BEHAVIOUR OF A PACKAGE FOR TRANSPORT OF SPENT FUEL ASSEMBLIES EXPOSED TO BEYOND REGULATION FIRES

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ABSTRACT

IRSN is performing a study relative to the thermal behaviour of a new TN International package design for transport of spent fuel assemblies called TN®112. The aim of this study is to evaluate the behaviour of the package submitted to fires, with durations and temperatures different from those required in the IAEA regulation TS-R-1 (respectively 30 minutes and 800 Celsius degrees). Its main objective is to provide quantitative data available for safety assessment in emergency situations involving fires. Moreover it can also be used for a cross comparison with the analysis of the thermal behaviour of the package during the IAEA regulatory fire test presented by the applicant in the package design safety report.

This study is based on numerical calculations performed with the code THERMX-PROTEE. The three-dimensional model used represents a quarter of the upper half of the package, where is located the closure system. The thermal behaviour of the resin located in the plug, the trunnions and between the inner and outer shells was modelled considering endothermic reactions of vaporization. During the heating phase of the fire test, the water vapour produced in heated elements is transferred and condensed in the nearby colder elements; the associated thermal transfers can increase very fast the temperature of the latters. The part of the vapour which cannot be condensed when most of the nearby elements reach a temperature above 100 Celsius degrees is evacuated through the holes that are distributed throughout the external envelope of the packaging and closed by fusible plugs. A specific calculation module has been developed to take into account the corresponding energy transfers. This module was qualified by comparison with the results of experimental fire tests.

The calculations performed in the framework of this study cover temperatures of fire between 400 and 1000 Celsius degrees. One of the results of those calculations is the time necessary to reach the maximum allowable temperature of the elastomer gaskets.

INTRODUCTION

According to IAEA regulation [1], type B packages should be submitted to a fire test of 800 Celsius degrees during 30 minutes.

During the emergency situations, the duration of real fires could be higher than 30 minutes and the flame temperatures depend on the properties of the inflammable products involved and the fire configurations.

A new TN International package design for transport of MOX irradiated fuel, called TN®112 has just been approved by the French competent authority. To get better knowledge about its resistance to fire, the *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) decided to evaluate the fire temperatures and durations that could lead to containment failure.

DESCRIPTION OF THE TN®112 PACKAGE DESIGN

The package has a general cylindrical shape with two independent leaktight barriers.
The main components of the packaging body, from internal to external surfaces, are:

- a primary shell in stainless steel;
- aluminium sections with lead inside;
- a secondary shell in stainless steel;
- copper conductors surrounded with polymerized resin;
- copper plates welded on the external surface of the secondary shell of the packaging. These elements form fins on the external surface of the packaging.

The first barrier is composed by a primary shell, a bottom welded to this shell and a plug made of a stainless steel structure comprising a resin neutron shielding. The second barrier is composed of a secondary shell, a bottom welded to this shell and a stainless steel lid. The cavity plug and lid are equipped with orifices closed by plugs. The lid, the plug and all the orifices are sealed by elastomer gaskets. Each of these two barriers ensures the leaktightness of the package.
Two shock absorbers fitted on both extremities of the packaging ensure a mechanical protection. They are composed of an aluminium ring in contact with the external flange of the packaging and a wood protection confined in a stainless steel structure.
The internal arrangement is composed of a basket with twelve square section lodgements in which are placed the spent fuel assemblies. The basket model includes different sectors, made of boronated aluminium, fitted together on 24 levels. In the upper part of the basket, axial pins ensure a contact between the basket and the plug which closes the cavity.
The radioactive contents consist in twelve PWR spent fuel assemblies. Each spent fuel assembly includes 264 fuel rods in a square lattice.

DESCRIPTION OF THE *THERMX-PROTEE* SOFTWARE

THERMX-PROTEE is a finite element software used to determine the temperature distribution in steady or unsteady states in two or three dimension geometries. The calculation module, called *PROTEE*, developed by IRSN, is used to model the heat exchanges associated to water vapour transfers through resin during the fire test.

THERMX-PROTEE allows to consider the different modes of heat transfer (conduction, radiation and convection), on the one hand between the internal elements of the package (radiation face to face or convection in cavity), on the other hand between the external surfaces of the package and ambiance (infinite convection and radiation). It is also possible to model the evolution of gap sizes as a function of the thermal expansion of the materials. This functionality has been used in the study to evaluate the thickness of the gap between the basket and the primary shell of the package at each time step of the calculation. Thus more realistic thermal transfers in transient conditions are considered. Finally, *THERMX-PROTEE* can take into account the thermal behaviour of the endothermic materials such as resin with an accurate modelling of the water vapour transfers. The condensation of the vapour and the energy transfers at the different nodes of the mesh during the cooling phase of the package, after the fire test, are also modelled. Moreover, it is assumed that the thermal properties of the resin no longer vary with the temperature decrease during the cooling period. The development of this thermal model has been established on the basis of specific experimental tests. The corresponding experimental conditions were presented during the PATRAM’2007 conference [3].

The temperatures of the rods are determined with a complementary calculation tool considering the temperatures of the basket walls and heat transfer by radiation within the rod lattice and between rods and basket.

DESCRIPTION OF THE PACKAGE MODEL

The package design geometry has been modelled in three dimensions. Just the half upper part of the package, where the closure system is located, has been modelled. Moreover, according to symmetry axis, only a quarter of the package section has been considered.

The total number of mesh elements is equal to 73 300. The mesh includes 35 subassemblies and 49 surfaces have been defined to apply the boundary conditions.

The figure 1 presents general views of the package model.

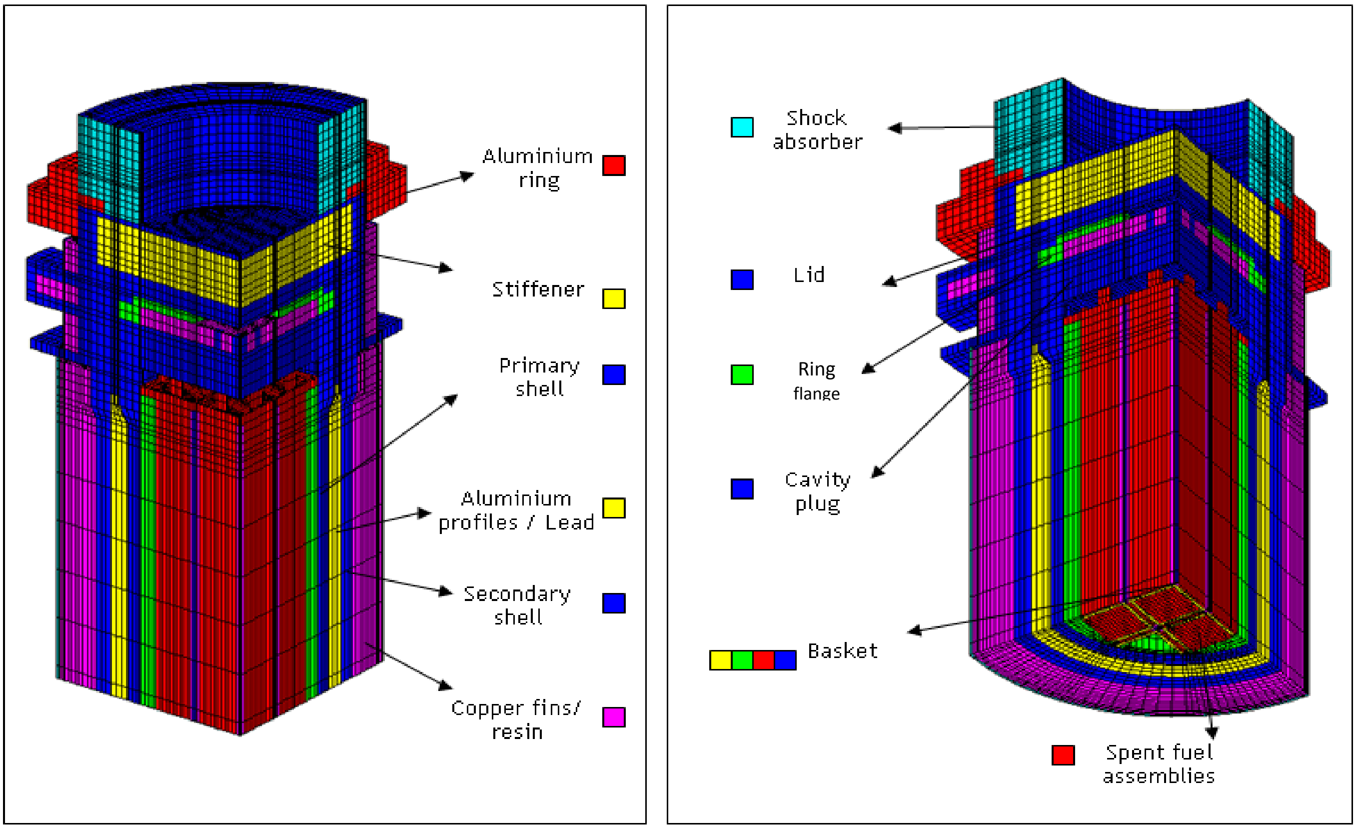


Figure 1. General views of the TN®112 package mesh

A special attention was paid to the modelling of the package internal elements. The structures between the walls of the basket, the crossings of the beams and their periphery have been represented by equivalent materials which take into account, on the one hand the thermal properties of the different materials and the filling gas (helium) present in the cavity of the package, on the other hand the directions of the main heat transfers.

The figure 2 presents the different elements of the basket model geometry.

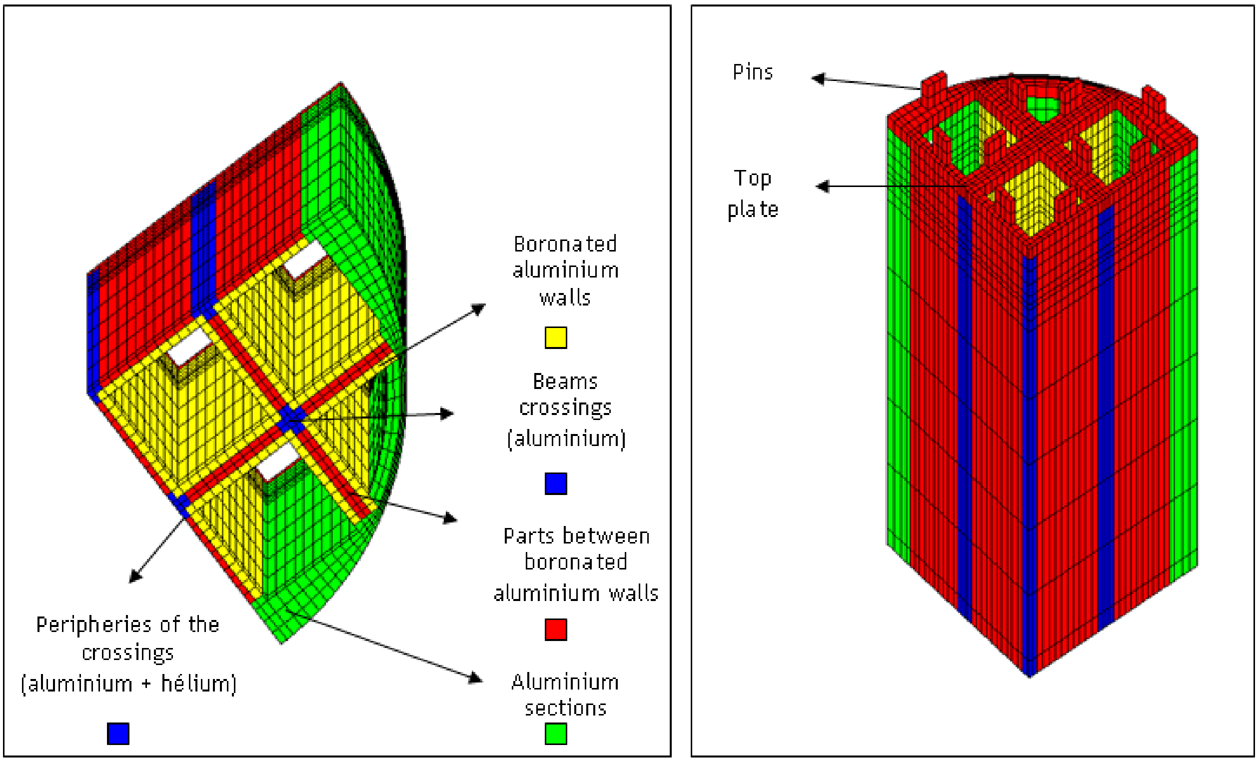


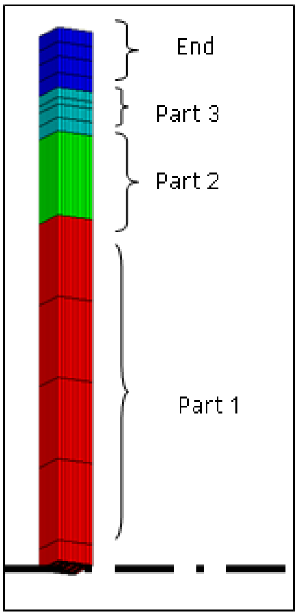
Figure 2. General views of the TN®112 basket mesh

The half upper part of the spent fuel assemblies have also been modelled to consider the thermal transfers by conduction through the filling gas (helium) and the radiation between the top of the assemblies and the lower surface of the cavity plug. For this, four major parts are distinguished to represent a realistic longitudinal profile of heat power dissipated by the PWR spent fuel assemblies. The thermal power of the content taken into account in the study is equal to 48 kW uniformly distributed in the twelve basket lodgements, that is to say 4 kW per assembly. The table 1 presents the different part lengths of the spent fuel assemblies and the thermal powers associated.

The maximum fuel rod temperatures have been determined considering the heat transfers by radiation inside the rod lattice.
The evolution of the thermal properties of the package materials with the temperatures have also been taken into account in the calculations.
Finally, the model of aluminium sections with lead inside, the copper conductors with resin inside and the stiffener was simplified in terms of geometry and thermal properties.

Table 1. Heat power profile of the upper half of the spent fuel assemblies

Part	Length (m)	Thermal Power (kW)	Linear Power (kW/m)
End (Inactive)	0.240	0	0
Part 3	0.139	0.364	2.619
Part 2	0.308	1.635	5.308
part 1	1.264	9.129	7.222



BOUNDARY CONDITIONS

The additional effects of the normal and accident thermal conditions have been considered in the study. Thus, the temperatures of the package components were initialized, at the beginning of the fire tests, with those obtained in normal conditions of transport in steady state.

Normal conditions of transport

The temperatures of the package in normal conditions of transport have been evaluated in steady state using the maximum regulatory insolation and ambient temperature defined in [1].
IRSN has considered a contact between the basket pins and the cavity plug which is the most penalizing configuration for the gasket temperatures. The upper part of the spent fuel assemblies is also in contact with the cavity plug. The internal gap between the primary shell and the basket has been modelled. The thickness of the gap is determined at each time step of the calculations depending on the thermal expansion of the materials. The other manufactured gaps between the package components have been taken into account according to their nominal values.
The influence of confined environments during transport of the package has been evaluated. IRSN finally considered the temperatures of the components when the package is transported under tarpaulins or canopies. In this regard, the convective coefficients applied in the calculations lead to the same package external surface temperatures as those determined by the applicant in the thermal analysis of the package in confined environments.

Accident conditions of transport

The thermal behaviour of the package, during the fire tests, has been studied with a convective coefficient applied on the external surfaces equal to 10 W/m².K, as recommended by the IAEA safety guide [2], taking into account the actual surface of the copper fins.

The thermal emissivity of the external surfaces of the package, during and after the fire, is equal to 0.8, to simulate the soot covering. The flame emissivity is equal to 0.9, as defined by the IAEA regulation [1].

Finally, to consider the damages caused to the package components by the mechanical tests simulating the normal and accident conditions of transport, gaps, where radiation transfers occur, have been replaced by contact areas, especially between the lid and the inner flange of the package. In addition, a sliding of the spent fuel assemblies due to the deformation of the assemblies top nozzles and a small gap (4 mm) between the upper part of the spent fuel assemblies and the cavity plug were considered.

CALCULATION OF THE MAXIMUM ALLOWABLE FIRE DURATIONS

Containment criteria

The durations of fire that could lead to reach the maximum allowable temperatures within the components important for the package safety have been determined.

The first criterion is the maximum allowable temperature of the elastomer gaskets, present in the containment system of the package, which is equal to 220°C in transient state. Above this temperature, the performances of leaktightness of the gaskets are not justified by the applicant.
IRSN has evaluated the temperature of the following gaskets:

- inner plug gasket;
- inner lid gasket;
- plug orifices gaskets;
- lid orifice gasket.

The second criterion is the maximum allowable temperature of fuel rods, which is considered equal to 550°C. This criterion is not precise due to lack of knowledge of behaviour of heated spent fuel rods previously submitted to a high energy mechanical loading.

Main results

The main results of the calculations, providing the time necessary to reach the maximum allowable temperatures of the fuel rods and the gaskets mentioned before, are presented in table 2.

Table 2. Maximum allowable fire durations

Fire temperature (°C)	Fire duration to reach gaskets criterion	Fire duration to reach fuel rods criterion
400	7 h 33 min	19 h 57 min
600	3 h 39 min	11 h 29 min
800	2 h 07 min	6 h 24 min
1000	1 h 21 min	4 h 35 min

Thus, IRSN has established the fields, defined by temperature and duration of fire, for which the leaktightness of the package is guaranteed (see figure 3).

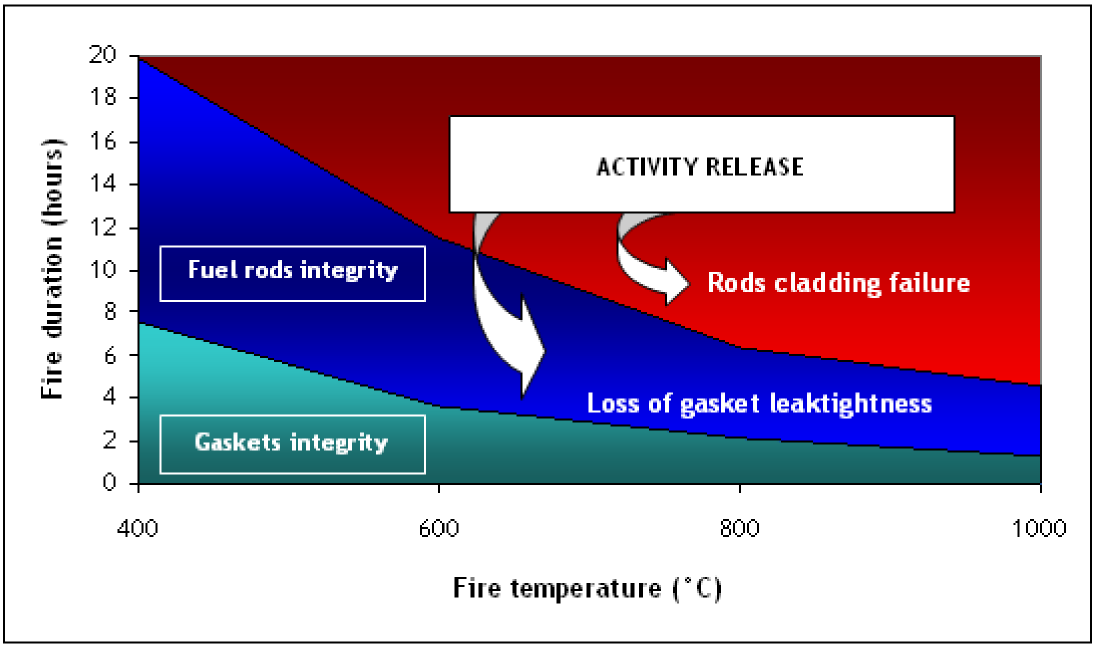


Figure 3. Maximum allowable fire durations

Simple equations can be extracted from the previous results to estimate, in case of emergency situations involving fire, the fire duration leading to a risk of loss of containment of the package.

The equation (1) could be used to analyse the behaviour of elastomer gaskets depending on duration or temperature of the fire.

$$(\text{Fire Temperature}_{\,(°C)})_{gaskets} = 10\,521 \times (\text{Fire Duration}_{\,(minutes)})^{-0{,}5334} \qquad (1)$$

This equation (2) could be used to analyse the behaviour of fuel rods transported in the package depending on duration or temperature of the fire.

$$(\text{Fire Temperature}_{\,(°C)})_{rods} = 30\,323 \times (\text{Fire Duration}_{\,(minutes)})^{-0{,}6073} \qquad (2)$$

Moreover, to complete the results presented by the applicant in the safety analysis report in the case of a regulatory fire test (800°C for 30 minutes), IRSN has performed calculations with several fire temperatures for a fire duration of 30 minutes. The maximum gaskets temperatures, exposed to 30 minutes fire tests (with a temperature range from 400 to 1 000°C) are presented in figure 4.

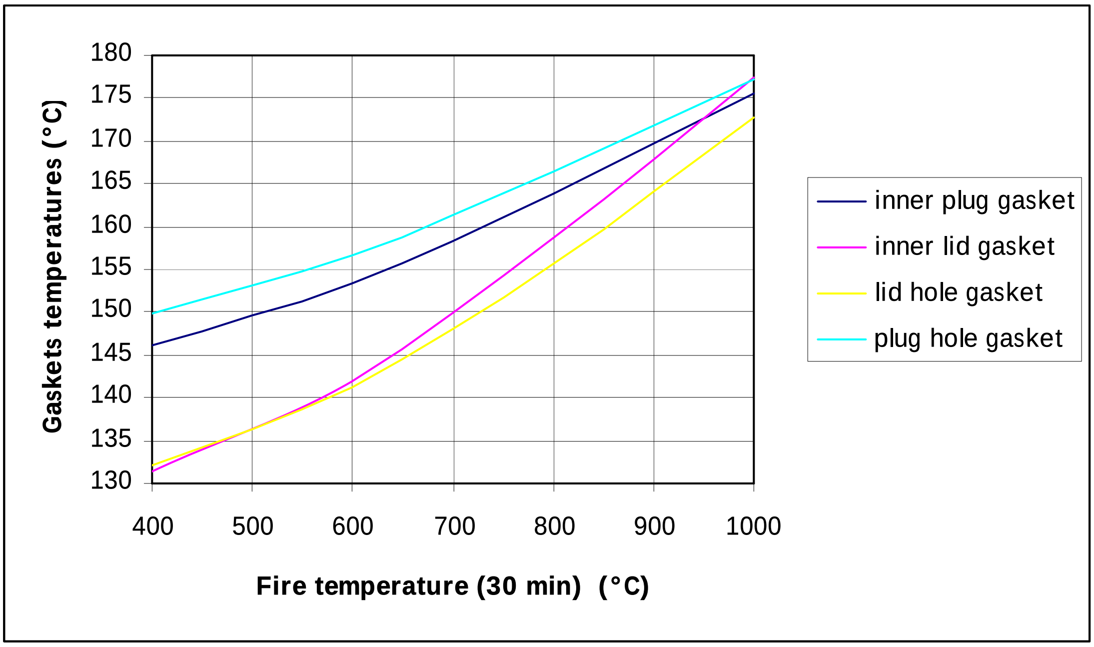


Figure 4. Maximum temperatures of the package gaskets after 30 minute fires

DISCUSSIONS AND CONCLUSIONS

The numerical modelling of the TN®112 package, exposed to 30 minutes fires, has highlighted the safety margins for this package concerning the gaskets of the containment system and the fuel rods integrity. In this regard, it has been shown that the leaktightness of the package is still guaranteed after 2 hours of a fire with flames at 800°C.

It should be noted that the calculations have been performed with an internal thermal power of 48 kW uniformly distributed in the twelve basket lodgements. Consequently, this study should be completed considering heterogeneous thermal loadings in the cavity of the package to cover the other possible transport configurations of the package.

The simplified equations (1) (2), issued from the results of the calculations performed, give a tool to evaluate quickly, in case of emergency situations involving fire, the consequence of the fire on the leaktightness of the package depending on the duration and temperature of the fire.

However the degree of engulfing of the package by the flames during the fire time should also be appreciated by the IRSN emergency analyst in charge of evaluation of the package condition after fire.

REFERENCES

[1] Regulation for the Safe Transport of Radioactive Material (IAEA, TS-R-1, Edition 2005)

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

[3] Numerical study of the thermal behaviour of two types of packages exposed to long duration fires, O.Doaré, F.Armingaud, G. Sert, H. Issard – IRSN – PATRAM 2007