Numerical study of the thermal behaviour of two types of packages exposed to long duration fires

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Abstract

The thermal behaviour of two types of package exposed to long duration fires is studied. The TN™ 12/2A and TN™ 28VT packages, respectively used for spent fuel and vitrified waste transports, are modelled. Three-dimensional meshes are used. Attention was paid to the model of the thermal protective resin of the packages because of its complex thermal behaviour. During heating several endothermic reactions occur: water vapour is produced and a part of it diffuses though the resin and condensates on the cold parts of resin, increasing the global heat transfer within the material. The other part of the water vapour exits the package by fusible holes. The thermal characteristics of these reactions have been established thanks to specific tests performed in a laboratory. A model taking into account all these phenomena was developed and integrated to the global thermal model of the packages in order to simulate the thermal behaviour of the packages exposed to long duration fires. Four fire temperatures were considered and, for each of them, the maximum fire duration that packages can withstand without activity release was calculated. The results show safety margins regarding the IAEA regulatory thermal test (800°C-30 min). The use of the complex model of resin led to calculate safety margins about 40% greater than those calculated with a model of resin taking only conduction into account. The results were used to prepare a guideline for safety assessment in emergency situations involving fire. This emergency tool provides safety limits for containment according to fire duration, fire temperature, package heat power and ambient temperature.

1. Introduction

The type B and fissile packages are designed to withstand the IAEA regulatory thermal test, which corresponds to an engulfing fire at 800°C for 30 minutes [1]. Nevertheless, it was decided to study the thermal behaviour of some packages submitted to fires the duration of which can exceed 30 minutes and involving temperatures other than 800°C. The objectives were to estimate the safety margins of packages designed to the regulatory thermal test, to estimate the thermal behaviour of packages submitted to fires more severe than the regulatory thermal test and to verify the conservatism of the thermal models currently used in safety analysis reports.

2. Description of the two packages considered

The TN™ 12/2A cask is designed to transport PWR spent fuel assemblies with a gross weight of 110,000 kg. The cylindrical package is 6,150 mm long with a 2,500 mm external diameter. The body of the cask is made of a 303 mm thick carbon steel shell. A carbon steel plate is welded on the bottom of the shell and the inner cavity is closed by a lid held in position by a steel ring flange fixed by bolts to the shell. The containment vessel is leaktightened by FKM (fluorocarbon elastomer) type O-ring gaskets equipping the lid and the orifice stoppers. The shell is fitted with approximately 42,000 welded radial cooling fins made of copper. A 115 mm thick layer of resin, designed for neutron shielding and thermal protection, is located around the shell, between the fins. The two extremities of the shell are fitted with wood shock absorbers. The cylindrical fuel assembly basket is made of an aluminium alloy; its diameter is 1218 mm and presents 12 square lodgements. Each fuel assembly is composed of 264 fuel rods held in position by steel end pieces and spacer grids. The total inner thermal power of the 12 fuel assemblies is 93 kW.

The TN™ 28VT cask is designed to transport high level activity vitrified waste with a gross weight of 112,000 kg. The cylindrical package is 6,600 mm long with a 2,410 mm external diameter. The body of the cask is made of a 256 mm thick carbon steel shell. A carbon steel plate is welded on the bottom of the shell and the inner cavity is closed by a lid screwed on the shell. The containment vessel is leaktightened by the EPDM type O-ring gasket equipping the lid. Blocks of resin, designed for neutron shielding and thermal protection, are fitted around the inner shell, and covered by a 25 mm thick external steel shell. Copper plates for heat dissipation are located between inner and external shells, through the resin. The two extremities of the shell are fitted with wood shock absorbers. The cylindrical basket is made of an aluminium alloy; its diameter is 1218 mm and presents 5 cylindrical lodgements. The vitrified waste is packed in steel drums called canisters. The basket contains 20 canisters stacked in 4 rows. The total inner thermal power of the 20 canisters is 40 kW.

The process for resin installation is different for each of these two designs: it is poured in place for TN™ 12/2A but cast blocks are provided for TN™ 28VT. However, the resin compositions are similar; they are mainly composed of polyester and fire retardants comprising hydrated minerals.

3. Development of the heat transfer model for the protective resin

One of the key element in the packaging modelling is to take into consideration the complex thermal behaviour of the protective resin, which has been established thanks to specific tests performed in a laboratory. The experimental conditions were designed in order to be representative of the resin in packages (Fig. 1). Resin is poured in a closed vessel made of stainless steel. The resin layer and each steel wall are respectively 50 mm and 6 mm thick. The vessel is in a furnace and a radiant panel is designed to heat the lower steel wall. The gas resulting from resin heating can come out of it through holes in the steel walls. These holes simulate the fusible holes designed in the external wall of the TN™ 12/2A and TN™ 28VT packages to avoid overpressure. The installation is designed to collect the gas exiting the resin. Several thermal sensors are placed within the resin layer in order to measure temperature at different depths. The experiment consisted in heating the lower steel wall by the radiant panel maintained at 800°C during 30 minutes.

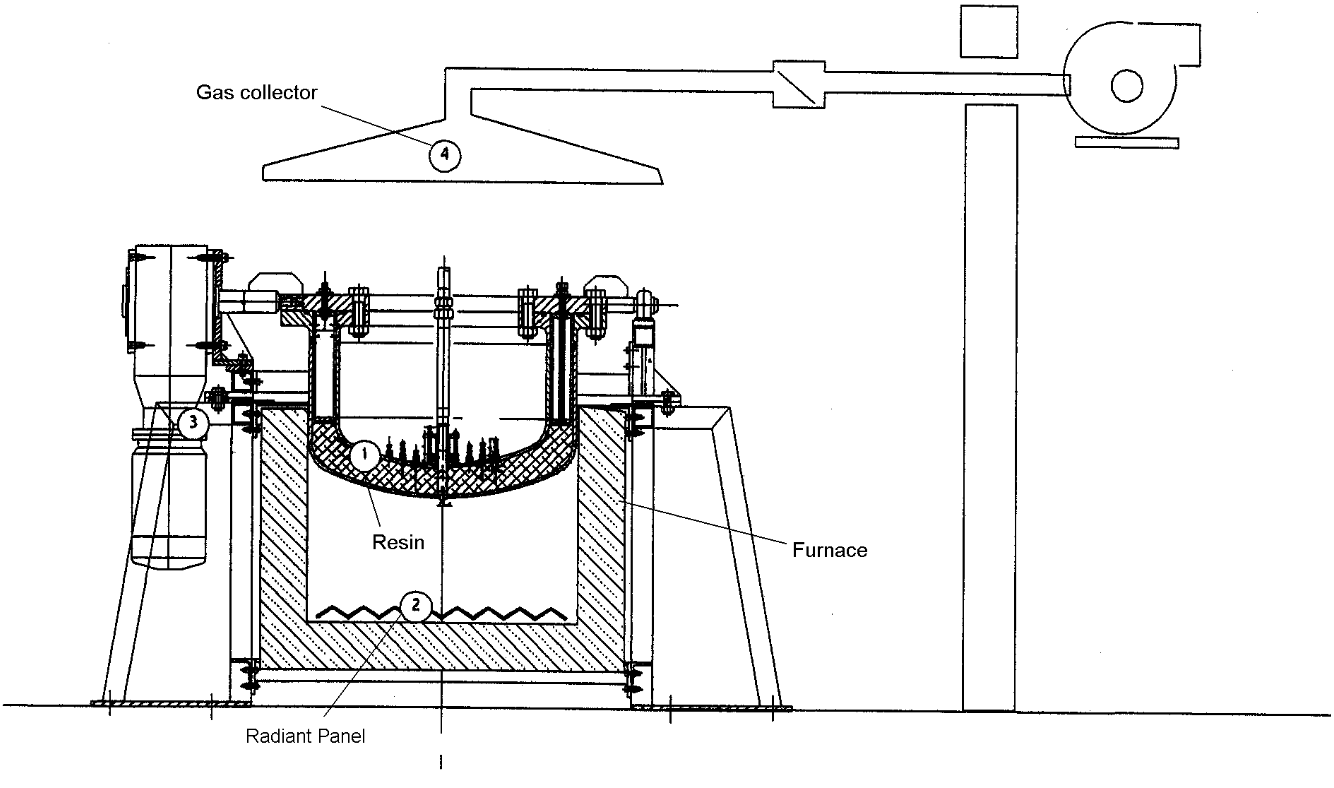

Fig. 1. Heating device for testing thermal behaviour of resin

The next step was the development of a thermal model for integration in a computer code using the finite element method. This model was intended to reproduce correctly the temperatures measured during experiment. Firstly, only were considered conduction in the resin and energy involved in endothermic reactions occurring within the resin during heating. These reactions are due to several dehydration stages in the resin leading to gas release, mainly water vapour. Independent experiments were performed in order to measure the conductivity and the heats of reactions. The use of these measured characteristics did not permit to get good agreement between the results of the calculations and the experimental results. It was noticed that the conductivity measured was too small to explain the increase in temperature of the resin. In particular, the heating is especially rapid in the areas distant from the heated side of the resin.

These results led to take into account the influence of gas diffusion on heat transfers: water vapour diffuses through the resin cracks and along the material boundaries and condensates on the cold surfaces of resin which increases the global heat transfer. During heating of resin, at each time step and at each node, the program calculates the quantity of water vapour produced and then the heat corresponding to the condensation of the vapour is distributed to the nearest nodes whose temperature is below 100°C. A parameter allows the limitation of the number of nodes to which heat can be distributed. The nondistributed heat corresponds to the vapour exiting the package by fusible holes. Moreover, it was also assumed that the thermal properties of the resin no longer vary with the temperature during the cooling period. This model was successful to reproduce the results of the experiment with accuracy.

In the TN™ 28VT package copper plates for heat dissipation are located between inner and external shells, through the resin. In order to evaluate the validity of the use of the resin model in this configuration, an additional experiment, where three copper plates were fixed between the two walls of the vessel, was performed. The other characteristics of the experiment were similar. A three-dimensional mesh using the resin model was developed to simulate the experimental installation. The results of the calculations showed a good agreement with the measured temperatures, which confirm the validity of the resin model for this kind of configuration.

4. Description of two package models

In order to get realistic results, a three-dimensional mesh models each package. Symmetry considerations allow to consider only an eighth of the TN™ 12/2A package with a mesh of 44,000 elements (Fig. 2) and only a quarter of the TN™ 28VT package with a mesh of 48,000 elements (Fig. 3). Geometrical details like trunnions and precise shape of lid, basket and shock absorber are modelled. It should be noted that no mechanical damage of the package is considered.

Moreover, variation of the gap between the basket and the inner shell is calculated at each step in order to determine precisely heat transfers between the two components.

Each canister inside the TN™ 28VT package is modelled assuming a homogeneous heat release in the canister. Each fuel assembly inside the TN™ 12/2A package is modelled but it is considered as a homogeneous component with a homogeneous heat release. However, an additional model taking into account radiation between fuel rods permits the calculation of the cladding temperature of each fuel rod at each step.

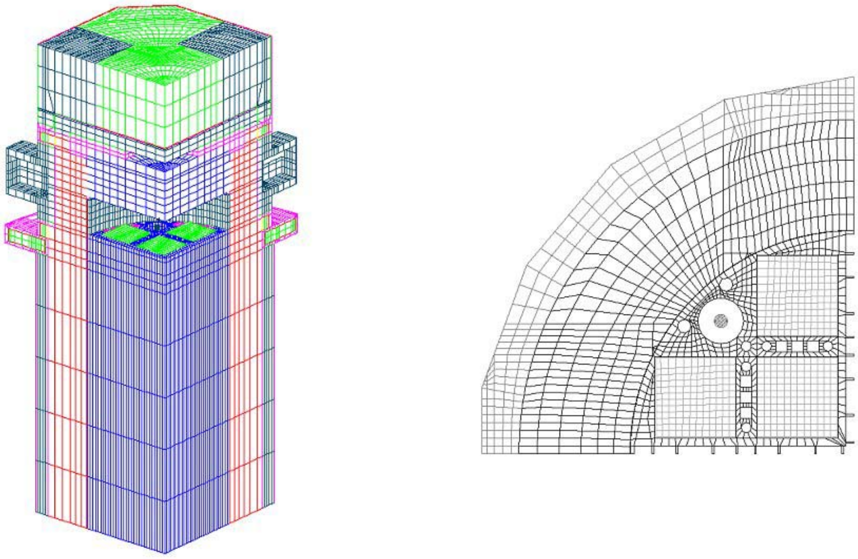

Fig. 2. TN™ 12/2A mesh – General view and cross section at mid-length of the package

5. Boundary conditions

Packages are considered horizontal during transport and during fire. Due to convective phenomena, the convective coefficient is considered as varying along external circumference of the packages in normal conditions of transport and during the cooling period. Its value is higher at the bottom than at the top of the package. The values used result from measurements on a TN™ 12/2A package. The same circumferential dependence law was used for the TN™ 28VT package.

The fire is considered all around the package. The emissivity of the fire is 0.9 and the convection coefficient between the package and the fire is 10 $W.m^{-2}.K^{-1}$ as recommended by [2]. After fire, the convection coefficient depends on temperature and is calculated at each time step. Before the fire and during the cooling period, regulatory insolation is considered and the ambient temperature is 38°C.

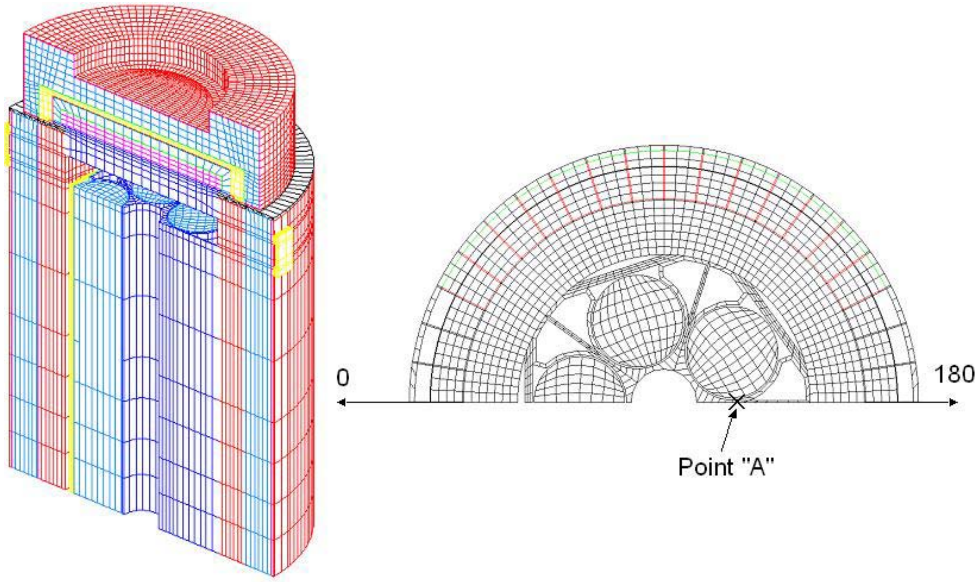

Fig. 3. TN™ 28VT mesh – General view and cross section at mid-length of the package

6. Calculation of the allowable maximum fire durations

6.1. Objective of calculations

The aim of the study is to calculate the maximum fire durations that packages can withstand without activity release. Four fire temperatures were considered: 400°C, 600°C, 800°C and 1000°C.

6.2. Containment criteria

For each package two criteria were established. Each criterion consists of a maximum temperature that a component of the package, important for the safety, can withstand without damage leading to activity release.

The first criterion for the two packages is the maximum allowable temperature of the gaskets of the containment vessel. For the TN™ 12/2A package the criterion is 250°C for FKM gasket, for the TN™ 28VT package the criterion is 180°C for EPDM gasket.

The second criterion for the TN™ 12/2A package is the cladding failure temperature of fuel rod: 550°C. This value was estimated in accordance with results of cladding failure test of unirradiated PWR fuel rods (the time leading to failure was established for several values of rod temperature and for several values of internal pressure of the fuel rod) and by taking account of the additional pressure in the fuel rod caused by the fissions gas produced during irradiation. The second criterion for the TN™ 28VT package corresponds to the temperature at which the deformation of the basket is excessive under action of the weight of the canisters and the resulting creep. An excessive deformation of the basket leads to major changes in heat dissipation and then in canister temperatures.

The criterion corresponds to 590°C at point A of the basket (see Fig. 3), which corresponds to the most reduced thickness.

6.3. Main results

For each fire temperature, several calculations were performed in order to determine the maximum fire duration that permits each criterion to be met.

Tab. I. TN^{TM} 12/2A package - maximum fire durations

Fire temperature	Criterion 1 (gasket temperature)	Criterion 2 (fuel rod clad temperature)
1000°C	1 h 03 min	49 min
800°C	1 h 42 min	1 h 25 min
600°C	3 h 05 min	not calculated
400°C	6 h 58 min	not calculated

Tab. II. TN^{TM} 28VT package - maximum fire durations

Fire temperature	Criterion 1 (gasket temperature)	Criterion 2 (basket temperature – point A)
1000°C	1 h	12 h 07 min
800°C	1 h 42 min	18 h 22 min
600°C	3 h 05 min	not calculated
400°C	6 h 42 min	not calculated

7 Analysis of the results and discussion

These results show that significant safety margins concerning the risk of activity release exist regarding the IAEA thermal test: the TN^{TM} 12/2A and the TN^{TM} 28VT packages can withstand a 800°C fire duration of about 1 h 40 min.

These 3D models allow the estimation of the thermal effect of some details frequently not taken into account in 2D models: in the IAEA thermal test conditions, the trunnions induce a gasket temperature increase of approximately 5°C for the TN^{TM} 28VT and 12°C for the TN^{TM} 12/2 when submitted to the regulatory fire, the effect of a non-homogeneous convection around the package in normal conditions of transport induce a gasket temperature increase of approximately 3°C for both packages. These models, in which heat transfers in shock absorbers are modelled, permit to get rid of uncertainties due to the frequently used assumption of adiabatic conditions.

But the thermal effect of the model of resin, taking into account endothermic reactions, water vapour recondensation and irreversibility of thermal properties, is globally the most important. Calculations show that for the IAEA regulatory fire, the gasket temperature increase of the TN^{TM} 28VT packages is 23°C (from 124°C to 147°C), with this model of resin and 36°C with a model of inert resin taking into account conduction only.

8. Conclusions on package designs

The development of representative models has permitted the estimation of the safety limits of packages exposed to fire. The packages considered in this study, designed in the 1980’s with thermal models available then, present safety margins of about 3 regarding the duration of the IAEA thermal test (800°C – 30 min).

9. Use of the results in emergency situations involving fire

The results of the study were used to establish a guideline for safety assessment in emergency situation involving fire. The aim of this guideline is to synthesize useful elements for estimation of the risk of activity release for a given fire situation involving a TN^{TM} 12/2A or a TN^{TM} 28VT cask.

The first part of the guideline consists of curves representing the temperature of several components of the packages as a function of the fire duration, for various temperatures of the fire. Those curves are derived from the numerous calculations performed.

Curves of the temperatures of the gaskets of the containment vessel and of the cladding of fuel rods for the TN™ 12/2A package and curves of the temperatures of the gasket of the containment vessel and of the thinnest area of the basket (point A) for the TN™ 28VT package are as follows (Fig.4 an Fig 5)

If the temperature and the duration of the fire are known, this kind of curve allows the estimation of the maximum temperatures that may be reached by the components of the package.

In the second part of the guideline, simple rules to adjust the models to the real accident scenarios are given.

The main characteristics that are used to correct the maximum temperature results are:

- The contents thermal power: this power has a direct influence on the temperatures of the package just before the fire. The lower the temperatures, the higher the safety margins. In the context of an emergency assessment, a linear relation between the inner power and the temperatures of the package can be assumed.

- Ambient temperature before fire and transport under a protection (tarpaulin, canopies, …).

- Mechanical damage: some mechanical damage of the packages may have a significant influence on the temperatures of the package during the fire. For example, it was estimated that a puncture (equivalent to the regulatory IAEA puncture test) of the wood shock absorber, associated with the deformation of the head of vitrified waste canisters after the regulatory 9 meter drop test, would lead to an increase of 25°C in the temperature of the gaskets of the lid of the containment vessel when the package is exposed to a 800°C fire for 30 min. Nevertheless, in real accident conditions, it may be difficult to determine precisely and quickly the mechanical damage and then best estimates are recommended.

- Fire and surrounding characteristics: fire may not be engulfing, flame temperature not homogenous and some kind of surrounding may disturb cooling of the package after fire; it may happen that heat dissipation capacity is affected by external parameters (such as mud or external damage to the cask). The case of a fire in a tunnel or near walls differs also significantly from the conditions assumed in the model. In particular, in a tunnel the temperature of the ambient air is higher than 38°C long after the end of the fire, the shape of the tunnel may disturb the airflow, and the heated walls may radiate additional energy to the package, delaying cooling [3].

In conclusion, the developed methodology has permitted the elaboration of an emergency tool capable of providing estimations of the temperatures reached by the important components for the safety of the TN™ 28VT and TN™ 12/2A packages exposed to fire.

Since many other package designs involve the same kind of neutron shielding material, it should be easy to extend this methodology to them, so as to have a thermal emergency tool with as wide a scope as possible.

10. References

[1] Regulation for the Safe Transport of Radioactive Material, IAEA Safety Standards Series N° TS-R-1

[2] Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, IAEA Safety Standards Series N° TS-G-1.1

[3] L'incendie dans les tunnels français – Rapport DSMR/SSTR/00-993 rév. 0 – IPSN, juillet 2000

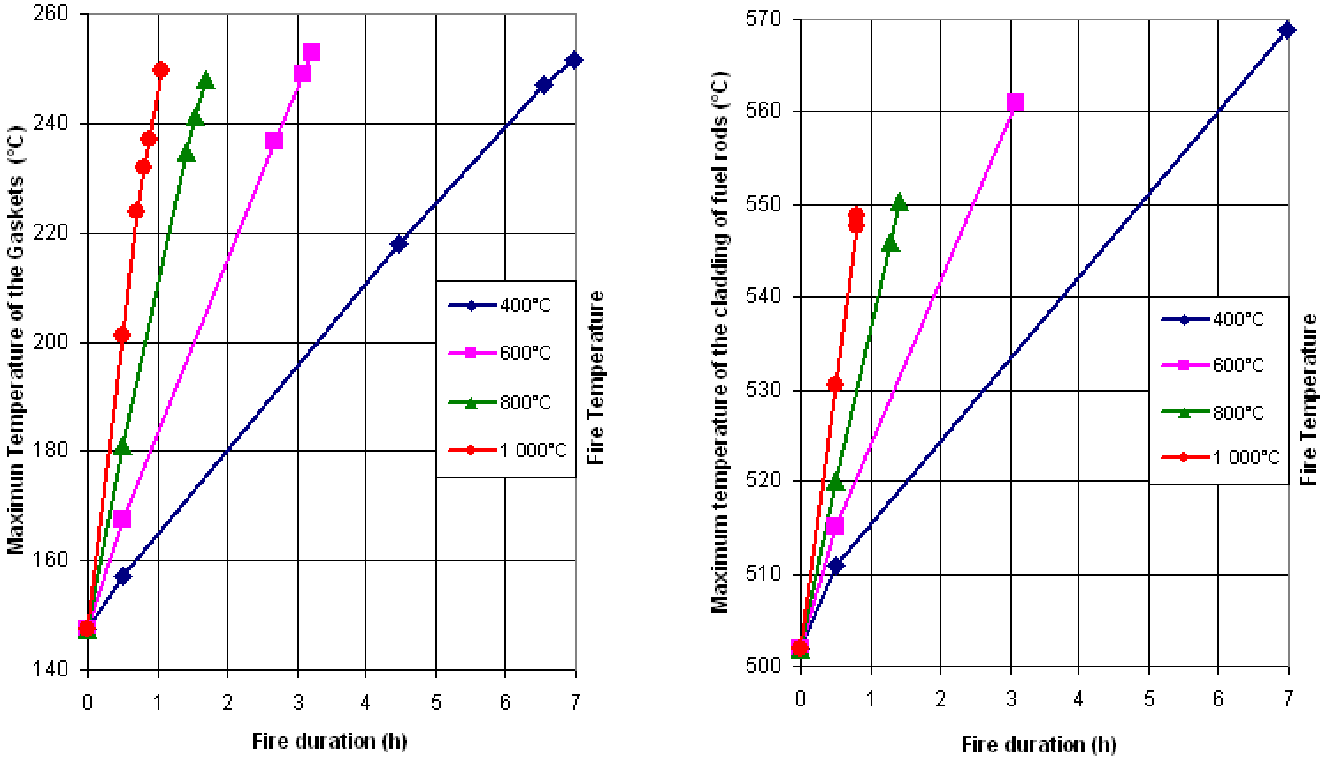

Fig 4. TN^{TM} 12/2A Maximum temperature of the gaskets and of the cladding of the fuel rods as a function of the fire duration

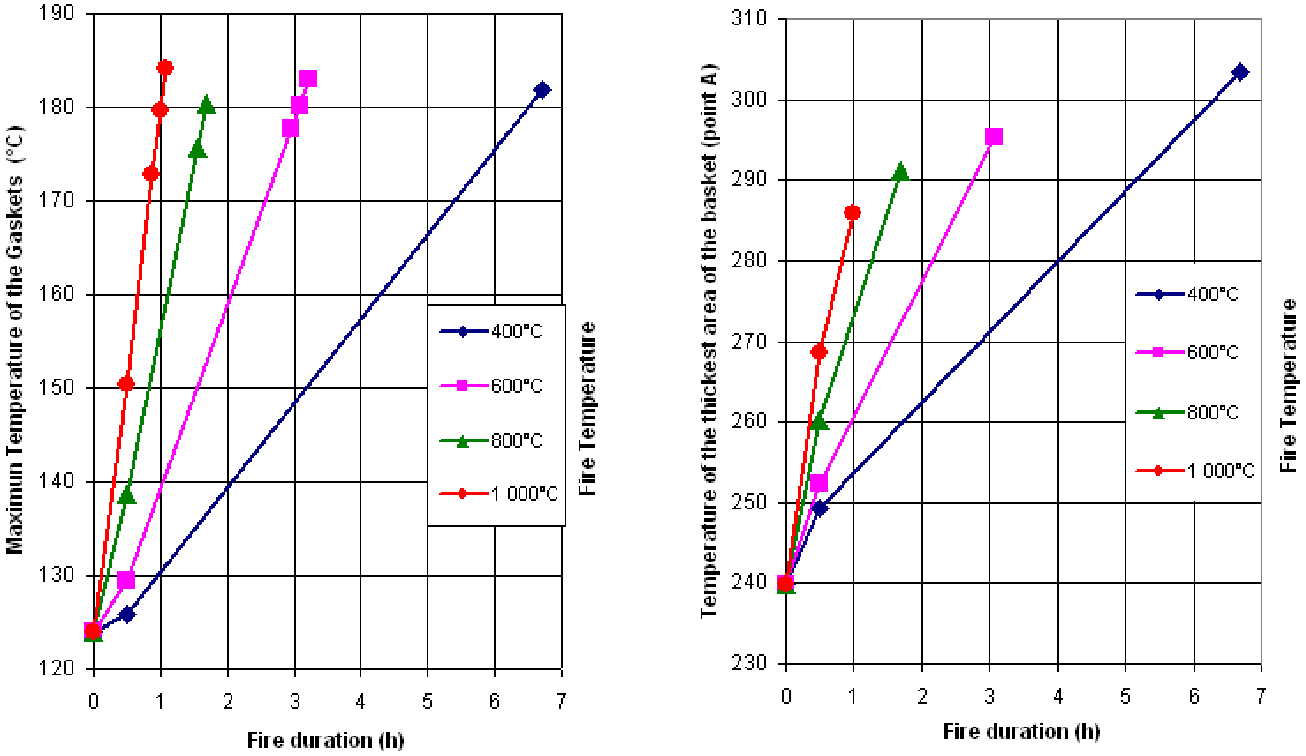

Fig 5. TN^{TM} 28VT Maximum temperature of the gaskets and of the thinnest area of the basket (point A) as a function of the fire duration