Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

EVALUATION OF SAFETY OF FRENCH TYPE B PACKAGE DESIGNS IN SEVERE ACCIDENT ENVIRONMENTS OTHER THAN REGULATORY

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ABSTRACT

Packages used to transport radioactive materials in France must be designed to meet the safety performance requirements when subject to the test conditions set forth in the International Atomic Energy Agency (IAEA) Regulations. During actual use, the packages may be subject to quite different accident conditions. The Institut de Radioprotection et de Sûreté Nucléaire (IRSN) has evaluated the behaviour of typical packages designed to transport spent fuel, high activity waste, fresh mixed oxide (MOX) fuel and plutonium oxide powder under realistic conditions of mechanical impact and fire. The studied designs remain safe after impact onto targets present in the real environment of transport. The energy absorption by the package ancillary equipment (transport frame) compensates for the kinetic energy increase by comparison to the energy expended during the regulatory tests. New software was developed to correctly simulate the thermal behaviour of the neutron shielding materials. The studied package designs exhibit large margins of safety concerning resistance to fire. The results obtained have been used to develop tools in support of the appraisal of emergency situations.

INTRODUCTION

With the aims of better understanding the behaviour of transport packages containing radioactive materials under realistic conditions of accident and of evaluating whether their qualification by the regulatory drop and fire tests achieves adequate margins of safety, the IRSN carried out several programmes of study using digital simulation, adjusted on the results of experiments.

The objective of the applicable transport regulations is to limit to a low level the risks to workers, public and the environment, even in case of accidents. The containment of the radioactive materials must be maintained when they are subjected to mechanical and thermal tests defined to simulate severe accident conditions. These tests consist, for type B packages or containing fissile materials, of a free drop test from 9 m onto an unyielding flat target (impact speed 50 km/h), a perforation test by free drop from a height of 1 m onto the flat end of a vertical 15 cm diameter steel bar, and a fire test with completely engulfing flames, at a temperature of at least 800°C for a period of 30 min.

These conditions of test have been defined 40 years ago. They differ notably from those of the real life accidents which may occur during the transport of these packages on road, rail or in transit. Actual environments are characterised by favourable factors, such as softer targets and ancillary equipment structures, which tend to reduce the severity of mechanical impacts, and by unfavourable ones, such as increased impact speeds (above 50 km.h^{-1}). Ultimately, it is not possible to confirm whether the success in passing regulatory test conditions ensure safety for any particular set of accident circumstances. However, the assessment of the history of recorded accidents does not reveal any event for which the radioactive material was the cause of severe injuries or death to persons during transport. The IRSN therefore carried out an evaluation to check the existence of margins of safety, with financial support from AREVA NC (Compagnie générale des matières nucléaires).

PACKAGES CONSIDERED

First, two typical package designs were preselected to stand for packages designed for transport of spent fuel and plutonium oxide powder. These packages were the most likely to potentially produce the most severe consequences in an accident because of their frequent use, the large quantities of radioactivity they contain and the high dispersibility of their radioactive contents. In a second step, packages for high activity vitrified waste and fresh mixed oxide (MOX) fuel assemblies were also assessed. Table 1 summarises the features of the packages tested in the programme.

Table 1. Features of typical packages

Package contents	Weight (kg)	Length (m)	External dia.(m)	O-ring grade*	Neutron shielding	Shock absorber	Power (kW)
12 PWR spent fuel assemblies	110 000	6.2	2.5	FKM	Resin	Wood	93
8 fresh MOX fuel assemblies	22 000	5.2	1.4	EPDM	Resin	Wood	8.8
20/28 containers Vitrified Waste	112 000	6.6	2.4	EPDM	Resin	Wood	40
19 kg of PuO_2 powder	1 500	2.2	0.6	EPDM	Plaster compound	Wood	0.55

*: FKM: fluorocarbon; EPDM: ethylene–propylene–diene monomer.

FIRE TESTS

The packages equipped with resin and plaster compounds react to overheating by vaporisation followed by partial condensation when subjected to fire. These reactions are due to several dehydration stages in the material. No software being available to realistically simulate this behaviour, new software was developed. The evaluation programme included four steps:

(i) Developing a realistic heat transfer model based on the results of samples of the thermal protection materials and mock-up experiments
(ii) Accurate modelling of each package with the realistic heat transfer model and fine meshing
(iii) Calculating the temperatures in the package components for various fire durations and temperatures (400, 600, 800 and 1 000°C)
(iv) Determining the maximum fire durations before activity release.

Development of a realistic heat transfer model for thermal protection materials

The thermal protection materials are of two kinds:

(i) Resin: mainly composed of polyester and fire retardants comprising hydrated minerals
(ii) Plaster and compounds which are mainly composed of plaster mixed with polythene.

Fire simulation tests were performed in a laboratory with resin and plaster samples poured in a hemispherical vessel (see Figure 1) equipped with holes simulating the fusible plug holes provided to avoid overpressure in packages; one side of the material layer was heated by a radiant panel to a temperature close to 800°C during 30 min [1].

Using a thermal model with only conduction in the material and energy involved in vaporisation within the material did not allow reproducing the rapid heating in the areas distant from the heated side of the material. Therefore, a refined model was prepared with gas diffusion: water vapour diffuses through the material cracks or porosities and along the material boundaries and condenses on the cold surfaces of the material, which increases the global heat transfer. During heating of the material, at each time step and at each node, the programme calculates the quantity of water vapour produced, and then the latent heat of condensation of the vapour is distributed to the nearest nodes whose temperatures are below 100°C. A parameter limits the number of nodes to which heat can be distributed. The non-distributed heat corresponds to the vapour exiting the package through the fusible plug holes. This model was successful in reproducing the results of the experiments accurately. The validity of the model was confirmed by comparison to the results of a test with a specimen subjected to a 3.4 h hydrocarbon fuel fire.

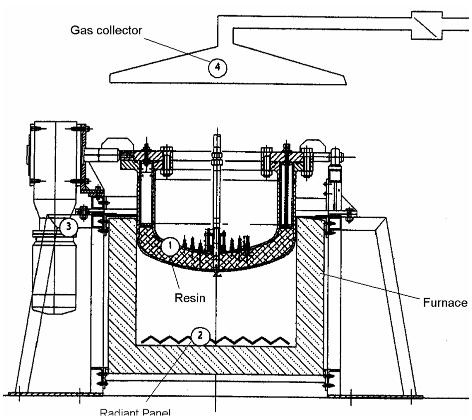

Figure 1. Heating device for testing thermal behaviour of resin

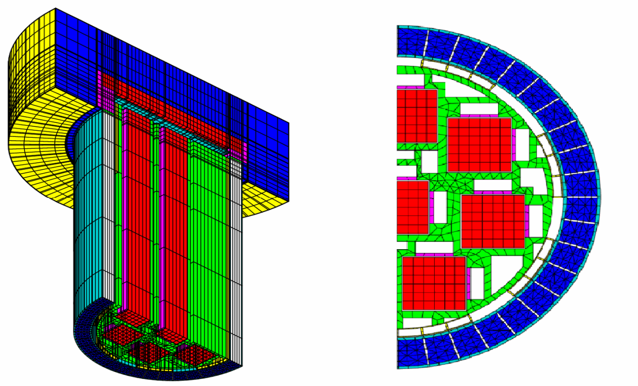

Figure 2. Modelling of package for fresh MOX fuel assemblies

Modelling of package components

A 2-D axisymmetrical mesh was used for the PuO_2 powder transport package. The other packages were modelled by 3D meshes of one-eighth or a quarter of the package: about 50 000 elements were used per mesh (see Figure 2). In order to get realistic results, geometrical details of lids, trunnions, inner structures and shock absorbers were modelled as well as the time dependent gaps between the inner structures and the packaging shell. The cladding temperature of each fuel rod was calculated by an additional model taking into account heat transfer by radiation between rods.

Temperature criteria

For each package, two criteria were associated to the absence of activity release:

(i) The maximum allowable temperature for the gaskets: 180°C for EPDM, 250°C for FKM

(ii) The maximum allowable temperature for the fuel rod cladding or inner structures: 550°C for the cladding of PWR spent fuel; 750°C for MOX PWR fresh fuel; 590°C for major deformation by creep of the basket supporting the vitrified waste containers.

Main results of calculations

Fire temperatures were considered between 400 and 1 000°C. Table 2 and Table 3 respectively summarise the maximum fire durations each type of package was predicted to be capable of withstanding without loss of leaktightness (criterion i) or before the maximum allowable temperature of the contents occurred (criterion ii).

Table 2. Maximum fire durations regarding leak tightness of gaskets of containment system

Fire temperature	**1 000°C**	**800°C**	**600°C**	**400°C**
Spent fuel assemblies package	1 h 03 min	1 h 42 min	3 h 05 min	6 h 58 min
Fresh MOX fuel assemblies package	25 min	**43 min**	1 h 37 min	4 h 27 min
High activity vitrified waste package	1 h	**1 h 42 min**	3 h 05 min	6 h 42 min
PuO_2 powder package	5 h 03 min	**6 h 49 min**	10 h 26 min	20 h 56 min

Table 3. Maximum fire durations regarding maximum temperature allowable for content

Fire temperature	**1 000°C**	**800°C**	**600°C**	**400°C**
Spent fuel assemblies package	49 min	**1 h 25 min**	not calculated	not calculated
Fresh MOX fuel assemblies package	8 h 30	16 h 15 min	not reached	not reached
High activity vitrified waste package	12 h 07 min	18 h 22 min	not calculated	not calculated

These results show that, with respect to the risk of activity release, the packages considered in this study present significant safety margins on fire duration, from 1.5 to 13 when compared with the regulatory requirement. The packages could also withstand a 30 min fire at 1 000°C but there would then be no longer any safety margin for the fresh MOX fuel assemblies package.

Use of results in emergency situations involving fire

The results of the study were used to establish a guideline for safety assessment in transport emergency situations involving fire. This guideline provides fire times after which there is a risk of activity release. It contains:

(i) Curves indicating the temperature of important components of the packages as a function of the fire duration, for various temperatures of the fire (see examples in Fig. 3)

(ii) Simple rules to adjust the results to real accident scenarios including ambient temperature, contents heat power and estimated temperature and duration of the fire.

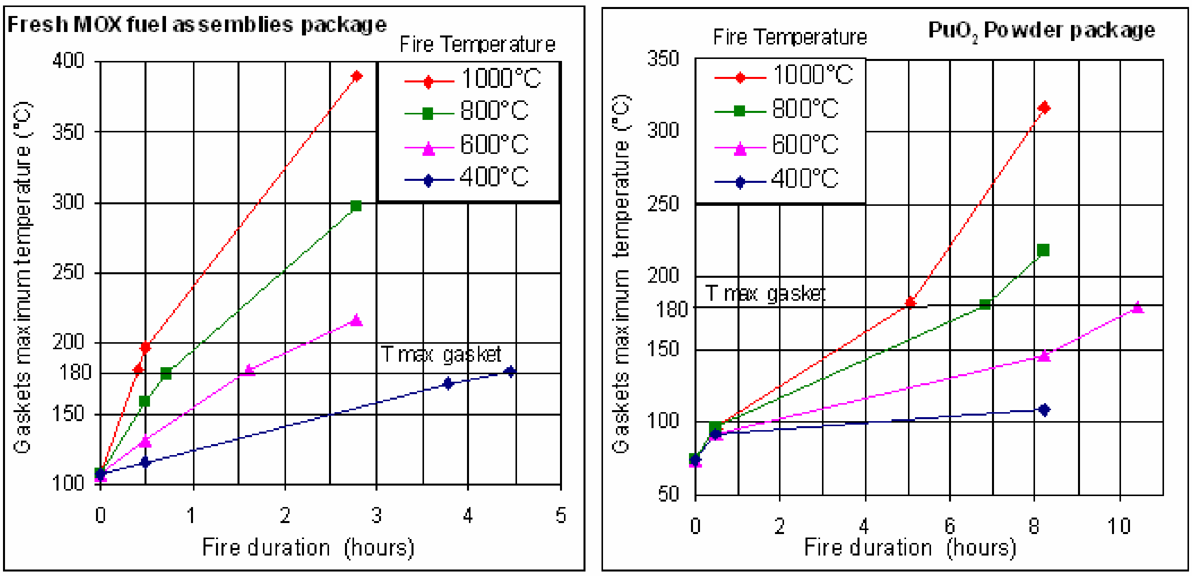

Figure 3. Packages for fresh MOX fuel assemblies and for PuO_2 powder: maximum temperature reached in gaskets as function of fire duration and temperature

The potential influence of other factors is pointed out: initial mechanical damage to the package; transport under tarpaulin or canopies; heterogeneous, non engulfing fires; perturbation of the heat dissipation by mud or debris; fire in a tunnel with walls remaining at high temperatures.

MECHANICAL TESTS

The structural integrity of two packages designed for the transport of spent fuel and plutonium oxide powder has been evaluated under impacts onto a selection of realistic targets such as soils, metallic structures, reinforced concrete and another package of the same design.

For each impact scenario, several configurations, depending on the package orientation, the impact point on the target and the drop height, have been simulated.

The packages have been modelled by finite element methods [2]. Each finite element model was calibrated by comparison with the already available results of 9 m drop tests.

Meshing, contacts and materials

For the spent fuel package, two simplified numerical models were first developed with the non-linear structural dynamic code ABAQUS to simulate drops of the package in a vertical orientation, with impact onto a shock absorbing cover and in a horizontal orientation, with impact onto the trunnions. In a second phase, two complete numerical models with 3D-volume elements were developed with the dynamic codes DYNA3D (50 000 elements) and PAMCRASH (17 000 elements) and calibrated.

For the plutonium oxide package, two complete numerical model analyses have been performed, one for DYNA3D and one for PAM-CRASH. The body and the closure system were modelled by volume elements, 48 000 for DYNA3D and 16 000 for PAM-CRASH.

Impacts onto soft and hard soils

Impact of the *spent fuel package* was studied for drop heights of 9, 20 and 40 m and for nine different targets: clay, sand and rock, each having three levels of hardness: soft, semi-hard and hard, modelled by bilinear elastic–plastic relationships.

For sand, clay and soft rock, the spent fuel package suffers no damage, while its penetration into the target varies between 80 and 510 mm. For the semi-hard and hard rocks, the crushing of the wood shock absorber increases rapidly with drop height. Drop heights from 13.5 m in vertical orientation and 9 m in oblique attitude result in the same crushings of the shock absorber as the drops from 9 m onto an unyielding target. For a 9 m drop with horizontal orientation, impacts onto rock and onto an unyielding target produce similar crushings in the trunnions.

For particularly soft soils, the penetration of the package into the ground may result, however, in a loss of the package heat dissipation capacity thereby causing excessive temperatures. However, a period of about 2 days is allowed for a completely buried spent fuel package to take emergency actions to restore safe conditions for the package.

Impacts onto metallic targets

Five targets representative of the environment of the packages during transport and handling were selected: the lower spacer beam of a crane (Fig. 6a), the bilge of a ship, the side of a ship, the side rail of a railcar (wagon), the axle of a railcar (Fig. 4) and the trunnion supports (Fig. 5). The first four are made from welding ordinary steel plates less than 25 mm tick and are deemed to be non-perforating for the spent fuel package. However, the trunnion supports made from thick plate (40–70 mm) and the railcar axle are deemed perforating. Realistic drop heights between 3 and 19 m have been studied for both spent fuel and plutonium oxide packages.

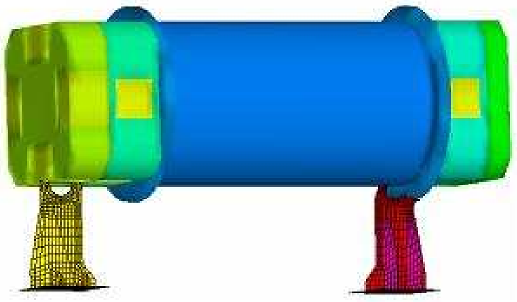

Figure 4. Impact of spent fuel package onto railcar axle

Figure 5. Impact of spent fuel package onto trunnion supports

For impacts of the *spent fuel package* onto the non perforating targets, regardless of the orientation used, more than 96 % of the impact energy is dissipated into the target and the frame: the stresses within the package are always low in relation to the allowable values. The secondary effects (crane instability…) were not studied.

For perforating targets, the numerical model of the package was improved to incorporate the connections between components of the closure system: gaps and bolts were modelled and the contacts were controlled. On the covers, the mesh was improved and a failure criterion was used. Finally, the model allowed the failure risks of the various bolts to be analysed.

For a drop onto a railcar axle, only 10–30 % of the impact energy is absorbed by the target, the remainder being absorbed by the package. The maximum acceleration of the package is 30 g. The railcar axle perforates the shock absorber and causes local plastic deformation in the closure system (5–6 %). The stresses on the bolts remained below the failure limit.

For an impact onto the trunnion supports 55 % of energy is absorbed by the target and the acceleration is 45 g. The trunnion support perforates the shock absorber and causes local plastic deformation. Unlike the previous case, one of the 12 plug cover bolts is destroyed; however, the ring flange bolts did not show any sign of failure, so that package leaktightness is preserved.

In all impact configurations, the *plutonium oxide package* was undamaged. Its rack behaved as a mechanical damper and was severely damaged, particularly during impact on the bilge of a ship. The most critical impact configuration for the packaging was that on the side of a ship, subject to a perfectly centred impact.

Impacts onto reinforced concrete structure (pier)

Reinforced concrete structures have specific behaviours. The case of impacts on concrete therefore had to be dealt with using a specific example. The case chosen is that of the Flamands pier within the port of Cherbourg, France, this being the point at which all MOX fuel and vitrified wastes leaving France by sea and spent fuel entering France are loaded or unloaded.

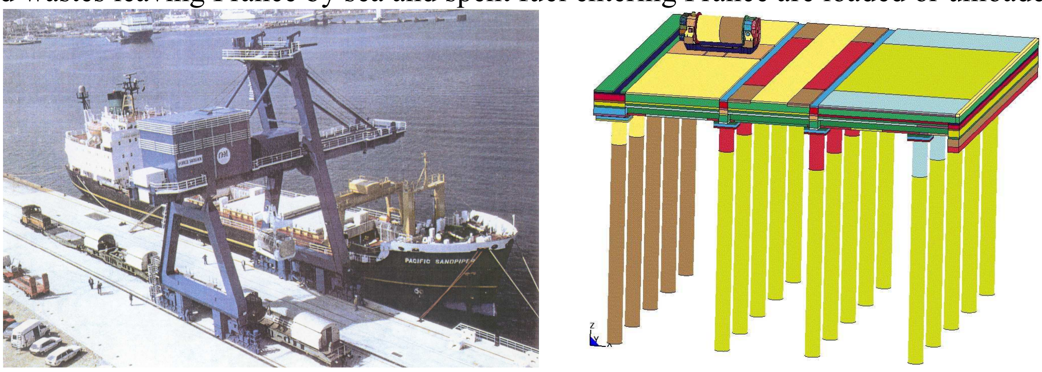

Figure 6. a) Package handling over a pier b) Modelling the impact of package onto pier.

The pier consists of a dozen bays 36 x 30 m, supported by pillars. From top to bottom, the bay and pillar consist of a cover slab, a layer of backfill material, a thick slab and a network of beams, caps and piles anchored into the rock. The pillar model consisted of 160 000 elements and 115 different materials due to the significant variation in reinforcing materials (Fig. 6b).
For the *spent fuel package*, the results showed that there is a real risk of perforating the pier for a drop height of 6 m: the concrete reinforcements undergo plastic deflections up to 1 m and the steel-concrete cohesion should be lost. The predicted damage to the package is low compared to the results of the regulatory 9 m drop and there is no risk of releasing radioactive material.
For the *plutonium oxide package*, the most damaging drop from a height of 8 m for both the package and the concrete slab is in oblique attitude in the middle of a bay: the package causes a 200 mm indentation in the slab and the plastic deformation at the bottom of the package reaches 15 %. For a drop from the maximum handling height of 50 m, the package causes a 400 mm indentation in the concrete and is distorted to the same extent as for a regulatory 9 m drop.

Impact of package onto another package of same design

Simulations of the impact of packages onto each other have been performed with DYNA3D software for the spent fuel and plutonium oxide packages.
For *spent fuel packages* both horizontal on their frames with parallel longitudinal axes, the frames absorbed half the total energy and the containment systems are undamaged. When one horizontal spent fuel package without frame drops onto another horizontal spent fuel package with a frame, with perpendicular longitudinal axes (Fig. 7), an ovalization of several mm is observed in the shells. This ovalization is much dependent from the stress–strain relationship of the neutron shielding; considering elastic–plastic behaviour instead of elastic increases the ovalization by a factor of 10. An improved knowledge of the behaviour of neutron shielding under impact is needed to assess the potential consequences of the drop.

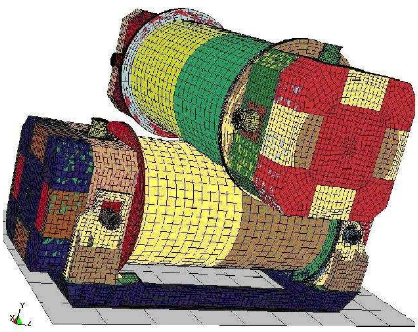

Figure 7. Spent fuel packages one onto another

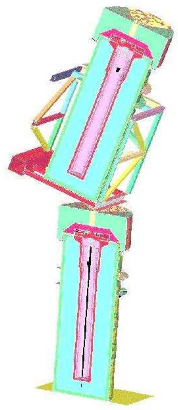

Figure 8. PuO_2 packages one onto another

When one spent fuel package without its frame drops in oblique attitude onto the closure system of the lower horizontal spent fuel package with a frame, the frame absorbs 53 % of the impact energy and the spent fuel package that drops is undamaged, but the plug cover of the lower package is subject to a 4 % deformation, without loss of the leak tightness of the containment system.
Furthermore, when both spent fuel packages are horizontal, parallel and with frame, a height of 50 m is necessary to get same levels of acceleration, deformation and energy as those calculated for the regulatory drop test.
For the *plutonium oxide package* dropped in a vertical orientation, without its rack, onto the

other package, with its rack, the shock absorber and the rack of the target package are destroyed and absorb 99 % of the impact energy, but its closure system is undamaged.
When the plutonium oxide package drops in an oblique attitude onto the shock absorber of the second package with its rack, as shown in Figure 8, the target package absorbs 70 % of the impact energy, mainly within its shock absorber, and a part of the closure system is damaged, but the modelling was not precise enough to determine whether or not the leaktightness is lost.
A 'regulatory test equivalent height' has also been determined for the plutonium oxide package. For drops in a vertical orientation, a height of 35 m causes the same damage, and for drops in an oblique attitude, an equivalent height of 40 m is calculated.
Many configurations of impact have pointed out that the packages maintain their integrity and that the ancillary equipment (frame or rack) and the real target absorb most of the impact energy. The consequences of drops of packages in actual environments, with their ancillary equipment, should be limited and below those of the regulatory impact test.

CONCLUSIONS

Resistance to thermal loads

Using the new software developed to correctly simulate the thermal behaviour of neutron shielding materials, the package designs exhibited large safety margins as concerns their resistance to fire by reference to the regulatory test conditions. The results obtained have been used to develop tools in support of the appraisal of emergency situations.
However the potential fire conditions that may develop in a tunnel have not been considered in this study. New provisions are provided in the ADR 2007 agreement, concerning the restrictions for the passage of dangerous goods vehicles through road tunnels which are to be categorised according to their 'resistance to events': explosion, fire and release of toxic gas or toxic volatile liquids [3]. Under this new regulatory context, it appears desirable to assess the safety of transit of the various radioactive materials through tunnels.

Resistance to mechanical loads

Calculations carried out showed that drops onto realistic targets, present in the real environment of transport, do not call into question the maintenance of the safety functions of the studied package designs. In most of the evaluated configurations, the stresses experienced by packages are lower than those experienced in the regulatory drop test conditions. In the remaining cases, refined work would be needed to check for the absence of failure of containment.
The shock absorbing feature of the soft targets and of the ancillary equipments of the packages compensates for the increase in kinetic energy above the energy specified for the regulatory tests.
Because the calculations performed for the selected package designs have not identified any safety issues of concern, there is no need to envisage any change in the current definition of the drop tests I and II. However, it should be kept in mind that other typical package designs have not been investigated. For example, performances of lightweight type B(U) packages could be the subject of further assessments.

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