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NUMERICAL STRESS ANALYSIS OF SPENT NUCLEAR FUEL TRANSPORT PACKAGE IN NORMAL AND ACCIDENT CONDITIONS

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Abstract

Russian Federal Nuclear Center – VNIIEF has designed a package for transportation of the cartridges with bundles of spent fuel elements. The paper presents the results of application of 3D numerical simulation technology to prove the ability of the package to withstand the normal condition of transport and the hypothetical accident conditions. The detailed finite element model is developed to carry out the analysis. 23 loading cases, including combinations of different loads, are investigated. The comparison of the numerical results to the experimental data, obtained using full-scale model of the package, shows high accuracy of the numerical analysis. The computer simulations are performed using highly parallel computer code LOGOS («STRENGTH» module), developed by Russian Federal Nuclear Center - VNIIEF.

Introduction

Since 1990s, one of the fields of activity of Russian Federal Nuclear Center – VNIIEF is developing of spent fuel transport packages. At present time RFNC-VNIIEF develop a family of transport packages, including TUK-109T – the package for transportation and temporary storage of RBMK-1000 spent fuel. A batch of TUK-109T packages is produced for transportation of Kurskaya APP spent fuel.

The problem of safe spent nuclear fuel transport is important and experts from all over the world work on it [1÷10]. One of the most important tasks of the package developing is ensuring of the package's containment in accidental conditions in accordance with domestic [11] and international [12] requirements. The type B packages must resist consecutive 9 m drop onto hard surface and puncture (1 m drop onto a pin).

The spent fuel transport packages usually have quite complex design and large size and mass. Because of this, manufacturing and testing of the package's models are quite expensive and time consuming. Application of the up-to-date numerical simulation codes and supercomputer technologies allows obtaining fast and accurate prediction of the structure behavior under different kinds of loadings and, therefore decreasing expenses on package testing by using only one final test instead of series of tests.

The paper presents some of the results of TUK-109T package stress analysis in normal condition of transport and hypothetical accident conditions. High accuracy of numerical simulation is confirmed by comparing of the calculations results with experimental data, obtained later using full-scale model of TUK-109T.

Calculations are carried out using Russian CAE code LOGOS (module STRENGTH) developed by RFNC-VNIIEF [13-16].

The TUK-109T package description

The construction of the package is shown in Figure 1. The height of the package is 5635 mm. The container case is a multilayer cylindrical shell with outer diameter of 2420 mm. Between the inner and the outer steel shells there are solid steel radiation protection rings and neutron protection blocks (aluminum rings, which cavities filled with polypropylene). Top and bottom ends of the inner and the outer shells are welded to the coamings. In the bottom section there is a flat thick-walled bottom plate welded to the bottom coaming. In the top section the container is closed by means of two lids. The inner lead is fixed to coaming with a ring by means of 36 M48 studs. The outer lid is attached to the coaming with 24 M36 studs.

The polypropylene blocks of neutral shielding are also installed on the bottom plate and the inner lid. The package has two shock absorbers installed at the bottom of construction and at the outer lid. They consist of sets of alternating vertical flat plates of different heights welded to cylindrical skirt. The purpose of the longitudinal fins, which are welded to the outer shell of the package, is to increase the heat dissipation. They are used as side limiters as well.

The basket with the cartridges with bundles of spent fuel elements is installed inside the container. The basket consists of set of tubes of different diameter, which are connected via spacing disks.

The total weight of the loaded TUK-109T package is about 106 tons [17].

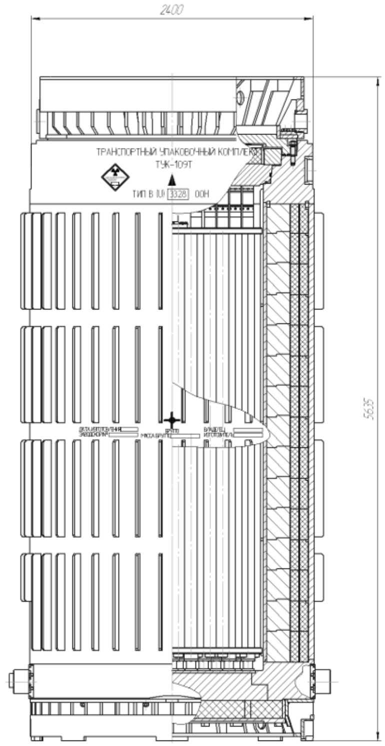


Figure 1 TUK-109T package scheme

Description of computer code LOGOS («STRENGTH» module)

Russian multifunctional computer code LOGOS [13] is intended to 3D-simulation of coupled problems of fluid dynamics, heat transfer, static and dynamic strength and failure of structures using parallel computer cluster systems. One of the main components of the code is the «STRENGTH» module, based on algorithms from finite element code LEGAK-DK [14-16]. Among other, the «STRENGTH» module is intended for simulation of the dynamic deformation and failure of structures. The code is based on the finite element method in Lagrangian, Eulerian and ALE formulations using an unstructured computational grid.

The spatial discretization is achieved by the use of fully integrated and one integration point 2D and 3D solid, shell and beam elements. The following boundary and loading conditions are supported: pressure, concentrated and distributed loads, rotational and/or translational boundary constraints, sliding plane, prescribed velocities, initial temperature, flow, convection, etc.

LEGAK-DK capabilities allow effective simulating of such processes as the dynamic deformation and thermal resistance of the spent nuclear fuel packages.

The computer model

Detailed 3-D computer model of TUK-109T construction is created for the numerical simulation. The model is represented in Figures 2 and 3. The following features, which are essentially important for the package stress analysis, are allowed for in the model:

- dynamic elastic-plastic deformation of load-bearing elements of the package, including threaded fasteners;
- nonstationary contact interaction between the package elements with friction;
- deformation of the package lids' joints;
- the main package's welds configuration;
- deformation of the impact limiters;
- relative displacement of the of the cartridges with spent fuel.

The computer model consists of about 6,000,000 finite elements, both solid and shell type. The shell elements are used for the basket's tubes only. The size of the finite elements is chosen after preliminary mesh convergence investigations. The fragments of the package finite element model are shown in Figure 4.

Dynamic deformation of the package elements is modeled using mechanics of continua governing equations and theory of plasticity with kinematic hardening. The coefficient of friction $f = 0.2$ is used for all the contact pairs. The gravity is also allowed for in the simulation.

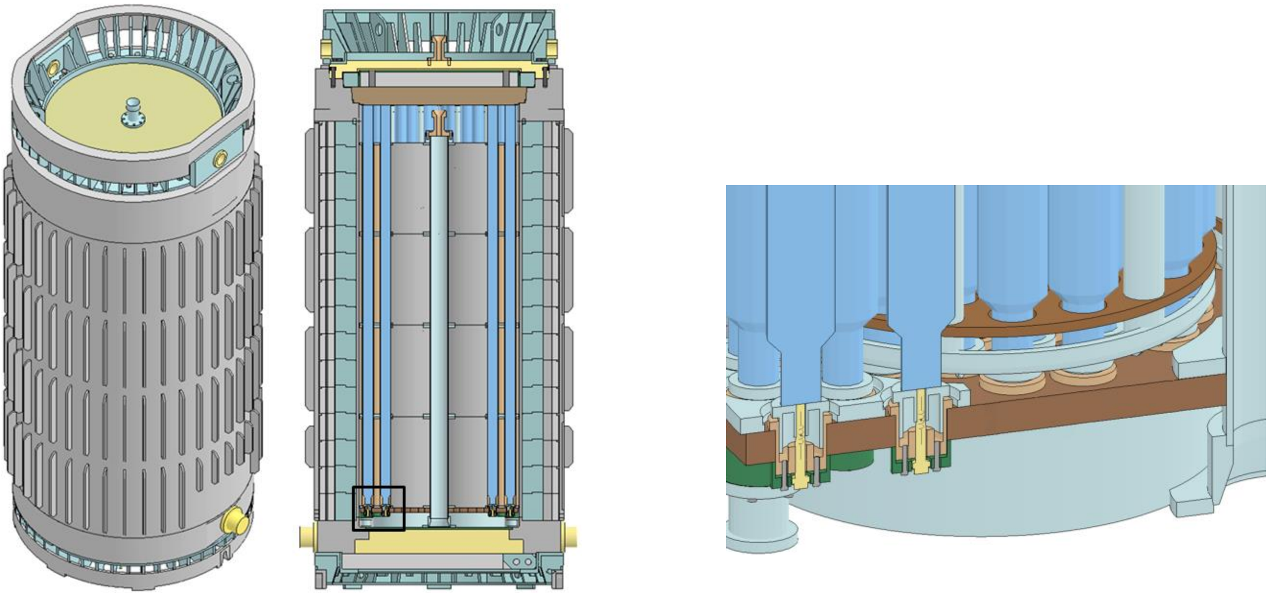


Figure 2 TUK-109T package computer model

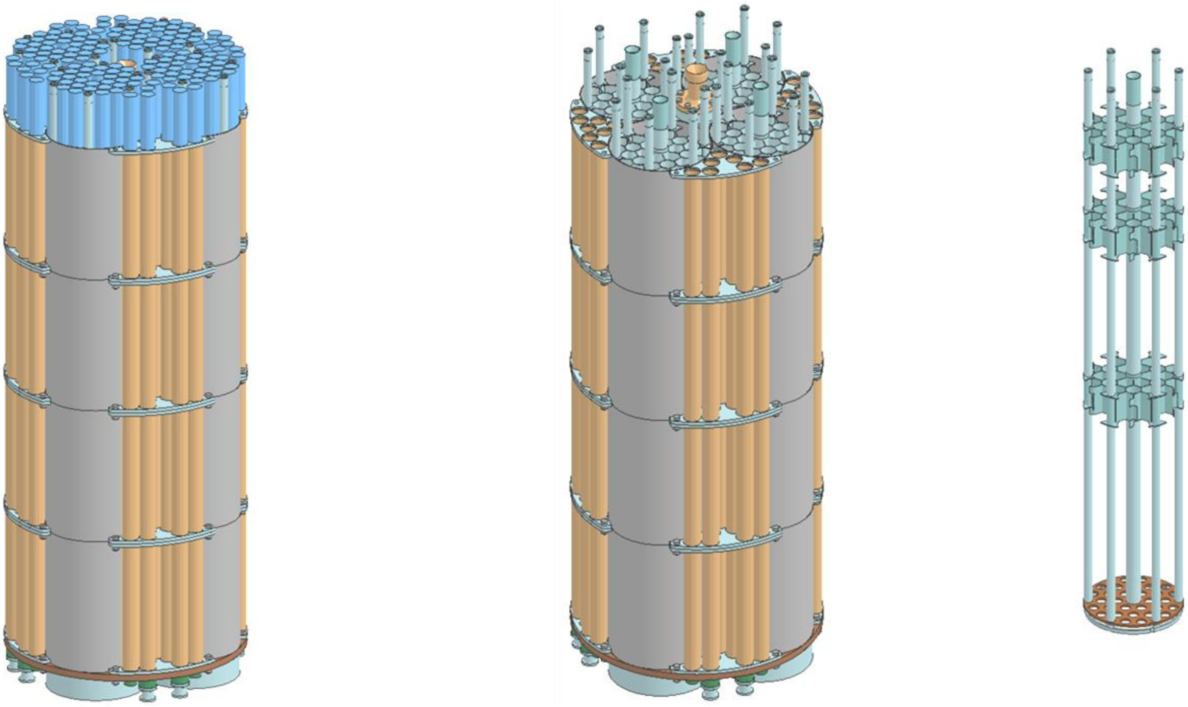


Figure 3 The computer model of the basket

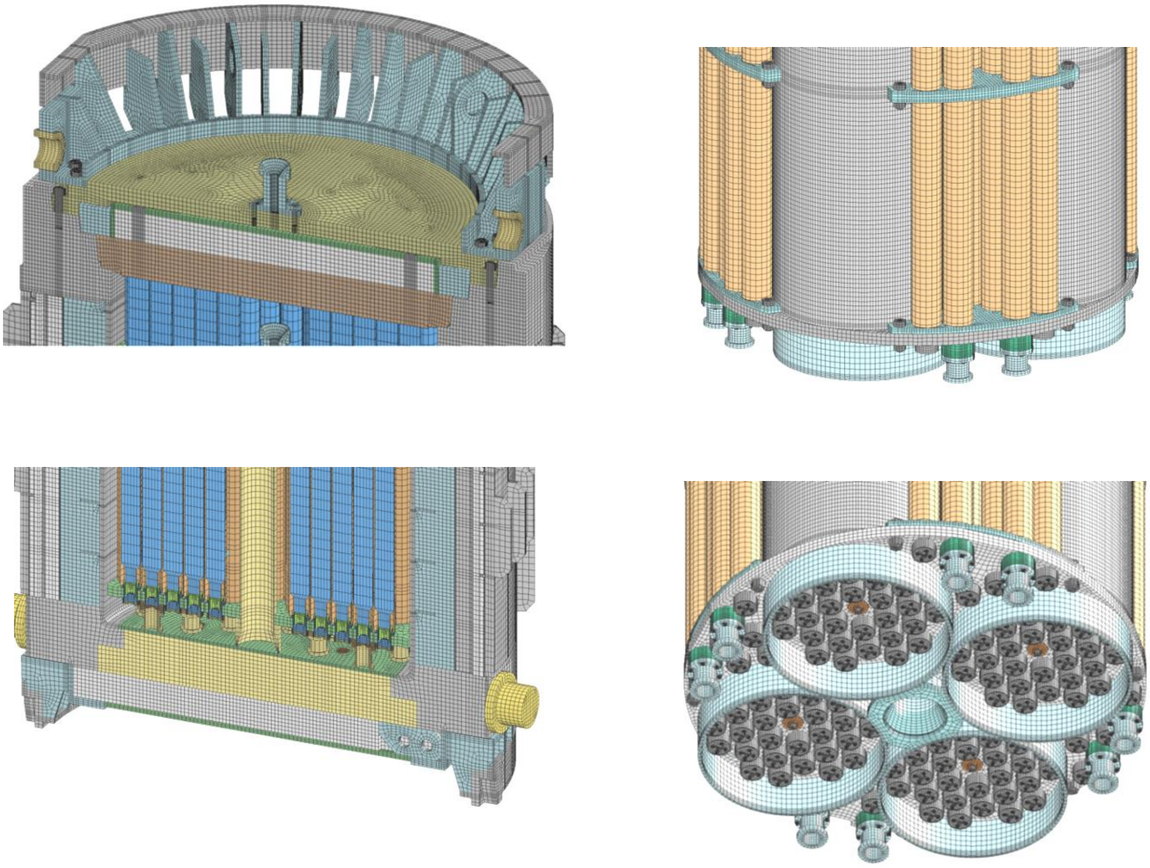


Figure 4 Fragments of the finite element mesh

Validation of the numerical simulations results

The full-scale model of the TUK-109T package was manufactured for the experimental investigations. The model was sequentially subjected to the following tests:

- 9 meters axial drop to the bottom;
- 9 meters side drop;
- puncture test (1meter side drop onto a pin).

The experimental results show that TUK-109T package successfully withstands the loads described above. In addition, the experimental data confirm the high accuracy of the numerical results, obtained before the tests. Comparison of the numerical and experimental data is presented below.

Figure 5 shows the calculated time history of the bottom impact limiter's height in 9 meters axial drop (blue solid line). The minimum calculated height of the limiter is 244 mm (about 67% of initial height). The residual calculated height of the limiter can be estimated as 280 mm. According to the experimental data, the residual height of the limiter after the 9 meter axial drop test was from 265 to 290 mm (red dotted lines on Figure 5). The relative difference between the calculated and the average experimental residual heights is about 1%.

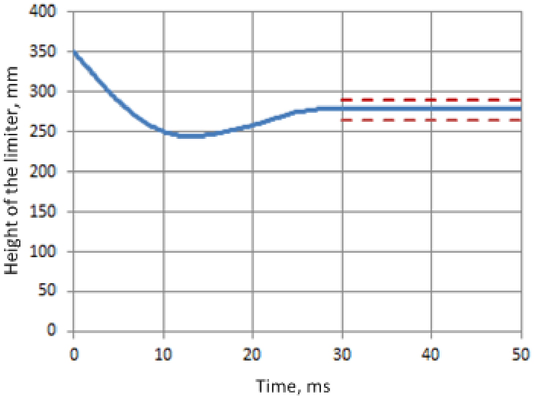


Figure 5 Height of the bottom limiter
(9 meters axial drop)

Figure 6 shows the deformed shape of the package after 1 meter side drop onto a pin. Time history of calculated depth of the dent in the outer shell is shown in Figure 7. Maximum calculated dent’s depth is about 100 mm (see blue solid line on Figure 7). The calculated residual dent’s depth can be estimated as 76 mm. The residual depth of the dent in the outer shell, measured in experiment, was about 75 мм. Therefore, the relative difference between the calculated and the experimental dent’s depths is about 1.3%.

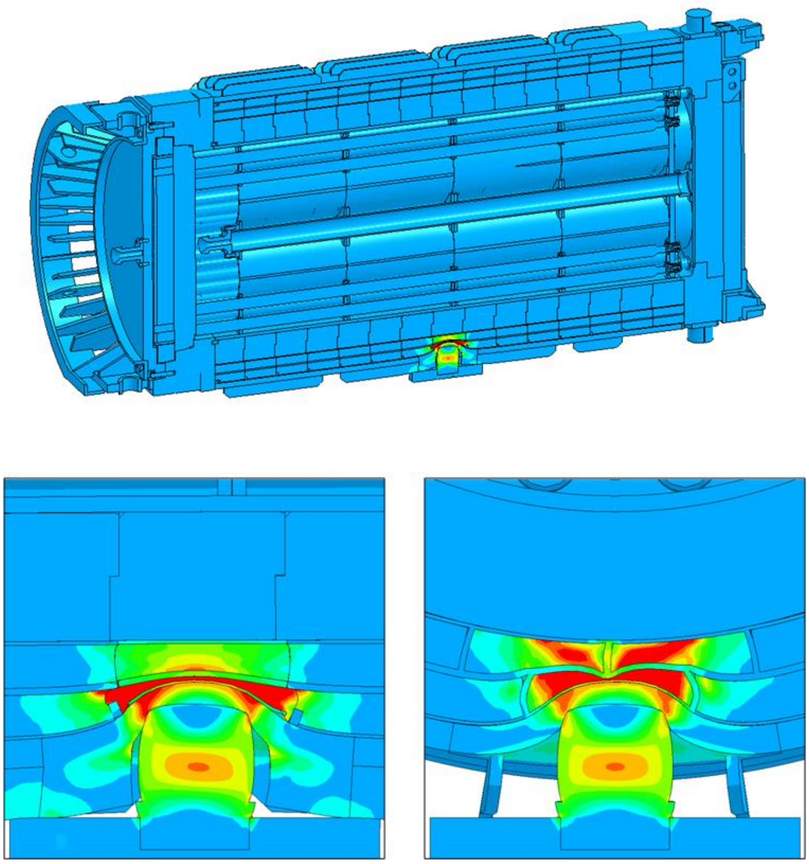


Figure 6 Deformed shape of TUK-109T package

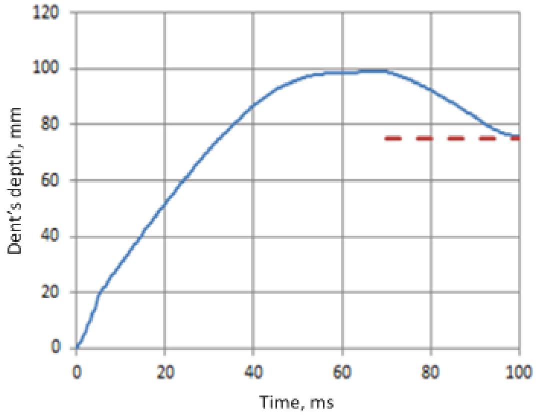


Figure 7 Depth of the dent in the outer shell

Figures 8, 14 and 22 show schemes of the accelerometers' disposition used in the experiments. Calculated (blue lines) and experimental (red lines) time histories of overloads of the accelerometers are presented in Figures 9…13, 15…20 and 23. It should be noted that some of the accelerometers failed during the experiments, so their data are not presented here.

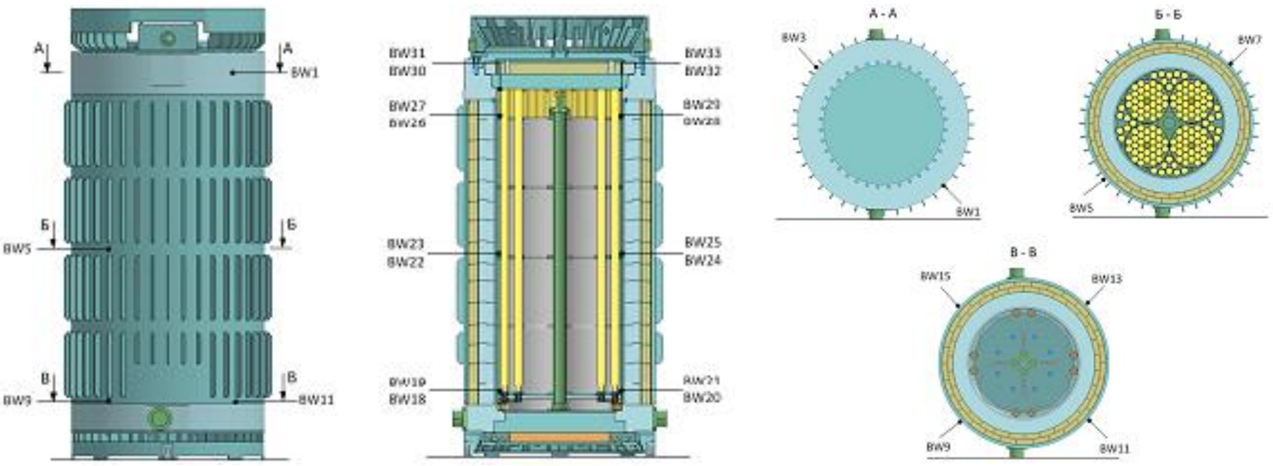


Figure 8 Scheme of the accelerometers' disposition

(9 meters axial drop to the bottom)

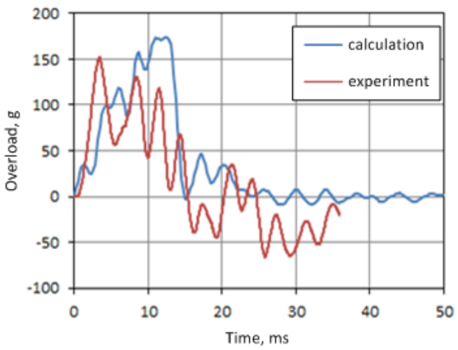


Figure 9 Vertical overload of the container. Accelerometer BW3

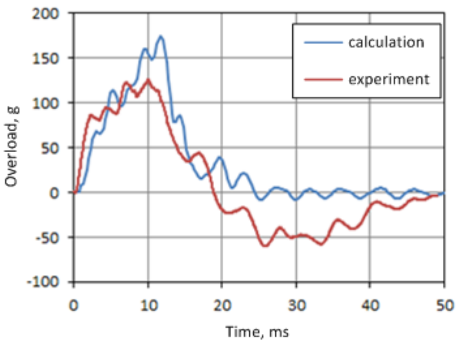


Figure 10 Vertical overload of the container. Accelerometer BW15

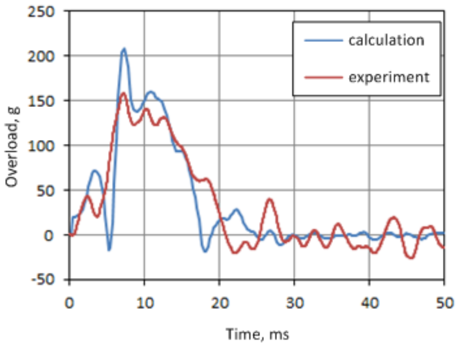


Figure 11 Vertical overload of the basket. Accelerometer BW18

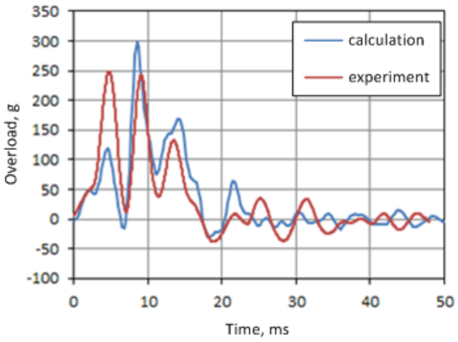


Figure 12 Vertical overload of the basket. Accelerometer BW26

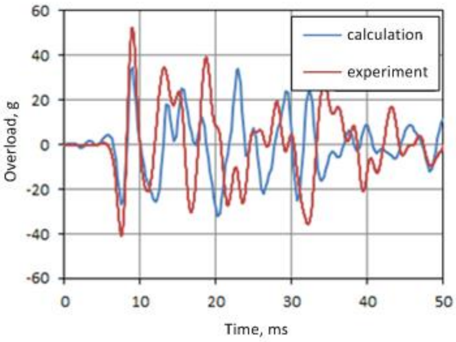


Figure 13 Horizontal overload of the basket. Accelerometer BW29

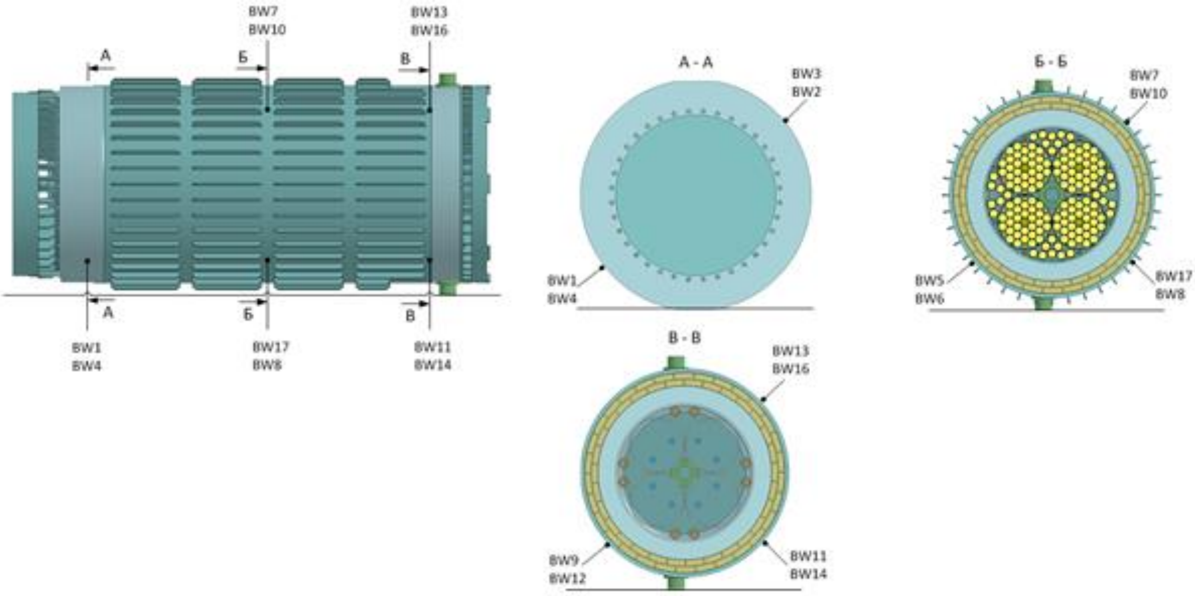
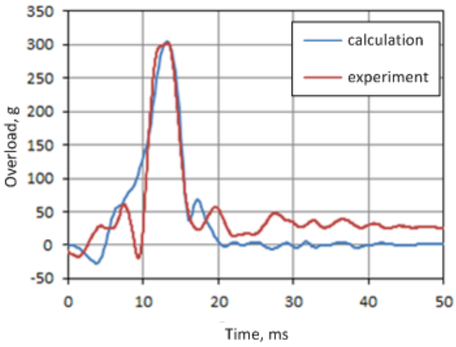


Figure 14 Scheme of the accelerometers' disposition

(9 meters side drop)



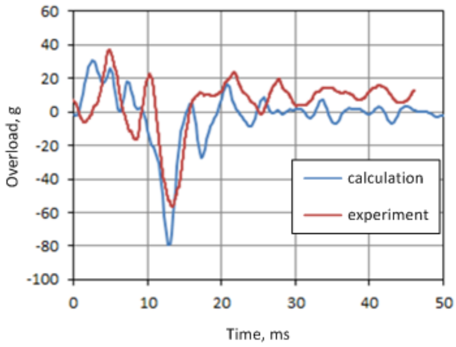
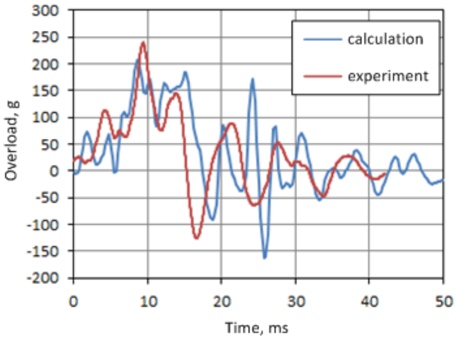


Figure 15 Vertical overload of the container. Accelerometer BW1

Figure 16 Vertical overload of the container. Accelerometer BW2



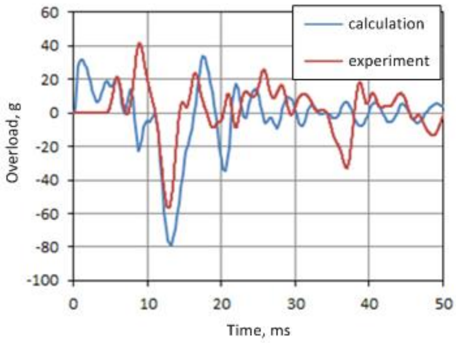
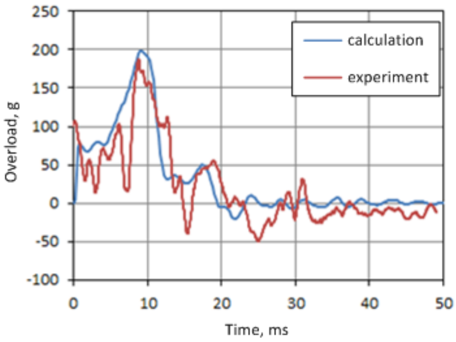


Figure 17 Vertical overload of the container. Accelerometer BW7

Figure 18 Horizontal overload of the container. Accelerometer BW16



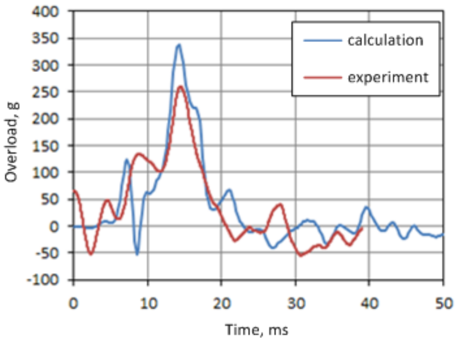


Figure 19 Vertical overload of the container. Accelerometer BW9

Figure 20 Vertical overload of the basket. Accelerometer BW23

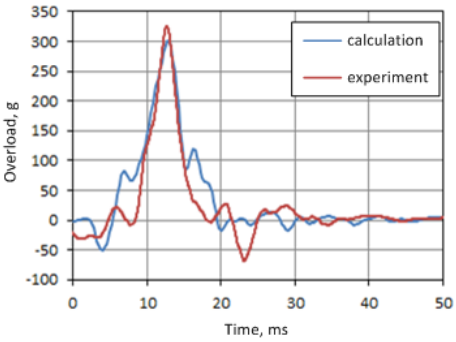


Figure 21 Vertical overload of the inner lid. Accelerometer BW31

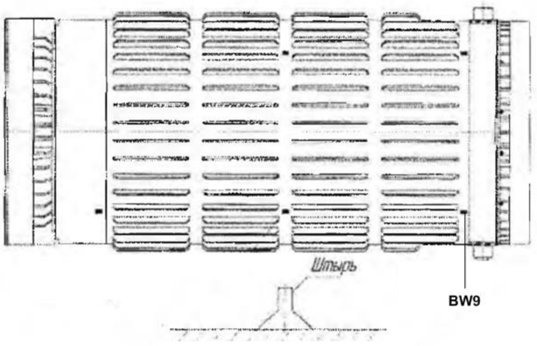


Figure 22 Position of accelerometer BW9
(1 meter side drop onto a pin)

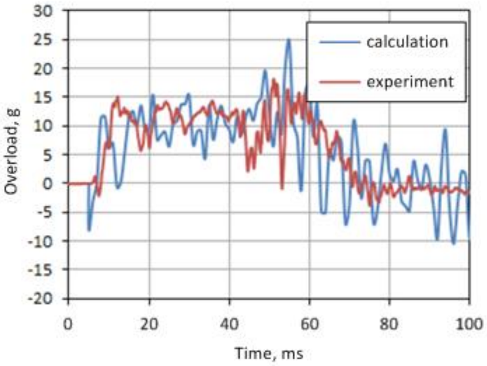


Figure 23 Vertical overload of the container. Accelerometer BW9

Comparison of the calculated and experimental data shows that there are in a good agreement.

The results of the calculations

Using the validated computer model of TUK-109T package, a number of calculations is carried out to prove that the package withstands the normal conditions of transport (NCT) requirements. The following load cases are considered:

- drop from the height of 0.3 m onto a hard surface. Axial, angle and side drops are considered (5 load cases);
- stacking. The package is compressed by the five times of it’s weight (1 load case);
- penetration resistance. The package is subjected to impact of 6 kg steel rod dropped from the height of 1 m. Impacts to the outer lid and the center of the outer shell are considered (2 load cases).

The results of the calculations show that in the normal conditions of transport all the load-bearing elements of TUK-109T package deforms elastically. The package withstands the considered NCT loadings with sufficient safety factors. The minimum value of the safety factor is S.F.=1.4 for the studs of the inner lid in the case of top axial drop from the height of 0.3 m.

The type B packages must resist consecutive 9 m drop onto a hard surface and puncture (1 m drop onto a pin) as hypothetical accident conditions (HAC). Because of this, model of TUK-109T package in initial (not deformed) state is used for 9 meters drops simulations. The deformed shape and stress and strain fields, obtained in 9 meters drops calculations, are used as initial conditions for the puncture (1 m drop onto a pin) simulations. In total, to prove that the package withstands the HAC requirements, 15 load cases are considered as follows:

- free drop from the height of 9 m onto a hard surface. 10 load cases are investigated: 2 axial drops, 3 corner drops and 5 side and close to side (at small angle) drops;

- puncture (1 m drop onto a pin). 4 scenarios of combined loading are investigated: 2 cases of puncture after 9 meters side drop and 2 cases of puncture after 9 meters top corner drop (see Figure 24);
- immerse to water at the depth of 15 m.

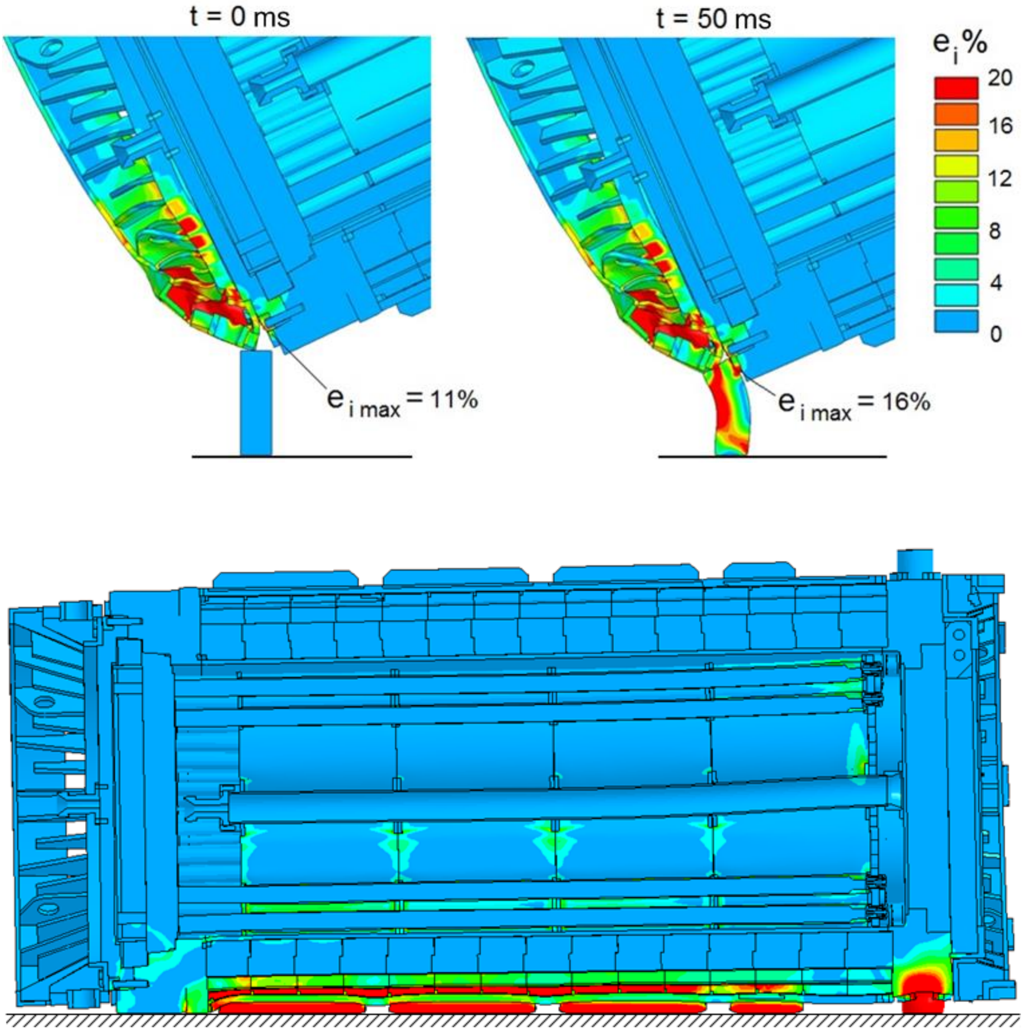


Figure 24 Numerical simulations results

The results of the TUK-109T package numerical simulations in HAC show that the package withstands the considered loadings. The load-bearing elements of TUK-109T package deforms plastically, but the maximum stress and strain levels not exceed the allowable values. The only damaged elements of the package are the impact limiters and their fasteners in the cases of 9 meters drops. Analysis of the gaps values in the inner and outer lids joints shows that they are small enough to conclude that the package keeps hermetic after HAC loadings. Mutual bracing of the cartridges with spent fuel is also obtained as the basic data for the criticality safety analysis.

Conclusions

1. TUK-109T package designed by RFNC-VNIIEF is used as example to show that up-to-date finite element codes are cost- and time-effective tools for modeling of spent nuclear fuel packages behavior under mechanical loadings.
2. Using Russian CAE code LOGOS (module STRENGTH) developed by RFNC-VNIIEF and detailed 3D finite element model of 6,000,000 finite elements, TUK-109T package behavior in normal and accident conditions of transport is investigated.
3. Comparison of the numerical and experimental data, obtained using full-scale model of TUK-109T, shows high accuracy of the calculations, which were carried out before the experiments.
4. 23 load cases, including combinations of different loads, are investigated to prove that TUK-109T package meets the normal and accident conditions of transport requirements.

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