Designing a Radioactive Material Storage Cask against Airplane Crashes with LS-DYNA®

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Abstract

For 50 years, AREVA TN has been supplying customer-focused, innovative transportation and storage solutions for radioactive material with the highest levels of safety and security.
Transportation and storage casks are designed to comply with stringent regulations. For instance, the TN NOVA™ system, designed to store used fuel assemblies, is required to withstand the impact of a 20-ton aircraft at a velocity of 215m/s, despite the extremely small probability of such an event actually occurring.
The TN NOVA™ system is composed of a sealed NUHOMS®-69BTH Dry Shielded Canister and a TN NOVA™ Overpack. The overpack has been designed to house the canister during the storage period and provide it with an efficient protection against airplane crash events.
To achieve this, LS-DYNA® was invaluable in helping us to improve the preliminary design and to select the most damaging impact configuration.
LS-DYNA® analyses also made it possible to design an equivalent missile that causes deformations at least equal to those caused by an airplane crash. The equivalent missile model was updated thanks to a real test onto a concrete wall.
Finally, the overpack design was successfully validated by a real test. The equivalent missile impacted a 1/3-scale mock-up of the canister-loaded overpack, fitted with strain gages and accelerometers. Leak tightness was preserved.
The present paper will focus on the crashworthiness LS-DYNA® calculations and benchmarks that made this success possible.

Introduction

Casks dedicated to the transportation and storage of radioactive material are designed to comply with stringent regulations.

For instance, the TN NOVA™ system, designed to store used fuel assemblies, is required to withstand the impact of a 20-ton aircraft at a velocity of 215 m/s, despite the extremely small probability of such an event actually occurring.

Designing an efficient protection proved to be a challenging task for US and French teams of AREVA TN.

After a short description of the TN NOVA™ system, we will focus on the crashworthiness LS-DYNA calculations and benchmarks that led to a successful design against airplane crashes.

Description of the TN NOVA™ System

The TN NOVA™ system is AREVA TN's breakthrough solution for used fuel dry storage and transport.

The system allows both transportation of used fuel assemblies (up to 69 fuel assemblies) from the Leibstadt Boiling Water Reactor fuel pool to the ZWILAG storage facility, and storage of these used fuel assemblies at the ZWILAG storage facility, pending final disposal or recycling.

The used fuel assemblies are inserted into a stainless steel Dry Shielded Canister (NUHOMS®-69BTH DSC, see Fig. 1 left). After being sealed, the canister is transported from the nuclear power plant to the storage site inside a NUHOMS®-MP197HB transport cask (see Fig. 1 right). Once at the storage site, the canister is transferred into the TN NOVA™ metallic overpack for vertical storage (see Fig. 2).

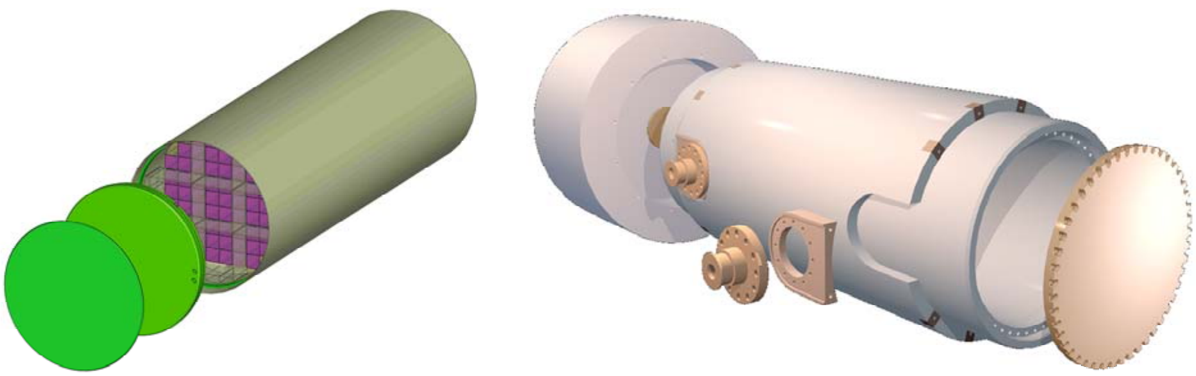

Figure 1:
Left: General view of the NUHOMS®-69BTH DSC and its basket
Right: General view of the NUHOMS®-MP197HB Transport Cask

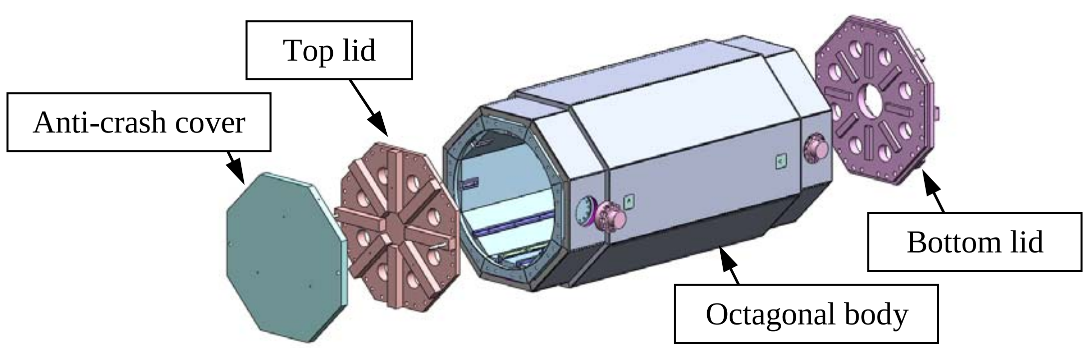

Figure 2: General view of the TN NOVA™ overpack

The system provides separation of transport and storage functions, the canister being either in the transport cask or the storage overpack. Consequently it made it possible to design the overpack without needing to comply with irrelevant transport regulations.

The overpack has been designed to house the canister during the storage period and provide it with radiation shielding, passive cooling (natural convection) as well as an efficient protection against airplane crash events.

The TN NOVA™ overpack has an octagonal body constituted by thick plates in carbon steel, which are welded together longitudinally. It is closed at the top and bottom by top and bottom lids. An anti-crash cover is also mounted on the top lid to ensure protection against an axial aircraft crash.

The overpack is about 6-meter high and 3-meter wide (20ft × 10ft).
Once loaded, it weighs up to 138 metric tons (152 short tons).

As we are going to see, LS-DYNA [1] was invaluable in helping us to design the airplane crash protection.

Designing the TN NOVA™ System Against Airplane Crashes

The product development required resources from both US and French teams of AREVA TN.

Leaving aside radiation shielding and thermal design studies, we will focus on the crash-worthiness LS-DYNA calculations and benchmarks that led to a successful design of the TN NOVA™ system.

The main objective was to design a protection so that the canister remains leaktight after an airplane crash.

The airplane crash is characterized, according to [2], by:

- aircraft type: military aircraft; mass: 20,000 kg
- velocity: 215 m/s (i.e. 774 km/h or 481 mph)
- impact surface area: 7 m^2 (i.e. a diameter of 2.99 m)
- curve of the impact force onto a rigid wall as a function of time (see Fig. 3).

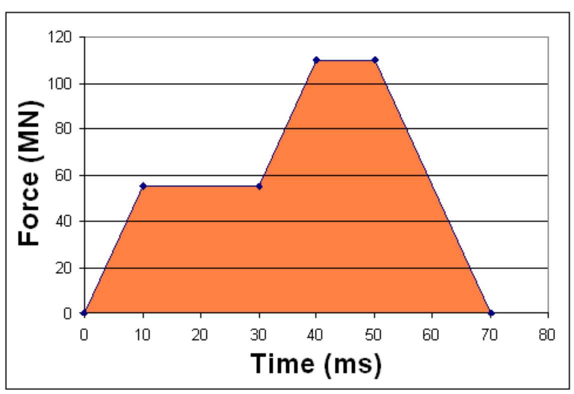

Figure 3: Aircraft crash – Specified impact force vs. time curve

The approach consisted of:

- designing the TN NOVA™ system so that it withstands an airplane impact, considering all possible impact locations through finite element calculations,
- determining the most damaging airplane impact configuration of the containment system (canister components) through finite element calculations, with the intention of carrying out a single real test,
- designing an equivalent missile whose impact on a 1/3-scale mock-up of the package would be representative of the impact of an aircraft on the full-scale TN NOVA™ package,
- checking the design of the missile with a preliminary experimental test on a nearly rigid target by comparing the expected impact load to the real one,
- carrying out the impact test on a TN NOVA™ mock-up in order to verify the expected good behavior of the overpack and to measure the leaktightness of the canister.

1) Designing the TN NOVA™ system so that it withstands an airplane impact

Starting from a preliminary overpack design, we checked its behavior when it is impacted by an airplane, considering all possible impact locations through LS-DYNA calculations.

We improved the preliminary design until achieving a good behavior of the whole system.

Three impact configurations were studied:

- an axial impact on the center of the anti-crash cover,
- an oblique impact on the top of the overpack, oriented toward the center of gravity,
- lateral impacts at different locations and heights.

The impact consequences were assessed via the strain induced on the canister which is the containment boundary for radioactive material.

The study was carried out in three steps:

Step 1: we determined the equivalent impactor which reproduces the aircraft crash onto a rigid wall.

Indeed, it would not be realistic to apply the specified force vs. time as a follower force the overpack since the latter does not behave like a rigid wall: it will fall over once impacted.

The aircraft benchmark was made to fit the target curves: load and internal energy vs. axial crushing.

Three benchmarks were been studied to validate the three models used for Step 2:

- half lateral model
- complete lateral model
- half axial model.

The impactor modeled with hexahedral elements is made up of (see Fig. 4):

- a one-meter-long rigid part, at the bottom, almost taking up the whole mass,
- a ten-meter-long compressible part, modeled with LS-DYNA material type 126 *MAT_MODIFIED_HONEYCOMB. The compressive stress vs. relative volume curve is the same in the 3 directions and was tuned iteratively.

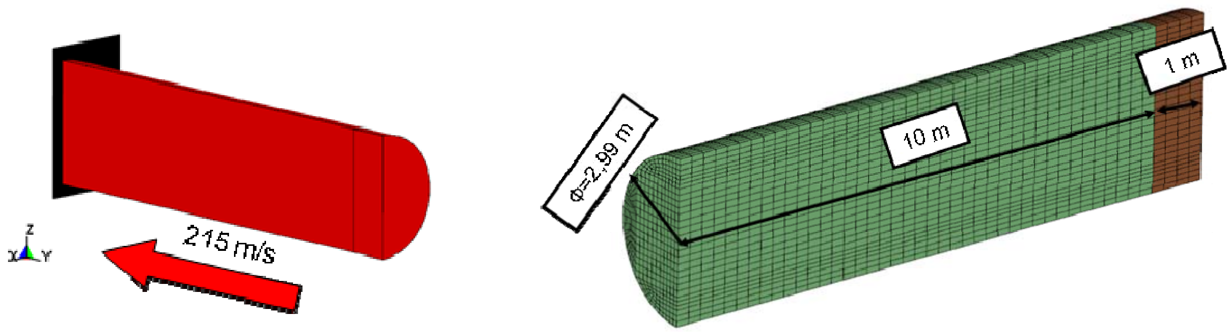

Figure 4: Finite element model of the impactor

Whatever the impactor model, we obtained (see Fig. 5) a maximum load slightly over the target value, 110 MN (+5%), and energy absorption is a bit quicker (+15%), which is conservative.

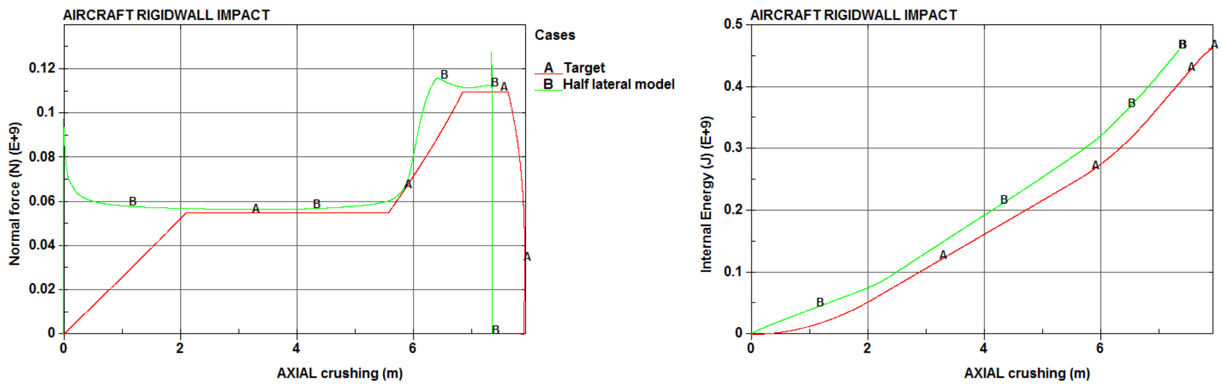

Figure 5: Impactor compared to specified aircraft in terms of load and internal energy vs. axial crushing

<u>Step 2</u>: structural calculations of the aircraft crash on the TN NOVA™ overpack using the impactor defined in Step 1.

The finite element model is made up of:

- a detailed model for the overpack which is constituted by the thick body with its longitudinal welds and all the pads and rails into the cavity (acting as interfaces between the overpack and the canister), the top and bottom lids with their screws and the anti-crash cover; some outer features surrounding the body (neutron shielding for example) are only modeled by their weight distributions;
- a simplified model of the canister, detailed calculations being performed in Step 3;
- a simplified model of the canister contents (basket + fuel assemblies): this homogenized cylinder is given a constitutive law adjusted so that the load-deflection curve of a statically loaded short section agrees with that of a detailed basket model.

The mesh is made up of:

- 466,000 nodes and 465,000 elements (72,000 shells, 16,000 beams, 377,000 solids)
- fully integrated S/R hexahedral elements (ELFORM = 2) with material type 24 *MAT_PIECEWISE_LINEAR_PLASTICITY and material type 3 *MAT_PLASTIC_KINEMATIC (with isotropic hardening and null Poisson's ratio for the homogenized canister contents),
- shell elements with material type 9 *MAT_NULL (to account for the mass of unmodeled parts).

Screws were modeled with solid hexahedral elements (see Fig. 6) and preloaded thanks to a layer of elements defined with material type 21 *MAT_ORTHOTROPIC_THERMAL.

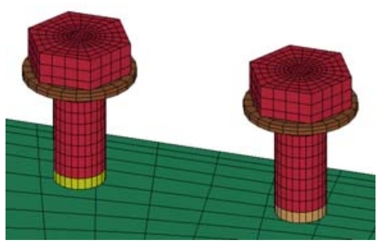

Figure 6: modeled overpack screws

The actual preload was checked by defining a cross-section through the screws (keyword *DATABASE_CROSS_SECTION_PLANE).

Several calculation cases were considered to cover every possible impact location onto the overpack, as well as a minimum or maximum possible lateral gap between canister and overpack.

The equivalent plastic strain on all parts including screws was found to remain well under the ultimate strain.

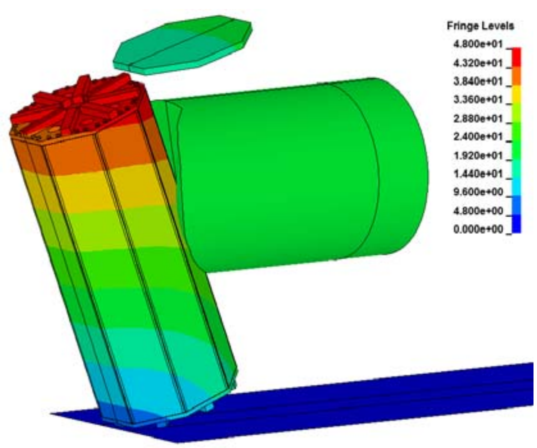

Figure 7: Velocity field [m/s] on overpack and impactor 80 ms after impact start

Step 3: detailed structural calculations of the canister using the displacement and velocity fields of Step 2 calculations.

The model of Step 2 was used to obtain boundary conditions for the detailed canister model. The interface mapping uses LS-DYNA keyword *INTERFACE_LINKING_SEGMENT.

Strain-based acceptance criteria [3] (expressed as ratios of equivalent plastic strain to allowable value) were used to assess the integrity of the design.

The analyses showed that all strain-based acceptance criteria were met, ensuring the leaktightness of the canister (containment boundary). This was achieved by improving the design of the interfaces between the overpack and the canister (pads and rails).

2) Determining the most damaging airplane impact configuration

Because the behavior of the system was defined by calculations only, real tests were necessary to confirm the design.

In order to limit the number of expensive real tests to one, the most damaging airplane impact configuration was identified, i.e. the configuration leading to the maximum risk of rupture of the overpack itself and the canister.

The corresponding maximum strains had to be reproduced during the real test.

3) Designing the equivalent missile

For practical and economical reasons, the impact test had to be carried out on a 1/3-scale mock-up of the TN NOVA™ package.

This mock-up is a representative model of the actual TN NOVA™ system. The appropriate scaling laws were applied to all dimensions of all parts, including plates, welds and screws. Screws were tightened with scaled torques. Material properties were also representative. Nevertheless, the radioactive content was replaced with an equivalent dummy weight.

Due to the geometric limitation of the air cannon barrel (diam. 300 mm), the missile could not have the same 1/3 ratio as the mock-up.

LS-DYNA analyses made it possible to design an equivalent missile that would cause risks of fracture on the 1/3-scale mock-up at least equal to those caused by an airplane crash on the full-scale package.

These calculations helped us to design a missile as an assembly of welded steel tubes of different thicknesses and diameters, with a thick steel disk at the rear (see Fig. 8).

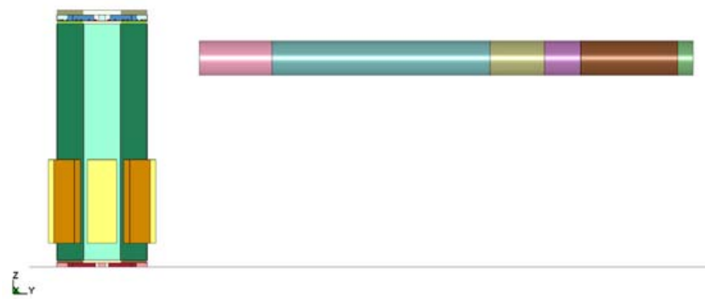

Figure 8: Finite element model of the final test

The missile material properties were the as-built static properties, corrected to account for strain-rate dependency. This correction was adjusted thanks to a calibration test (see below).

4) <u>Performing a calibration test of the missile</u>

In order to validate the missile design and initial velocity for the final real test, a missile calibration test was carried out: the missile was made to impact a deformable target made up of concrete blocks covered by a thick steel plate (see Fig. 9).

A comparison between the real calibration test and the simulated one would validate the missile.

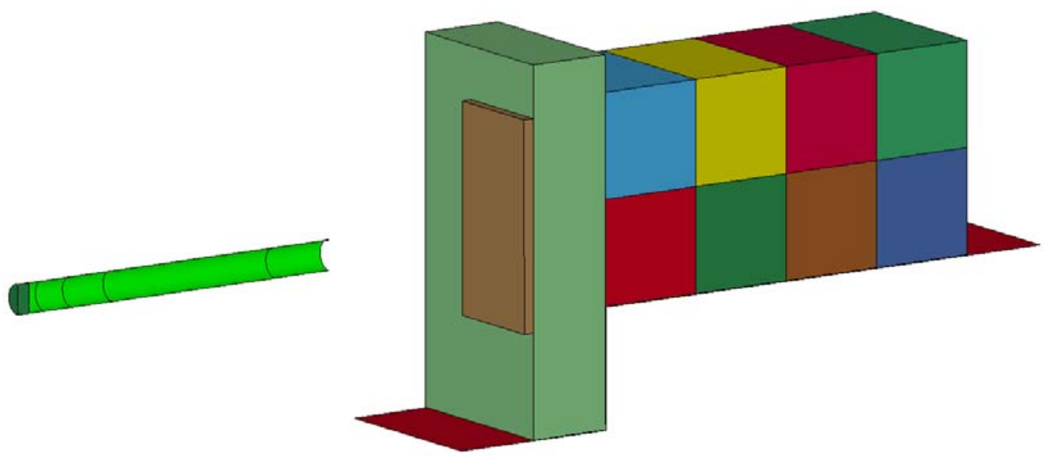

Figure 9: Finite element model of the missile calibration test

The maximum measured missile acceleration was found to be close to the calculated value (see Fig. 10), except at the end of the impact where the calculation overestimates the impact force.

However, previous calculations showed that the maximum plastic strains in the canister occurred during the first step before the acceleration peak. The first step was about 10% higher in the test, which is conservative. Indeed, the calculation slightly underestimates the acceleration (see Fig. 12) and then the impact force of the missile, and consequently the damages on the package. It is then ensured that the damages on the mock-up are higher than the maximum ones during a real airplane crash.

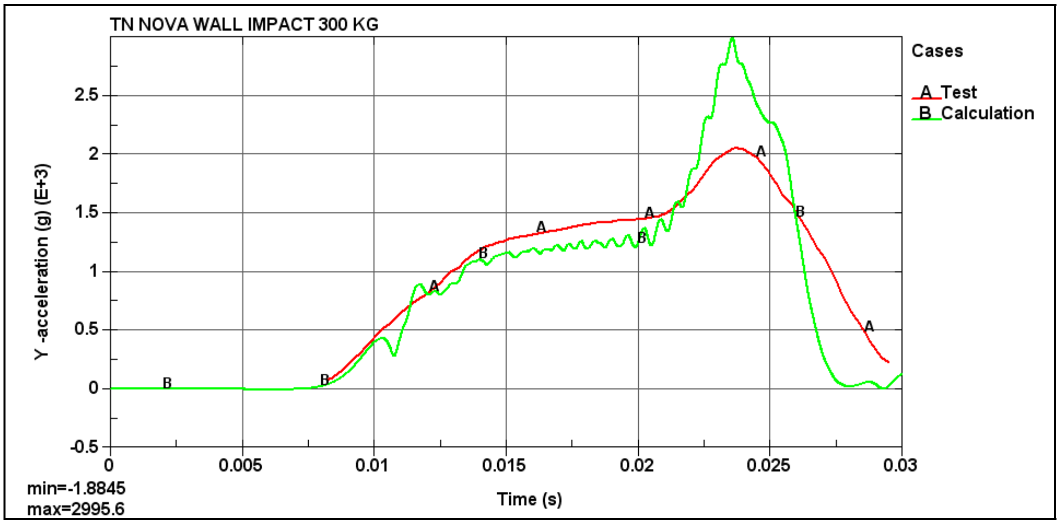

Figure 10: Simulated/real missile calibration test – Missile acceleration vs. time

5) Carrying out the real impact test on a mock-up of the TN NOVA™ package

The overpack design was successfully validated by a real test.

The test was carried out in November 2010 in the CEA CESTA experiment and research center near Bordeaux, France, in the presence of the Swiss Competent Authorities (ENSI).

The 300kg missile, propelled at 240m/s by the air cannon, impacted a 1/3-scale mock-up of the canister-loaded overpack, fitted with strain gages and accelerometers (see Fig. 11).

The impact was filmed with a high-speed camera (see Fig. 13).

As expected, the maximum measured acceleration was slightly higher than calculated at the first step of the impact (Fig. 12). At the end of the impact, the missile acceleration was higher than expected because the third tube of the missile had begun to get crushed (Fig. 14).

Figure 11: Real test – TN NOVA™ mock-up before missile impact

Following the impact test (Fig. 15), the integrity of the overpack mock-up was checked and a measurement of the canister leaktightness was performed with success: the safety of the design regarding an airplane crash event was definitely confirmed.

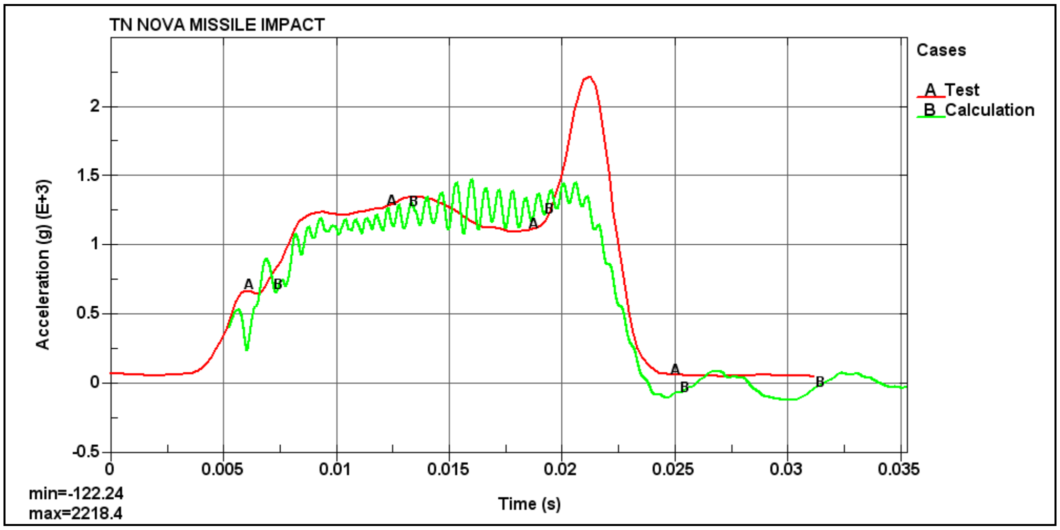

Figure 12: Simulated/real final test on the
TN NOVA™ mock-up – Missile acceleration vs. time

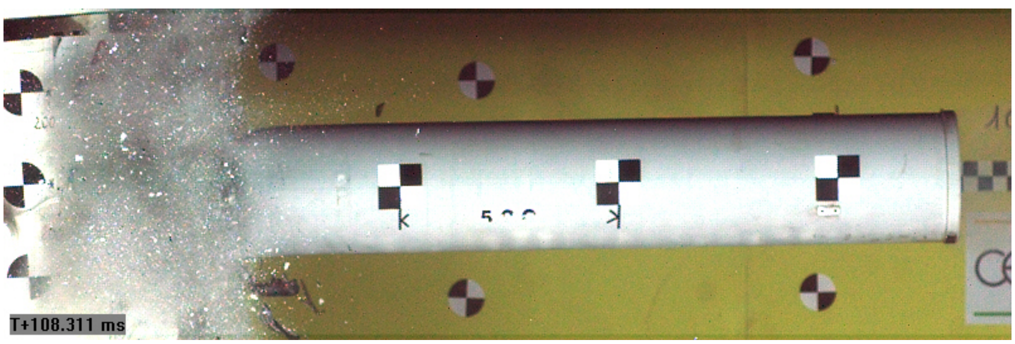

Figure 13: Real test – Missile impacting TN NOVA™ mock-up

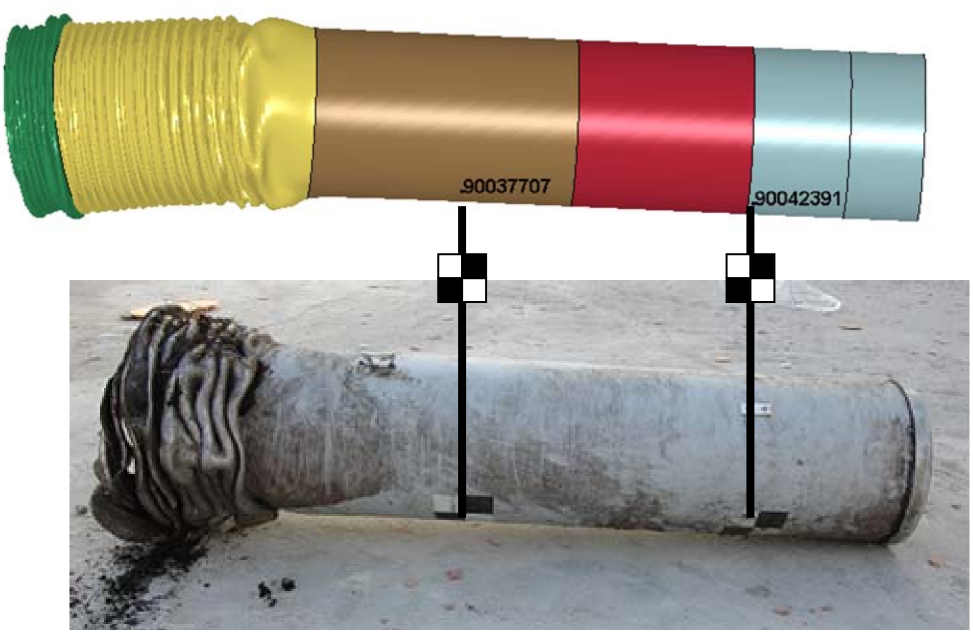

Figure 14: Simulation/real test – Deformed missile after impact

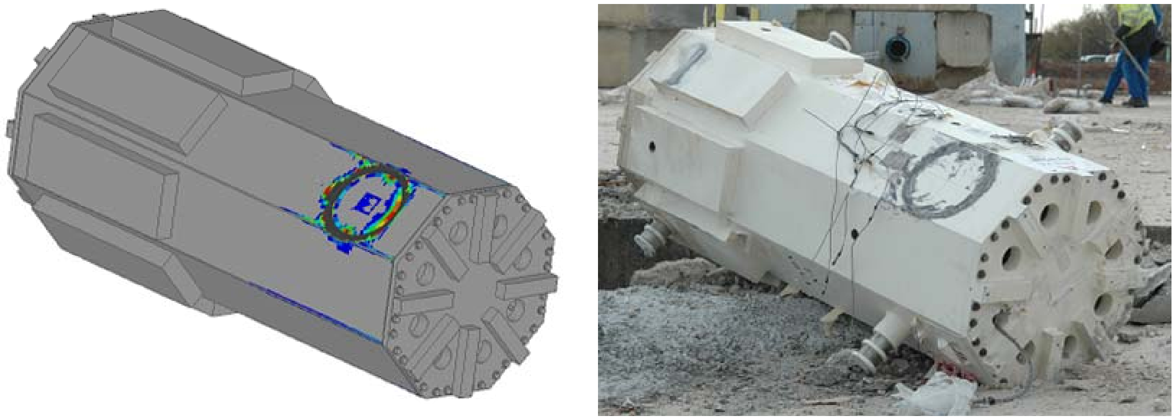

Figure 15: Simulation/real test - State of overpack after missile impact

Conclusions

The TN NOVA™ Overpack has been developed by US and French teams of AREVA TN in order to protect the sealed NUHOMS®-69BTH Dry Shielded Canister loaded with used fuel assemblies, during its storage period.

Designing an efficient protection against aircraft crashes proved to be a challenging task.

Significant methodological and technological improvements were achieved.

LS-DYNA proved to be invaluable in helping us:

- to improve the preliminary design,
- to select the most damaging impact configuration, thus limiting the number of expensive real tests,
- to design an equivalent 1/3-scale missile as well as the corresponding 1/3-scale mock-up of the TN NOVA™ system, avoiding the costly realization of a full-scale real test.

References

[1] LS-DYNA® Keyword User's Manual, Volumes 1 & 2, Version 971, May 2007, Livermore Software Technology Corporation (LSTC).

[2] Guidelines of the ENSI (Swiss Federal Nuclear Safety Inspectorate), HSK-R102/d, "Design Criteria for the Protection of Safety Equipment in Nuclear Power Stations against the Consequences of Airplane Crash", January 1993.

[3] INL Document INL/CON-09-15509, "Strain-based acceptance criteria for energy-limited events", S. Snow, D. Morton, E. Pleins, R. Keating, 2009 ASME Pressure Vessels and Piping Division Conference, July 2009.