The Protection of Containers for Fresh and Spent Fuel at External Transportation Operating Modes In and Around a Nuclear Reactor's Portal

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Abstract. The certified containers for fresh and spend fuel (further the containers) are able to survive dropping from a distance of 9 meters on a concrete table top. The goal of the paper is the substantiation of a new shock-absorbing gravel-sand cushion that is designed to be installed under a Nuclear Reactor's Portal. There are determined the physical and mechanical specifications and the dimensions of the new shock-absorbing gravel-sand cushion.

1. INTRODUCTION

In modern nuclear power plants during the loading and unloading operations in the area of a portal reactor compartment a lifting height of a container with fresh or spent fuel can reach up to 40 meters.

The security requirements [1, 2] for certified container with fresh and spent fuel are guaranteed for an arbitrary position of fall from a height of 9 m onto a rigid concrete barrier, i.e., the impact overload is guaranteed not to exceed the permissible values.

A container with spent fuel is a steel vertical cylinder with a base diameter D = 2060 mm, height H = 5500 mm, wall thickness of 350 mm and total weight Q = 1200 kN.

A container with fresh fuel is a welded steel structure, consisting of: base, shell, hexagonal tubes, grating and cover.

The study is devoted to justify the application of shock-absorbing properties of a stationary three-layer cushion asphalt-gravel-sand instead of a removable shock absorber at the containers falling from a height of H = 27.8 m.

Fig.1 shows a diagram of the stationary shock-absorbing cushion. Dynamic characteristics of materials [3, 4] composing the cushion are shown in the Table 1.

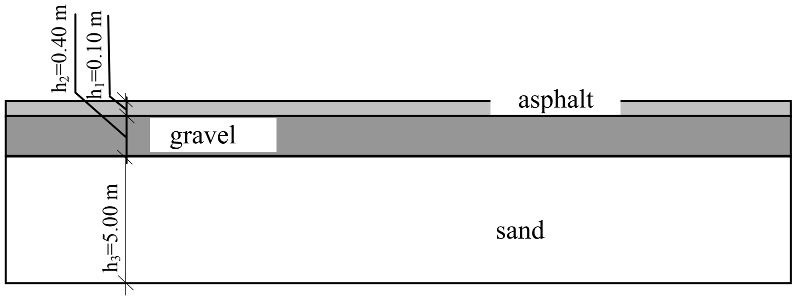


Fig. 1. Scheme of the stationary shock-absorbing cushion

Table 1. Dynamic behaviour of materials of the shock-absorbing cushion

Material	Density ρ (kN·s²/m⁴)	Modulus of deformation E (MPa)	Poisson ratio μ
asphalt	2.40	1000	0.30
gravel	2.00	300	0.32
sand	1.80	100	0.35

2. KINEMATIC ANALYSIS OF THE TRAJECTORY AT FALL OF THE CONTAINERS

A finite-element model of the container with spent fuel used for determination of kinematic parameters of its movement due to various failures is depicted in Fig. 2.

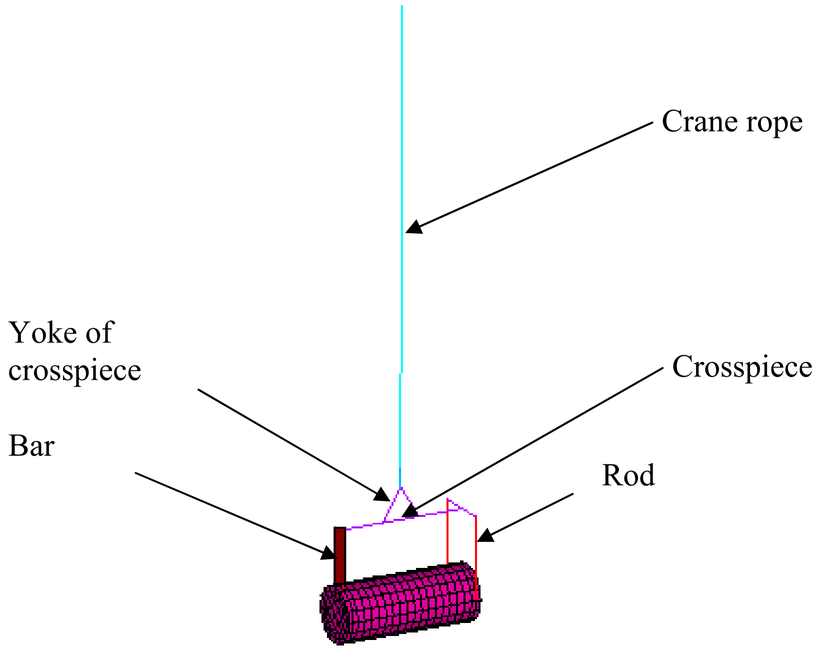


Fig. 2. General view of the finite-element model of the container with spent fuel

The model consists of volumetric, beam-type and slack cable elements. Volumetric elements were used to model the container's content; beam-type elements were used for modelling crosspiece, yoke and rods of crosspiece; slack cable elements were used to model the crane rope. Totally there are 1020 elements and 4756 nodes in the model.

The following failures of elements were considered in the course of study of kinematics of movement of the container:

(a) break of a crane rope when horizontal velocity of a trolley is zero;
(b) break of a crane rope when horizontal velocity of a trolley is 1 m/s;
(c) break of the bar and further break of two rods of the crosspiece when the container reaches its maximum horizontal velocity;
(d) break of two rods of the crosspiece and further break of the bar when the container reaches its maximum horizontal velocity;
(e) the break of a rod and the bar of the crosspiece and further break of the last rod when the container reaches its maximum horizontal velocity.

The plan of conceivable locations of the container on the surface of the cushion at the initial time of impact under the considered failures is depicted in Fig. 3.

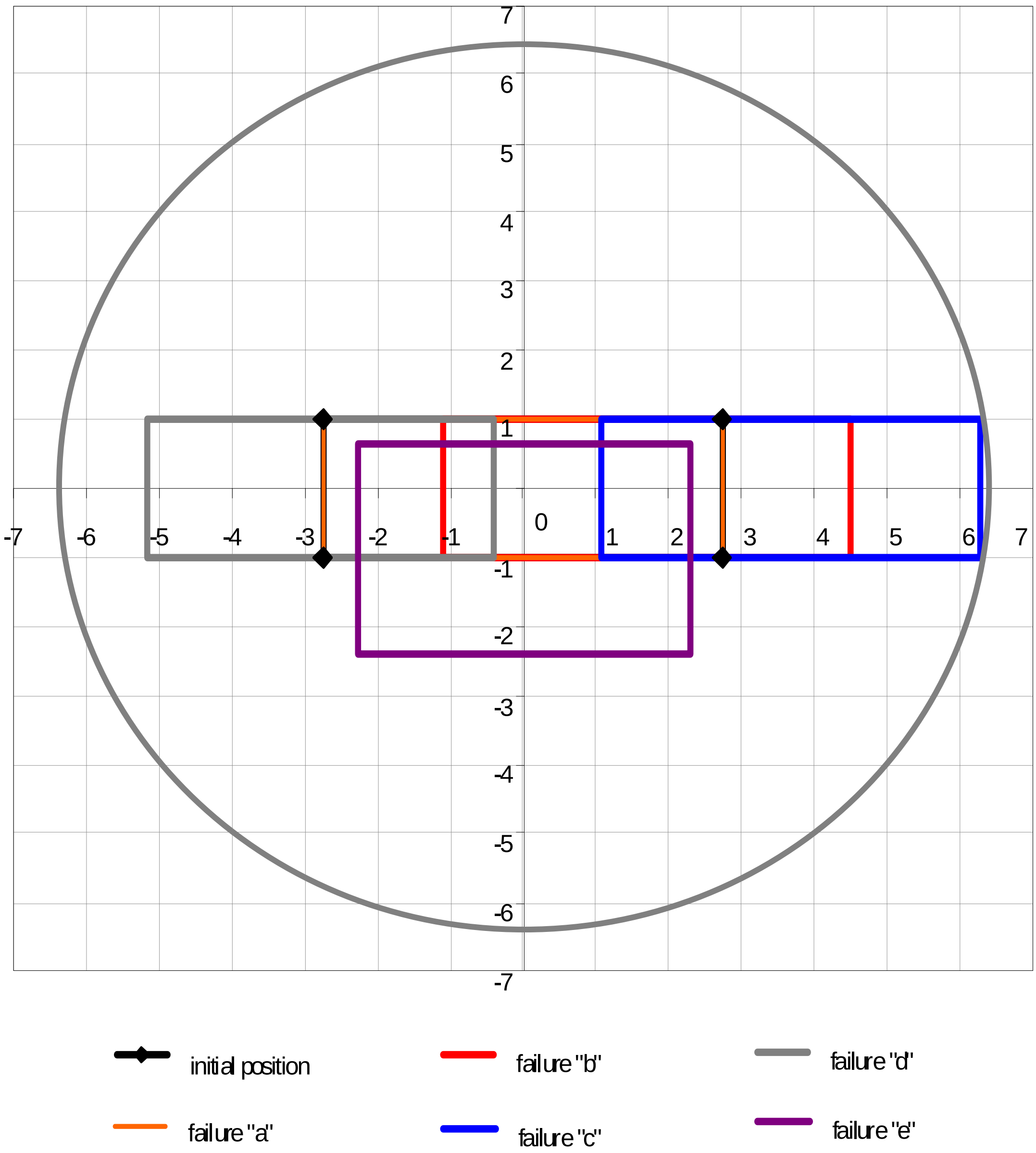


Fig. 3. Plan of conceivable locations of the container on the surface of the cushion under various failures. Radius of scatter is R=6.35 m

The finite-element model of the container with fresh fuel to determine the kinematic parameters of its motion due to various failures is shown in Fig. 4.

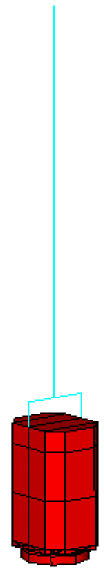


Fig. 4. General view of the finite-element model of the container with fresh fuel

The model consists of a bulk container, beam-type and slack cable elements. To simulate the container and its contents used three-dimensional elements, beam elements are used for simulation traverse, forks and traverse rods; slack cable elements used to model the cable crane. The total number of elements in the model is 178, the total number of nodes 1151.

The following failures were analysed in the course of study of kinematics of movement of the container:

a) break of a crane rope with horizontal speed of a trolley equals 1 m/s;
b) break of a crane rope with horizontal speed of a trolley equals 0;
c) break of a right rod of the crosspiece and further break of the left one.

Breaks of element were modelled by instantaneous change of rigidity of finite element in location of break from actual value down to zero.

The plan of conceivable locations of the container under the considered failures is depicted in Fig. 5.

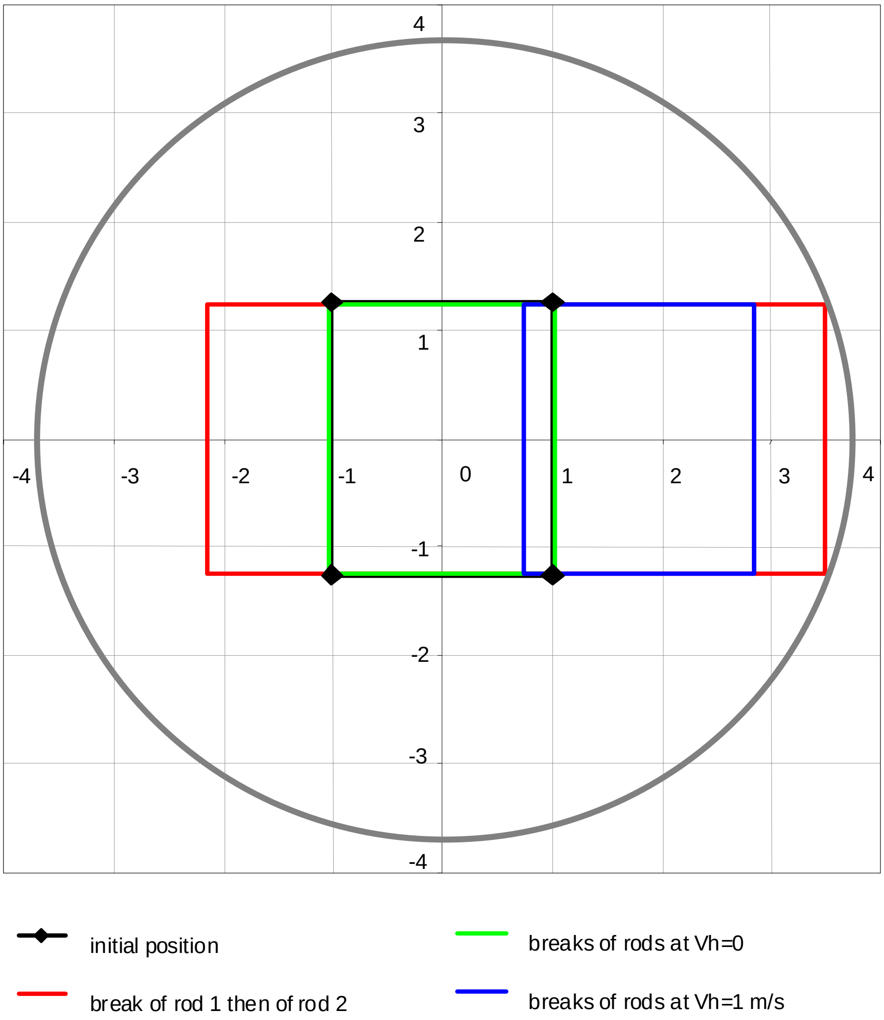


Fig. 5. Plan of conceivable locations of the container under various failures. Radius of scatter is R=3.7 m

It follows from the obtained results that the widest scatter in plan occurs when the container with spent fuel inside falls.

Thus, based on study of kinematic behaviour of the containers with spent and fresh fuel the size in plan of the stationary shock-absorbing cushion must be as big as 15.0 x 15.0 m.

3. DYNAMIC ANALYSIS OF THE CONTAINERS IMPACT AGAINST THE SHOCK-ABSORBING CUSHION

For dynamic analyses of the stationary shock-absorbing cushion with regard to various falls of the containers, relevant behavioural finite-element models of 'shock-absorbing cushion – the container with spent fuel' system and 'shock-absorbing cushion – the container with fresh fuel' system were prepared (Figs. 6 and 7).

A problem of impact of the containers against the shock-absorbing cushion is solved in geometrically and materially nonlinear formulations with destruction in the moment of ultimate strain. So the elastic-plastic model with kinematic hardening is used for modelling steel elements, asphalt and concrete; a Drucker-Prager model is used for modelling crushed stones and sand. The developed models number 9000 finite elements and 13000 nodes. Interaction between various elements of the model (the container against the cushion) is implemented through contact elements. The solution is carried out by explicit integration, that the most optimal for fast processes.

The following cases of fall of the containers with spent and fresh fuel (from a height of 27.8 m) onto the shock-absorbing cushion, consisting of layers of: asphalt (0.1 m), crushed stones (0.3 m) and sand (4.5 m), were considered in dynamic analyses:

— vertical drop of the containers,
— horizontal drop of the containers,
— fall of the containers at an angle of 30 ° to the vertical axis.

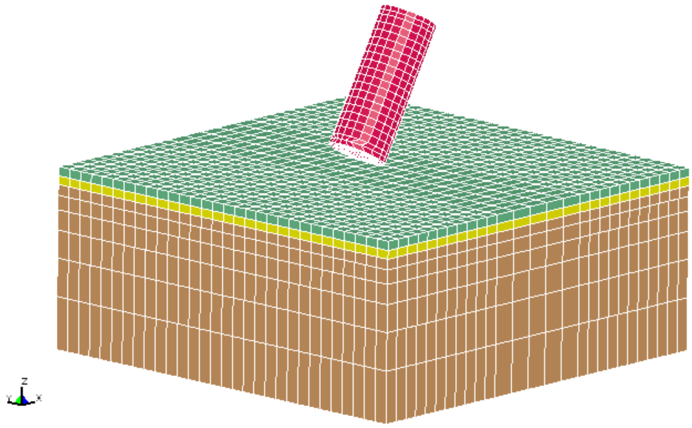


Fig. 6. General view of the finite-element model of 'shock-absorbing cushion – the container with spent fuel' system

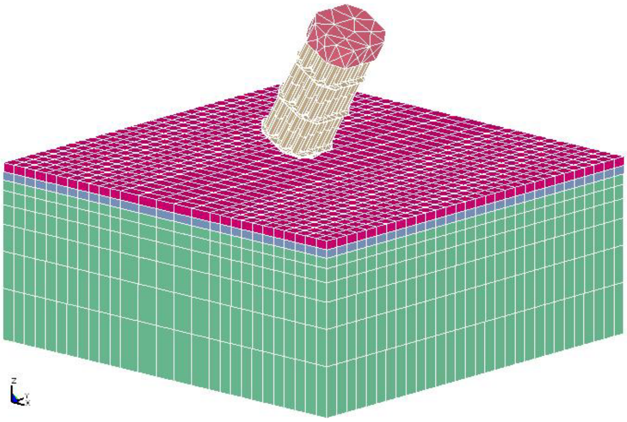
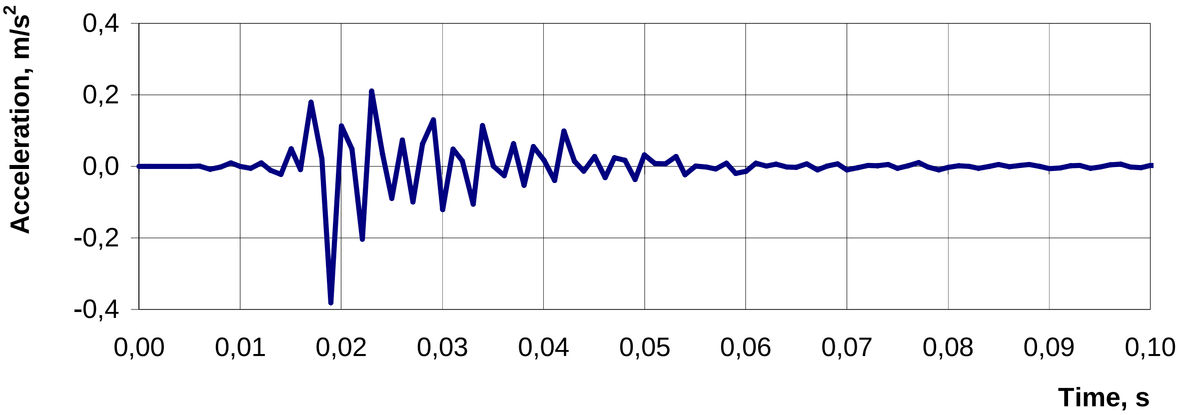
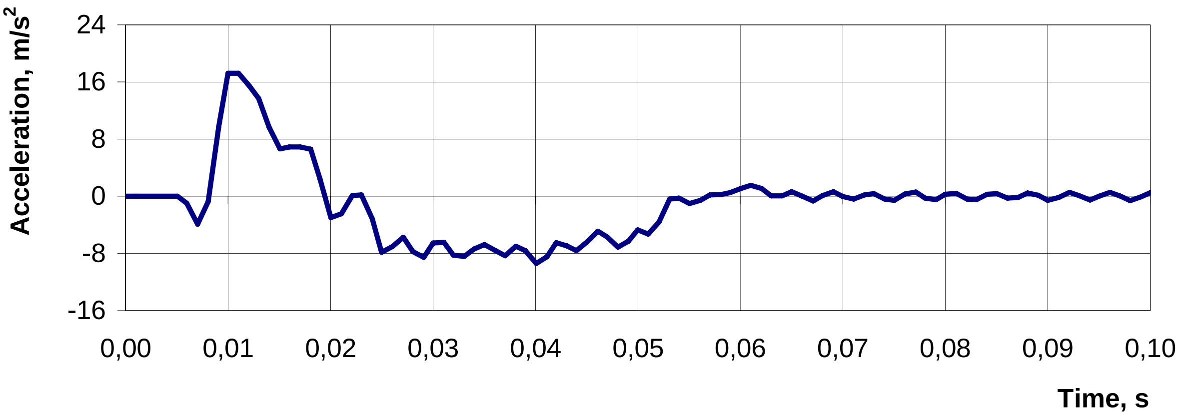


Fig. 7. General view of the finite-element model of 'shock-absorbing cushion – the container with fresh fuel ' system

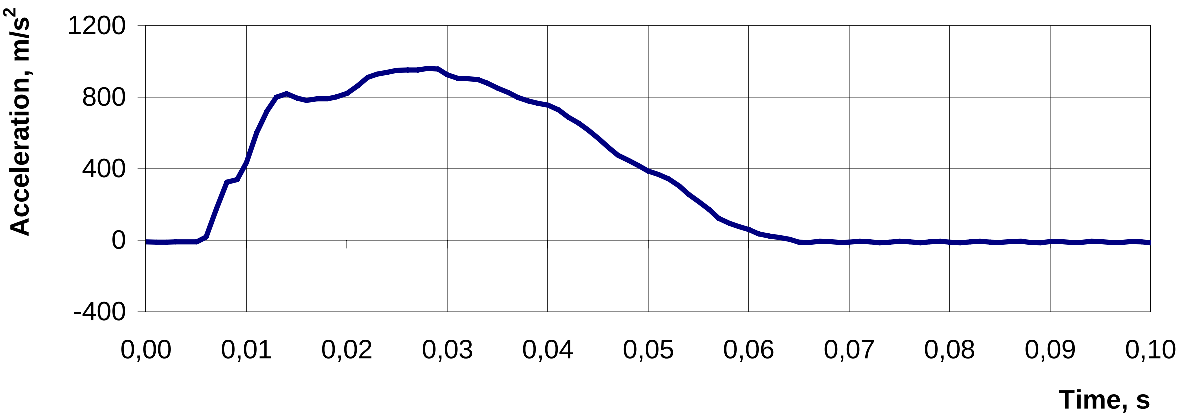
Figs. 8-13 show graphs of three-component impact accelerations of the containers with fresh and spent fuel in contact with the shock-absorbing cushion at different initial fall positions from a height of 27,8 m.



a) along horizontal axis x

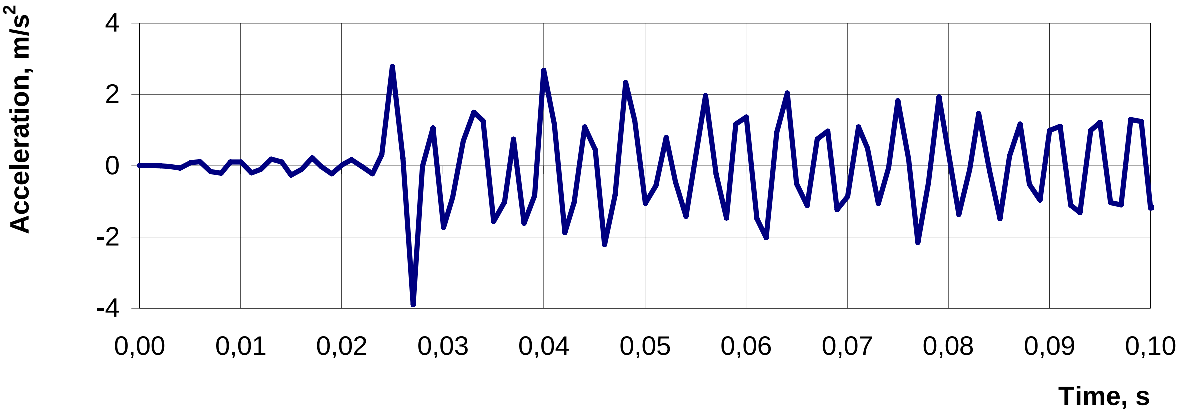


b) along horizontal axis y

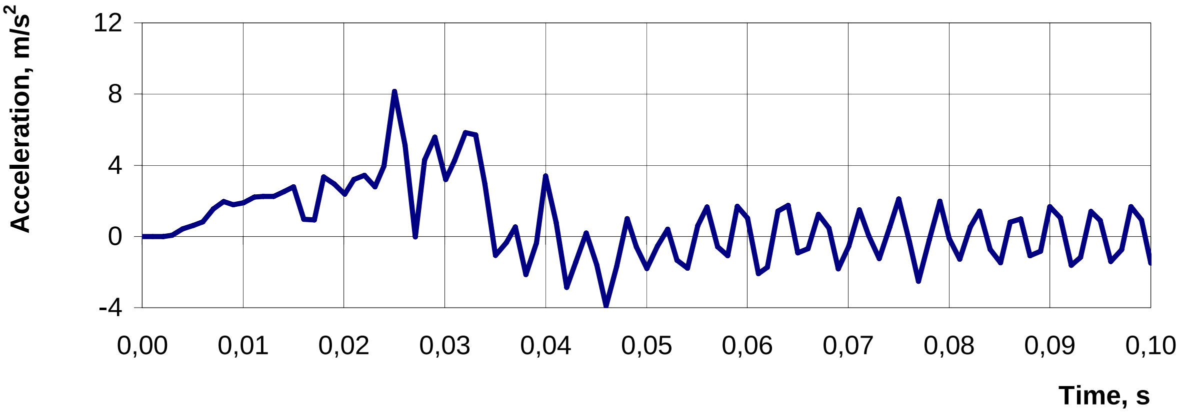


c) along vertical axis z

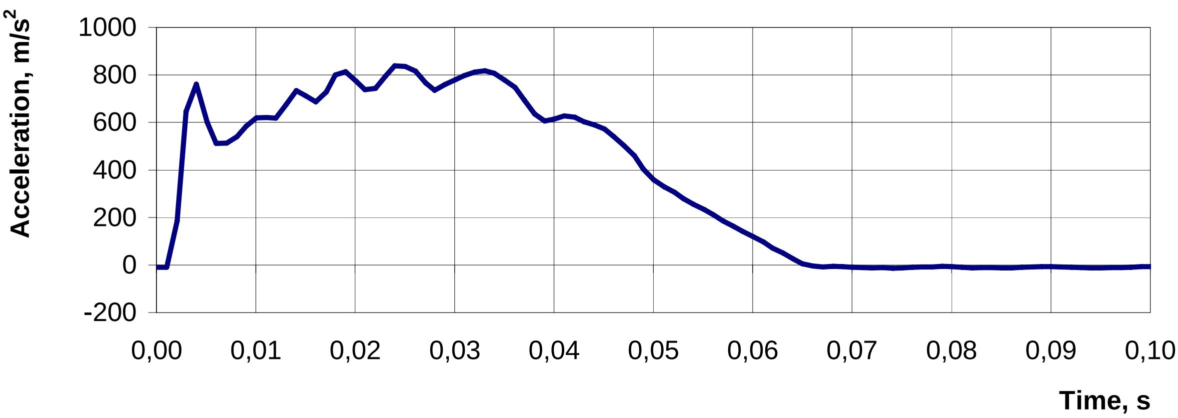
Fig. 8. A three-component impact accelerogram in the centre of gravity of the container with the spent fuel at its horizontal falling from a height of 27.8 m on the shock-absorbing cushion



a) along horizontal axis x

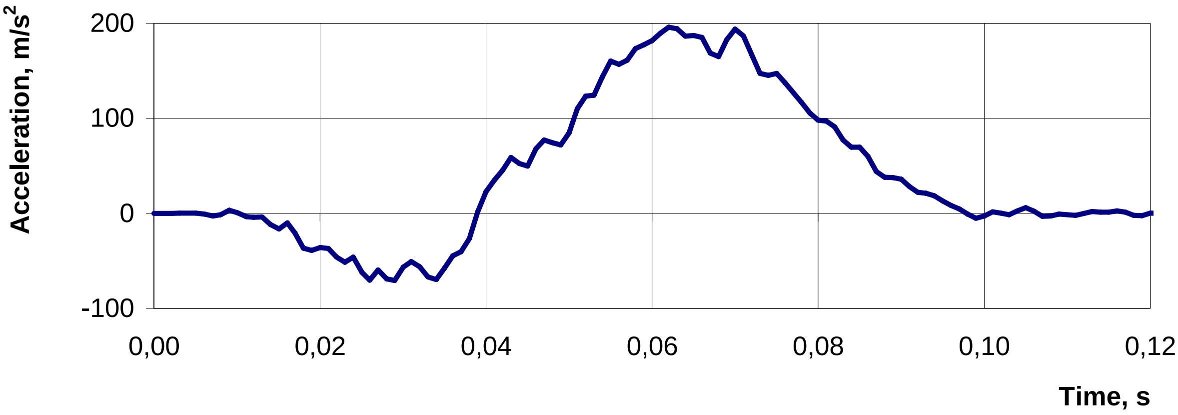


b) along horizontal axis y

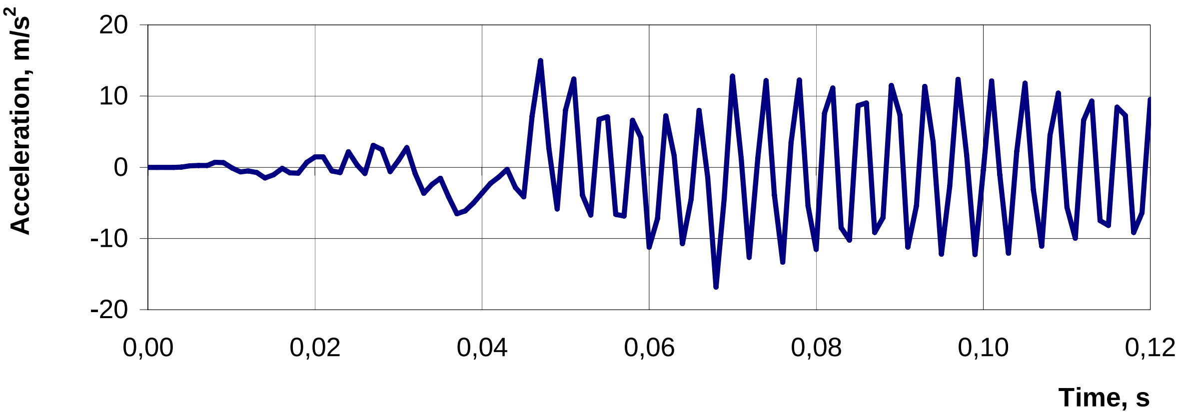


c) along vertical axis z

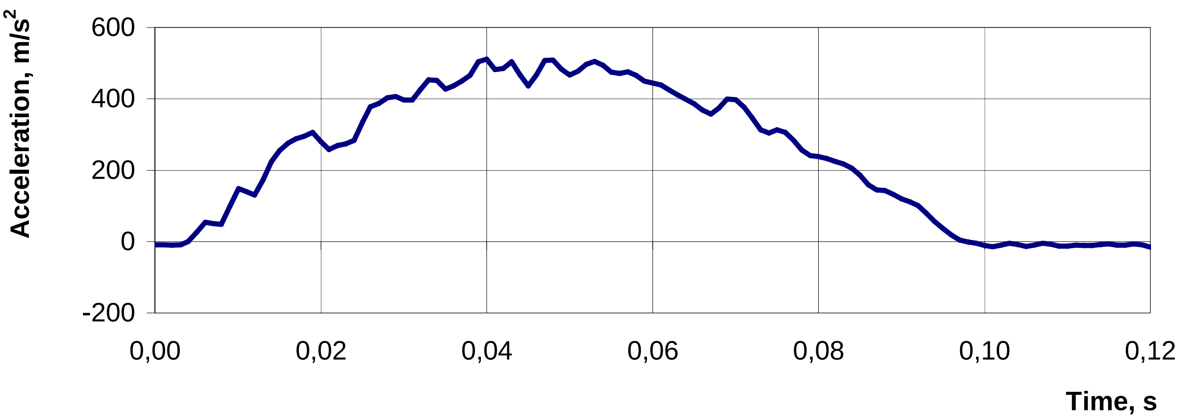
Fig. 9. A three-component impact accelerogram in the centre of gravity of the container with spent fuel at its upright falling from a height of 27.8 m on the shock-absorbing cushion



a) along horizontal axis x

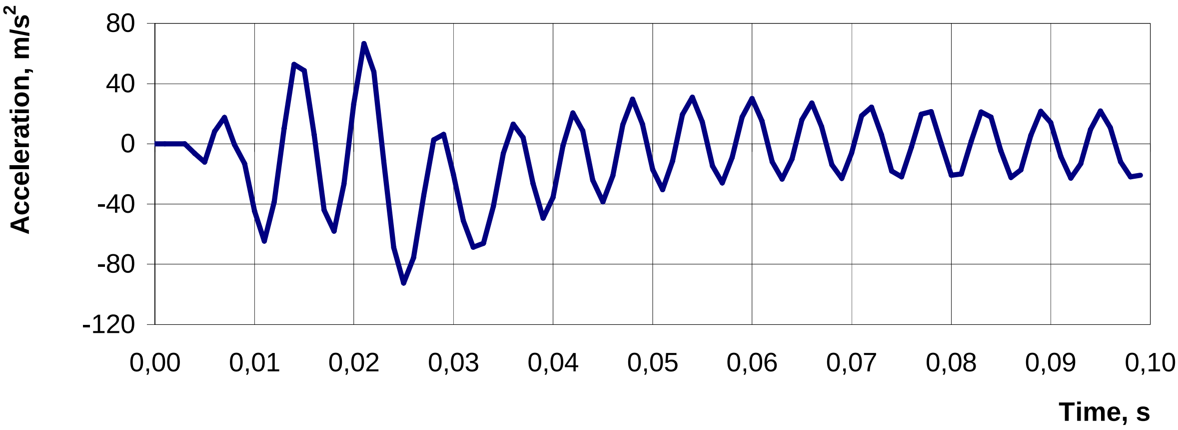


b) along horizontal axis y

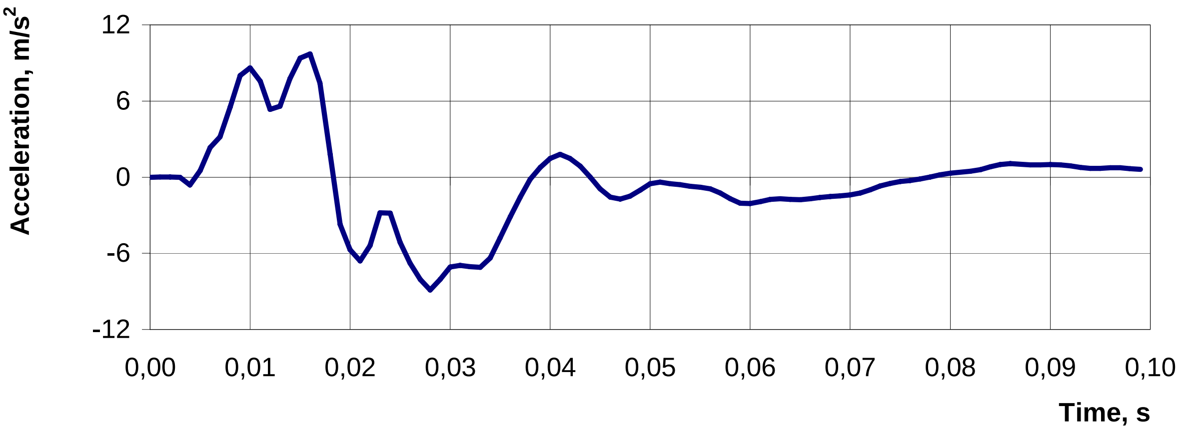


c) along vertical axis z

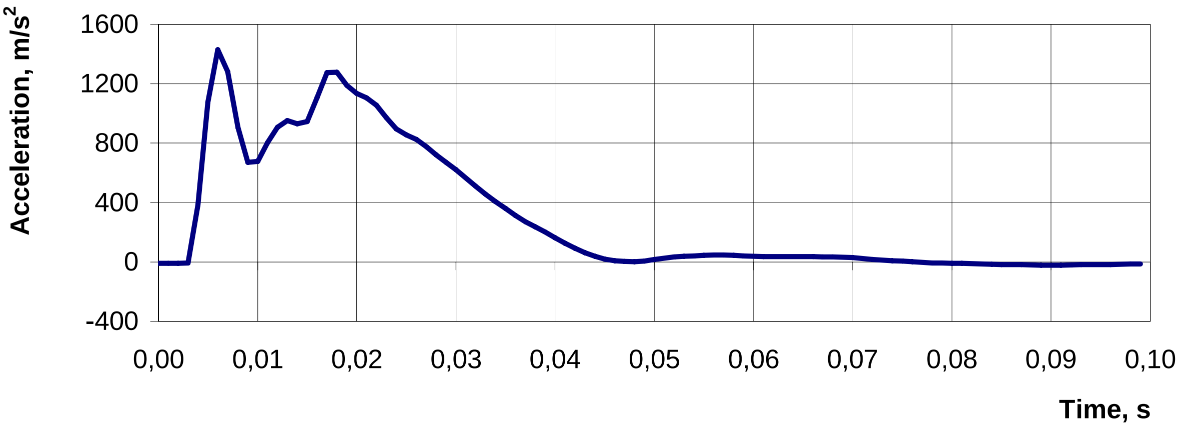
Fig. 10. A three-component impact accelerogram in the centre of gravity of the container with spent fuel at its inclined fall (angle of 30 ° to the vertical) from a height of 27.8 m on the shock-absorbing cushion



a) along horizontal axis x

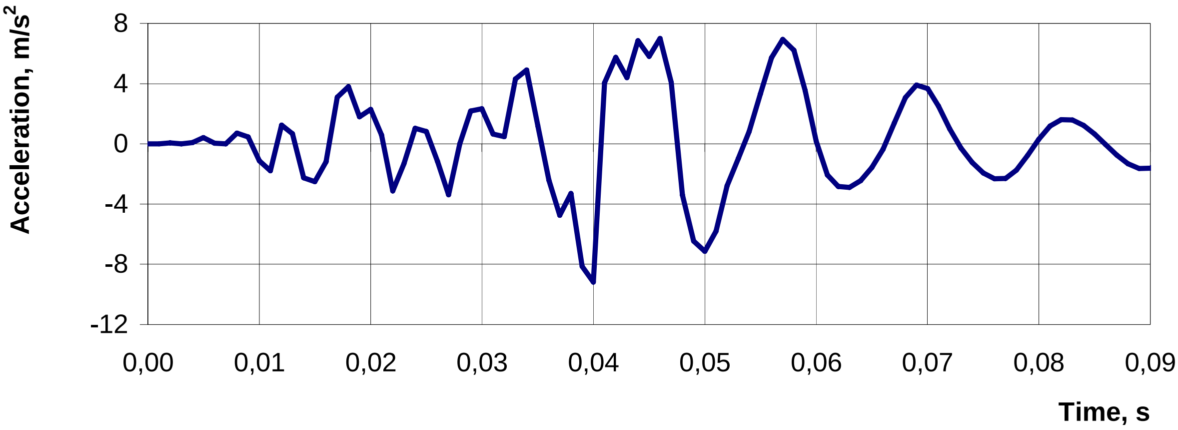


b) along horizontal axis y

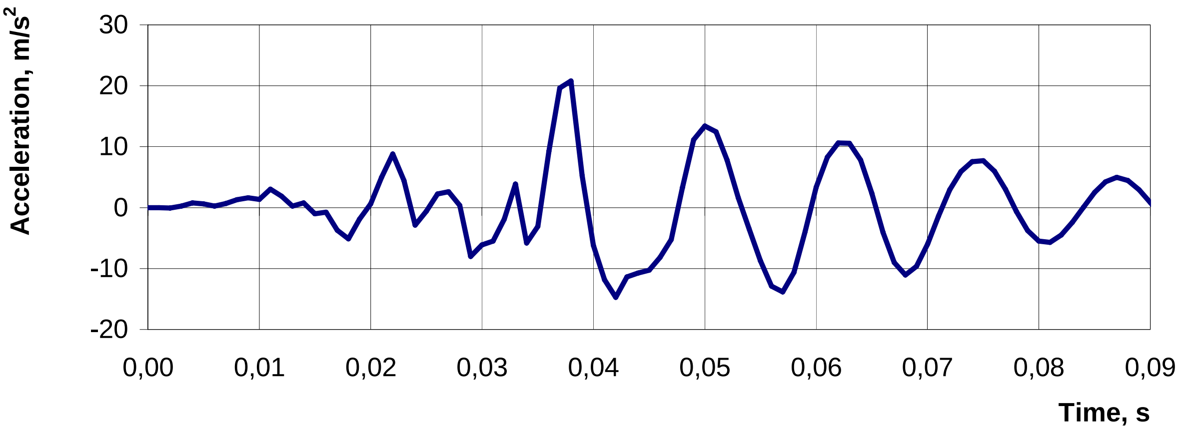


c) along vertical axis z

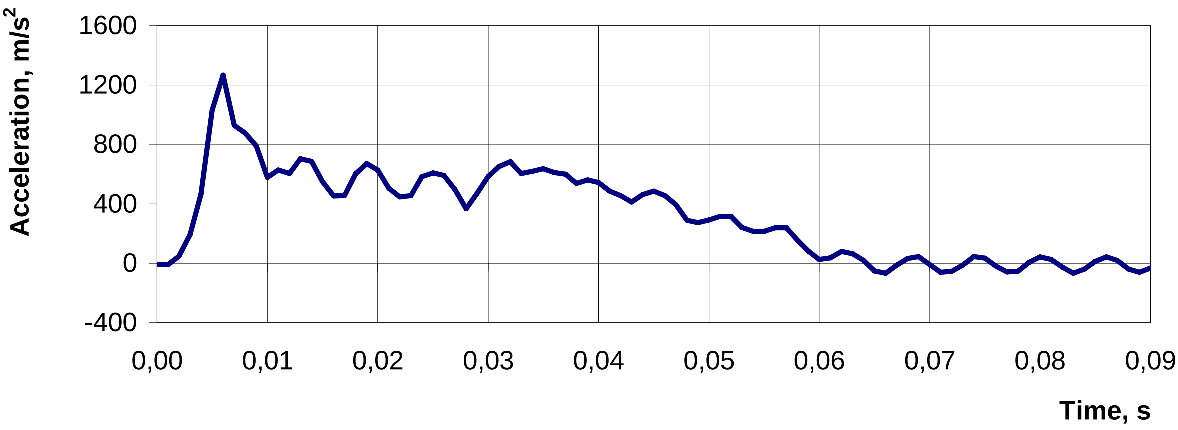
Fig. 11. A three-component impact accelerogram in the centre of gravity of the container with fresh fuel at its horizontal falling from a height of 27.8 m on the shock-absorbing cushion



a) along horizontal axis x

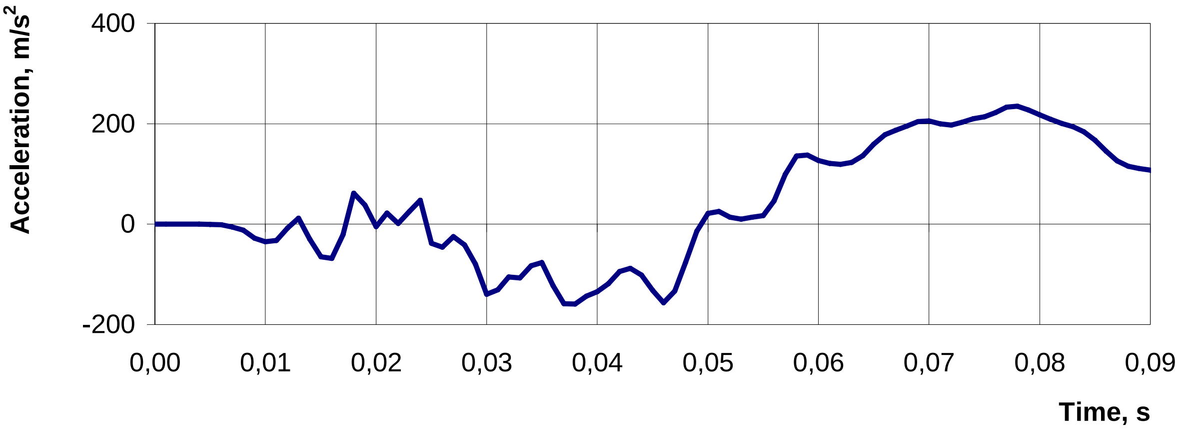


b) along horizontal axis y

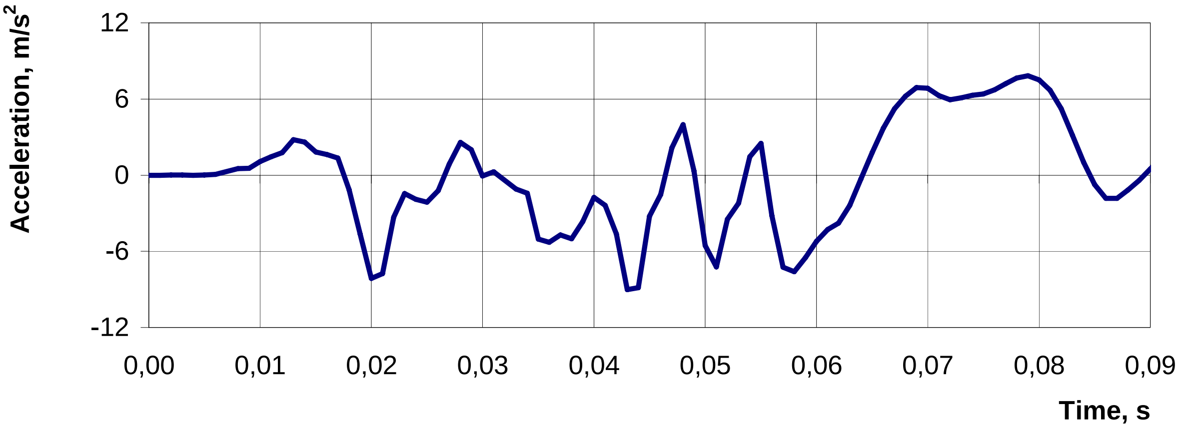


c) along vertical axis z

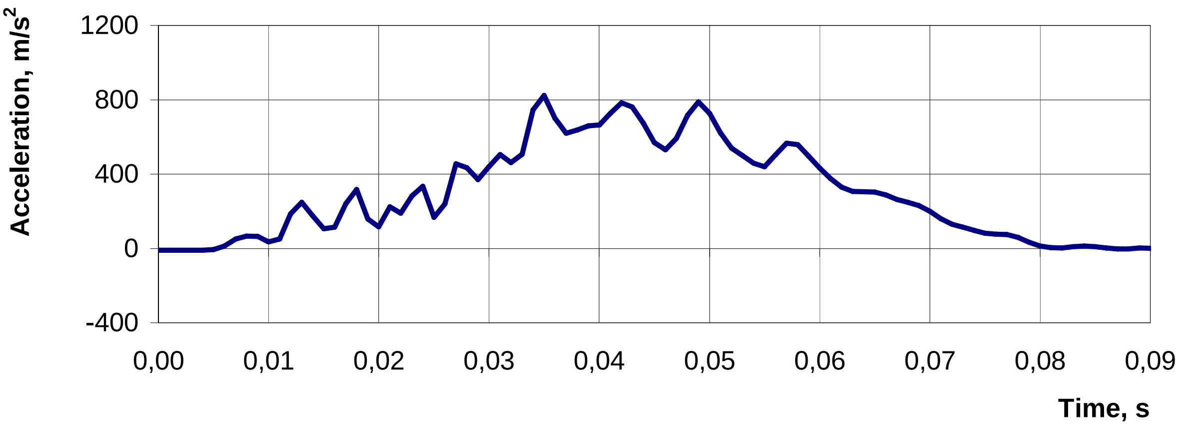
Fig. 12. A three-component impact accelerogram in the centre of gravity of the container with fresh at its upright falling from a height of 27.8 m on the shock-absorbing cushion



a) along horizontal axis x



b) along horizontal axis y



c) along vertical axis z

Fig. 13. A three-component impact accelerogram in the centre of gravity of the container with fresh fuel at its inclined fall (angle of 30 ° to the vertical) from a height of 27.8 m on the shock-absorbing cushion

The calculated and permissible values of the overload factor $K_z = \frac{|\ddot{u}_{z,max}(t)|}{g}$, i.e. the ratio of the absolute maximum value of a vertical impact acceleration component of the movement of the container arising from the interaction with the cushion, to the acceleration of gravity are presented in Table 2.

As can be seen from Table 1 the calculated values of overload factors both for the containers do not exceed the permissible values at every possible kind of fall from a height of 27.8 m onto the stationary shock-absorbing cushion.

Table 2. Comparison of the calculated and permissible values of overload factors during fall of the containers onto the three-layer shock-absorbing cushion from a height of 27.8 m

Type of analysis	Overload factor, K_z	Permissible overload factor
	Spent fuel container	
Fall in horizontal attitude position	98.1	176.0
Fall in vertical attitude position	85.5	197.0
Fall in inclined attitude position at 30°	52.1	186.0
	Fresh fuel container	
Fall in horizontal attitude position	145.8	266.0
Fall in vertical attitude position	129.1	266.0
Fall in inclined attitude position at 30°	83.9	266.0

4. CONCLUSION

In accordance with the initial data the spatial finite-element models of the containers with spent and fresh fuel were developed for analysis of kinematics of motion in the process of falls for various cases: breaks of the crane rope, yoke or rods of the crosspiece. Based on results of these dynamic analyses the size of the stationary shock-absorbing cushion was determined to be in plan as big as 15.0 x 15.0 m.

Then the finite-element behavioural models of 'shock-absorbing cushion – container with spent fuel' and 'shock-absorbing cushion – container with fresh fuel' systems were developed in this study.

Numerical analysis was done and the time-history accelerations were determined for the impacts of the containers against the three-layer shock-absorbing cushion.

Overload factors were determined and the obtained overload factors for both the containers were compared with the permissible values for the considered types of falls. The permissible values of overload factors correspond to values of falls from a height of 9 m onto concrete cushion.

Thus, in line with the valid regulations this study substantiated the applicability of the stationary three-layer shock-absorbing cushion to ensure safety of the containers with spent and fresh fuel in case of conceivable falls in the area of the nuclear reactor portal.

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[4] ASCE STANDARD, Seismic Analysis of Safety Related Nuclear Structures (1998).