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Research Article

Calculation and experimental studies for the spent nuclear fuel shipping cask sealing assembly*

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Abstract

One of the safety requirements regarding the shipping cask for spent nuclear fuel is that its leak-tightness should be maintained by preserving the cask body structural integrity and the sealing system tightness under normal and accident transportation conditions. The cask under design has a cylindrical process penetration (port) in its bottomб which is sealed using a plug with a radial seal composed of two rubber O-rings. The cask sealing assembly design was justified by the ANSYS LS-DYNA code calculation results. In particular, the strains of the cask components were calculated when dropped from a height of 1 m with the sealing assembly hitting a vertical bar. The cask was concluded to be leak-tight or leaky based on the strain nature and amount. To verify the adequacy of the results, computer-aided and realistic simulations were undertaken with a 1/2.5 scale mockup cask dropped on a bar from a height of 1 m. The computational and experimental results show a good agreement in terms of the impact response accelerations (overloads) for the mockup cask and bar collision and in terms of the plastic strains for the key components of the mockup bottom port sealing assembly. This proves the adequacy of the numerical cask model that has been developed and the efficiency of the LS-DYNA simulations. The inner rubber O ring compression is reduced by the plastic strains in the cask's bottom port area, leading to a loose inner radial seal, as shown by the calculations. But the outer seal remains leak-tight, ensuring so the mockup cask tightness. The physical test results have also confirmed that the mockup cask remains leak-tight.

Keywords

cask, leak-tightness, tests, numerical simulation, sealing assembly, strain, seal

Introduction

To design a new cask for transportation of irradiated nuclear fuel, the developers are guided by respective safety regulations (NP-053-16, SSR-6, GOST R 51964-2002, PBYa-06-09-2016, SanPiN 2.6.1.1281-03, SP 2.6.1.2612 10, GOST 9833-73). The ways and methods to justify safety of the new cask structure are strictly regulated and may include both experiments and calculations. They aim to describe how the cask structure and content will behave during routine, normal, and accident conditions of transport.

One of the cask structural safety indicators is that its leak-tightness is maintained, which is achieved by preserving the cask body integrity and the leak-tightness of the cask's detachable joints. When justifying the cask structural safety by calculations, one can find out if the detachable joints are leak-tight from the results of analyzing the strain of the detachable joint parts and the state of the sealing components (gaskets, seals, etc.), primarily in accidents, such as

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a drop onto a rigid surface from a regulatory height, a drop on a vertical bar, or a fire (NP-053-16, SSR-6).

The adequacy of such approach to justifying the cask leak-tightness can be proved by full-scale simulations using scale mockups (GOST 9833-73) of the cask under development or a part of it with the sealing assembly of interest.

This paper presents results of computational and experimental studies into the strain and leak-tightness of the cask bottom penetration sealing assembly which is a plug with a radial seal during the drop tests with the mockup cask dropped on a vertical bar from a height of 1 m.

Target

This cask for shipping the nuclear reactor irradiated fuel elements has a cylindrical penetration in its bottom to facilitate withdrawal of the cask content by pushing it through the upper throat and water drainage when drying the full cask (Fig. 1). The penetration is sealed with a special plug and two rubber O-rings (radial seal), which must fit the plug slots, as shown in Fig. 1. Distance *S* between the surfaces that compress the sealing components is a priori smaller than the cross-section diameter of the O-rings.

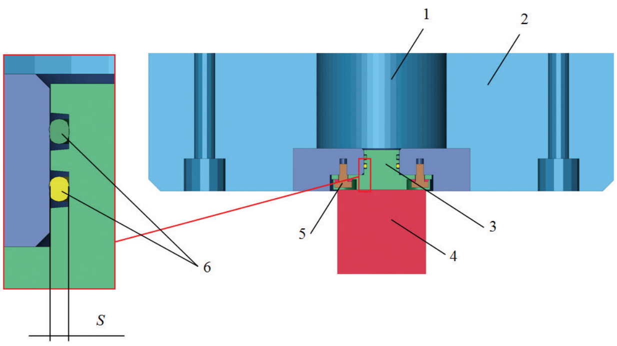

Figure 1. Design of the cask bottom with the sealing plug during drop tests with the cask dropped on a vertical bar from a height of 1 m: 1 – cask inner space; 2 – cask bottom; 3 – plug; 4 – bar; 5 – plug to cask bottom attachment; 6 – rubber O-rings.

A strain to components of the cask bottom penetration sealing assembly can cause distance *S* to increase, this resulting in a smaller rubber O-ring compression in the radial seal and in the cask leak-tightness being lost.

The most dangerous strains to the cask's sealing assembly components are likely to occur as the result of accidents in the process of transportation simulated specifically, as defined in regulatory documents NP-053-16 and SSR-6, by dropping the cask with its bottom hitting a bar (Fig. 1).

A strain to the cask bottom penetration sealing assembly was simulated by a numerical method using a multipurpose code, LS-DYNA. To verify the obtained results, numerical and full-scale simulations were undertaken with a 1/2.5 scale cask mockup dropped on a vertical bar of the diameter 60 mm from a height of 1 m.

The mockup cask for numerical and full-scale simulations is a steel cylinder with a diameter of 316 mm, a length of 2197 mm, and a weight of 1217 kg. Its inner space is filled with helium and sealed at the bottom with a plug and a radial seal (two O-rings of standard size 020-024-25-2 (GOST 9833-73) made of rubber mix under TU 2531-002-2894 3826-009. The cask bottom and the plug are made of 12Cr18Ni10Ti steel (GOST 5632-2014). The plug is attached to the cask bottom with eight M6 bolts of 14Cr17Ni2-grade steel (GOST 5632-2014).

The seal leak-tightness is controlled by the mass spectrometer method (GOST R 50.05.01-2018) based on the helium pressure drop rate inside the mockup cask; it amounts to $3.9 \cdot 10^{-7}$ Pa·m^3·s^{-1} in the initial (pre-test) state which is several times smaller than the allowable value of $1 \cdot 10^{-6}$ Pa·m^3·s^{-1} adopted for the design.

The cask mockup and bar collision was simulated numerically using a code for analyzing highly linear dynamic processes in solid body mechanics problems, ANSYS LS-DYNA (LS-DYNA Software, Software Certificate No. 394, 2016). The LS-DYNA is a multipurpose code designed to analyze a nonlinear dynamic response from 3D inelastic structures. The fully automated process for the contact problem solution and the set of functions for checking the obtained solution make it possible to solve complex impact, failure, form change and other problems.

The simulation of the cask mockup collision on a vertical bar involved several stages:

- make a geometrical model suitable for problem solving with the use of the finite element method;
- break down the model into a finite element mesh;
- apply boundary conditions to the model (impose displacement constraints, define boundary conditions);
- the LS-DYNA solver numerically solves the system of equations in an automatic manner;
- analyze the results.

The 3D geometrical model of the mockup cask was made in accordance with the cask design documentation. The finite element mesh was built with a built-in mesh generator of the ANSYS code's Workbench pre-postprocessor (Barulina MA 2012). A hexahedral Lagrange mesh was used, and the total number of elements in the computational model was nearly 2 million.

The numerical simulation of the mockup cask collision on a vertical bar used the following assumptions:

1. The contact interaction of deformable and rigid bodies was simulated based on the condition that there was no penetration on the agreed meshes with regard for the arising friction forces.
2. The structure's fasteners were simulated by solid elements which allowed defining the loads on each of the bolts and to simulate its potential failure.
3. Welded joints, as specified in Physical Properties of Steels and Alloys Used in the Power Industry (1967), were assumed to be as strong as the parent material and were realized in the computational model in the form of contacts without the potential for separation.

4. The vertical bar's flat base was simulated by a rigid member (Rigid Wall) (LS-DYNA Software).
5. A multilinear model based on deformation curves in accordance with Bankina et al. 2000 and reference data in accordance with PNAE G-7-002-86, Physical Properties of Steels and Alloys Used in the Power Industry 1967), Khoroshkina et al. 1982 was used as the base model for the structural material behavior.
6. No kinematic hardening in the materials model was taken into account conservatively due to the small velocity at the time of the structure's collision on the obstacle.
7. For fasteners, a material failure model was used based on the pre-failure strain limits in accordance with PNAE G-7-002-86 and suggesting the complete removal of the elementary module linked with the finite element as the failure criterion is reached.

To take into account the own weight of all computational model parts when simulating the mockup cask drop on a bar, all nodes in the finite element mesh were in the gravity acceleration field. As the initial condition, all cask model nodes were assigned initial rate V_0 at the time the collision with the bar starts ($t_0 = 0$), which is computed from the energy conservation law:

$$V_0 = (2 \cdot g \cdot h)^{1/2} \approx 4.43 \text{ m/s}, \quad (1)$$

where $g = 9.806$ m/s^2 is the gravity acceleration; and $h = 1$ m is the height of the drop on the bar.

The stress-strained state of the computational model was analyzed as of the time the cask starts to bounce off the bar surface.

A dedicated bench (Fig. 2) was used for the full-scale simulation of the cask mockup drop on the bar. The mockup cask was suspended inside a frame-type pile installed on a base of 20t reinforced concrete plates, on which the bar was also installed. The bar was made of St.3 steel (GOST 380-2005). The pre-test height of the bar (without the support) was 200 mm. During the drop testing, the mockup cask was aligned against the bar using guides, along which it slid as it was dropped on the bar. A shock ICP-accelerometer of the 350C04 type (Accelerometers Series 350) was installed on the mockup cask body to measure the acceleration (overload) during the tests.

Figure 2. Test bench with the mockup cask: 1 – mockup cask; 2 – pile; 3 – pit; 4 – bar; 5 – plate.

Numerical and full-scale simulation results

The numerical simulation results have agreed satisfactorily with full-scale simulation results.

Fig. 3 shows how the mockup cask vertical overload change starts when the sealing assembly touches the bar surface measured by the accelerometer and obtained computationally, and smoothed by the moving average method. The acceptable fit for the calculated and experimental overload data confirms the reliability of the computer simulation.

Fig. 4 presents the overall pattern obtained from computer simulations for the mockup cask sealing assembly deformation at the time the mockup cask bounces off the bar surface. As the result of the impact on the bar, the bottom surface, on which the plug rests, displaces by 8.5 mm towards the cask inner space. The bottom penetration in the form of a cylindrical hole with a diameter of 24 mm prior to the deformation, into which the plug is inserted, is deformed taking the form of a truncated cone with the base diameters of 23.92 mm (on the cask bottom outside) and 28.92 mm (on the cask bottom inside). There is no plastic strain on the plug's side surface with two circular slots for the O-ring installation and retention.

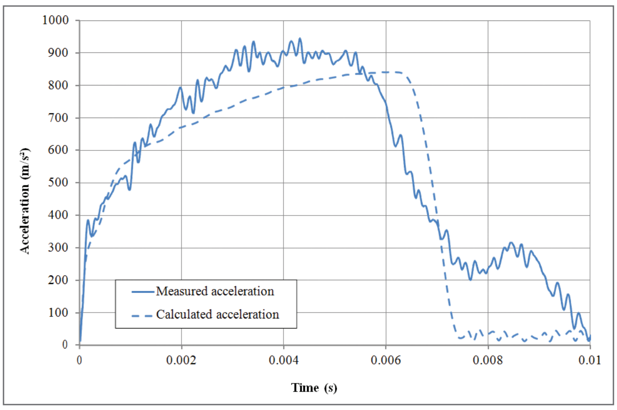

Figure 3. Diagrams of the mockup mass center acceleration (overload) change in the mechanical impact process when dropped on the bar.

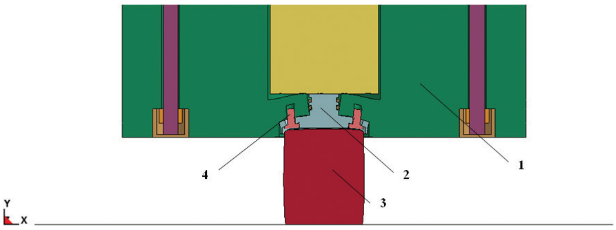

Figure 4. Package scale mockup model at the time of bouncing off the bar: 1 – cask bottom; 2 – plug; 3 – bar; 4 – plug to cask bottom attachment.

Therefore, the coned shape of the bottom penetration that results from the mockup cask impact on the bar leads to a reduction in the rubber O-ring compression forces expected to lead, in turn, to the loss of the mockup cask integrity.

Fig. 5 presents diagrams of changes in the O-ring thickness and distance S between the surfaces that compress the O-rings (Fig. 1) in the process of the mockup cask collision on the bar. The leak-tightness conditions for these radial seals shall meet the following requirements:

- distance S shall be smaller than the rubber O-ring cross-section diameter in a free state (equal to 2.5 ± 0.1 mm);
- the rubber O-ring thickness in the radial (horizontal) direction shall be a priori smaller than its cross-section diameter in a free state;
- the rubber O-ring thickness in the radial direction shall be equal to distance S.

The figure demonstrates that the internal seal has fully lost its leak-tightness since the penetration surface does not exert any pressure on the O-ring. The gap between the O-ring and the sealing surfaces is ~0.6 mm, while the external gasket (as the calculation results show) is expected to remain leak-tight since the three above-mentioned criteria are fulfilled.

This conclusion obtained as the result of the computer simulation was confirmed experimentally by measuring the helium pressure drop rate inside the mockup cask after the drop tests. The helium pressure drop rate was $3.9 \cdot 10^{-7}$ $Pa \cdot m^3 \cdot s^{-1}$, which coincides with the pre-test pressure drop rate and indicates that the mockup cask remains leak tight.

After the mockup cask drop tests, the cask bottom penetration sealing assembly was dismantled, and the dimensions of the plug components (Fig. 6a) and the penetration (Fig. 6b) affecting the cask leak-tightness were measured.

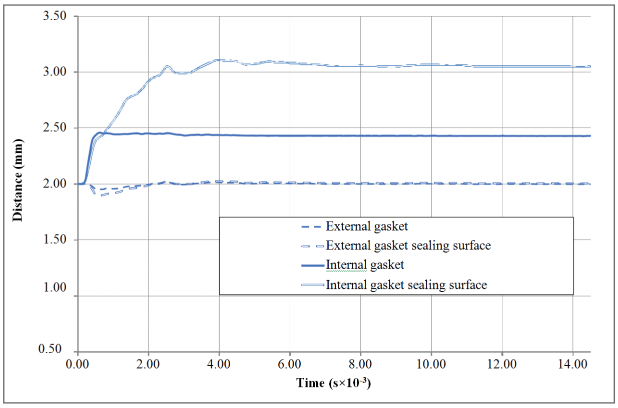

Figure 5. Change in the O-ring seal thicknesses and the distances between the surfaces that compress the O-rings in the process of the mechanical impact on the mockup.

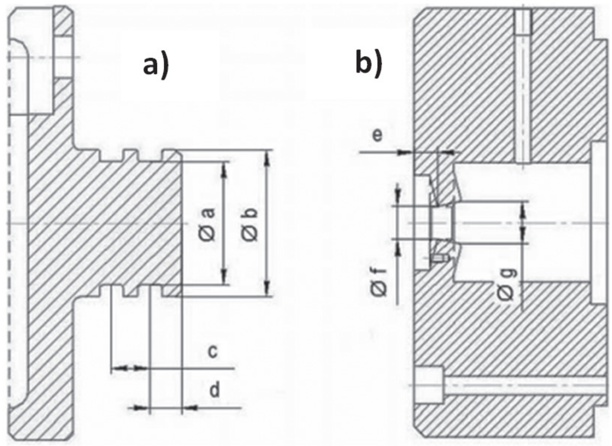

Figure 6. Designations of the dimensions for the penetration plug side surface responsible for the O-ring seal retention and the mockup bottom components.

An analysis of the data in the Table 1 shows a satisfactory description of the deformation process for components of the cask mockup sealing assembly using a numerical experiment (computer simulation). The maximum discrepancy between the calculated and experimental data on the strain to the sealing assembly components was 16%, and the discrepancy in the diameters of the penetration in the cask mockup bottom, which affect directly the leak-tightness, was 0.1% (dimension f) and 2.2% (dimension g). The calculated values of the penetration strain leading to a reduction in the O-ring compression

Table 1. Typical dimensions of the mockup cask end components after the drop on the bar from a height of 1 m obtained from the calculation and tests

Dimension as in Fig. 6a and Fig. 6b	Dimension value before testing (mm)	Experiment		Calculation		Relative deviation of calculated value from dimension value after testing (%)
		Dimension value after testing (mm)	Change in value after testing(mm)	Dimension value before testing (mm)	Change in value after testing (mm)	
(a)	20.3	20.3	0.00	20.3	0.00	0
(b)	23.8	23.82	+0.02	23.92	+0.12	0.42
(c)	6.0	6.0	0.00	6.0	0.00	0
(d)	5.0	5.0	0.00	5.0	0.00	0
(e)	11.0	16.8	+5.80	19.52	+8.52	16.19
(f)	24.0	23.9	-0.10	23.92	-0.08	0.08
(g)	24.0	28.3	+4.30	28.92	+4.92	2.19

forces exceed the experimental data, which demonstrates that the obtained calculation results are conservative.

Conclusions

The ANSYS LS-DYNA code was used to simulate numerically the drop of a spent nuclear fuel cask mockup on a vertical bar from a height of 1 m. Specifically, the collision of the mockup cask penetration sealing assembly on the bar was simulated, which is the most dangerous event during drop tests leading potentially to the loss of the cask pressure.

To verify adequacy of the numerical model and the drop test computer simulation results, a mockup cask was manufactured with the sealing assembly under study. The full-scale tests included the mockup cask dropping on a vertical bar from a height of 1 m with its sealing assembly hitting the bar. The comparison between the calculated and experimental data resulted in the following conclusions:

1. The proximity of the mockup cask simulation and full-scale test results confirm the reliability of the numerical calculations based on a computational model of the cask mockup with a dimensionality of about 2 million finite elements.
2. Computer calculations showed that the dynamic deformation of the mockup cask sealing assembly during its drop on the bar results in plastic strains on the mockup bottom close to the penetration, which causes the internal radial seal to lose its leak-tightness, but the external seal remains leak tight and ensures the mockup cask leak-tightness. The full-scale tests confirmed the conclusions on the leak-tightness of the internal and external radial seals and the mockup cask.

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