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New Generation of Transport Cask for Used Fuel Assemblies – TN®-G3 Breakthrough New Drop Test Program

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Abstract

TN International has vast experience in domestic (in France) and international transport of used fuel assemblies. Up to 2,400 fuel assemblies are transported every year from EDF Nuclear Power Plants to the AREVA La Hague recycling facility. The TN®-G3 package currently under development will ensure these shipments for the next 40 years.

It is designed to comply with the latest regulations and the more demanding requirements of the French Competent Authority such as the double-leak tight barrier and the delayed impact effect. The leaktightness of the double barrier in accident conditions of transport is one of the key criteria for the safety demonstrations.

The TN®-G3 drop test program is based on an extensive calculations program reviewed by the French Competent Authority. The program is not just copied from previous packages. All possible drop test configurations have been studied so as to challenge the lid leaktightness and to maintain shock absorber integrity during the drop tests. For each selected configuration, the drop angle, impact line on the cask, were evaluated to maximize the drop effect. Dynamic calculations with FE models were made, in particular to verify the influence of material data scattering.

The 1:3 scale drop test mock up was designed to be representative of all TN®-G3 packages to be manufactured. The drop test mock up geometry and the structural characteristics of the materials were downgraded compared to the full-scale package to take into account the effects of temperature on mechanical properties and also on scattering due to procurement specifications.

The drop test campaign took place in 2014-2015 at the Areva TN test facility. Innovative drop test configurations are discussed below, such as the drop test with delayed impact, and the “wide-angle” side drop test.

Introduction

As described in a previous PATRAM article [1], the TN®-G3 package is a challenging design to be used to transport used fuel assemblies with high characteristics (enrichment up to 5%, average burn-up of up to 70,000 MWd/tU, and a short cooling time of 2 years) taking into consideration the latest regulatory requirements without changing the operation systems of the existing cask fleet.

The TN®-G3 package (figure 1) is mainly composed of a thick-walled forged shell and its welded bottom, both in high-grade carbon steel. The cavity is closed by two lids (inner lid on the cavity side, and outer lid on the impact limiter side) secured by bolts. This closure system complies with the double leaktight barrier definition of the IAEA regulations [2] which takes into account the “water exclusion” assumption, meaning limited water ingress inside the cavity for the criticality analysis. The thick-walled forged shell is compliant with double leaktight barrier definition and is possible because of the high level of control during manufacturing process and qualification regarding brittle fracture.

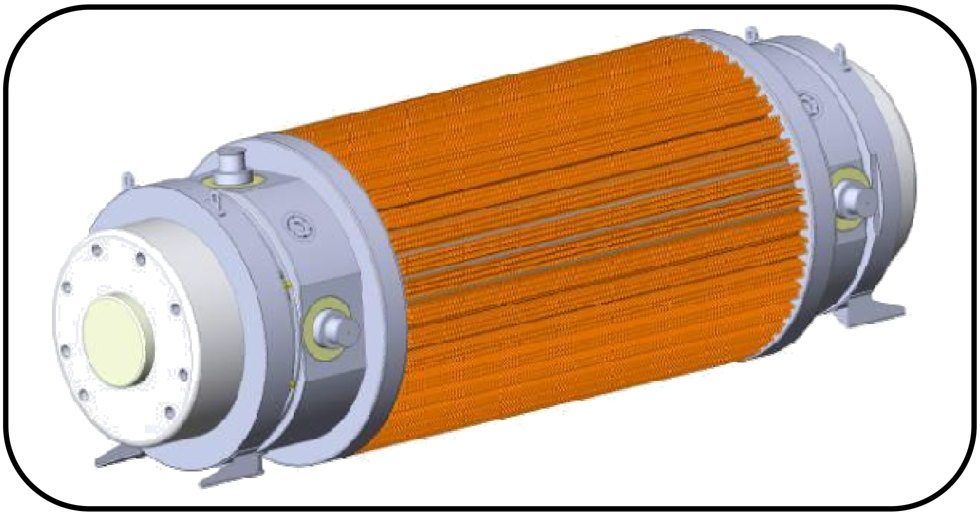


Figure 1 General overview of the TN®-G3 package

Impact limiters on both ends of the cask body ensure the protection of the closure system during the regulatory drop tests.

The purpose of the drop test program is mainly to challenge the leaktightness of the double closure system. Leaktightness is directly related to the behavior of containment components (lids, bolts…) under drop test conditions. Also, impact limiters shall remain on the cask to protect the containment boundary from fire test. The following paragraphs explain how the drop test program was constructed. Some remarkable drop test configurations are detailed.

Drop test program

To establish the drop test program, all the drop test configurations were studied, a 9-meter free drop as well as a 1-meter drop onto a punch bar, and their possible interactions. Twenty four different drop directions were considered, as represented on the following diagram (orange arrows represents angles studied for the puncture drop test; red for the 9-meter drop test).

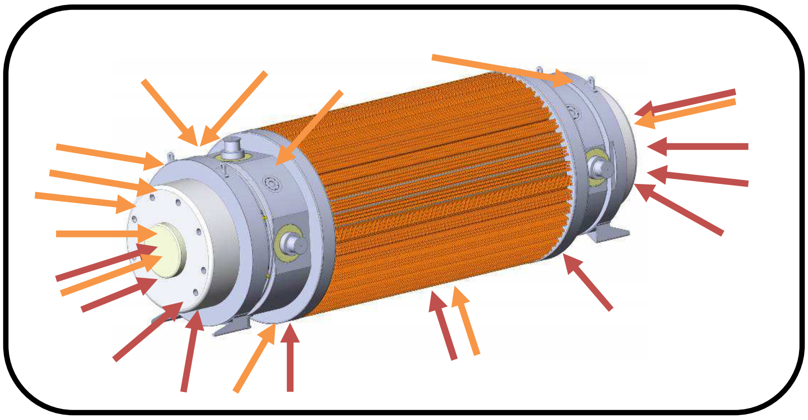


Figure 2 Drop test configurations of the TN®-G3 package

Some drop tests can be justified by simple analysis or with dynamic calculations with FEA (finite element analysis) models. Configurations having a potential impact on the leaktightness of the double lid are selected to be physically examined using a 1:3 scale drop test model. The mock up of the TN®-G3 package was specifically designed and fabricated following the guidelines explained in the Patram article[4] for the TN843 package. Its geometry and the structural characteristics of the materials were downgraded compared to the full-scale package so as to take into account the effects of temperature on the mechanical properties and on the scattering due to procurement specifications. This ensures the drop test mock up to be more penalizing than any fabricated package.

Based on this analysis, the final drop test sequences was:

Sequence code	Drop code	Description	Purpose
AT (Axial top end)	AT.1	9-maxial end drop test on the top end of the package (lid side) with delayed impact	Challenge double lid leaktightness
	AT.2	Puncture drop test on the lid center	
AF (Axial bottom end)	AF.1	9-maxial end drop test on the bottom impact limiter	Challenge double lid leaktightness

Sequence code	Drop code	Description	Purpose
OT (Oblique top end)	OT.1	Puncture drop test on the corner of the top end impact limiter: The center of gravity is not aligned with the impact point maximizing damage on the impact limiter.	Challenge double lid leaktightness
	OT.2	9-m corner drop test on the lid side: The center of gravity is aligned with the impact point on the impact limiter corner.	
LT (Lateral top end)	LT.1	Puncture drop test on the corner of the top end impact limiter to damage it before the next drop.	Challenge double lid leaktightness
	LT.2	9-m side drop test with a wide angle (around 45° with horizontal direction) a first impact on the top end (lid side)	
OC (Lid Port)	OC	Puncture drop test on the outer lid port	Challenge the outer lid port leaktightness
QH (Quasi-horizontal)	QH	9-m side drop test with a first impact on the bottom end, with a slap down effect (angle of 5° with horizontal direction)	Challenge the top end limiter bolts

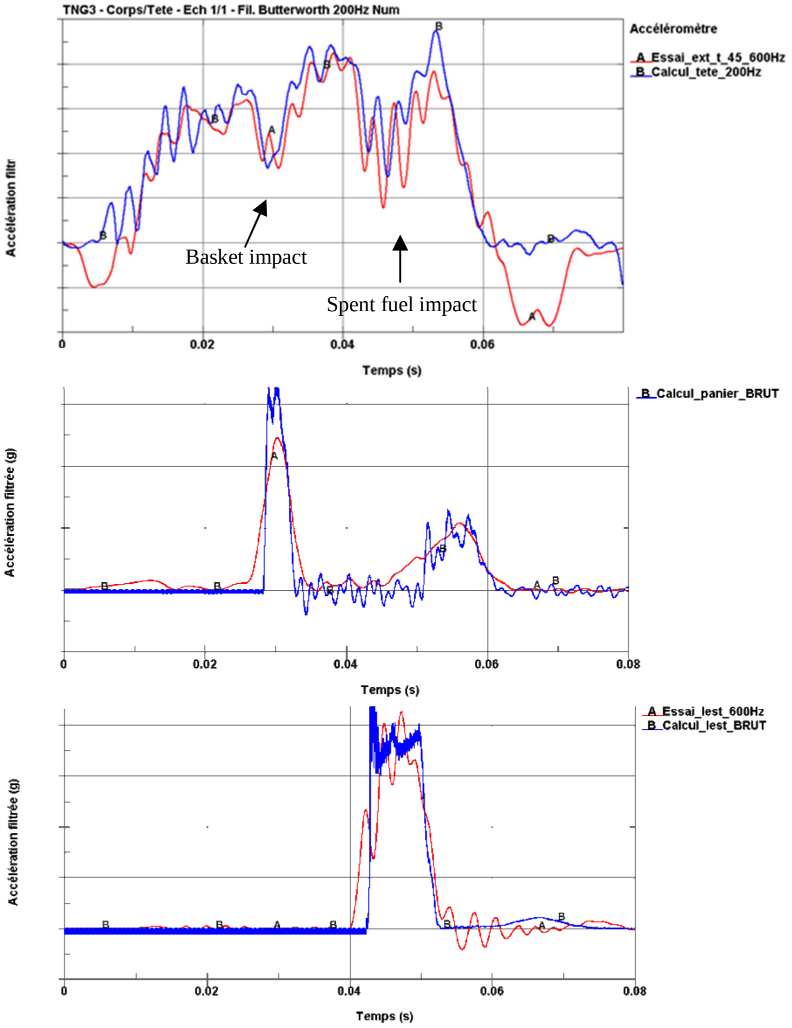
As required by the IAEA regulations [2], the puncture and 9-meter drop tests may be carried out in any order so as to maximize damage to the package. This is more penalizing than the 10CFR71.73 regulation [6] requiring that the puncture drop test be conducted subsequent to the 9-meter drop test. Thus, drop tests numbered OT.1 and LT.1 are configured so that the puncture drop test would damage the impact limiters in the target area foreseen for the 9-meter drop test.

Top End Drop Test Sequence (AT) - Delayed Impact

As described in the paper by Gordon S. Bjorkman, Jr. [3], the delayed impact is a new configuration for the lid-end drop which entails keeping the maximal gap between the content and the lid, even during the drop fall, until the impact of the package on the target. The content impacts the lid with a certain time delay resulting in dynamic load amplification.

The TN®-G3 drop test was carried out with the delayed impact. The dead weight representing the content (one for the basket and one for the used fuel) was maintained by a specific device on the bottom of the cavity to ensure the maximal gap remain during the fall. The gap for the basket is smaller than the gap for the spent fuel.

Accelerations were measured by sensors on the body, on the dead weight representing the basket, and on the dead weight representing the used fuel. The results are presented on the curves below: the red curve from the actual measurements, the blue one from FEA results.



Outer acceleration on the body:
The body acceleration manifests two falls corresponding to the impact of the two dead weights (one for the basket and one for the spent fuel).

Inner acceleration on the basket:
The gap between the basket and the lid is smaller than that of the spent fuel. The basket is the first to impact. A secondary impact occurs at the end of the drop with a low level of acceleration.

Outer acceleration on the spent fuel:
The second impact occurs with the spent fuel. High amplification of acceleration is observed between the outer acceleration and that of the spent fuel.

Figure 3 Drop test results and FEA benchmark

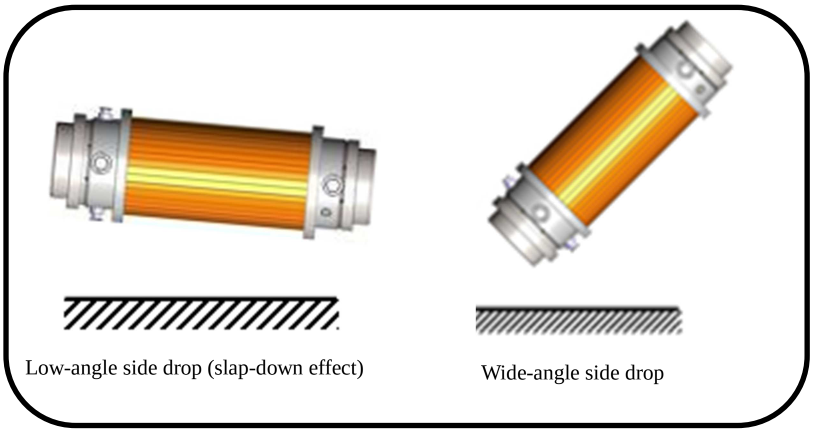
Such amplification indicates that delayed impact is a very penalizing configuration that requires early consideration in the design process. For the TN®-G3 package, the solution was to add an impact limiter on the inner surface of the plug to absorb the content energy and to minimize the load in the plug bolts.

In addition, extensive FEA calculations were made during the design process, with detailed modeling of the components. As shown in the previous figures, the benchmark with actual measurement points perfectly fits with the curves (blue one for the calculations, red one for measurements). Thanks to this expertise, the closure system design is strong enough to resist the delayed impact effect. After the drop test, the leaktightness of the model was successfully verified by a Helium leakage test.

Side drop test sequence (LT) – wide angle effect

Side drop tests are usually conducted with a small angle, between 5° to 15°, in a horizontal direction. It creates a slap-down effect, meaning a secondary impact with load amplification from the package rotation.

For the TN®-G3 package, the slap-down effect was considered, as well as a drop test with a wide angle up to 60°. The following figure illustrates both configurations.



Low-angle side drop (slap-down effect)

Wide-angle side drop

Figure 4 Side drop configuration

The particularity of the wide-angle drop is that it creates a concentration of load and stress on the corner of the impact limiter and on the corner of the secondary lid. FEA calculations determine the impact of the drop angle on the leaktightness of the lid. About 50% of the drop energy is absorbed during the first impact in a direction where impact limiters may have a weakness. As explained in a Patram article, it may be necessary to re-design the impact limiter to meet the requirements of this “often-ignored 45-degree impact orientation.” [5].

The consequence of such a configuration may be illustrated by the FEA results, for example with the opening of the gasket sealing, as illustrated in the following figure.

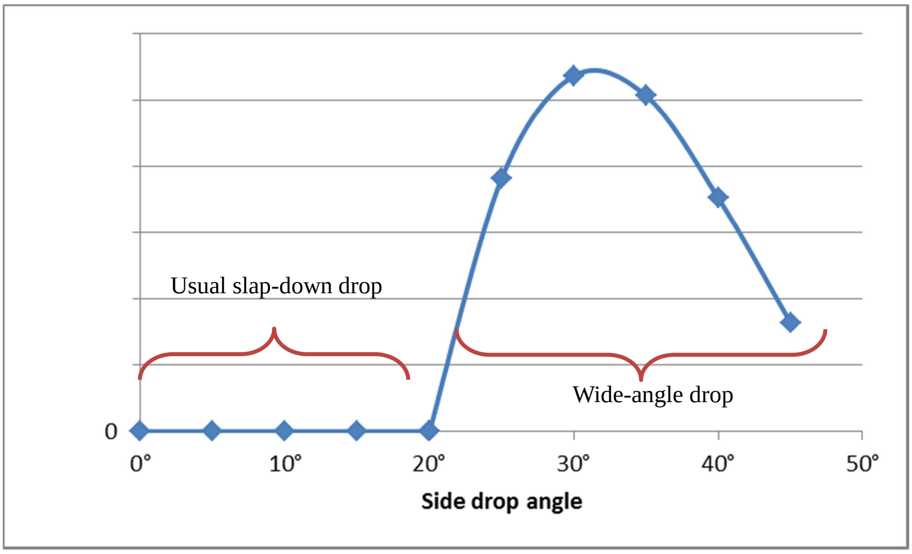


Figure 5 Typical opening of seal area against drop angle

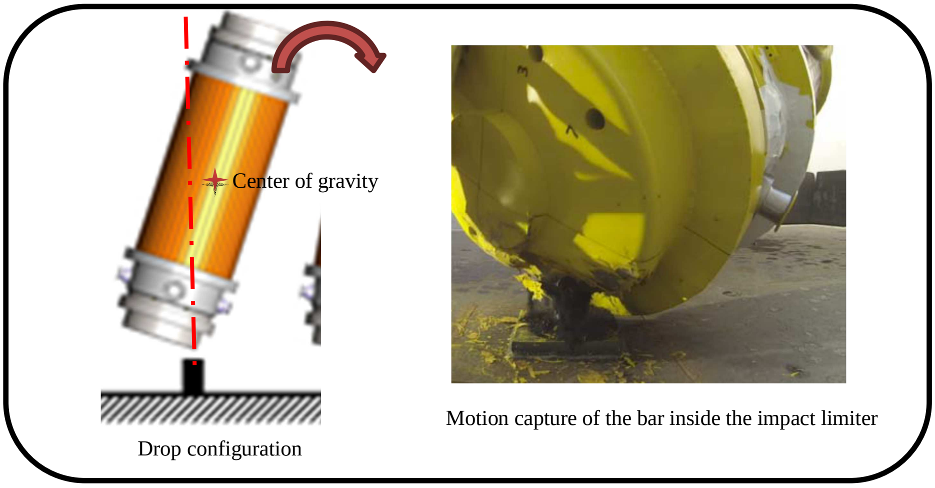
During the low-angle side drop test, no opening of the package is expected. However, the risk grows with the wide-angle, topping out at a specific angle.

Such behavior is closely linked to the closure system and impact limiter design. But it is not directly linked with the overall acceleration of the package during the drop test. Therefore, the simple verification of the acceleration may not be sufficient in determining the most penalizing drop configuration regarding the leaktightness of the lids.

Corner drop test sequence (OT)

Two noticeable events during this sequence are particularly noteworthy: the puncture drop test without alignment of the target point with the center of gravity, and the natural delayed impact during the drop test.

First event: The purpose of the puncture drop test is to damage the impact limiter before the subsequent 9-meter drop test. Contrary to usual practice, the drop angle did not align with the center of gravity so that the mock-up rotated after the impact on the puncture bar. Because of that, the puncture bar spread the damage inside the impact limiter during the swing of the mock-up.



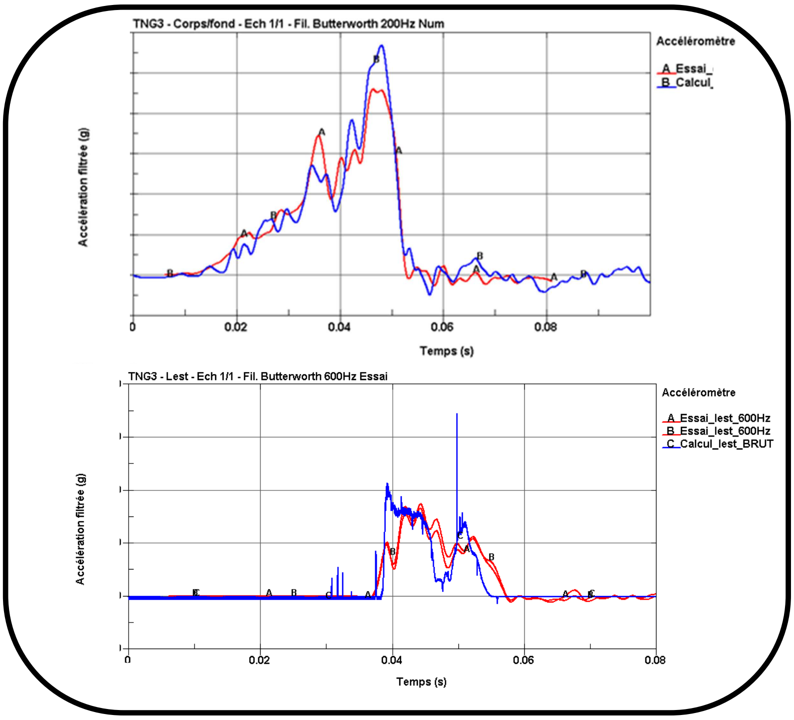
Drop configuration

Motion capture of the bar inside the impact limiter

Figure 6 puncture drop test

The damage of the impact limiter did not prevent the success of the subsequent 9-meter drop test.

Second event: The results of the 9-meter drop test showed a natural delayed impact. As in figure 3, the subsequent acceleration of the body and the content measured by sensor shows a delayed impact of the content, even though no specific device was used to maintain the content at the bottom of the cavity.



Outer acceleration shows a fall similar to that of figure 3.

Inner acceleration shows the impact of the content with a delayed impact.

Figure 7 Results of the 9-meter drop test

The benchmark with the FEA calculations was performed assuming a gap between the content and the lid. The FEA results (blue curve) fits perfectly the measurements (red curve) demonstrating the accuracy of the model.

For the package, additional FEA calculations were made to extrapolate the results considering the maximal gap between the spent fuel and the plug. The impact on the leaktightness of the closure system remained acceptable.

Conclusions

Extensive calculations using a detailed FEA model were essential in determining the drop test program of the TN®-G3 scale mock up. New configurations such as the delayed impact and the wide-angle side drop test were addressed and tested.

Thanks to the design work, the TN-G3 model successfully passed the drop test program.

References

[1] S. Brut, “Used Fuel Assembly Transport Cask – TN®G3 Family,” (paper presented at 17th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM) in San Francisco, 2013), Article 109 .

[2] IAEA Safety Standards, "Regulations for the Safe Transport of Radioactive Material," N° TS-R-1 (2012 Edition).

[3] Gordon S. Bjorkman, Jr., “The Effect of Gaps on the Impact Response of a Cask Closure Lid,” SMiRT 20-Division 5, Paper 1941.

[4] J. Baudouin, S. Brut, and H. Ripert, “Design Methodology to Ensure Similarity Between Scale Model and Model: Application to TN®843,” (paper presented at 17th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM) in San Francisco, 2013), Article 221.

[5] David C. Harding, David Garrido, and Doug Ammerman, “Protecting Against Corner Impacts: Sensitivities Discovered During a Rail Cask Impact Limiter Design,” (paper presented at 17th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM) in San Francisco, 2013), Article 109.

[6] Code of Federal Regulations (CFR), Title 10 – Energy, Part 71 – Packaging and Transportation of Radioactive Material (2016 Edition).