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PACKAGE PERFORMANCE EVALUATION: OUR LATEST 30-YEAR EXPERIENCE

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ABSTRACT / INTRODUCTION

Packages for the transport of radioactive material have to comply with national and / or international regulations. These regulations are widely based on the requirements set forth by the International Atomic Energy Agency (IAEA) in the "Regulations for the Safe Transport of Radioactive Material".

The packages designed to transport the most demanding contents are submitted to tests for demonstrating their ability to withstand accident conditions of transport. These tests are typically:

- a nine-meter drop onto a flat and unyielding surface,
- a one-meter drop onto a punch,
- a 800°C / 30 minutes fire, and
- an immersion under a head of water of either 0.9 m, or 15 m or 200 m (depending of the criteria to be considered).

During the last 20 years, on several of its package designs, TN International has performed tests and analyses to simulate extremely severe accidents. These tests and analysis include:

1. long duration fire test and deep immersion test on a package designed to transport plutonium oxide powder,
2. deep immersion tests on scale model of packages designed to transport used fuel, high level vitrified waste and fresh MOX (uranium and plutonium mixed oxide) fuel,
3. burial in a soft ground of packages designed to transport used fuel, and
4. numerical study of the thermal behaviour of packages designed to transport used fuel and high level vitrified waste,
5. aircraft crash test on scale models of dual-purpose packages for the transport and storage of used fuel.

The paper will:

- review the tests and analysis which were performed,
- show that our designs are able to withstand extremely severe conditions,
- demonstrate that there is no cliff effect: should a failure occurs, it appears gradually and there is no sudden collapse of the package, and
- explain how compliance with all the regulatory requirements lead to high performances regarding each of them (for instance, in many cases, the need to meet radiation exposure criteria induces a mechanical resistance higher than that required to pass the regulatory requirements).

1. PACKAGE FOR PLUTONIUM OXIDE POWDER: DEEP IMMERSION AND LONG DURATION FIRE

1.1. Packaging design

The FS 47 packaging has been developed to transport plutonium oxide powder. Its weight is less than 1500 kg, and it can accommodate 17 kg of plutonium. It fits the facilities of the AREVA NC reprocessing plant in La Hague (France).

The plutonium oxide powder is contained in metallic cans, whose lids are crimped with the cylindrical part of the cans. The cans are stacked in an inner container, whose lid is welded on the body of this inner container. Eventually, this inner container is installed in an outer container. The lid of the outer container is screwed on its body, and a metallic gasket assures leaktightness. This set of "Russian dolls" is transported in the FS 47 packaging itself.

The FS 47 packaging design make-up includes from the inside to the outside:

- a steel inner shell,
- a layer of neutron shielding,
- a layer of thermal protection,
- a steel outer shell.

1.2. Deep immersion test

In September 1984, a test was performed to evaluate the behaviour of the FS 47 package design if submitted to a deep immersion.

The test was performed in a compression chamber in a CEA (Commissariat à l'Energie Atomique – French Atomic Energy Commission) facility, in Vaujours. The chamber was able to withstand a pressure of 4000 bars. The test model was restricted to the steel inner shell (see above description of the packaging design), the bottom end and the closure system. These components were full-scale model. This constitutes the containment system, as defined in the safety analysis report and the application for approval of the package design.

When the pressure reached about 930 bars, the first significant plastic deformations appeared, but the vessel was still leaktight. The test was further pursued, and leaktightness was lost for a pressure of 3430 bars (equivalent to a head of water of tens of thousands of meters!).

It must be noticed that the test was performed on a simplified model, as described here above. This model was by nature conservative, as the other structures of the FS 47 packaging were omitted, whilst they increase its resistance. In addition, the entire internal arrangements described in paragraph 1.1 were not modelled. This was twofold conservative. On one hand, the internal arrangements act also as spacers for the containment system, restrain the deformations and, consequently, increase the capability of the containment system to withstand an external pressure.
On the other hand, all these containers can also contain the radioactive material, and are additional containment barriers, even if they are not formally taken into account in the safety analysis.

1.3. Long duration fire

In November 1993, a test was performed to evaluate the behaviour of the FS 47 package design if submitted to a long fire. Before the test, a series of calculations was run in order to optimise the design of the test.

The test was a hydrocarbon fuel / air fully engulfing fire performed in the Moronvilliers facility, which was managed by AREVA NC. In fact, this test was identical to the regulatory test, as set forth in the "Regulations for the Safe Transport of Radioactive Material" by the International Atomic Energy Agency (IAEA), except the duration (the regulatory fire test lasts 30 minutes). The test model was a full-scale packaging, issued from a batch of manufactured packagings and planned to be used for routine transport. The test was conducted during 3 hours and 30 minutes. Experimental deficiencies led to stop the test at that time.

Following the test, the leaktightness of the FS 47 packaging was measured. It was still better than 10^{-8} $Pa.m^3.s^{-1}$. In other words, the fire test did not alter the leaktightness of the package.

In addition, considering the presence of the other containment barrier, it can be assured that the plutonium oxide powder will remain contained in the FS 47 packaging during a very severe fire test, which goes far beyond 3 hours and 30 minutes.

Note - With an "historical" perspective, it can be noticed that the effect of a long duration fire was already partially calculated in 1984. The evaluation was at this time limited to duration of 1 hour and 30 minutes. It was demonstrated that even if the temperature of the tests is increased up to 1000 °C, there was still significant margins compared to the risk of loss of leaktightness of the elastomer sealing 0-rings.

1.4. Drop test

In the frame work of a Common Interest Program which involved the French IRSN (Institut de Radioprotection et de Sûreté Nucléaire - Institute for Radiological Protection and Nuclear Safety) and AREVA NC, the mechanical behaviour of several Type B(U) radioactive packages impacting real targets was assessed through a numerical study. This was reported during PATRAM 2001 [4].

Several scenarios were considered. Beside the realistic drops onto real targets, a drop height of 50 m was also considered. It was shown that a 50-meter drop, onto a concrete structure (representative of a pier in a port) had not unacceptable consequences for a FS 47 package. Effectively, this drop was not more severe than a regulatory 9-meter drop onto an unyielding surface.

2. PACKAGE FOR USED FUEL AND HIGH LEVEL VITRIFIED RESIDUES: DEEP IMMERSION, AND BURIAL IN A SOFT GROUND AND LONG DURATION FIRE

2.1. Packaging designs

2.1.1. Transport of used fuel

Spent fuel assemblies are shipped to AREVA NC reprocessing plant in La Hague (France) with flasks belonging to the TN™ 12 family. This family includes the TN 12/1 and TN 12/2 packagings to transport - typically – twelve PWR fuel assemblies, or thirty-two BWR fuel assemblies. It includes also the TN 13/2 flask to transport - typically - twelve long foot PWR fuel assemblies. Eventually, there is the TN 17/2 packaging to transport seven PWR fuel assemblies, or seventeen BWR fuel assemblies. The TN 17/2 flask is used in nuclear power plants with restricted handling capacity and which cannot use the TN 12/1 and TN 12/2 containers.

The TN 12 family flasks are characterised by thick forged steel body (about 300 mm).

2.1.2. Transport of high level vitrified residues

High level vitrified residues assemblies are returned to their country of origin (Japan, Belgium, the Netherlands) from the AREVA NC reprocessing plant in La Hague (France) with TN 28 VT flasks. The TN 28 VT and the TN 12 family flasks have in common a thick forged steel body.

2.2. Deep immersion

In 1996 and 1997, a large program was launched to assess the behaviour of the TN 12 family and TN 28 VT flasks against a deep immersion. For that purpose it was decided to combine calculations and tests.

First, a series of detailed calculations, using the finite element method, was run.

Then a series of test was conducted in a compression chamber in the IFREMER facilities, in Brest. The test model was restricted to the thick forged steel body (see above description of the packaging design), the bottom end and the closure system. This constitutes the containment system, as defined in the safety analysis report and the application for approval of the package design. Due to the size of the test chamber, the models that were tested correspond to the actual packaging scaled down to ¼. Models corresponding to the TN 12/2 and TN 28 VT flasks were tested.

The actual tests allowed benchmarking the calculations. It was then possible not to consider modes of rupture which appeared in the simplified assessment and not in the actual tests. It was also possible to better analyse what happens in areas which analysis is complex, such as the vicinity of the closure system, because of the interaction between different components and the subsequent discontinuous character of the structure.

In the meantime, with the calculations, the differences between the scale model (with its actual properties for its materials) and the packaging designs could be analysed and taken into account.

The final results were that these TN 12 and TN 28 VT casks can withstand an immersion with a head of water of thousands of meters.

These values are hugely higher than those required by the IAEA Transport Regulations, namely 200 meters for this kind of packages.

Note - With an "historical" perspective, it can be noticed that a test was already performed in December 1976 on a 1/12-scale model of the TN 12/1 packaging. The hydraulic test bench had limited capacity, and it was not possible to go as far as in the tests here above mentioned. Nevertheless, even considering correction due to the mechanical properties of the test model compared to those specified for the packaging design, the ability of the flask to withstand an immersion with a head of water several dozens of times higher than 200 meters was already demonstrated by this "old" test (200 meters is the head of water specified for the enhanced water immersion for Type B(U) packages containing more than 10^5 A_2 specified in the 2005 Edition of IAEA Transport Regulations).

2.3. Burial into a soft ground

Beside the assessment of the ability of the packages to withstand accidents beyond the regulatory requirements, by increasing one parameter of the test specified in the IAEA Transport Regulations, we have also conducted evaluation of the behaviour of the flasks in non-conventional accidents.

A typical example of that is the study we performed from 1994 to 1998 about the burial of a cask in a soft ground like a swamp. This was reported during PATRAM '98 [1].

Beside the assessment of the probability of such an accident, and the evaluation of the depth to which the package sinks, the gradual heating of the components of the flasks was considered. This gradual heating arises from the loss of the heat dissipation capability of the packages when they are buried: the fins that surround the flasks lose their efficiency. It was determined that the first sensitive components were the elastomer sealing O-rings.

It was demonstrated that, in the case of partial sinking, sinking of half the package should not cause the sensitive components to overheat. It was also demonstrated that, even in the case of a complete sinking of the package, a flask loaded with the maximum authorised heat load would not lose its leaktightness before two days. This duration is quite acceptable when compared to the response time needed to set up a cooling system.

2.4. Long duration fine

In the recent years extensive analysis was performed by the French IRSN (Institut de Radioprotection et de Sûreté Nucléaire – Institute for Radiological Protection and Nuclear Safety) regarding the behaviour of packages in realistic / conservative situations, and also for extra-regulatory accidents. This is reported during PATRAM 2004. [3].

In this study, the thermal protective materials are modelled in accordance with the results of thermal tests specifically performed. This allows to better estimate the safety limits of the packages exposed to fire. The packages considered in the study (TN 12/2 and TN 28 VT), designed in the 1980's with thermal models available then, present safety margins larger than 3, regarding the IAEA Transport Regulations fire test (800°C / 30 minutes).

3. PACKAGE FOR FRESH MOX FUEL: DEEP IMMERSION

3.1. Package design

The FS 65 packaging was designed in the middle of the 1990s to transport fresh MOX (uranium and plutonium mixed oxide). Each packaging can be loaded with one PWR fuel assembly or two BWR fuel assemblies. For sub-criticality purpose and in order to assure the integrity of the fuel assembly for its use in the nuclear reactor, the fuel assembly is clamped in a basket that is inserted in the cavity of the packaging.

3.2. Deep immersion

In 1997, a series of two tests was performed to evaluate the behaviour of the FS 65 package design if submitted to a deep immersion.

The series of tests was conducted in a compression chamber in the IFREMER facilities, in Brest. The capacity of the compression chamber was 2400 bars. The test models were a true copy of the actual design, except a few minor details without any consequence on the behaviour of the model for this experiment. Due to the size of the compression chamber, the models that were tested correspond to the actual packaging scaled down to 3/8.

After assessment of the test results, and corrections to take into account:

- the minimum mechanical characteristics as specified in the packaging design specification and in the safety analysis report (whilst the models that were tested had – as usual – better properties than the minimum which is required),
- the temperature which can be reached during the transport (whilst the tests were conducted at room temperature),

it appears that the FS 65 package design can withstand the enhanced water immersion test for Type B(U) packages containing more than 10^5 A_2 specified in the 2005 Edition of the IAEA Transport Regulations, namely 200 meters, with a safety margin ranging from 2 to 9, according to the type of basket which is fitted in the packaging.

4. DUAL-PURPOSE PACKAGES FOR THE TRANSPORT AND STORAGE OF USED FUEL: AIRCRAFT CRASH TEST

4.1. Packaging designs

TN International has provided Belgian and Swiss utilities with dual-purpose casks for the transport and storage of their used fuel assemblies. These casks belong to the TN 24 family. Requirements from the customers and their competent authorities include for the packages to be approved against the IAEA Transport Regulations. They also include, as part of the storage licensing process, the demonstration of the ability of the cask to withstand an airplane crash test.

In the case of Belgium, the scenarios to be considered include the crash of a F16 military fighter, with a total mass of 14600 kg and a speed at the moment of impact of 150 $m.s^{-1}$.

In the case of Switzerland, the scenarios to be considered include the crash of a F18 military fighter, with a total mass of 20500 kg and a speed at the moment of impact of 215 $m.s^{-1}$.

4.2. Crash tests

In both cases, the method to demonstrate the ability of the cask to withstand such aircraft crash test was identical. It has already been reported in details during PATRAM '95 [2] on the basis of the Belgian package designs.

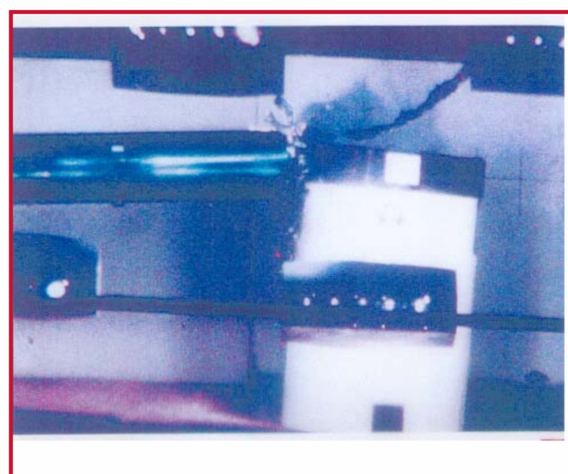
The ability of the cask to withstand these test conditions is demonstrated by both calculation and testing.

Two cases were considered. In the first one, the projectile hits the cask vertically at the centre of the anti aircraft crash cover. In the second one, it hits the cask in the plane of the closure system.

The first step of the qualification is based on calculations performed with a code specially designed to study the effects of crashes. The aim of the calculations is mainly to determine the characteristics of the missile which has to be shot in the subsequent test, and to select the worst orientation for the impact.

It is shown that in this first case the impact has no effect on the cask leaktightness, since the anti aircraft crash cover provides a fully efficient protection of the closure system. In the second case, the calculations show that the impact will cause a slight movement of the metallic gaskets in their plane, but which is not expected to impair the cask leaktightness.

To provide a full justification of the acceptability of the impact as concerns leaktightness, tests have been performed on one third scale models of the TN 24 D cask for Belgium, and of the TN 24 G for Switzerland. The tests were performed, respectively, in June 1993 and in 1997, in a CEA test centre in the Southwest of France. The projectiles were steel pipes, with different thicknesses versus the location, in order to recreate the effects that are expected due to the aircraft crash. The projectile was shot using a compressed air gun.



In both instances, a very low leak rate was maintained after the test, several orders of magnitude better than required.

5. LESSONS TO BE LEARNT AND MESSAGE TO PASS

5.1. Margins

The first lesson from these various assessments is obvious: our the package designs designed by TN International present significant margins against most of the regulatory tests, and also against non-conventional accident.

5.2. Gracious failure

The second lesson is that there is no cliff effect. The TN International package designs meet the Regulations and, furthermore, will limit activity releases to accepted levels until the accident environments are well beyond those provided in the performance standards.

- When the Transport Regulations require that a package withstand a 30-minute fire test and a package passes this test, that does not mean that it will fail after 31 minutes.
- When the Transport Regulations require that a package withstand a 200-meter immersion test and a package passes this test, that does not mean that it will fail when sunk to 201 meters.

In addition, we observed that, when the tests was were conducted up to failure, there was no sudden collapse of the package. For accident environment such that the activity release exceeds the regulatory criteria, this release only gradually increases.

- For long duration fire or burial, the lost of leaktightness is due to the alteration of the elastomer sealing O-rings when overheated. From tests that were run in other circumstances specifically on gaskets, we know that the leak will appear gradually.
- For the deep immersion, we observed that there was no collapse of the structure, but the leak appeared in the vicinity of the closure system. That means that no breach in the packaging and no complete and sudden release of the contents of the package could occur when the package is deeply immersed.
- For the aircraft crash test, the weak point is again the closure system and particularly the metallic gasket. That means that the packages can afford an aircraft crash without any breach in the packaging and without any complete and sudden release of the contents.

5.3. Compliance with individual requirements and global high performance

The third lesson from these studies is that compliance with all the regulatory requirements leads to high performances regarding each of them.

- For a TN International flask designed to transport used fuel assemblies or high level vitrified residues, to meet radiation exposure criteria involves thick gamma shielding. If this is provided by a forged steel body, as this is the case for most our designs, this thick body will provide:
  - a high mechanical resistance (and consequently the capacity to withstand very deep immersion or an aircraft crash), and
  - a high thermal capacity (and consequently the capacity to withstand a long duration fire, or burial in a soft ground).

- For a packaging designed to transport plutonium oxide powder, to meet radiation exposure criteria involves thick neutron shielding. If this is provided by a material that has also good fire retardant properties, this package will have high performances when submitted to a long fire.

- For the same packaging designed to transport plutonium oxide powder, to withstand the 9-meter regulatory drop test involves also a high capability to withstand a deep immersion. This is completed by operational constraints, which involves several containment barriers, and therefore additional mechanical resistance.

- For a packaging designed to transport fresh MOX fuel, the need to restrain the assembly in a basket for criticality purpose enhances the resistance of the body of the packaging. It provides higher mechanical performance and the capacity to withstand immersion test with a head of water larger than that required by the IAEA Transport Regulations.

6. REFERENCES

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