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TN® 24 Dual Purpose Casks: 20 years of Licensing Experience

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Abstract

The TN®24 cask family is composed of dual purpose casks designed and licensed for both transport and dry storage in various countries such as France, Germany, Belgium, Switzerland, Italy, the United States and Japan. The TN®24 casks have been loaded with various PWR and BWR fuel assemblies for more than 20 years. The licensing capability of dual purpose casks for their entire lifetime is key to guaranteeing a long term solution for dry storage of fuel assemblies. For the TN®24 such capability is based on a solid cask design with a containment shell made of thick carbon steel forging and narrow gap weld and supported by robust safety demonstrations and material qualifications.

The safety demonstrations addressed complex phenomena, especially for mechanical analysis of the containment body under very stringent accident conditions such as 9-meter drop tests, military aircraft crash impact directly on cask, and resistance to brittle fracture at -40°C. The key elements ensuring the safety performance of the TN® 24 are the following:

- The qualification of the forging and welding processes and associated non-destructive tests: The methods for qualification of the manufacturing processes are performed with an extended mechanical test program to define the most vulnerable area of the forging and containment weld. In the same manner, the performance of the Non Destructive Tests (NDT) is essential to prevent the risk of brittle fracture. The NDT should detect the expected surface and volumic defects of the forging and welding process.
- Advanced experimental drop and crash tests demonstrating the leak-tightness of the cask with direct measurement of the helium leak-rate before and after tests: These tests are used for both safety demonstrations and benchmarks for numerical calculations. These benchmarks ensure the deep understanding of these complex phenomena and a reliable capability to accurately assess the cask safety margins.

The purpose of this document is to present the basis of the TN® 24 cask safety performance and associated qualification methodology through relevant examples issued from 20 years of licensing.

Introduction

The TN®24 core technology is its containment shell made of a thick-walled forged shell (at least 200 mm) in high performance carbon steel grade and its welded bottom. The containment shell is closed at its top by bolted lids. The thick-walled forged shell and its welded bottom are submitted to a high level of controls for brittle fracture at -40°C during manufacturing and qualification. The containment shell is surrounded by an outer shell mainly made of neutron absorbing resin crossed by copper conductors and closed by painted carbon steel. In transport configuration, the cask is equipped with top and bottom shock absorbers in wood and with aluminum rings to protect the containment shell in accident conditions.

Figure 1 TN®24 DH cask in transport configuration

Since the licensing of the first TN®24 cask in Europe in the 1990s the state of the art has changed due to the evolution of the regulatory requirements and characteristics of the radioactive content. To guarantee a safe and reliable long term solution for dry storage of fuel assemblies, the TN®24 cask designs, depending on customer needs, regularly obtain renewals and extensions of their transport certificate of approval: the design, safety demonstrations, material qualifications, and control of the TN®24 cask are consequently regularly improved.

The following sections summarize the main impacts of the state-of-the-art evolution in 20 years of licensing experience and explain how AREVA TN has managed these changes. The focus is made on European casks in the present article.

Licensing experience of the TN®24 casks in Europe

In 20 years, AREVA TN has licensed 13 different cask models from the TN®24 cask family in 5 European countries (Figure 2). Each cask is adapted to customer needs and installations in terms of dimensions, weights, and radioactive content.

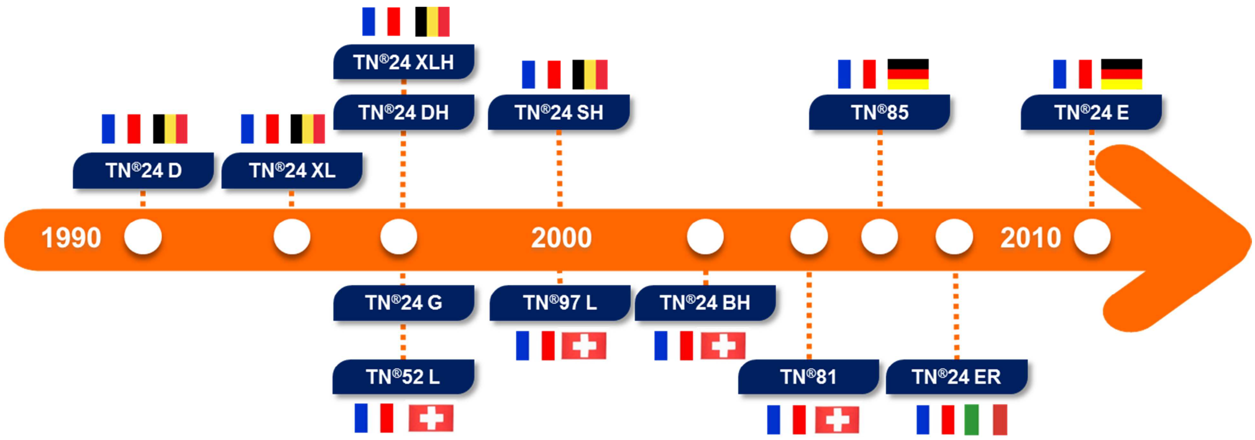

Figure 2 Issuance of the Transport Certificate of Compliance for the TN® 24 casks

Note: TN®81 and TN®85 are specific casks from the TN®24 cask family licensed for transport and interim storage of High Level Waste (HLW) issued from the recycling process.

The main challenge associated with this long period of cask development and licensing is the capability to manage state-of-the-art and radioactive content evolutions for both existing and future casks. The licensing strategy for the TN®24 cask family relies on the following principles:

- All TN®24 casks are made of the thick-walled forged shell and its welded bottom as the core technology.
- High level of performance of the forging and the bottom-to-shell weld against the risk of brittle fracture are ensured.
- Design of outer shell, basket, and shock absorbers are regularly improved. Each component modification is introduced in new cask developments to enhance safety and robustness of TN®24 casks.

The most important evolutions in 20 years are likely related to the mechanical demonstration of the cask leak-tightness in transport accident conditions even if major licensing breakthroughs have also been performed in other fields such as first time use of burn-up credit for the TN®24E cask in Germany. Relevant examples of these evolutions based on AREVA TN experience are discussed below.

Evolution of the regulatory requirements: Slap down and delayed impact effects

In the mid ’90s the slap down effect (the consideration of a low angle, below 15°, during the 9-meter horizontal drop) appeared as a new regulatory requirement. The angle generates a second impact with an increased acceleration which results in higher stresses in the containment system. The safety demonstration was based on an experimental test with 1:3 scale cask mock-up. Originally the TN®24D shock absorbers were not designed to resist the slap down effect. As a number of TN®24D casks had already been loaded with fuel assemblies when the regulation for the slap down effect came into force, the challenge was to manage it without modifying the cask design and without re-conducting experimental tests with an additional cask mock-up. The solution developed by AREVA TN was to modify the design of the top and bottom shock absorbers to include aluminum rings and their supports (Figure 3) which have since been included on all TN®24 cask designs and attached to the body for improved mechanical behavior.

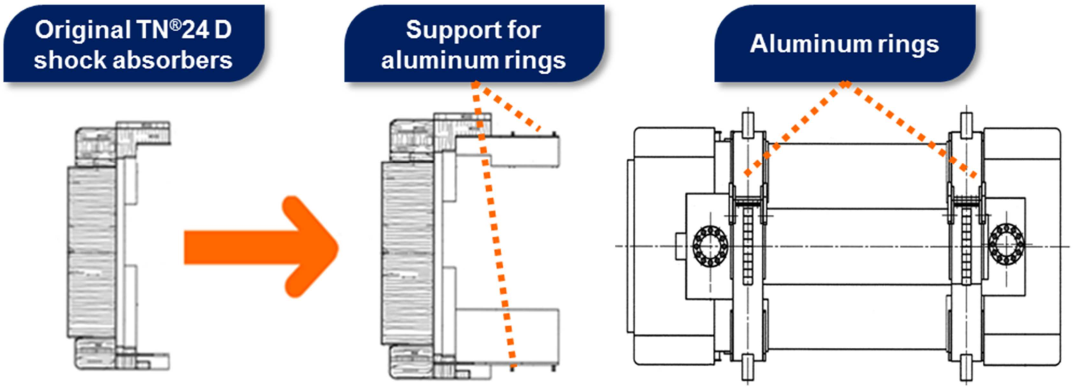

Figure 3 Evolution of the TN®24D shock absorbers to manage slap down effect

To avoid additional experimental tests with an additional cask mock-up, experimental tests on the aluminum rings were conducted to qualify their mechanical behavior and demonstrate that the TN®24D cask equipped with aluminum rings subjected to the slap down effect generates lower stresses in the containment system than in the originally designed TN®24D without slap down.

More recently, the delayed impact effect (impact of the content into the lid after the cask had already hit the ground during 9-meter axial drop test) has appeared as a new regulatory requirement. As the TN®24E cask was under development when the regulation came into force, internal shock absorbers made of horizontal tubes attached to the basket (Figure 4) were added to the design to manage the delayed impact effect.

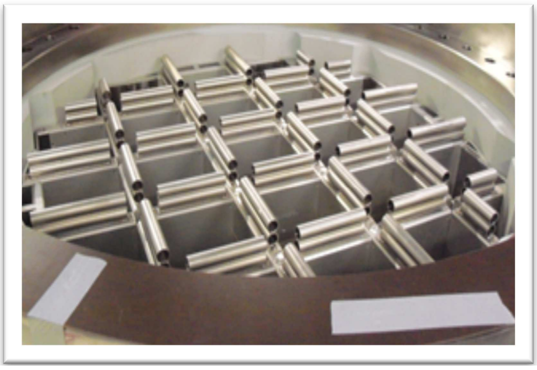

Figure 4 TN®24E internal shock absorbers

Evolution of the regulatory requirements: Ageing effect

The ageing effect is considered for all the dual-purpose TN®24 cask designs for which the ageing-related degradation mechanisms of the materials and components need evaluation (more details in reference [1]) particularly the basket and its neutron poison material, the seals, and the resin. The forged shell is not sensitive to the ageing effect. It is required to take the understanding of the degradation mechanisms due to the ageing effect into account in the Safety Analysis. For example, extensive evaluation of the ageing effect on the resin properties was conducted so that the ageing effect is fully characterized and taken into account in the shielding evaluation of the TN®24 casks. Since the first TN®24 cask, the regulatory requirements related to the ageing effect have increased and the qualification program of the key material and components are regularly discussed and improved with the Safety Authority. In addition, to increase the safety margins, cask design is also improved. For example, the TN®24 basket, designed for PWR high burn-up fuel assemblies such as the TN®24DH or TN®24XLH casks, has been reinforced with high performance stainless steel to increase the safety margins.

Improvement of dynamic numerical simulation: Example with the TN®81 cask

Due to the nature of the complex phenomena, the demonstration of the cask leak-tightness in 9-meter drop tests is mainly addressed by experimental tests with cask mock-ups. In 20 years, numerous experimental tests were conducted on scaled (mainly 1:3 scale) mock-up casks (Table 1). Each mock-up included the containment shell, the bolted lids, a simplified outer shell and the shock absorber systems.

Table 1 Examples of experimental 9-meter drop tests conducted by AREVA TN

1993	1997	1999	2000	2005	2009	2013	2015
TN®24D	TN®24G	TN®97L TN®106	TN®24GET TN®81	TN®112 TN®17/2	MX6	CN2700	TN®G3

Each mock-up was instrumented with strain gauges or accelerometers on the containment shell parts (forged shell, lids, and bolts). In addition, leak-tightness of the mock-up was measured before and after the tests to demonstrate that the containment of the radioactive content was ensured. This leak-tightness measurement is the key element of the safety demonstration.

The casks of the TN®24 family were originally developed and justified by comparing them to casks which had actually undergone the drop tests. For example the TN®24XL, TN®24XLH, TN®24DH, and TN®24SH casks were all based on the TN®24D, TN®24G, and TN®97L casks and experimental drop tests. With the development of the dynamic numerical simulation software, the cask models are more and more accurate and are used to complete the safety analyses. Thanks to the wide range of experimental drop tests (Table 1), AREVA TN has a large database available to continuously benchmark its dynamic numerical model of any new cask design and make the numerical model reliable. The key element in the validation and qualification of the TN®24 models is that the leak-tightness measurements were taken on a complete mock-up both before and after the drop tests. This qualifies the numerical model in its entirety, the shock absorbers and the containment system, resulting in a very good understanding and modeling of the complex phenomena occurring during the 9-meter drop tests.

The improvements to the numerical models are regularly discussed with the Safety Authorities and introduced in the Safety Analysis Report. For example the modeling of cask and shock absorbers were significantly improved with the numerical benchmark of the TN®81 with 9-meter experimental drop test. The numerical benchmark shows a very good general correlation between numerical results and experimental drop tests (Figure 5). More precisely, the deformation of the containment shell was numerically benchmarked with the 9-meter experimental drop test of TN®81 mock-up with very good accuracy.

Figure 5 TN®81: Comparison of numerical benchmark with experimental drop tests

Resistance to brittle fracture of forgings and bottom-to-shell weld with improved qualification and control

With the evolution of the IAEA 85 to the IAEA 96, TN®24 casks licensed in France are considered as a double leak-tight barrier cask. It requires a high level of control of the brittle fracture at -40°C during the manufacturing process and qualification. All materials have small discontinuities with crack like shapes which may lead to unstable propagation with subsequent brittle fracture at low temperature when subjected to a 9-meter drop test. The TN®24 cask performance in such conditions relies on the required characteristics of the ferritic carbon forging materials and their associated welds. The safety analyses consider the impact of the potential defects as well as the performance of the non-destructive method applied for the inspection of these parts. Qualifications are necessary to guarantee the properties of the forging and the weld. The improvements of the technology for controlling the forgings and welds have led to an increase in the guaranteed level of forged shell and weld quality and, therefore, to an increase in the safety margins.

Due to its thickness, Charpy tests are used to verify the homogeneity of the mechanical characteristics of the TN®24 shell at different depths and according to the directions parallel and perpendicular to the main working direction. The quality control acceptance criteria must be met for all orientations. The qualification may also include other tests such as drop weight tests or dynamic toughness tests – CT25.

The weld between the shell and bottom is a discontinuity in the containment. The robustness of this area is essential. This is why for TN®24 casks, its performance is demonstrated by an extended welding qualification with specific additional samples compared to ASME IX [2] to check the weld toughness through the wall thickness ("T" in Figure 6) at different positions in the weld and also in the heat affected zone (HAZ). Impact test samples are located in at least three zones; at the root, mid-thickness ("T/2" in Figure 6), and the surface in order to detect the most vulnerable zone. In the latter, more elaborated toughness tests such as the drop weight test or dynamic toughness tests (CT25) verify the compliance to the characteristics required by the brittle fracture analysis.

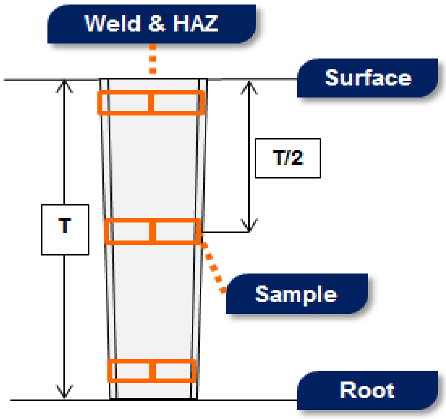

Figure 6 Location of Charpy impact test samples in the weld deposit

The brittle fracture analysis is based on a reference flaw size. The applied Non Destructive Test (NDT) must detect the critical flaw (defined by its dimensions) with a margin that defines a reference quality level. Sophisticated surface and volumetric NDT methods are developed to satisfy these acceptance criteria. Ultrasonic Testing (UT) based on the manual pulse echoe method is the state of the art for the forging. Due to the forging operations, there is a preferred orientation parallel to the external surface to achieve a potential volumetric indication according to the material flow (Figure 7).

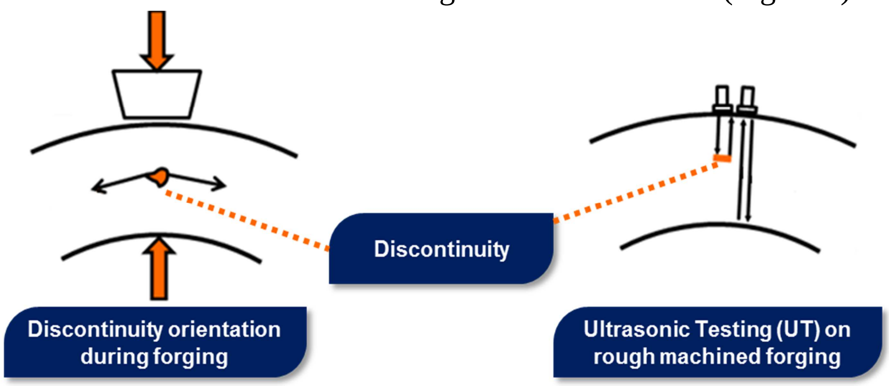

Figure 7 Discontinuities orientation due to the forging operation

Thus, reflection of the ultrasonic signal will be optimal on such a potential discontinuity. This is why the control capability of forging is considered as excellent. In addition, the scanning of the shell and bottom forging is carried out on all the surfaces of the forging with straight beam and shear beam transducers to avoid dead zones for the UT scanning. Moreover, the compactness of the forged material is generated by the high compression load used to shape the material. The soundness of the forging material is excellent. Even for very large forging, such as the shell of a TN®24 cask, the current acceptance criteria is based on Quality level 3 according to EN 10228-3 [3] with no isolated discontinuities greater than 5 mm and no grouped discontinuities greater than 3 mm.

The weld between the bottom and the shell of the containment also requires an efficient volumetric NDT method in addition to the surface examination. Detection of non-volumetric indications such as cracks, or lacks of fusion is essential since they are very detrimental discontinuities. In the case of the narrow gap weld of TN®24 cask, foreseen discontinuities, for example lack of fusion parallel to the weld seam at mid thickness, are detected thanks to additional scanning from the bottom (Figure 8): the strategy of control is defined following the analysis of the geometry of the cask (supported if necessary by simulation and tests on representative mock-ups). In such thick welds, the strategy of control defined by ASME V article 4 [4] may not be sufficient: it should take into account the specific geometry of the cask. This additional scanning offers a very good reflectivity of the signal and the adequate detectability and therefore should increase the guaranteed level of the forged shell and weld quality.

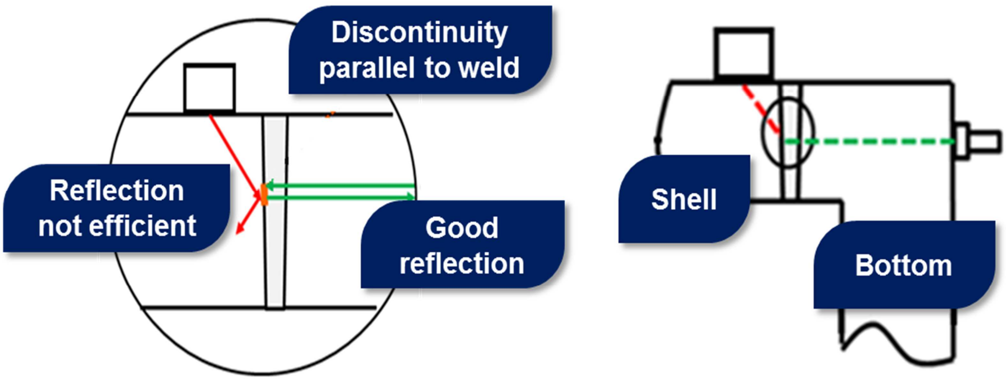

Figure 8 Detectability of lack of fusion in the bottom-to-shell weld

Evolution of radioactive content evolution

Since the first TN®24 cask, the fuel assembly characteristics have increased with time to higher enrichment and burn-up (also MOX fuel assemblies). On average, the enrichment of fuel assemblies loaded in TN®24 casks has increased from 3.3% to 5% while burn-up has increased from 35 GWd/tU to 75 GWd/tU. The TN®24 cask outer shell and basket design have been upgraded to improve the shielding and criticality performance. For example, in the latest TN®24 design, the resin is contained in the trunnion areas to reduce the dose rate for operators.

Contents other than fuel assemblies can also be loaded in the TN®24 casks. This evolution in radioactive content are mainly managed by extension of the existing TN®24 certificate of approval as is the case, for example, with the TN®24DH casks which was adapted in 2008 to transport universal canisters of compacted metallic waste (CSD-C) from the La Hague recycling plant to Belgium. To meet the main technical challenges of the interfaces with new installations and a new content, the internal arrangement and the primary lid for of the TN®24 DH were modified.

In 2016, the TN®24SH obtained an extension of the transport certificate of approval to load defective fuel rods. Each defective fuel rod is loaded into a single capsule tube in stainless steel and is dried individually. The fastening is then screwed and welded onto the capsule tube to gain a tight capsule. The capsules are assembled into a skeletal form to create a structure looking like a fuel assembly (Figure 9). The main technical issue related to encapsulation of defective fuel rods is the radiolysis of residual water with the potential risk of H_2 explosion. To manage that challenge, an innovative drying process has been developed and qualified with extensive experimental tests to guarantee a very limited quantity of residual water compatible with the TN®24SH safety case.

Figure 9 Tight capsule for defective fuel rod

Conclusions

In 20 years of licensing, the TN®24 cask designs have regularly obtained renewals and extensions of their transport certificate of approval due to the robustness of their core technology: the thick-walled forged shell. This robustness relies on the appropriate qualifications, manufacturing control, and safety demonstrations which meet evolutions in the state of the art. As the state of the art continues to change, TN® 24 casks will have to manage new technical challenges to meet customer needs such as the management of nuclear power plant end of life and new evolutions in the regulatory requirements. The TN® 24 cask designs, safety demonstrations, and material qualifications will evolve consequently.

References

[1] H.Issard, J. Garcia, “Safety of Long-Term Interim Dry Storage of Used Nuclear Fuel,” (paper presented at the PATRAM Conference, London, England, 2013).
[2] EN 10228-3, Non-destructive testing of steel forgings - Part 3: Ultrasonic testing of ferritic or martensitic steel forgings
[3] ASME IX, Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators
[4] ASME V, Nondestructive Examination