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NEW OUTCOMES FROM COMBUSTION OF WOOD INSIDE PACKAGE SHOCK ABSORBERS AFTER FIRE TEST

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ABSTRACT

According to the IAEA transport regulation, a fire test (800°C for 30 minutes) is required following the mechanical tests in accident conditions of transport.

Some package designs are equipped with wood shock absorbers in a steel casing. After the mechanical tests, the casing may be damaged in some places, in particular due to the penetration of the 15 cm diameter steel bar used for the regulatory 1 m drop test. After the 30 minutes fire test, the heated wood, combined with air accessibility inside casing due to the damages, may provide the necessary conditions to maintain combustion of wood. Then, the heat generated by the combustion of the wood could increase the temperatures of the package components located near the shock absorber, as for example the elastomer O-rings of the closure system.

In order to investigate this phenomenon, and thus appraising its consequences on safety analysis, IRSN has performed recently a fire test. A full-scale model, representative of shock absorbers which equip packages used to transport fuel assemblies, has been manufactured with simulated damages on the casing resulting from the 1 m and 9 m regulatory drop tests.

A dedicated heat exchanger has been developed to simulate the thermal power of the radioactive content. This exchanger maintains the inner surface of the shock absorber at constant temperature. Moreover, a specific instrumentation was implemented to locate and characterize the heat flux between the shock absorber and the package (during the fire test and the cooling time).

After the end of the hydrocarbon fire, wood combustion continued for four days inside the steel casing inducing important heat fluxes towards the lid (up to 8 kW/m²) and high temperatures (up to 460°C locally) on the rear side of the shock absorber.

Finally, we evaluated by numerical calculations the temperature increases of the gaskets, which equipped the package components, taking into account the fire configuration and measurements performed on the specimen.

INTRODUCTION

According to the IAEA regulation [1], type B packages and packages used to transport fissile materials, must be submitted to a fire test of 800 °C for 30 minutes after the regulatory mechanical tests representative of the normal and accident conditions of transport (free fall drop onto unyielding target and drop onto a steel cylindrical bar).

Most of the package designs are equipped with shock absorbers containing different species of wood. The mechanical tests can lead to damage the external steel envelope of the shock absorbers, leading to expose wood blocks to the flame during the 30 minutes hydrocarbon fuel/air flames of the regulatory thermal test. In addition, the consecutive oxygen supply can maintain wood combustion initiated during the fire long after that.

Usually, studies of the thermal behaviour of packages, presented in safety analysis reports, don't take into account the consequences on the package components temperatures of the heat transfers associated to wood combustion which could occur during the cooling time after the fire test. However, this phenomenon could significantly increase the temperatures of the components of the package located near the shock absorbers. When those components are part of the closure system and include elastomer gaskets, this temperature increase could question the hypothesis considered to determine the activity release of the package in accident conditions of transport.

In this context, the *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) has performed a full-scale fire test with an hybrid model representative of two typical designs of wood shock absorbers equipping packages (later called B1 and B2 packages) to highlight the existence of the wood combustion phenomenon after the fire test and to estimate the heat transfers associated. In addition, we evaluated the gaskets temperature increase of the B1 package design, loaded with spent fuel assemblies, and taking into account those heat transfers.

DESCRIPTION OF THE TEST SPECIMEN

<u>Specimen characteristics</u>

We used a full-scale shock absorber. The specimen, presented in figure 1, was representative of 2 shock absorber designs equipping packages commonly used in France to transport up to 16 fresh BWR fuel assemblies (B2 package) and 12 PWR spent fuel assemblies (B1 package).

The outer stainless steel casing of the specimen is a parallelepiped. The specimen right half part, called B1, is filled with two different wood species (oak and high-density balsa). On the left part, called B2, we decided to use a unique low-density wood (balsa) to enlarge the experimental field.

The shock absorber specimen contains 450 kg of wood composed of approximately 130 kg of low-density balsa, 120 kg of high-density balsa and 200 kg of oak wood.

In order to take into account the effects of the regulatory mechanical tests, the following damages were represented on the specimen, as shown in figure 1:

- A linear opening, of 500 mm x 15 mm, centered in the lower part of the front stainless-steel sheet of the shock absorber. This damage simulates local rupture of the shock absorber welds regularly noticed after free-fall drop tests. This damage leads to uncover blocks n°6 and n°10.
- A punch hole, with a diameter equal to 150 mm, leaning 40° from vertical axis, centered in the upper part of the front steel sheet of the shock absorber. This type of damage can be observed after the regulatory drop test onto a punch bar. This approach leads to uncover blocks n°4, n°7 and slightly n°8.
- A gap between the wood blocks and the front stainless steel sheet of the shock absorber, equal to 7 mm taking into account the usual manufacturing rules.

<u>Experimental device designed to take into account the thermal loading and package inertia</u>

The main objective of the fire test performed is to analyse the thermal exchange due to the wood combustion inside the shock absorbers equipping packages. Thermal power of the content (which can reach 70 kW for the transport of spent fuel assemblies) and ambient conditions defined in IAEA regulation [1] can lead to already substantive wood temperature in normal conditions of transport. In this regard, we developed a dedicated electrically-heated oil exchanger to reproduce the internal flux transmitted through the lid. This experimental device, in contact with the rear surface of the specimen steel casing on a surface of 1.26 m², allowed to maintain a temperature of the steel casing of 120±2.5°C, representative of normal conditions of transport. Moreover, this approach has the advantage to reproduce the effect of the thermal inertia of the lacking part of the loaded package, not represented by the specimen. The experimental installation is presented in figure 2.

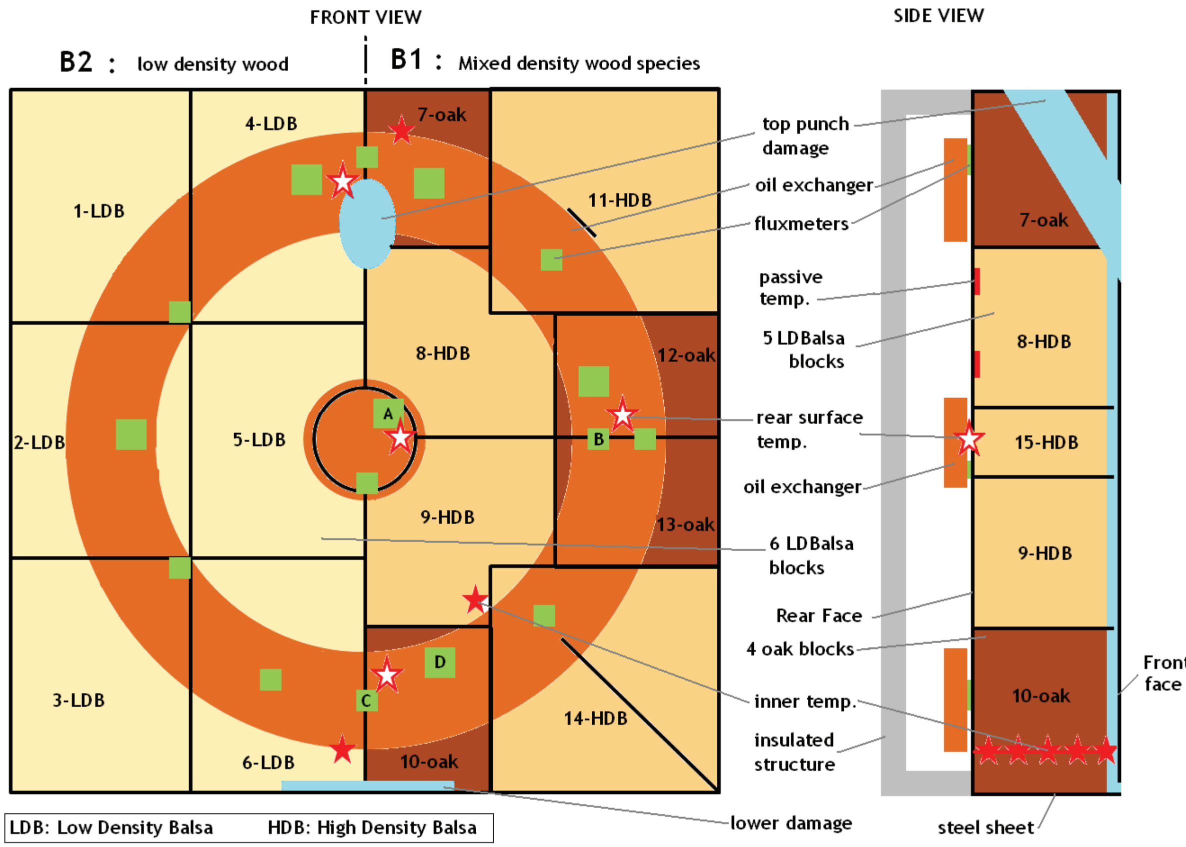

Figure 1: Detailed view of the specimen and its instrumentation

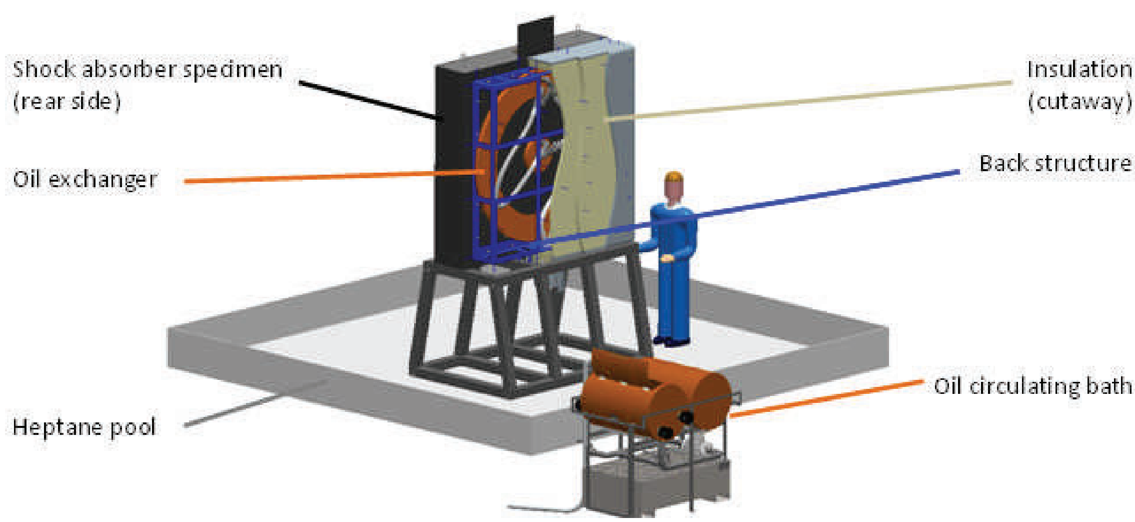

Figure 2: Global view of the experimental device

Instrumentation

The specimen was extensively instrumented, as presented in figure 1, including:

- rear inner surface passive maximal temperature indicators;
- 13 outer surface thermocouples;

- 3 wood blocks were equipped each with 5 thermocouples, covering different depths inside the wood from front to rear side.
- 17 ultrathin heat fluxmeters located between shock absorber and oil heat exchanger. Their number and localisation allow to follow combustion progress and to detect peak values.

HYDROCARBON POOL FIRE TEST DESCRIPTION

Several preliminary fire tests were performed in order to identify the influence of different parameters such as fuel type and wind screens. All these tests have been performed taking into account the IAEA recommendations [2] in particular for the characteristics of the fuel.
On the basis of the results of the preliminary tests performed at reduced scale (2.6 m² pools with shock absorber represented by a mock up made of SIPOREX®), it was decided to use heptane for the fuel, to remove wind screens and to impose stringent wind velocity criterion, lower than 0.5 m/s, as wind screens induced combustion rate limitation and instability.
In addition, two preliminary tests at scale 1 were performed. These two large fires confirmed a flame slope due to the site topography. Nevertheless, temperatures all over the external surface of the specimen were equal to 910±80°C and in-flame radiative thermal fluxes exceeded 100 kW/m². The thermal test duration was precisely monitored by fuel mass control.

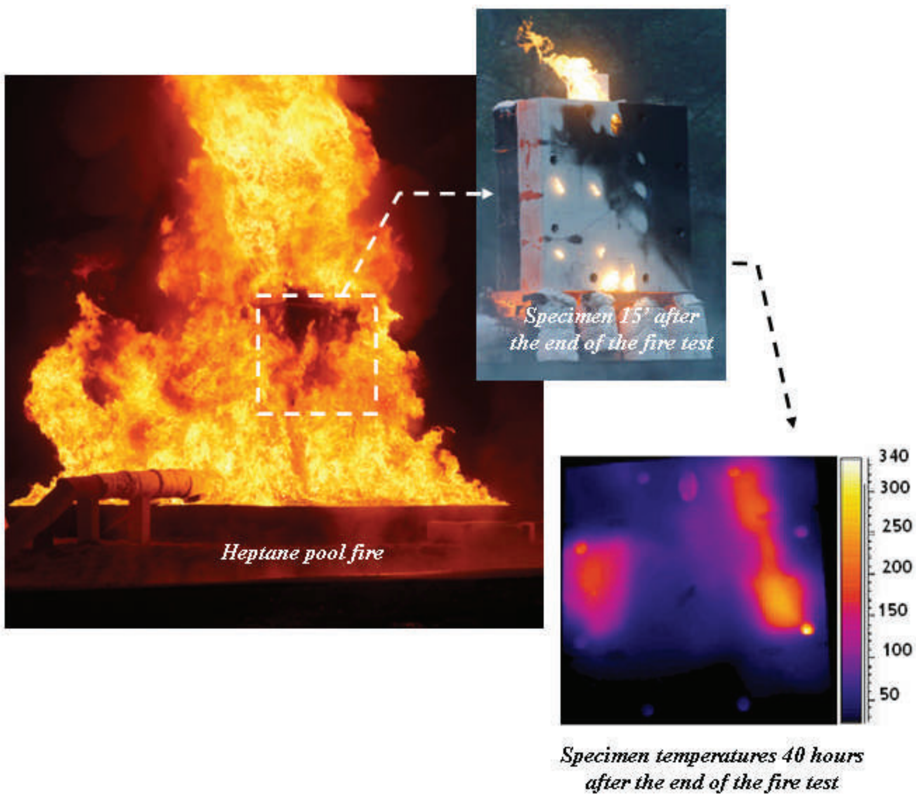

Figure 3: general views of the specimen during and after the fire test

The final thermal test took place outdoor in a 25 m² open pool. Before fire ignition, the shock absorber was preheated during 24 hours to reach a thermal steady state so that the inner average temperatures of the wood blocks reached 57°C.
Ambient temperature and wind velocity during the fire test were respectively around 13°C and lower than 0.5 m/s. Fire total duration was equal to 35 minutes including lighting and extinction periods for a developed fire duration equal to 33 minutes and 47 seconds.
As previous tests proved it, flame temperature always exceeded the recommended 800°C. During the first 13 minutes, the specimen was correctly engulfed by the flame. The time average of the 13 thermocouples measuring the package surface temperature was equal to 762°C with a standard

deviation of 61°C. Nevertheless, during the last 20 minutes, due to a flame slope inversed compared to preliminary tests, the shock absorber was partially and temporarily visible leading to an average temperature of the package external surface equal to 580°C with a standard deviation of 80°C. This unexpected flame behaviour is supposed to be a result of the meteorological conditions (inversion layer revealed by the presence of fog).
Based on the temperatures measured on the specimen external surface during 30 minutes, the test cannot be considered completely representative of a regulatory fire test since the flame does not surround perfectly the specimen during all the fire duration. Nevertheless, regarding the presence, several minutes after the end of the test, of flames located at the specimen damages and wood smouldering as shown in figure 3, we consider that the specimen thermal aggression by the flames was effective.

POST-COMBUSTION OF THE WOOD

The main experimental objectives were, on the one hand to observe how and how long wood combustion could take place inside the shock absorber and progress from one block to another and, on the other hand to estimate the heat fluxes generated by wood combustion. Thanks to measurements, thermal video camera recording and observation of smoke four days long, these goals were reached.
Concerning the specimen B2 half part, presenting low density wood charachteristics, combustion of the wood blocks ceased 72 hours after the end of the fire test. Maximum local heat flux exceeded 8 kW/m² for several hours on the rear specimen surface in the lower damage area. Local flame developments inside the specimen structure led to internal temperatures equal to 900°C.

Wood combustion progress inside the B1 top shock absorber half part is described in figure 4.

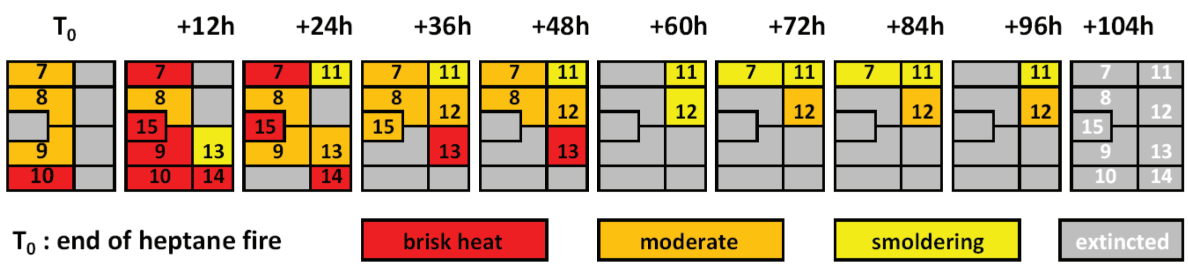

Figure 4: Wood combustion progress (synthesis)

The combustion of the wood blocks located in the B1 top shock absorber half part was initiated at the damage areas. Internal flames and embers have been observed until respectively 12 hours and 2 days after the end of the fire test.
The following noteworthy events, presented in figure 4, have been noticed:

- At the end of the fire test (T_0), important wood combustion is recorded on the direct path between damages located in the lower and upper parts (wood blocks n°7, 8, 9 and 10 are affected).
- Until T_0+12 h, oxygen inside specimen structure leads to create local flames spreading to new wood blocks (n°13, 14 and 15).
- At T_0+24 h, the wood block n° 10 stopped burning (total combustion).
- At T_0+36 h, the wood blocks n°9 and 14 stopped burning (total combustion), shortly followed by wood block n°15. Due to oxygen supply increase, combustion of the blocks n°12 and 13, located at specimen mid-height restarted.
- Between T_0+60 h and T_0+104 h, wood smouldering was noticed in the specimen top area.
- At approximately T_0+72h the combustion of the wood blocks n°7 and 11 restarted. The temperature of the specimen rear surface in this area reached 155°C with local thermal flux equal to 0,9 kW/m².

- At approximately T_0+96 h, a thermal flux reaching 1kW/m² was measured on the specimen rear surface, in front of the wood block n°12.

We noticed that the temperature in local areas of the specimen rear surface can reach 460°C. This temperature is higher than 200°C for 2.5 hours (h) between T_0+7.5 h and T_0+10 h. Concerning the fluxes recorded, peaks of 6.2 kW/m^2 and 8.1 kW/m^2 have been measured, with an average exceeding 5 kW/m^2 during this period. A second local noteworthy thermal flux has been measured between T_0+40 h and T_0+57 h, reaching a maximum value equal to 4.6 kW/m².
Average heat flux resulting from wood combustion and integrated at the oil exchanger is presented in figure 5, with 4 of the most interesting fluxmeters.

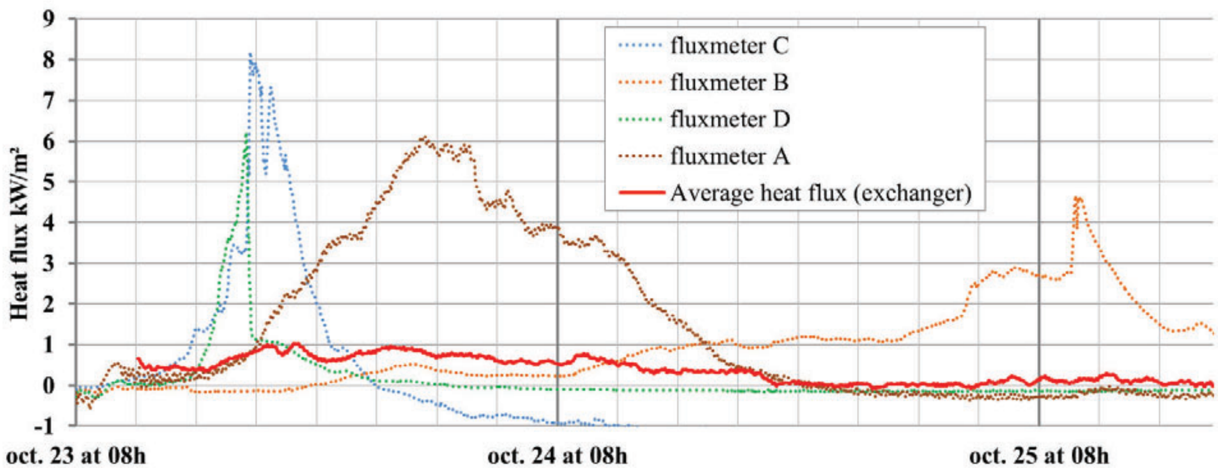

Figure 5: heat flux generated by wood combustion towards the oil exchanger, with recorded local heat flux evolutions exhibiting large peaks

POST-FIRE TEST ANALYSIS AND INTERPRETATION

Excepted the top corner blocks n°1 and 11, all the blocks were reduced to ashes. Complete disappearance of several passive temperature indicators, in front of blocks n° 7, 9, 10 and 13, confirmed temperatures of the specimen rear surface higher than 340°C.
Main difference between B1 and B2 top shock absorber behaviour concerns the flame front progression speed: 5 to 8 times faster for B2 half, leading to a 30 % shorter total combustion time, mainly explained by the different wood species.
The test highlighted that air access inside the shock absorbers is a key parameter concerning the wood combustion duration and intensity. Oxygen accessibility implies the possibility for the air to pass through the specimen, from a bottom opening to an upper one. In the present case, a limited lower air entrance (0.0075 m² cross sectional area) and an outlet of 0.05 m² were sufficient for the total combustion of the wood contained in shock absorber, as long as smoke outlet (504 cm² cross sectional area) was not restrictive. Considering air inlet, fusible holes contribution was found negligible (5% of air inlet cross sectional area).
After the test, the front surface of the specimen has been laser scanned in three dimensions. Due to the thermal distortion of the specimen steel casing (all weld spots were broken), the thickness of the gap between the wood blocks and the front steel casing increased 5 times which should have much contributed to air access and fire spreading.

IMPACT OF WOOD COMBUSTION ON THE THERMAL BEHAVIOUR OF PACKAGE COMPONENTS AFTER THE FIRE TEST

The experimental part of the study was completed by a numerical analysis to evaluate the impact of the heat fluxes, generated by wood combustion on the temperature of the package components important for safety, in particular the elastomer gaskets equipping the cavity closure system. To guarantee the containment of radioactive materials, the gaskets shall remain leaktight, which implies that their maximum allowable temperature is not exceeded. In this context, we used the heat flux measurments recorded from the B1 specimen half part.

DESCRIPTION OF THE PACKAGE MODEL

The half upper part of the package, including the cavity closure system located near the top shock absorber, has been modelled in three dimensions. According to symmetries axis, only a quarter of the package section has been considered. The numerical analysis was divided in two steps:

- Preliminary calculations have been performed to evaluate the temperature increase of the gaskets equipping the cavity plug and its orifices due to the heat transfers associated to the combustion of the wood blocks composing the top shock absorber. In this regard, the package geometry has been simplified as presented in figure 6. The wood blocks have not been modelled and the thermal fluxes measured during the test have been directly applied on the bottom of the shock absorber steel casing. In addition, the thermal power of the spent fuel assemblies has not been modelled in these calculations to evaluate the direct effect of the wood combustion on the temperature of the package components. Nevertheless, the geometry and the thermal properties of the spent fuel assemblies have been considered to model the thermal inertia of the content and to ensure the relevance of the heat transfers kinetic.
- In a second approach, the temperature increases of the gaskets due to the wood combustion have been added to the temperatures of the package submitted to the regulatory fire test (800°C for 30 minutes) specified in the IAEA regulation [1] (hypothesis of our modelling). These calculations have been performed taking into account all the package components including the wood blocks inside the shock absorber structure.

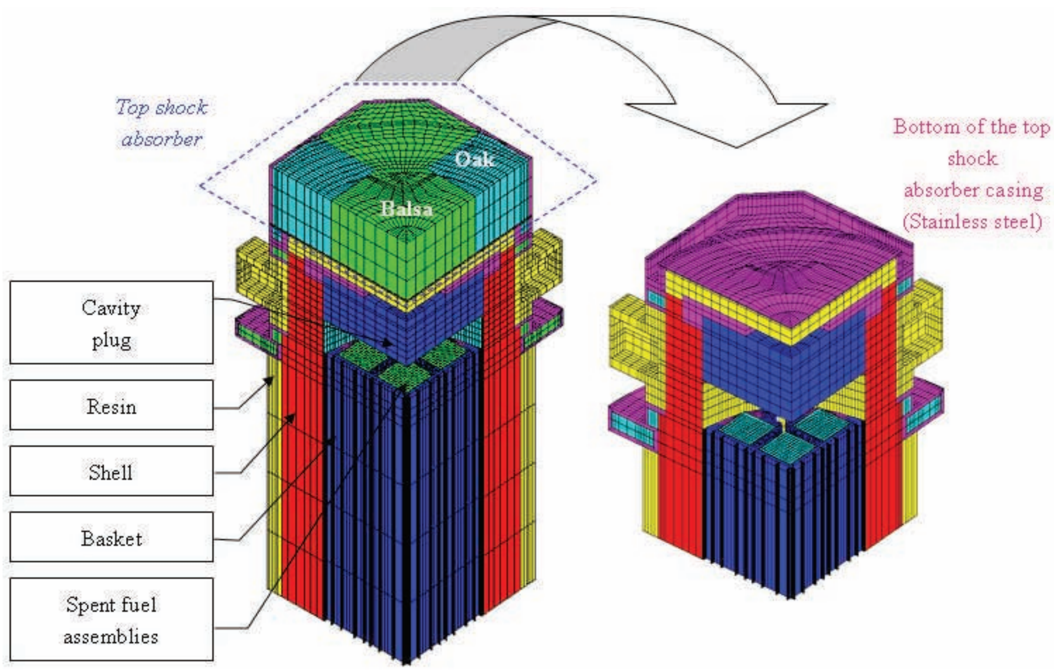

Figure 6: General view of the B1 package mesh

BOUNDARY CONDITIONS

The preliminary calculations used to determine the influence of the heat fluxes measured on the temperatures of the package components have been performed taking into account the heat exchanges by radiation and convection between the packaging external surfaces and the ambient environment. Regarding the wood combustion phenomenon occurring during the cooling time of package after the fire test, we considered an external thermal emissivity of steel components equal to 0.8 to take into account the presence of soot.

The wood combustion has been modelled by applying the thermal flux measured during the experimental test (see figure 5) directly on the bottom of the shock absorber steel casing located in front of the package cavity closure system as presented in figure 7. We also determined the averaged heat flux measured on all the surface of the specimen B1 half part, to evaluate its influence on the package thermal behaviour.

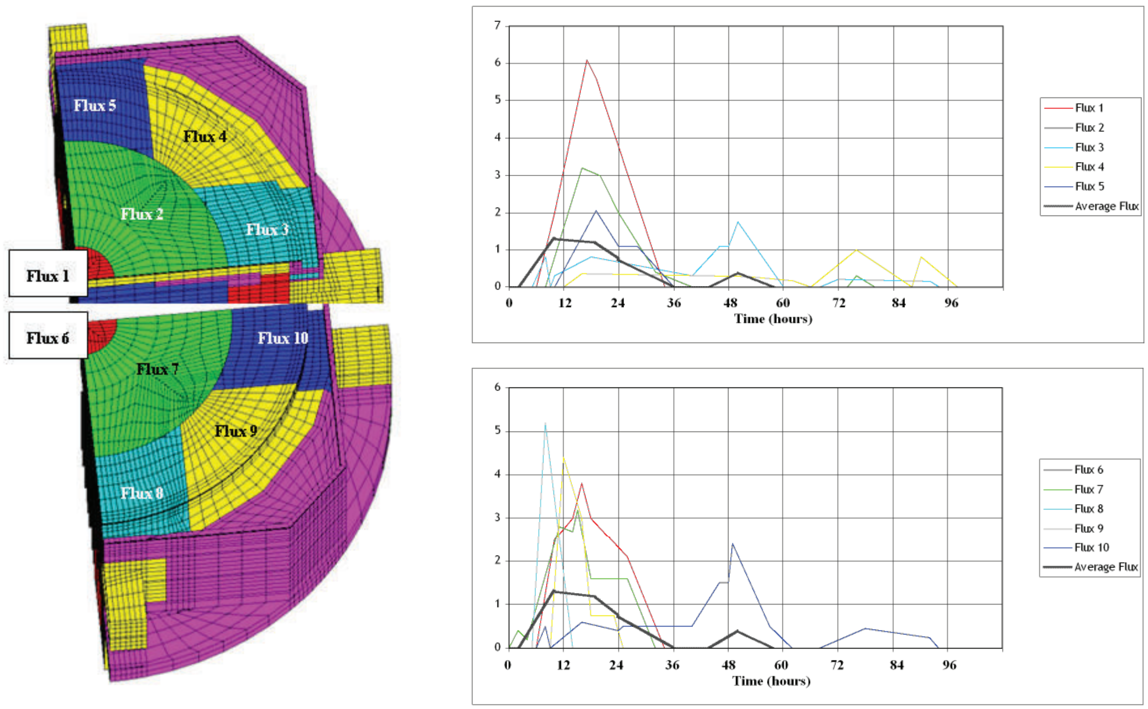

Figure 7: Thermal flux applied on the rear surface of the B1 top shock absorber casing (kW/m²)

RESULTS OF THE NUMERICAL STUDY

We focused this analysis on the temperature of the elastomer gaskets equipping the components of the cavity closure system. The maximum allowable temperature of the gaskets is equal to 250°C (FKM gaskets). Above this temperature, the gasket failure could lead to an activity release higher than the regulatory criterion of A_2/week applicable in accident conditions of transport. In addition, gaskets are subjected to thermal expansion. At high temperature, the gasket volume could exceed the volume of its groove and create high mechanical loads in the closure system forcing a gap between plug and body. Then gasket leaktightness could not be guaranteed any longer. In this context, the temperature increases of inner cavity plug and orifice plug gaskets were analysed.

The temperature increases of the B1 package gaskets due to the combustion of the wood blocks, confined into the top shock absorber steel sheet, are presented in Figure 8.

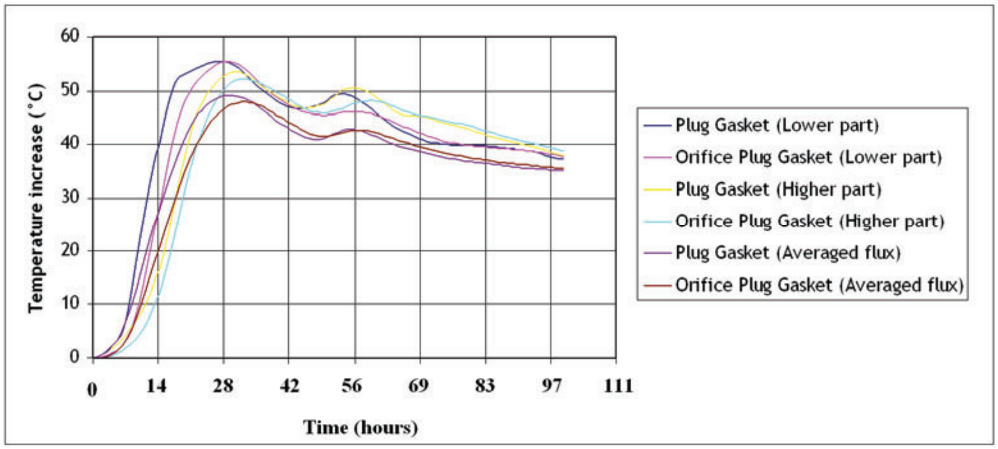

Figure 8: Temperature increases of the B1 package gaskets due to the wood combustion

Temperature distribution of the package in the lower shock absorber area, due to the combustion of wood blocks, at different times after the end of the fire test is presented in figure 9.

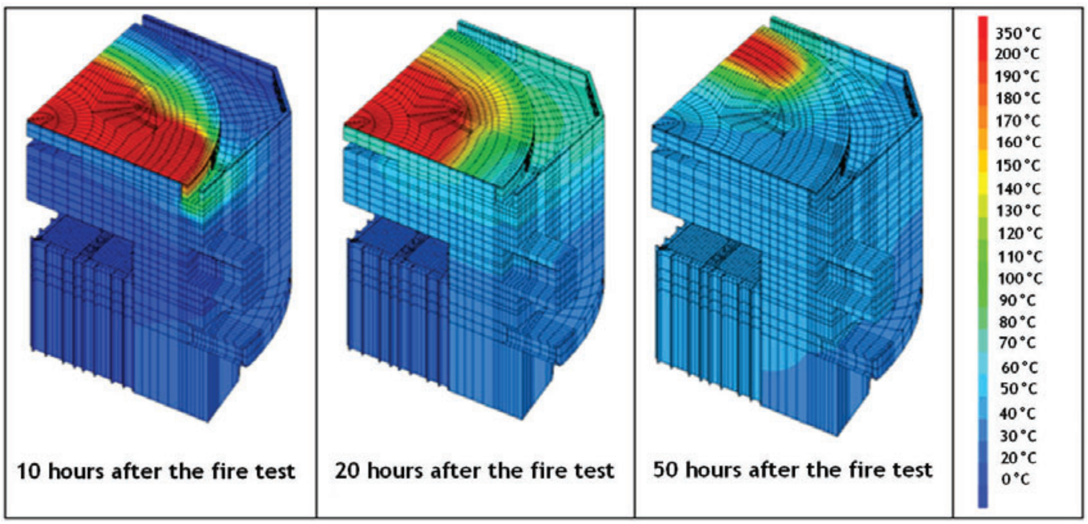

Figure 9: Package temperatures at different times after the end of the fire test

Regarding the results presented in figure 8, the thermal flux associated to the combustion of the wood blocks lead to a maximum increase of the gaskets temperatures higher than 50°C reached approximately 28 hours after the end of the fire test. In addition, the temperatures distribution in the bottom of the shock absorber steel casing, the kinetic of the heat transfers and the temperature of the steel casing, presented in figure 9, are consistent with the test measurements.

In a final approach, the thermal behaviour of the B1 package exposed to the regulatory fire test (800°C for 30 minutes) was studied taking into account the heat transfers by conduction in wood blocks as it is usually considered in the safety demonstrations. The thermal power of the twelve PWR spent fuel assemblies loaded in the packaging cavity has been considered. In addition, the calculation has been performed taking into account the regulatory boundaries conditions concerning the heat transfers by radiation and convection between the package and the flame or the ambient environment during the cooling time.

The temperatures of the gaskets, which equipped the containment system during the regulatory fire test, are presented in figure 10. In addition, we plotted on these graphics the temperature increases due to the wood combustion.

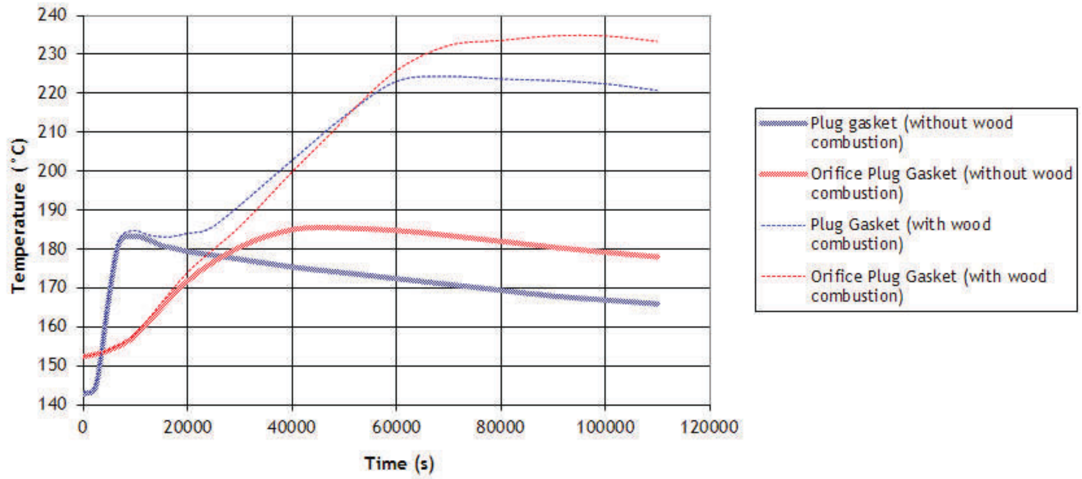

Figure 10: Maximum temperatures of the B1 package gaskets

We can notice that:

- The maximum temperatures of the cavity plug gasket and the orifice plug gasket due to the fire test are reached respectively 3 and 12 hours after the end of the fire.
- The maximum increases of the gaskets temperature due to combustion of the wood are reached approximately 28 hours after the end of the fire.

As a result, the post-combustion of the wood present in the top shock absorber of the B1 package leads to an increase of the gaskets temperature approximately equal to 50°C which is not negligible. Nevertheless, the maximum gaskets temperatures remain lower than the criterion (250°C). Finally, it is important to highlight that the thermal flux measured during the test, and taken into account in the calculations, are based on one fire test configuration. In this regard, these results could not be applied to other shock absorber designs and fire conditions without complementary demonstrations.

CONCLUSIONS

The Fire test involving a shock absorber evidenced a wood combustion until practically complete burning of the wood. The shock absorber damages, resulting from regulatory mechanical tests creating openings for air inlet and smoke outlet, have certainly enhanced the combustion of the wood allowing air circulation near the fire. Heat fluxes and temperatures measured during the fire test on the rear surface of the specimen were significant and combustion of the wood blocks kept on during 4 days, with local extreme peaks reaching 8 kW/m². On the basis of numerical calculations, we have shown that the heat fluxes measured during the test could significantly increase the temperature of elastomer gaskets equipping the containment system, around 50°C for the studied design. Such temperature increase is not negligible but will depend on the wood combustion phenomenon, linked to the shock absorber design and the wood species properties. Consequences of the wood post-combustion should therefore be evaluated considering each package and shock absorber design.

REFERENCES

[1] Regulation for the Safe Transport of Radioactive Material (IAEA, TS-R-1, Edition 2009)

[2] Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (IAEA, TS-G-1.1, 2008 edition)