three phases of the calculation.

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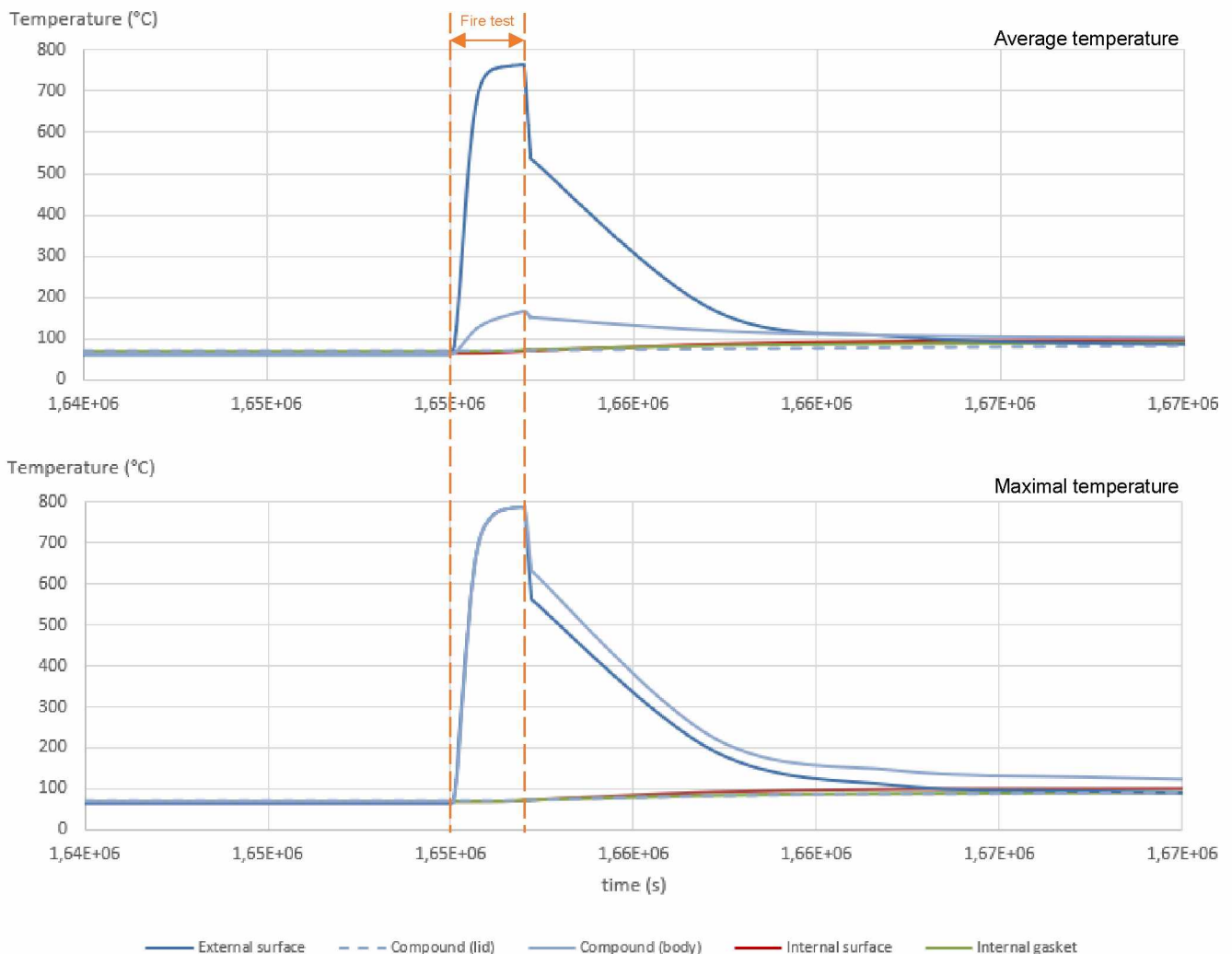


Figure 6. Temperature of the low thermal power package during the three phases of the regulatory thermal test.

Results of sensitivity calculations on high thermal power package

During the fire test, the maximal temperature of the components near the surface increases (from 220 to 390 °C for the external shell, from 360 to 600 °C for the resin), unlike the temperature of the other components which remains quite stable.

During the cooling phase, the endothermic material (resin) releases the heat absorbed during the fire. The sensitive components (gaskets and shielding materials) reach their highest temperature during this phase.

The maximum temperature in the package, for a range of convection coefficient from 0 (no convection) to 100 W.m⁻².K⁻¹, is presented in figure 7 and figure 8.

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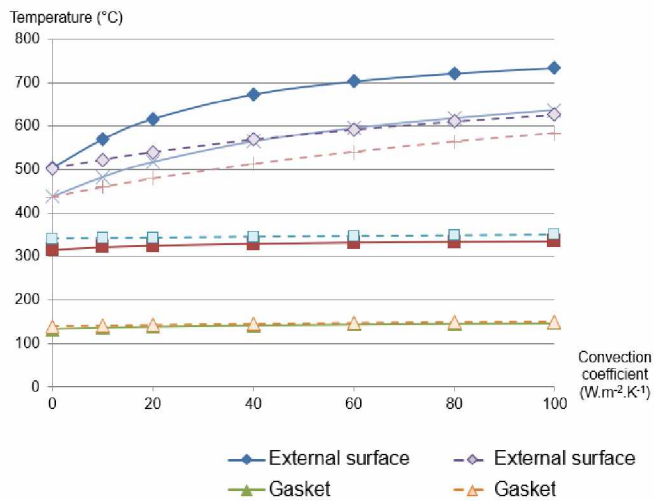


Figure 7. Maximal temperature of the package equipped (plain lines) or not (dashed lines) with heat exchangers, obtained during the cooling phase

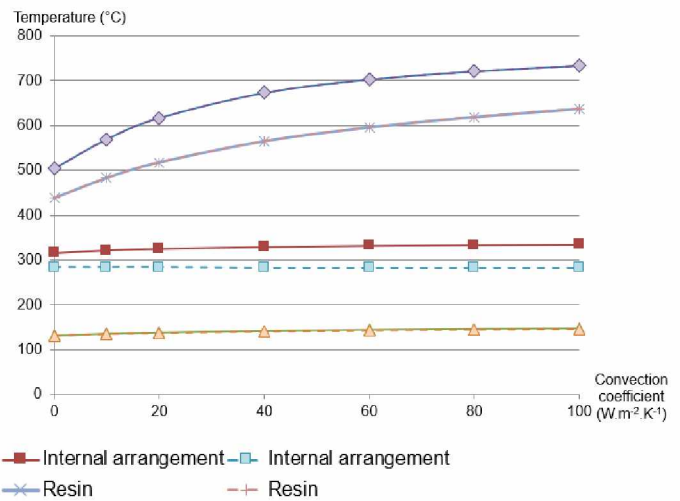


Figure 8. Maximal temperature of the package for high (plain lines) or moderate thermal power content (dashed lines), obtained during the cooling phase

The conclusions to draw from both figures are the following:

- the increase of the value of the convection coefficient during the regulatory fire has moderate to little effect on the temperature of the inner components, such as the elastomer gaskets, which temperature increases by less than 15 °C;
- the variation of the heat exchange surface of the package or of its internal thermal power has little to no effect on the temperature of the inner components.

Overall, the influence of the increase of the convection coefficient is the most visible on the outer layers. In particular, the temperature increase of the resin is located on its external layer, close to the external surface, and the inner part of the resin does not increase as much (less than 20 °C). At that stage, it must be underlined that these conclusions are specific to the package design. Due to its inertia, to the low diffusivity, to the high thickness of the resin and the wood, and to the absence of damage in the model considered, those results can be seen as the minimum expected influence. Further calculation will be needed to reach a more global conclusion.

Results of sensitivity calculations for low thermal power package - Variation of the convection coefficient during the fire test

During the fire test, the temperature of the endothermic material (compound) increases approximately by 100 °C. The temperature of the other components remains quite stable.

During the cooling phase, the compound releases the heat absorbed during the fire test. The sensitive components reach their highest temperature during this phase.

The maximum temperature in the package during the cooling phase, for a range of convection coefficient from 0 (no convection) to 100 W.m⁻².K⁻¹, is presented on the figure 9. The second graph on the right side of the figure is an enlargement of the temperature of the internal components (compound, internal gasket, and internal surface) from the graph on the left.

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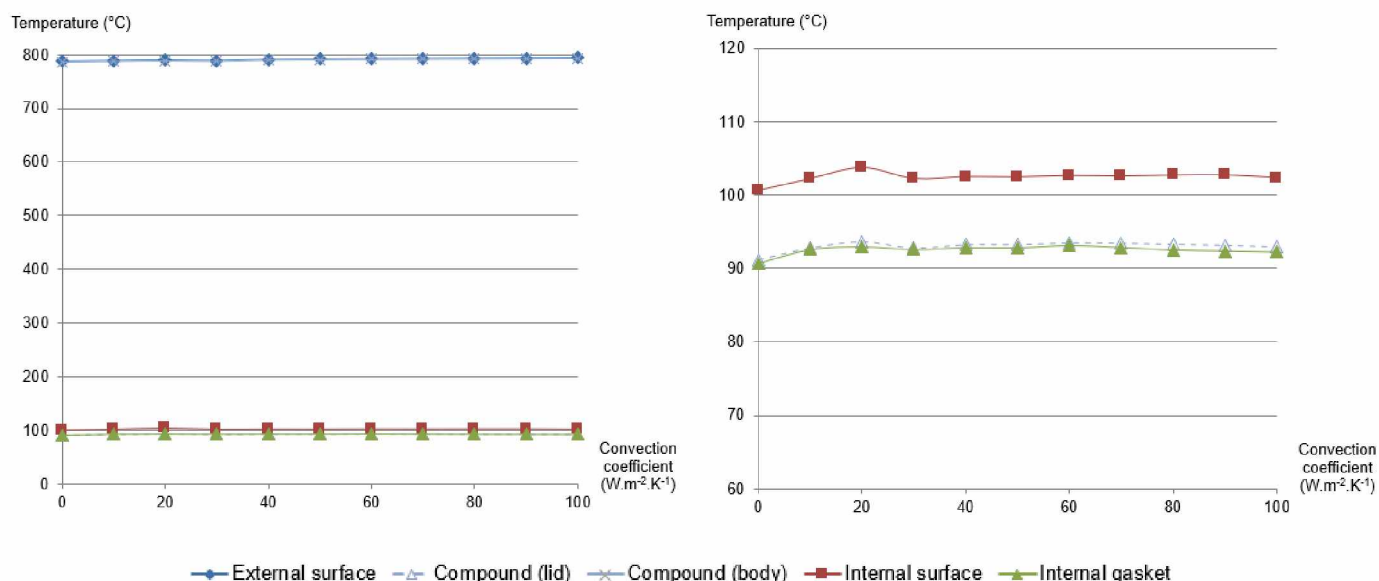


Figure 9. Maximal temperatures of the low thermal power package during the cooling phase (right chart: enlargement of the left chart).

The variation of the convection coefficient during the fire test has no effect on the maximal temperature of the inner components (internal arrangement, gasket and compound) during the cooling phase.

To determine if this can be explained by the thickness of the layer of compound, or of the wood inside the shock absorber, additional calculations were performed with numerically crushed material.

Results for low thermal power package - Variation of the overall thickness of the insulating materials

To consider the crushing of the materials, since the meshing stays at the original volume, the thermal conductivity is adjusted according to the following equation derived from, on the one hand, the fact that the variation of the conductivity is roughly a linear function of the crushed thickness, on the other hand, the conservation of the Fourier number related to heat conduction:

$$\lambda = \left(\frac{e_0}{e}\right)^2 \times \lambda_0 \text{ for a crushed material}$$

λ, e : thermal conductivity and thickness of the crushed material

λ_0, e_0 : thermal conductivity and thickness of the initial material

As the initial volume of the numerical model is maintained, the diffusivity, which is directly linked to the thermal conductivity, is therefore artificially increased for the numerical model.

As the influence of the thickness of the compound and the wood are here the only studied parameters, the convection coefficient during the fire takes the regulatory value of 10 W.m⁻².K⁻¹ for all the following calculations.

The graph in figure 10 presents the temperature of some components of the package as a function of the thickness of the crushed compound. The temperature of the external surface drops substantially with the decrease of the thickness, while the temperature of the other components tends to rise.

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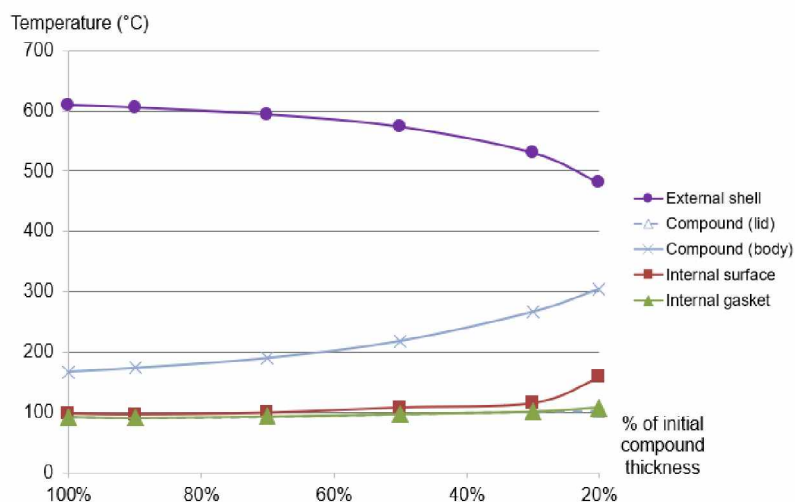


Figure 10. Average temperature of the low thermal power package during the cooling phase with crushed compound.

The drop of temperature of the external shell and the increase of the inner components are a result of both the increase of the thermal conductivity/diffusivity of the compound – which leads to transfer heat more efficiently, and its reduced thickness, and so limits the capacity to accumulate the heat. As the gasket is protected by the shock absorber and has no direct contact with the external surface, its temperature remains stable while the thickness of the compound decreases. Moreover, the proportion of heat from the compound that can be released on the gasket is low. As the external exchanges are more important on the external surface, the heat of the compound tends to evacuate in the direction where the compound is the thinnest, hence the radial direction in this case.

The graph in figure 11 presents the temperature of some components of the package as a function of the thickness of the crushed wood in the shock absorber.

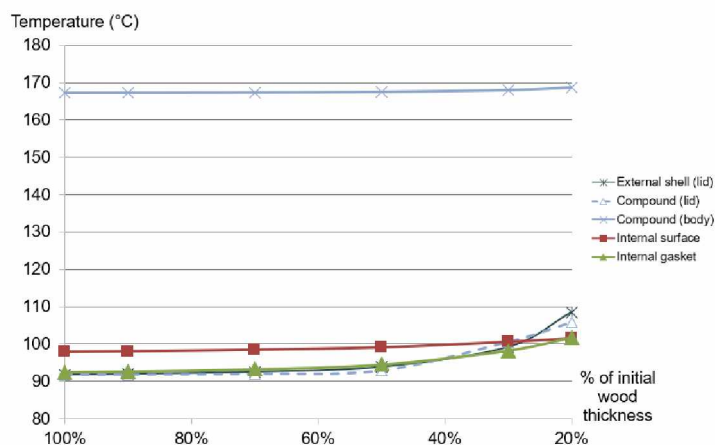


Figure 11. Maximal temperature of the low thermal power package during the cooling phase with crushed wood in the shock absorber.

The temperature of the external shell is not represented here, as it does not increase significantly on this interval. The temperature of the lid external shell rises moderately (less than 20 °C), as it is located right under the shock absorber. Overall, when the remaining thickness is less than 50 % of the initial thickness, the temperature of the inner components starts to increase. This reflects the effect of the low diffusivity of the wood.

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CONCLUSIONS

This sensitivity study shows that the convection coefficient during the fire test may have moderate effects on the temperature reached by the inner components, such as the containment gaskets.

For the high thermal power package studied, the variation of the heat exchange surface of the package or of its internal thermal power has little effect on the temperature of the inner components. For the low thermal power package studied, the crushing of the insulating materials (compound and wood) has moderate effect on the temperature of the inner components of the package, until a threshold value. As a matter of fact, the type B packages chosen for the calculations are of very different size, mass, and design. Yet the results showed that they both possess a very high thermal inertia, which minimizes the effects of the variation of the convection coefficient.

In both cases, the gasket is protected by the shock absorber and located far from the external surface, which prevents the increase in its temperature for all variations considered in the calculations. The thickness of the insulating components and the position of the sensitive components are likely two essential parameters to protect the latter from a fire. Regulatory drop tests tend to reduce the thickness of insulating components. In this regard, calculations show that, from 50 % of insulator compression, effects on temperature of the inner components appear. Thus, as those calculations are currently based on a convection coefficient of $10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, as usually considered in modelling, the effects of the increase in convection may become more significant on a thinner layer of such a material, by design or by crushing, or with a different sealing system design (for example, a gasket closer to the external surface, or less insulated). Further calculations are then needed to better appreciate the possible effect of an increase in heat exchange by convection.

The packages designed for fissile material (type A or IP) shall comply with the same safety standards, but their design can vary greatly from the two packages presented here. Thus, this study should also be completed with a package for fissile material of a much simpler structure, and with a lesser thermal inertia.

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