

# Simulation of 9 m Drop Test of the Cask for Transport of Radioactive Material

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**Abstract** The paper deals with finite element simulation of drop tests of the steel cask designed for transport of radioactive waste. Two simulations of hypothetical accident conditions defined as drops of the cask from height of 9 meters are described and results are analyzed for purposes of the cask qualification. The main attention is devoted to procedures and methods of evaluation of results.

**Keywords:** radioactive waste, transport, cask, drop test, Finite Element Simulations

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## 1. Introduction

Because of wide use of radioactive materials, many different types of radioactive waste are produced. As radioactive materials are extremely dangerous, safe handling with them is of extraordinary importance [1]. In order to eliminate risk of radioactive pollution, special accidental conditions defined by international rules have to be satisfied (e.g. [2,3]).

Evaluation of resistance of shipments and qualification for a given purpose practices by testing and/or computations. Testing of full-scale prototypes or their models of appropriate scale is demanding and expensive as special testing facilities are necessary ([4,5,6]). Moreover, usually several specimens have to be manufactured for repeated tests as they are damaged under test conditions. This is a reason for numerical simulation of tests by Finite Element Analysis (FEA). If tests results are available, simulations give very useful tools for improving knowledge and better understanding of tested specimen response [7].

As it follows from comparison of experimental and simulation data, FEA based simulations can give good agreement with tests and realistic estimation of product resistance ([8,9]).

This paper deals with assessment of resistance of the steel cask exposed to a fall from height of 9 m by explicit method using drop test simulation module of the CAD system SolidWorks®. Described and discussed are methods of results evaluation for assessment of qualification of the initial engineering design of the cask. Subsequent design modifications resulting from the assessment are beyond scope of this paper.

## 2. Theoretical Background

Equations of motion of a body discretized by finite elements at time  $t_i$  in matrix form are

$$\mathbf{M}\ddot{\mathbf{d}}_i + \mathbf{C}_i\dot{\mathbf{d}}_i + \mathbf{R}_i(\mathbf{d}_i) = \mathbf{F}_i(t) \quad (1)$$

where  $\mathbf{M}$  is mass matrix,  $\mathbf{C}_i$  is damping matrix,  $\ddot{\mathbf{d}}_i$ ,  $\dot{\mathbf{d}}_i$ ,  $\mathbf{d}_i$  are vectors vector of nodal accelerations, velocities and displacements respectively;  $\mathbf{R}_i$  is vector of nodal internal forces and  $\mathbf{F}_i$  is vector of nodal external forces.

Explicit method uses central difference approximations of nodal velocities and accelerations. The approximation can be done e.g. by formulas [10]

$$\dot{\mathbf{d}}_i = \frac{1}{2\Delta t}(\mathbf{d}_{i+1} - \mathbf{d}_{i-1}) \quad (2)$$

$$\ddot{\mathbf{d}}_i = \frac{1}{\Delta t^2}(\mathbf{d}_{i+1} - 2\mathbf{d}_i + \mathbf{d}_{i-1}) \quad (3)$$

where indices indicate nodal displacements at time instances  $t_{i-1}$ ,  $t_i = t_{i-1} + \Delta t$  and  $t_{i+1} = t_i + \Delta t$ . When substituting from equations (2) and (3), equation of motion (2) can be rearranged as

$$\begin{aligned} \left( \mathbf{M} + \mathbf{C}_i \frac{\Delta t}{2} \right) \mathbf{d}_{i+1} = \\ = (\mathbf{F}_i - \mathbf{R}_i) + 2\mathbf{M}\mathbf{d}_i - \left( \mathbf{M} - \mathbf{C}_i \frac{\Delta t}{2} \right) \mathbf{d}_{i-1} \end{aligned} \quad (4)$$

The displacements  $\mathbf{d}_{i-1}$  and  $\mathbf{d}_i$  are known from solutions of previous time steps, therefore unknown displacements  $\mathbf{d}_{i+1}$  are obtained by solution of the set of simultaneous linear algebraic equations (4).

Simplification of the solution is possible by introducing further approximations to setup mass and damping

matrices into diagonal (lumped) form. If the matrices are diagonal, no solution of set of equations is necessary as displacements

$$\mathbf{d}_{i+1} = [d_1^{i+1}, \dots, d_k^{i+1}, \dots, d_n^{i+1}]^T \quad (5)$$

can be determined directly as

$$d_k^{i+1} = \frac{(F_k^i - R_k^i)\Delta t^2 + 2M_{kk}d_k^i - (M_{kk} - C_{kk}\frac{\Delta t}{2})d_k^{i-1}}{M_{kk} + C_{kk}\frac{\Delta t}{2}} \quad (6)$$

where lower indices indicate rows and columns of matrices and upper indices indicate time step number.

As the most time demanding parts of computation, i.e. repeated solutions of large sets of algebraic equations are unnecessary, efficiency of explicit method is very high. Disadvantage of the method is its conditional stability. If time increments were larger than their critical value, solution would fail.

Estimation of the critical time increment gives the time necessary for transition of stress wave through the smallest element of a mesh. Velocity  $c$  of stress wave in three-dimensional continua discretized by finite elements is [10]

$$c = \sqrt{\frac{E(1+\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (7)$$

where  $E$  is modulus of elasticity,  $\rho$  is mass density and  $\mu$  is Poisson's ratio of the material. Then, upper bond of critical time increment is

$$\Delta t_c = \frac{h_{\min}}{c} \quad (8)$$

where  $h_{\min}$  is the smallest distance between nodes.

### 3. Computational Model

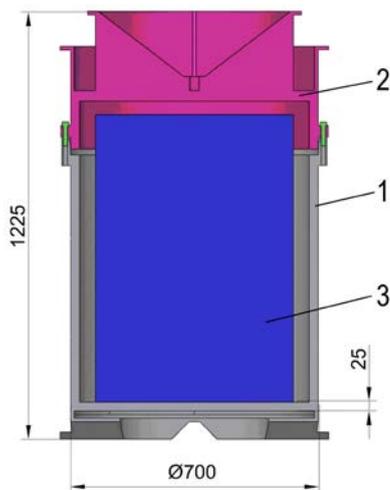


Figure 1. Scheme of the cask initial design

The scheme of initial engineering design of the cask intended for transport of radioactive waste is in Figure 1. The cask consists of cylindrical body 1 covered with lid 2. Thicknesses of these parts were determined from requirements on shielding of radioactive radiation. Upper

end of the lid is equipped with deformation elements serving for manipulation also. Another deformation zone is above foot of the cask created as weakening of cylindrical wall. At foot is the plate for fixation of the cask on a transport device. In order to enable loading and unloading of transported waste placed in a standard steel barrel 3, cask body and lid are joined by bolts.

Geometry simplified for computations is shown in exploded view in Figure 2. Transported waste, mostly pieces of structural parts, can vary from case to case therefore the barrel was modeled as a cylinder of homogenous material with density following from cargo maximum allowable weight and volume of the barrel.

Finite element mesh consisting of ten node tetrahedrons is in Figure 3. As obvious from the figure, smaller elements had to be used to model bolts and their connections to body and lid (see Figure 4).

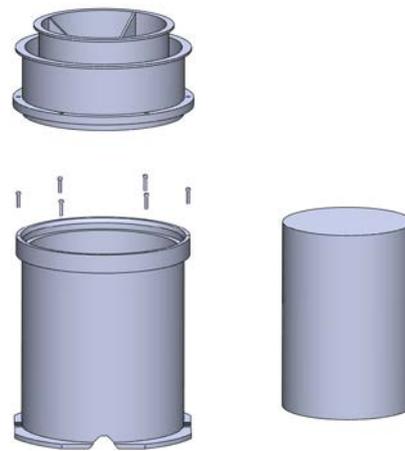


Figure 2. Geometrical model of the cask and transported material

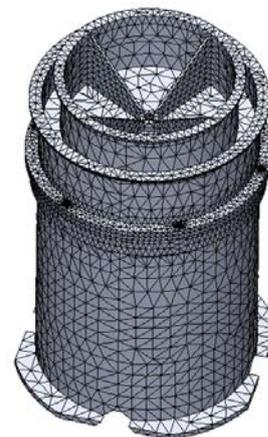


Figure 3. Finite element mesh

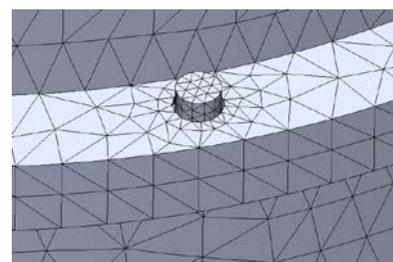


Figure 4. Detail of the finite element mesh

To avoid extremely long CPU times, comparatively course mesh was used for other parts. This enabled to

decrease number degrees of freedom and shorter CPU time for individual time steps. Lower accuracy of results in comparison with a uniform fine mesh was considered as acceptable because analyses served for initial design evaluation only.

The cask body and lid were designed of welded hot-rolled steel, designed material of bolts was heat treated steel, with high tensile strength and low ductility. For these parts was considered bilinear elastoplastic material model with kinematic hardening.

To define relevant material model of transported waste was difficult as only maximum weight and volume of it were defined. Due to these uncertainties, a linear material model was selected and material properties except for density were considered as for concrete. This represented a case when barrel was filled with pieces of low density material sealed by concrete.

Considered material properties are listed in Table 1, where  $R_e$ ,  $R_u$  and  $E_t$  are yield strength, ultimate strength and tangential modulus respectively.

The target was considered as rigid hence no material properties were defined.

Table 1. Material properties

Part	$E$ (MPa)	$\mu$ (-)	$R_e$ (MPa)	$R_u$ (MPa)	$E_t$ (MPa)	$\rho$ (kg/m <sup>3</sup> )
Cask	200 000	0,30	345	625	1 440	7 850
Barrel	14 400	0,22	-	20	-	1 600
Bolts	200 000	0,30	1 100	1450	4 700	7 800

### 4. Evaluation of Results

Evaluations of results of two types of 9 m drop test are described thereafter. The first one was the impact of the cask flatways by its bottom part on the target. The second type was the drop of the cask in horizontal position sidewise to target.

Evaluations were based on stress plots in individual time instances, plots of stress envelopes (i.e. their maximal values from all time instances), plots of strains and time courses of stresses and strain in selected points of model specified as sensors.

#### 4.1. Drop by Bottom Part of the Cask

Propagation of stress waves is illustrated by fields of von Mises stresses in time instances of 250, 500 and 750  $\mu$ s from beginning of impact shown in Figure 5, Figure 6 and Figure 7. The stress wave moves from bottom to top and then reflects from top surface and returns back as can be seen in Figure 7.

As it can be seen from Figure 7 the von Mises stress raised to value of 408 MPa which exceeds the yield strength of the material. This implies that the cask will plastically deform with change of mechanical properties of the material, specially increase of the tensile and yield strength and hardness at deformed area, but with decrease of ductility of the material.

To find maxima of stresses and strains during impact, it is necessary to store results for sufficient number of time steps. As volume of stored data depends of hardware limitations, it is necessary to store results from all time steps for selected nodes only.

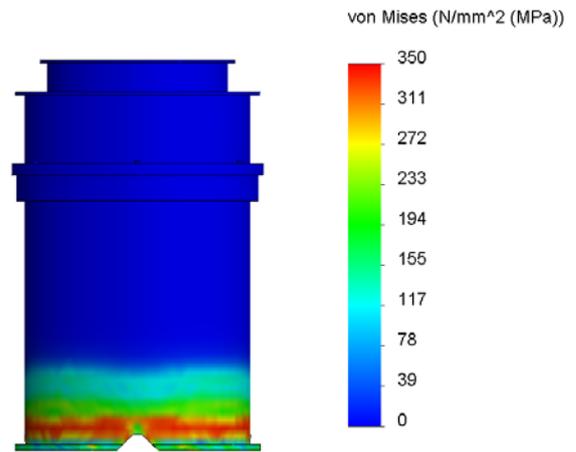


Figure 5. Von Mises stress at time of 250  $\mu$ s

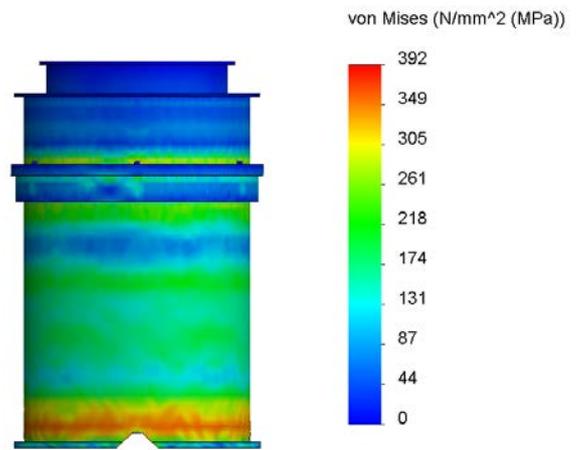


Figure 6. Von Mises stress at time of 500  $\mu$ s

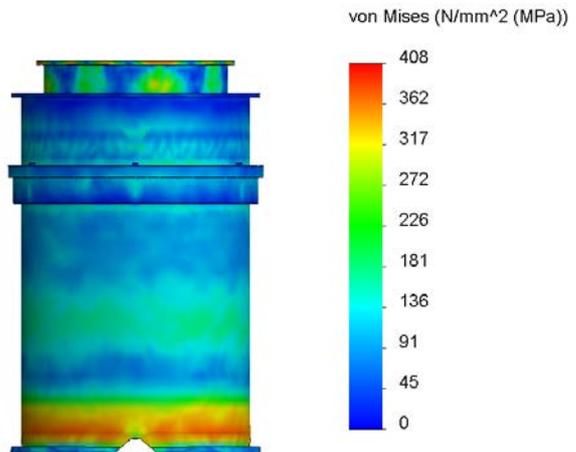


Figure 7. Von Mises stress at time of 750  $\mu$ s

Selected nodes that play a role of sensors at base of the cask are in Figure 8 and Figure 9. Sensor S1 is in center of outer circular surface of cask bottom, sensor S2 is at inner surface of weakened wall. The other sensors could be located on bolts to measure their stress during impact.

Time course of von Mises stress at sensor S1 is shown in Figure 10. It is visible, that maximum of stress occurs during the first millisecond from beginning of impact. Effect of reflected stress waves is observable as local maxima of the stress course.

Progress of stress wave is visible from time courses of von Mises stresses in sensors S3, S4 and S5 in Figure 11.

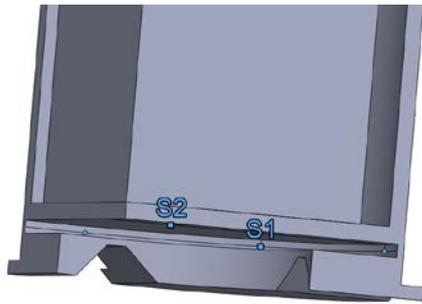


Figure 8. Sensors at cask foot

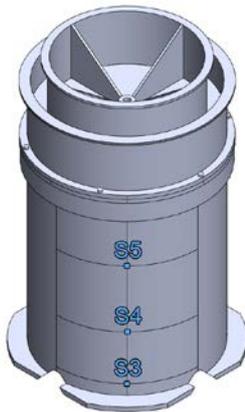


Figure 9. Sensors at cask body

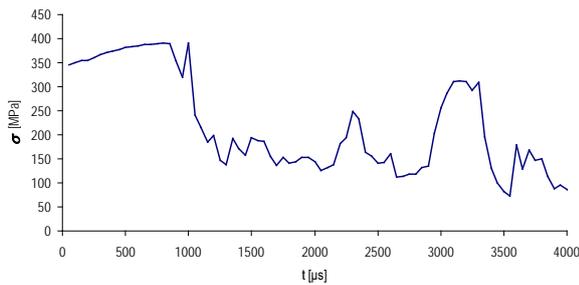


Figure 10. Time course of von Mises stress at sensor S1

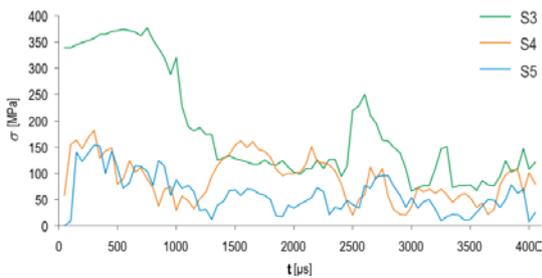


Figure 11. Time courses of von Mises stress at sensors

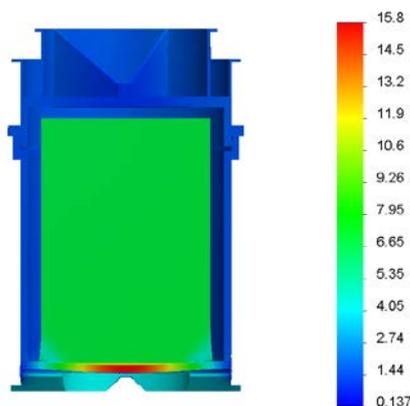


Figure 12. Displacement of the cask bottom at time 5000us

After the impact, the barrels pushes the bottom of the cask and deform it as illustrated in Figure 12 where are shown resultant nodal displacements at time 5 milliseconds.

Time course of resultant displacement at sensor S2 placed in the center of the cask bottom is in Figure 13.

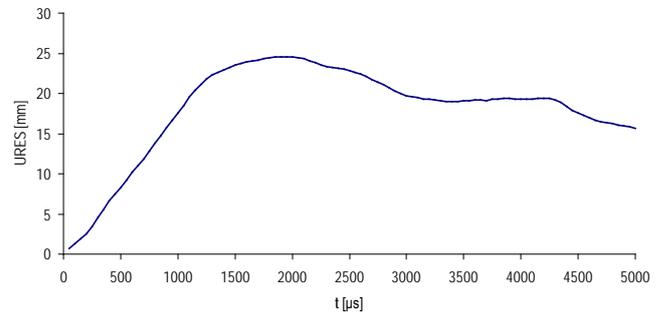


Figure 13. Displacement of the bottom of the cask (sensor S2) over time

It is obvious that the largest displacement was at time about 2 milliseconds from impact. Time at maximum is larger than times of maxima of stresses in bolts. This time delay is due to lower velocity of stress waves in computational model of the barrel. Decrease of displacements is gradual and its character implies that the bottom will be plastically deformed.

Maximal value of the stresses in bolts could be determined from time courses of stresses at relevant sensors. Time course in the most unfavorable loaded bolt during all the solution time is in Figure 14. Maximum value is far under the yield strength of the material, thus the bolts will not deform permanently. Maximal value was achieved at time 0.5 millisecond from beginning of impact.

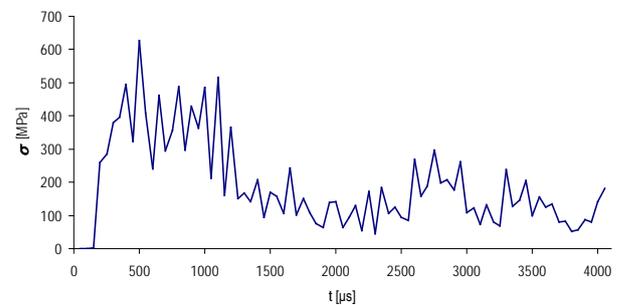


Figure 14. Time course of maximal reduced stress in the bolt

## 4.2. Drop Sideways to the Target

The cask dropped with its axis almost horizontal, in such a way that contact of bottom and upper part with the target occurred simultaneously.

Progression of stress wave is observable from stress fields in Figure 15 and Figure 16. It is visible that von Mises stress reached and in some areas exceeded the yield strength of material. This implies that plastic deformations of the cask will occur during impact and hence some portion of deformation will be permanent. As an accidental situation is investigated, permanent deformation of cask jacket can be tolerated (or they cannot be avoided) providing that they have no effect on its integrity.

To check structural integrity of the cask jacket, maximum values of nodal von Mises stresses are depicted in Figure 17. Setup of color map is that red represents

values of stress equal to ultimate strength. It is obvious that values of stresses are less than 418 MPa i.e. slightly above yield strength but markedly under ultimate strength. Deformation of the cask is notable in Figure 15.

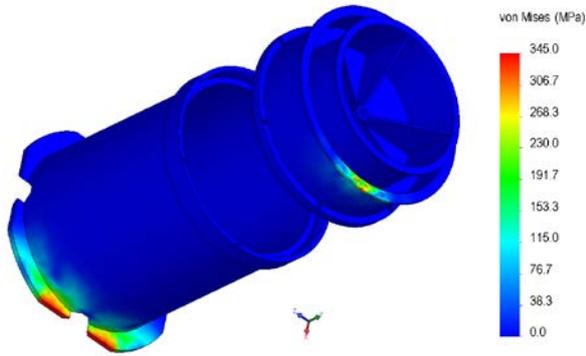


Figure 15. Von Mises stresses at time 50  $\mu$ s

On Figure 13 the stress wave is moving from the impact zone to the upper side of the container. The max value of von Mises stress in time 50  $\mu$ s is 347.4 MPa in the contact zones.

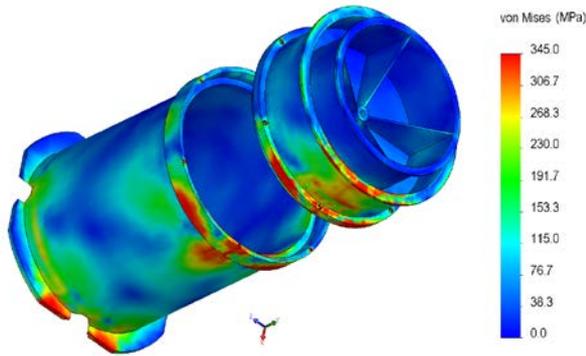


Figure 16. Von Mises stresses at time 750  $\mu$ s

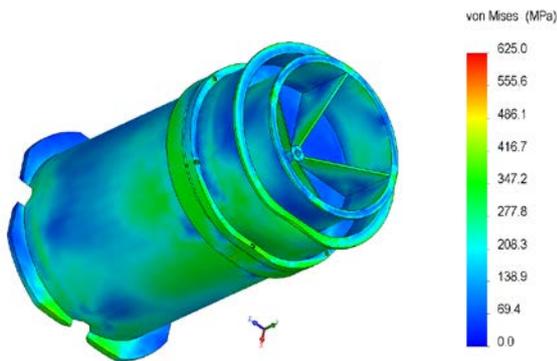


Figure 17. Envelope of von Mises stresses

In order to acquire more information about cask behavior during impact, other sensors were inserted on cask flanges, see Figure 18.

Time course of von Mises stress in sensor S6 (see Figure 19) shows that after sudden increase at beginning of impact, the stress does not change almost at all. This is a consequence of gradual deformation of contact zones. The maximal value of von Mises stress is over the yield stress of the material, therefore the cask will deform plastically. In contrary, values of stress in sensor S7 changes more frequently, see Figure 20. The maximal value of stress is below the yield strength of the material.

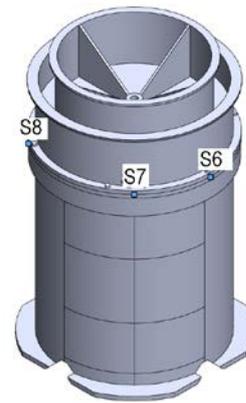


Figure 18. Sensors on flange of the cask

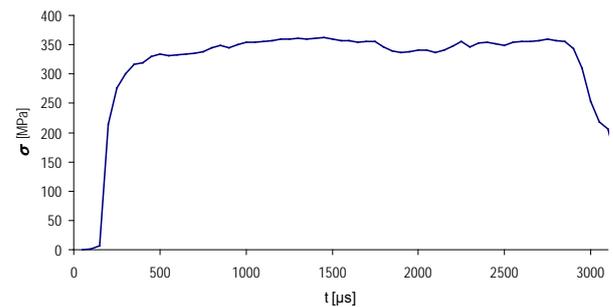


Figure 19. Time course of stress in sensor S6

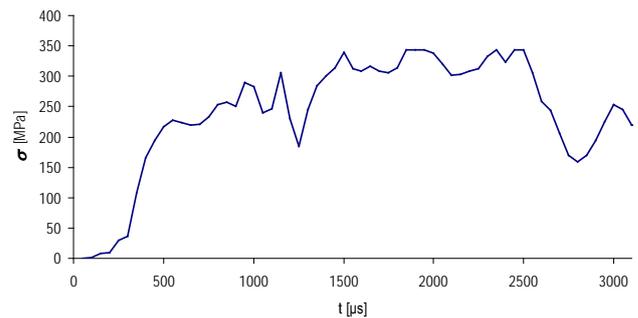


Figure 20. Time course of stress in sensor S7

For better understanding of the cask behavior after impact, it is necessary to evaluate displacements. Resultant displacements at time 2500  $\mu$ s are in Figure 21. Deformed shape is displayed in true scale, so it is obvious that barrel with transported waste does not touch inner cylindrical surface of the cask. Full contact of both bodies occurred later. This is visible in Figure 22 displaying resultant displacements at time 5000  $\mu$ s. As deformed shape is drawn in true scale again, comparatively large gap between cask body and lid flanges is obvious.

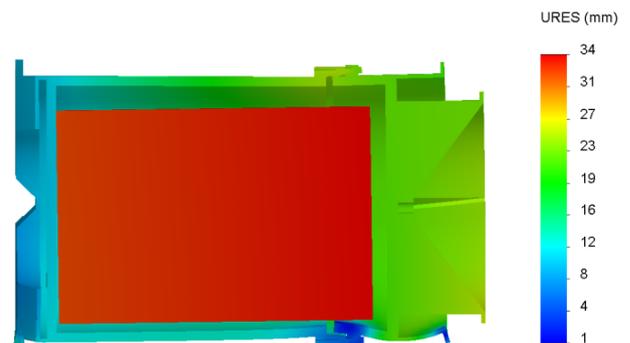


Figure 21. Displacements at time 2500  $\mu$ s

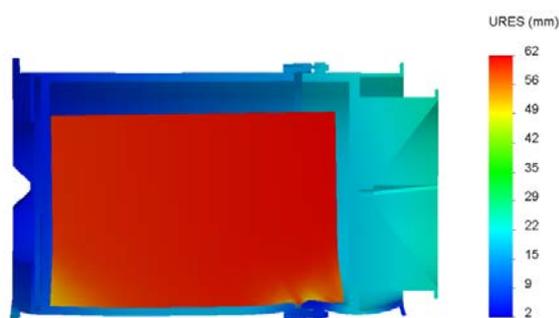


Figure 22. Displacements at time 5000  $\mu$ s

To investigate origination of the gap, time courses of displacements in  $y$ -axis direction (i.e. direction of cylindrical walls axis) of two adjacent nodes of both flanges are in Figure 21. It is clear that gap originated after 2500  $\mu$ s from impact. As stresses in flanges are small, the only explanation is that plastic deformation originated in bolts. This is documented by envelopes of tensional stresses in bolts in Figure 24.

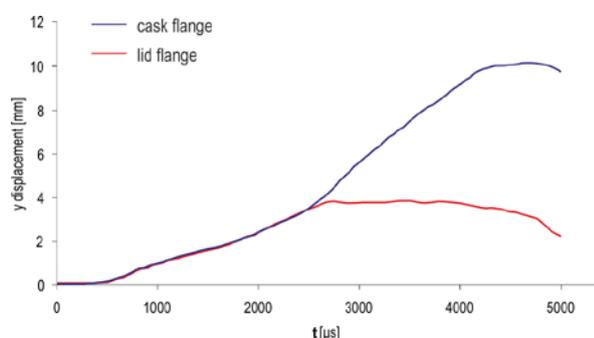


Figure 23. Horizontal displacements of adjacent nodes of flanges

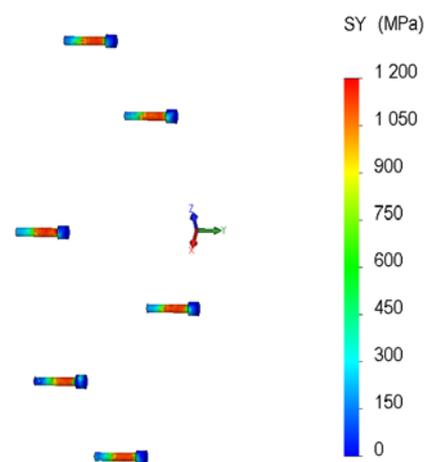


Figure 24. Maximum tensional stress in bolts

Stress range in Figure 24 was set from zero to 1200 MPa. It is visible that tensional stresses in all six bolts exceeded yield strength of material that is 1 100 MPa. Bolts deformed plastically which caused origination of gap between flanges.

The maximal nodal value of tensional stress is 1569 MPa (see Figure 25). This value is above the tensile strength of the material, meaning that the rupture of bolts would occur. It should be noted that simulation program does not enable to model damage and rupture of material, hence stress values could be larger than ultimate strength.

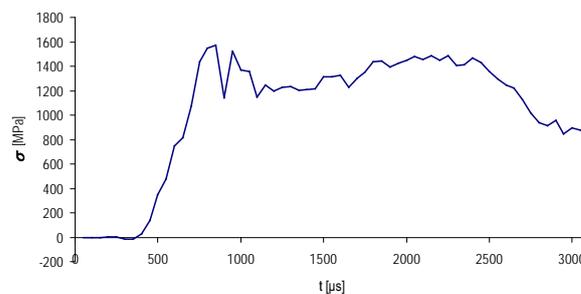


Figure 25. Time course of normal stress in maximally loaded bolt

## 5. Conclusions

Drop tests simulated for initial engineering design of the cask for transport of radioactive waste were studied. The two of tests demanded by relevant rules are described and methods of results evaluations are presented. From evaluations of results it follows that the design did not meet conditions of its qualifications and therefore changes of design were necessary.

## Acknowledgement

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