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DESIGN METHODOLOGY TO ENSURE SIMILARITY BETWEEN SCALE MODEL AND PACKAGE MODEL: APPLICATION TO TN®843

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ABSTRACT

The transportation of radioactive material requires a very high standard of safety of the packaging model imposed by international regulations. Particularly, a 9-meter free drop test onto an unyielding target is required.

The justification of the good behavior of the packaging model under the 9-meter free drop test is generally based on drop test results of a scale model, the similarity of which is proven with regard to the packaging model.

To facilitate the consideration of the drop test campaign results in the Safety Analysis Report, the design of the scale model relative to the packaging model must be as close as possible. The difficulty is to have a penalizing but still realistic scale model with regard to the packaging in terms of structural resistance.

This paper describes the approach adopted to guarantee the penalizing aspect of the mock up. Specific geometry (gaps, tolerances,...) and materials for various components (containment, bolts, shock absorber,...) of the scale model is necessary.

The scale model definition is explained by using the TN®843 packaging model as an example. This was one of the last packages to have undergone the 9-meter free drop. The TN®843 package has been developed for the transportation of compacted waste and requires a type B(U)F certificate of approval. Drop tests were performed using a TN®843 3:1 scale model.

INTRODUCTION

The TN®843 package has been developed for increasing the loading capacities of existing package (TN®28VT) for the transportation of compacted waste canisters. The TN®843 package allows the loading of 36 compacted waste canisters while the TN®28VT package authorizes the loading of 20 compacted waste canisters.

The TN®843 package design complies with the IAEA 2009 regulations [1]. The demonstration of the good behavior of the TN®843 package under drop tests (9-meter free drop and 1-meter drop onto punch bar) is based on the results of the campaign of drop tests performed using a TN®843 3:1 scale model.

The approach for designing the 3:1 scale model was to define it with lower mechanical resistance compared to the TN®843 package model one. So, the good behavior of the3:1 scale model enables to show margin for the package model and to guarantee the safety of the one.

The12 cells of the internal arrangement were represented by 12 tubes filled with 36 dummy canisters. The internal arrangement and canisters were representative of the mass which is stressing the closure system (lid and lid bolts) in axial drop onto the top shock absorber.

The dummy canisters were modeled with solid cylinders equipped in top end extremity with wooden block, representative of the deformable top end of the canisters.

This paper presents the adopted approach for defining the TN®843 3:1 scale model.

DESCRIPTION OF THE TN®843 PACKAGE

The body consists of a cylindrical thick-walled forged shell made of cryogenic carbon steel. The bottom is a thick forged cryogenic carbon steel part, full penetration welded with the forged shell. The assembly of the forged shell and the welded bottom defines the cavity.

The entrance of the cavity is closed by the closure system which is composed of a lid made of a thick forged carbon steel plate fixed to the top end of the forged shell by means of M42 bolts. The lid is equipped with 2 EPDM seals (internal EPDM seal ensuring the leak-tightness of the lid, external EPDM seal for check the internal EPDM seal leak tightness).

The forged shell with the welded bottom, the lid fixed by means of the lid bolts and the internal EPDM seal define the containment vessel.

Two pairs of trunnions are positioned in top and bottom part of the forged shell. They are used for the handling of the package and the stowage of the package on the transport frame.

The forged shell is surrounded by a layer of resin ensuring the radial neutron shielding; this last is protected by an external shell.

All these components define the body of the package, they consist in a set.

At each extremity, the body is protected with a shock absorbing cover against damages under drop tests both in normal conditions and in accident conditions of transport.

View of the TN®843 package is given figure 1.

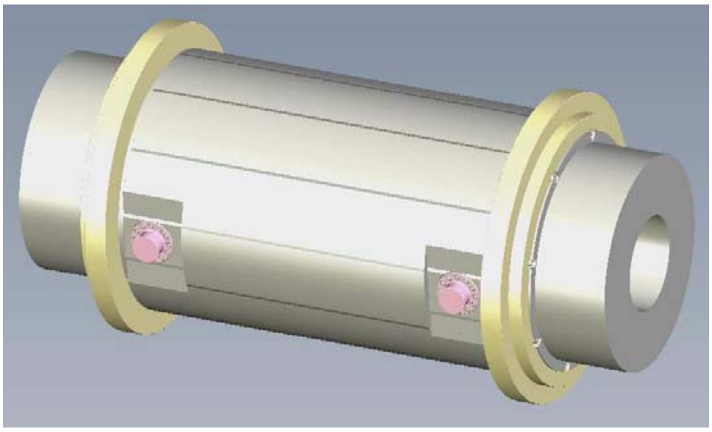

Figure 1: General view of the TN®843 package in transport configuration

DESCRIPTION OF THE TN®843 3:1 SCALE MODEL

The TN®843 3:1 scale model is representative of the TN®843 package in term of components constituting the package. The forged shell and its welded forged bottom are represented. In the same way the lid and its fixing bolts are part of the scale model. Several sets of the top and bottom shock absorbing covers were manufactured. Indeed the drop test campaign includes several 9-meter free drop sequences, and new shock absorbing covers are needed for each sequence.

Because of the 3:1 scale ratio, the drop energy is not the same between the package and its scale model. The scale model will have one third of crushing height of the shock absorber of the package. The total drop energy being proportional with the total distance of the drop (i.e. the drop height plus the crushing height), the scale model drop energy would be lower. To take into account this discrepancy intrinsic to scale model drop test, the drop height is increased of two third of the expected crushing height.

Discrepancies between the TN®843 3:1 scale model and the TN®843 package:

Resin (radial neutron shielding) + External shell

The resin ensuring the radial neutron shielding and the external shell was represented by a shell welded on the external surface of the forged shell. It was representative of the mass of the resin plus the external shell one. It was welded only at its extremities to the forged shell to avoid any influence on the forged shell inertia.

Lid

The depth of the seal grooves machined on the lid was increased. This point is analyzed in next paragraph.

The orifice for check the leak-tightness of the lid (internal EPDM seal) was not positioned on the lid (TN®843 package) but located on the forged shell of the TN®843 3:1 scale model. In addition a second orifice was machined on the forged shell for checking the leak-tightness of the containment vessel, this last does not exist on the TN®843 package. The presence of these two orifices on the forged shell locally decreases the strength of the one which is penalizing for the 3:1 scale model.

The TN®843 3:1 scale model (see figure 2) is representative in term of dimensions, the 3:1 ratio is applied. Indeed which is important for the representativeness of the seals are mainly the tightening force and the compression rate. This point is analyzed in next paragraph.


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Figure 2: View of the TN®843 3:1 scale model during drop test campaign


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Figure 3: View of the TN®843 3:1 scale model cavity filled with dummy canisters

APPROACH FOR DESIGNING THE TN®843 3:1 SCALE MODEL

The drop tests imposed by the international regulations [1] enable to check the strength of the package and of the internal arrangement if needed, under drop conditions.

The mechanical behavior of the package is mainly linked to the geometry of the components and theirs materials characteristics.

The scale model must have a penalizing behavior compared to the package one. So for the containment vessel, the materials must have lower mechanical characteristics and geometries which maximize the stresses in the components. This means that the part thickness for the shell, bottom and lid must correspond to the lower tolerance of the package. The absorber materials must be chosen in order to be envelope in term of crushing stress or risk of complete compaction to maximize the acceleration.

Moreover, the regulations impose that the drop conditions happen for the ambient temperature conditions in the range of -40°C to 38°C. In the situation of 38°C ambient temperature and taking into account the maximum heat load of the radioactive contents the part temperature is above room temperature, which means that the mechanical characteristics of the parts are lower than the one at room temperature.. At the opposite for -40°C ambient temperature and a minimum heat load the mechanical characteristics are higher than the one at room temperature.

The definition of the scale model must take into account all these parameters. However, for economic reasons it is not possible to manufacture several models of the scale model particularly for the body. Generally as the drop test campaign includes several sequences, several sets of shock absorbing cover are procured to cover all drop orientations. In the same way the procurement of several sets of lid bolts is done.

The drop tests are performed for the most harmful conditions for the package. If needed for additional justifications, numerical models can be created and benchmarked of the test results. Those models can be used to do sensitivity analysis on materials characteristics, geometry or drop test orientation.

Materials characteristics:

Components concerned by the materials characteristics are the parts constituting the containment vessel and any part having high stresses as the shock absorbers.

Containment vessel materials characteristics

The materials for the scale model containment vessel was selected with strength lower than the package ones for 38°C ambient temperature. The strength of materials is characterized by the Yield strength (Sy), the Ultimate strength (Su) and the Ultimate elongation (A%). Moreover, their behavior must be equivalent particularly in term of stiffness to be representative. The stiffness is characterized by the Young modulus, so the material type shall be respected (steel, aluminum …) but can have different grade.

As said above, the minimum materials characteristics are for the maximum temperature of the material obtained for 38°C ambient temperature and the maximum heat load of the radioactive contents. Generally the drop tests are performed at ambient temperature (≈ 20°C), which imposes to have the scale model materials characteristics lower than the package ones at temperature of transportation.

The materials for the TN®843 3:1 scale model containment vessel were chosen to be less strength than the package ones.

Table 1: Containment vessel materials characteristics

Containment vessel				
Component	**TN®843 3:1 scale model**		**TN®843 package**	
	Material	Mechanical characteristics	Material	Mechanical characteristics
Forged shell Bottom Lid	Carbon steel:	T = 20°C Sy ~ 400 MPa Su ~ 580 MPa A% ~ 29%	Criogenic carbon steel:	T = 100°C Sy ≥ 450 MPa Su ≥ 590 MPa A% ≥ 20%

Containment vessel				
Component	**TN®843 3:1 scale model**		**TN®843 package**	
Lid bolts	Standard carbon steel bolts	T = 20°C Sy ~ 890 MPa Su ~ 950 MPa A% ~ 19%	High strenght carbon steel bolts	T = 75°C Sy ≥ 900 MPa Su ≥ 990 MPa A% ≥ 9%
Washer of Lid bolts	Carbon steel	T = 20°C Sy ~ 840 MPa Su ~ 950 MPa A% = 19%	Martensitic steel	T = 75°C Sy ≥ 920 MPa Su ≥ 980 MPa A% ≥ 10%

In the table above we can check that the strength of the TN®843 3:1 scale model is lower than the TN®843 package one except for the Ultimate elongation A%.

In drop conditions we have to demonstrate that the leak-tightness is kept. To reach this goal, the TN®843 package containment vessel was designed so that there is no plastic deformation. The design option was not to exceed the Yield strength (Sy) for the containment vessel components, so the A% value was not a stringent criterion to be respected.

Shock absorber materials characteristics

The TN®843 package is equipped with 2 shock absorbing covers fixed by means of bolts in the top and bottom ends of the body. The shock absorbing covers are constituted with casings filled with wood for protection against axial and oblique drop and, an aluminum ring as absorber under lateral drop.

Figure 4: View of the TN®843 3:1 top shock absorber after axial drop

The woods filling the casings are in two different species. The crushing characteristics of the woods are depending on its moisture and the temperature. The moisture criterion was the same for the 3:1 scale model and the package. At low temperature (-40°C) there is a significant hardening of the wood and at temperature (85°C) a significant softening compared to values at 20°C temperature.

So that the drop tests are performed in a penalizing way, it is needed that the accelerations issued are maximal. In this aim the wood characteristics of the scale model must cover the package woods characteristics at -40°C temperature. The drop tests being performed at ambient temperature (≈ 20°C), the choice for the woods of the

TN®843 3:1 scale model shock absorbing covers was to change the wood species to have harder woods. Very low density wood was replaced by low density wood, and the middle density wood by hard wood.

The TN®843 3:1 scale model and TN®843 package woods characteristics are given in the table 2:

Table 2: Shock absorbing covers woods materials characteristics

Shock absorbing covers woods			
TN®843 3:1 scale model		**TN®843 package**	
Material	Mechanical characteristics	Material	Mechanical characteristics
Hard wood	T = 20°C ~ 70 MPa ≤ σ* ~ 33 ≤ ε**	Middle density wood	T = -40°C σ* ≤ 50 MPa ε** ≥ 50%
Low density wood	T = 20°C ~ 14 MPa ≤ σ* ~ 72% ≤ ε**	Very low density	T = -40°C σ* ≤ 10 MPa ε** ≥ 82%

*: crushing stress along fibers direction
**: limit of compacted material

We notice that the woods of the TN®843 3:1 scale model are harder than the TN®843 package ones. Moreover, the limit of compacted material are lower for the TN®843 3:1 scale model woods which maximize the risk of compaction of the woods, and consequently occurrence of acceleration peak.

Concerning the aluminum rings, the grade selected has mechanical properties which do not change between -40°C and 100°C temperature. Specific properties for $R_{p0,2}$, Rm and A% were selected to reduce the acceleration range caused by the dispersion of the mechanical properties.

For the lateral drop, the material characteristics of the TN®843 3:1 scale model aluminum rings were in the middle of the range for the Yield strength and Ultimate strength.

Concerning the Ultimate elongation of the TN®843 3:1 scale model values were practically equal to the minimum value which is penalizing.

Conclusion materials characteristics

The comparison between the TN®843 3:1 scale model materials and the TN®843 package ones show that the containment vessel materials have lower characteristics and the shock absorbing covers are harder. The combination of a containment vessel at temperature (75°C to 100°C) and -40°C temperature for the shock absorbing covers is a very penalizing configuration and corresponds to not real situation compared with the real conditions of transport.

However, the demonstration that the leak-tightness of TN®843 3:1 scale model is kept guarantees the good behavior of the TN®843 package in drop tests conditions.

Geometry:

Dimensions

The dimensions of the TN®843 3:1 scale model are the ones of the TN®843 package in the 3:1 ratio and, rounded if necessary for facilitating the procurement.

The breakdown of masses given in table 3 shows a good similarity between the TN®843 3:1 scale model and the TN®843 package. Then the representativeness of the TN®843 3:1 scale model is acceptable.

The weight of the content is overestimated for the mock-up in order to be penalizing in terms of stresses in the closure system in axial drop test on the top shock absorbing cover.

Table 3: Comparison of the TN®843 3:1 scale model masses and the TN®843 package masses

Breakdown of masses				
Component	**TN®843 3:1 scale model (kg)**	**TN®843 package (kg)**		**Discrepancy (%)**
		Full scale model	**Shifted to 3:1 scale**	
Body	2 628	71 300	2 640.7	- 0.5
Lid	244.5	6 720	248.9	- 1.8
Top shock absorbing cover	184	4 910	181.8	+ 1.2
Bottom shock absorbing cover	181.6	4 870	180.4	+ 0.7
Basket	90.8	2 500	92.6	- 1.9
Canisters	1 015.2	25 200	933.3	+ 8.8
TOTAL	**4 344.1**	**116 000**	**4 296.3**	**+ 1.6**

Gaps

The maximization of the gaps between the components has a harmful influence on the behavior of the package in drop conditions. The main gaps having an influence on the behavior of the scale model in drop conditions in the case of the TN®843 package are the diametric gaps of the lid with the top end of the forged shell, and the axial gap between the top external lid surface with the top shock absorbing cover.

The diametric gaps have an influence under lateral drop on the ovalization of the top end of the forged shell. Also the axial gap has an influence in particular under axial drop top side on the bending of the lid. These two situations have a direct effect on the leak-tightness of the internal seal of the lid.

The gaps of the TN®843 3:1 scale model and the TN®843 package are given in table 4. We notice that the TN®843 3:1 scale model is penalizing compared with the TN®843 package.

Table 4: Comparison of the gaps between the TN®843 3:1 scale model and the TN®843 package

<table>
<tr><th colspan="4">Diametric gaps</th></tr>
<tr><th></th><th>Scale model</th><th colspan="2">TN®843 package</th></tr>
<tr><th></th><th>Gap min.</th><th>Gap max.</th><th>Shifted to 3:1 scale</th></tr>
<tr><td>Lid (centring) / Forged shell</td><td>0.5</td><td>1.5</td><td>0.5</td></tr>
<tr><td>Lid (flange) / Forged shell</td><td>2</td><td>3</td><td>1</td></tr>
<tr><th colspan="4">Axial gap</th></tr>
<tr><th></th><th>Gap min.</th><th>Gap max.</th><th>Shifted to 3:1 scale</th></tr>
<tr><td>Lid / top shock absorbing cover</td><td>1</td><td>3</td><td>1</td></tr>
</table>

Seals and seals grooves:

The TN®843 package lid is equipped of 2 EPDM O-ring seals located in 2 trapezoidal grooves machined in the lid. The seals are compressed during the tightening of the lid bolts up to the contact metal/metal between the lid and the bearing surface of the forged shell. The compression of the seals generates a reaction force opposite to the pre-load of lid bolts.

The approach for the definition of the seals of the TN®843 3:1 scale model was to have 2 EPDM O-ring seals located in two trapezoidal grooves machined in the lid like the TN®843 package lid. However the constraints for defining the seals were:

- TN®843 3:1 scale model seals must have the same hardness than the package seal to be representative of the TN®843 package seals.
- Maximum compression rate must be lower than the minimum compression rate of the TN®843 package seals.
- The compression force of the TN®843 3:1 scale model seals is to be in line with the TN®843 package seals one.

The compression rate of the seals is governed by the depth of the groove and the tore diameter of the seal. The maximum compression rate of the scale model must not exceed the package one. Indeed the risk of loss of leak-tightness of the seal is due the loss of the compression of the seal, therefore the situation of the scale model is penalizing for small compression rate.

It is also necessary to check that the reaction force of the seals is not less harmful for the scale model lid bolts. For the scale model, the lid bolts pre-load is in the square of the scale ratio of the scale model. To be envelope the compression force of the scale model seals must be greater than the package. In this way the remaining capacity reserve of loading of the bolts compared to the pre-load is decreased and the tightening limit are more quickly affected. It is to note that for EPDM seals the tightening load is low compared to the pre-load of the bolts and has low influence on the lid leak-tightness.

For the TN®843 3:1 scale model and the TN®843 package the data for the lid O-ring seals are given in table 5.

Table 5: Comparison of the lid seals between the TN®843 3:1 scale model and the TN®843 package

Seals				
Lid	TN®843 3:1 scale model		TN®843 package	
	Compression rate (%)	Ratio Seal force/Bolts pre-load (%)	Compression rate (%)	Ratio Seal force/Bolts pre-load (%)
Internal and external seals	22.7 (max)	1.9	23.8 (min)	1.6

We notice that the TN®843 3:1 scale model seals characteristics are envelope of the TN®843 package ones.

To be in this configuration the groove seals dimensions are not in an exact 3:1 ratio, particularly for the depth and the opening.

The dimensions of the seal grooves for the TN®843 3:1 scale model are in a ratio lower than 3:1. That decreases the stiffness of the lid flange and is favorable for the loss of leak-tightness of the lid. The TN®843 3:1 scale model was penalizing compared to the TN®843 package.

Bolts

For the M14 bolts representing the lid and shock absorber bolts, the minimum diameter in the unthread area has been reduced from the dimension computed for 3:1 scale. The impact is the increase of the preload stress for the equivalent tightening torque. Since the bolts mechanical properties are lower than the TN®843 package at maximum temperature, the TN®843 3:1 scale model is quite penalizing.

CONCLUSION

The approach presented above was the one adopted for the design of the TN®843 3:1 scale model. The design of the scale model was penalizing because the containment vessel represented the package at the maximum service temperature and the wooden shock absorbers were representative of -40°C characteristics.

Moreover, the geometry of the TN®843 3:1 scale model was unfavorable compared to the TN®843 package one.

The drop test campaign was successful. The leak-tightness of the containment vessel in all tested configurations was achieved. Several drop tests (accumulation of 9-meter free drop and 1-meter onto punch bar) were performed by using a single body model, only several sets of the shock absorbing covers and of the lid bolts were procured.

This approach was a first and mandatory answer to the safety requirements in drop conditions. It was completed with additional analysis based on numerical calculation using models benchmarked with drop tests results. For example, this was performed for the analysis of the risk of brittle fracture at -40°C temperature.

REFERENCES

[1] IAEA Safety Standards "Regulations for the Safe Transport of Radioactive Material" N° TS-R-1 2009, Edition.