# SAFETY ANALYSIS OF CASKS UNDER EXTREME IMPACT CONDITIONS

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## ABSTRACT / INTRODUCTION

The determination of the inherent safety of casks also under extreme impact conditions has been of increasing interest since the terrorist attacks from 11th September 2001. For nearly three decades BAM has been investigating cask safety under severe accident conditions like drop tests from more than 9 m onto different targets and without impact limiters as well as artificially damaged prototype casks.

One of the most critical scenarios for a cask is the centric impact of a dynamic load onto the lid seal system. This can be caused e.g. by direct aircraft crash or its engine as well as by an impact due to the collapse of a building e.g. a nuclear facility storage hall. In this context BAM is developing methods to calculate the deformation of cask components and - with respect to leak tightness - relative displacements between the metallic seals and their counterparts. This paper presents reflections on modelling of cask structures for Finite Element analyses and discusses calculated results of stresses and deformations.

Another important aspect is the behaviour of a cask under a lateral impact by aircraft and fragments of a building. Examples of the kinetic reaction (cask acceleration due to the fragments, subsequent contact with neighbouring structures like ground, buildings or casks) are shown and discussed in correlation to cask stresses which are to be expected.

## 1 LOADING

To analyse the mechanical behaviour of the lid seal system in case of an impact due to aircraft crash or collapse of a building [1] a load vs. time function and a load contact area are needed. This paper will not discuss the derivation of the load vs. time function. Literature gives a lot of information about analytical approaches to estimate loadings resulting from a direct aircraft crash onto hypothetical rigid or soft targets like structures of buildings [2-5]. Transport casks can be hit directly whereas for storage casks the behaviour of the storage building must be assessed firstly to get the geometry, mass and velocities of fragments of buildings or aircrafts [6]. For the purpose of this investigation to show our methods how to analyze extreme impacts we chose impact scenario for both, a centric impact onto the lid seal system and a lateral impact hitting the cask in an area as shown in Fig. 1. The governing load function was taken from the licensing process in Germany for spent fuel interim storage sites [7]. For an example of analyzing a blast loading, see [8]. In the following, the centric impact onto the lid seal system and then the lateral impact onto the cask body will be discussed at first. The dynamic geometrically and materially nonlinear calculations were executed with the Finite Element program ABAQUS 6.3 [10].

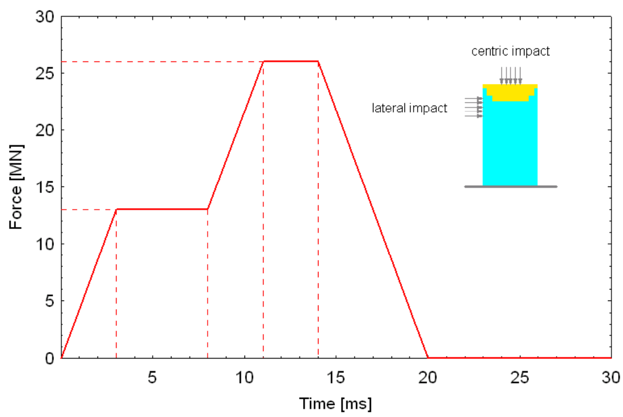



Fig.1: Load vs. time function for the MEPPEN test projectile described in [9]

## 2 CENTRIC IMPACT ONTO THE LID SEAL SYSTEM

### 2.1 MODELLING OF THE CENTRIC IMPACT ANALYSIS

With the exception of the lid bolts and the bolt holes of each lid, the geometry of the cask and the load is axisymmetric. In the same way as described in [11], the geometry of all bolts for each different lid was modelled with plane stress continuum elements in order to build a bolt submodel. For that two-dimensional submodel, the cross-

sectional areas of the shanks and the heads of the bolts must be calculated and redistributed to the bolt mesh appropriately using the area attributes of the 2-D solid elements. Figure 2 illustrates the cross-sectional views of the bolt head and the shank. Each plane stress element represents a length that extends out of the axisymmetric plane which corresponds to the dimension of the real bolt. The bolt holes in a lid can be smeared by using inhomogeneous material properties for the bolt hole area of the mesh that corresponds to a weaker material stiffness in this region. To determine the effective material properties it has to be calculated the elastic modulus reduction factor, which is the ratio of the ligament area in the pitch circle to the annular area of the pitch circle. For further details of the submodel, e. g. defining contact conditions, see [11].
The bolt shank should be supported inside the cask body along its circumference. Fig. 3 shows the Finite Element model for a typical reference transport and storage cask and in detail its lid seal system with the bolt submodels.
For a quick investigation it is sufficient to model only the top portion of the cask as shown in Fig. 3b. Using the whole cask, as described in more detail in [12], gives the opportunity to apply the material properties related to the thermal steady state of a loaded cask.

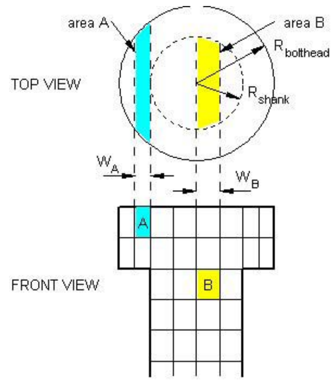


Fig. 2: Cross-sectional views of the bolt head and the shank [11]

With the exception of the linear elasticly behaving moderator plate elastic-plastic material data for all cask components have been used.

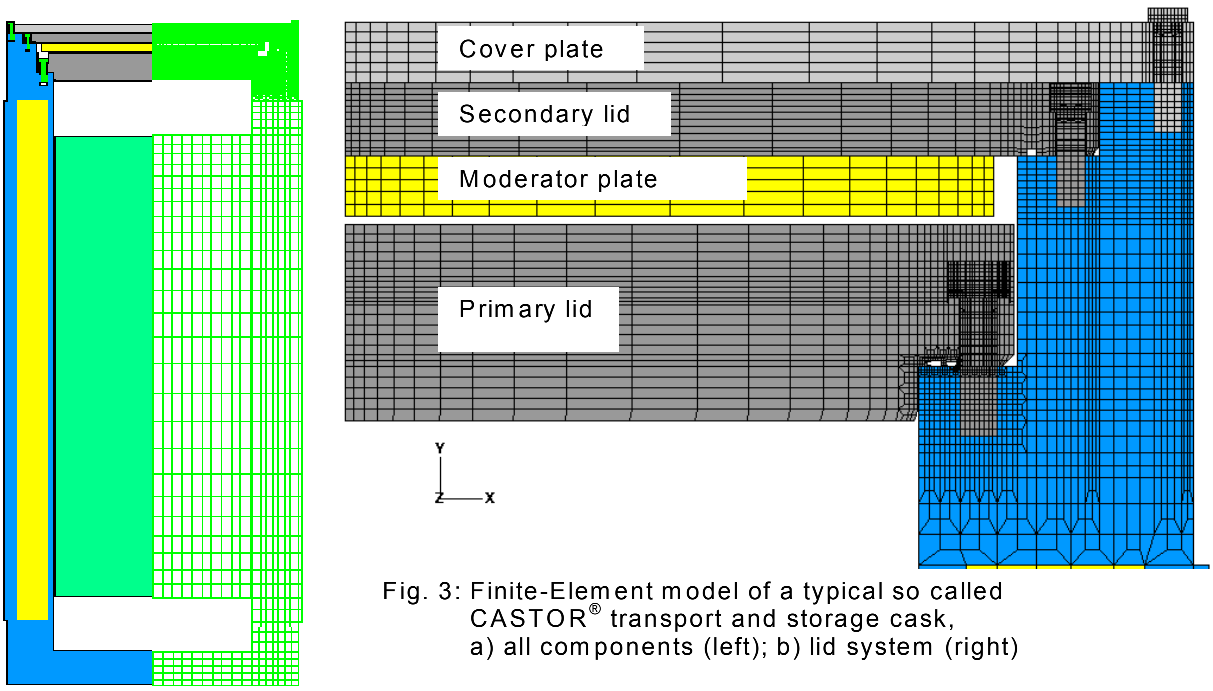


Fig. 3: Finite-Element model of a typical so called CASTOR® transport and storage cask, a) all components (left); b) lid system (right)

## 2.2 DISCUSSION OF THE LOADING CASE -CENTRIC IMPACT ONTO THE LID SEAL SYSTEM-

To estimate a maximum leakage rate for this cask design the stressing of its lid seal system has been compared to the test results for the CASTOR® IIa transport and storage cask as described in [9]. The main criteria for transferring the test results to another similar cask design are that the primary lid fastenings do not loose their pre-stressing and that deformations of the large primary lid seals are limited to a certain extend as will be discussed later. These criteria define the requirements for the accuracy and quality of the used Finite Element model.
Fig. 4a shows the lid seal system at its initial state with its pre-stressed fastening bolts according to its assembly loads and in Fig. 4b the stress distribution at the maximum impact load is displayed. Fig. 4c shows that the cover plate and the secondary lid bolts have lost their pre-stressing. Because of the dynamic load function, the primary lid starts to vibrate already when the load function (Fig.1) reaches its first plateau after about 3 ms as can be seen in Fig. 4d.

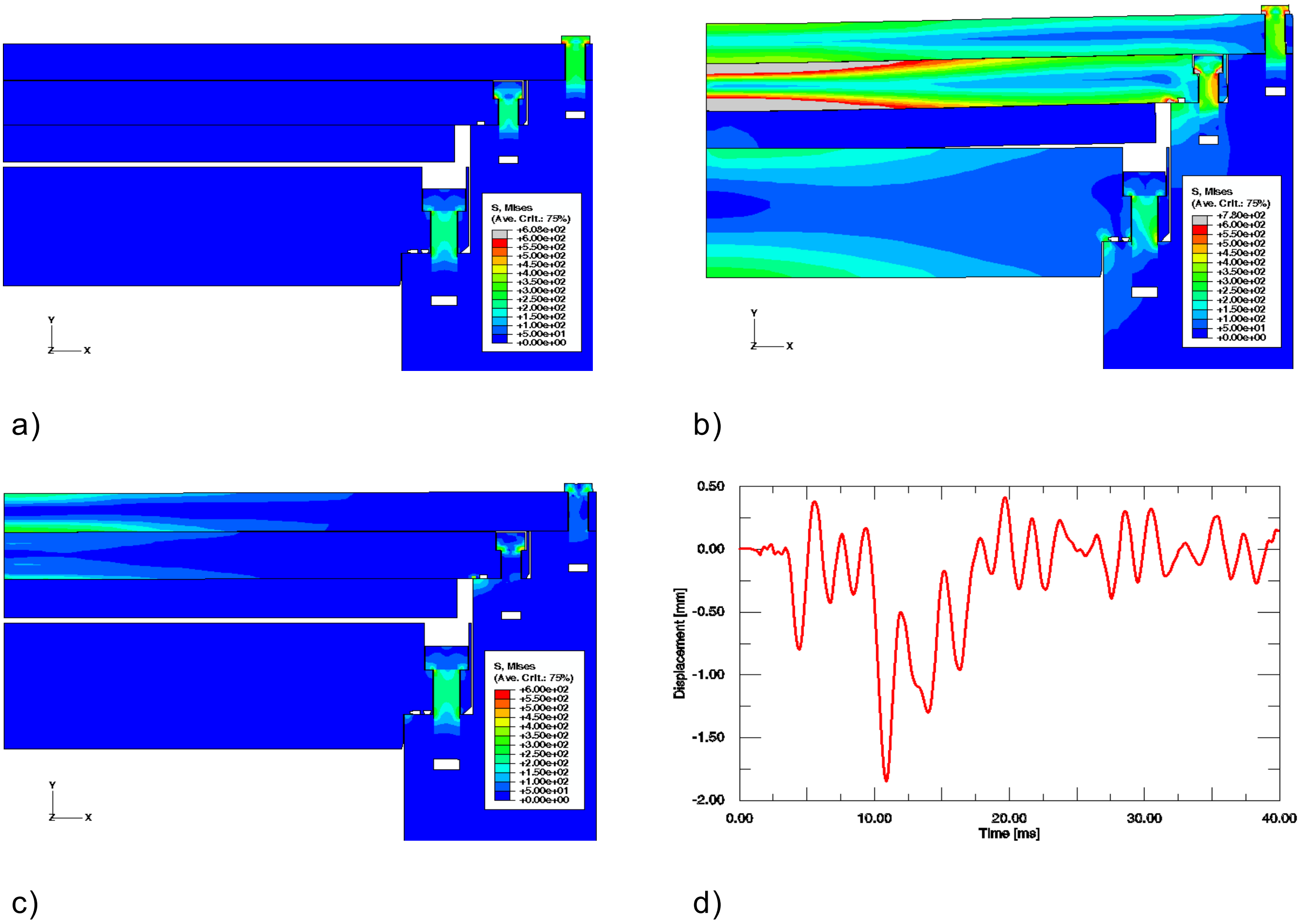



Fig. 4: Stress and deflection of the lid system
a) Lid system in initial situation (t=0); b) Stress profile in the lid system at t = 11 ms
c) Stress profile in the lid system at t = 40 ms; d) Primary lid deflection history

The tension stress in the primary lid bolts during the complete time period is displayed in Fig. 5. It can be seen that no major loss of the bolt pre-stressing occurs. Taking into account the stressing of the primary lid as well as of the primary lid bolts a loss of the mechanical integrity can be excluded.

In Fig. 6 the relative displacements between cask body and primary lid seal groove versus time is given. During the loading, the seal is exhibited to a temporary compressive deformation of 0.1 mm. Because of this limited value and the fact that the seal type used here also can bear several cycles of loading and unloading in principle [13] a conservative leakage rate for an assessment of a radioactive release can be assumed.

Summarizing, the mechanical calculations have shown that statements concerning the integrity and leak tightness of these casks are transferable in a conservative manner by the results of former CASTOR® projectile tests. This indicates that for this cask design correspondingly a standard helium leakage rate can be derived conservatively. At present, a quantitative relationship between the calculated deformations of the lid system and leakage rates is not possible. Therefore correlations particularly between calculated deformation states and leakage rates have to be confirmed experimentally. BAM would

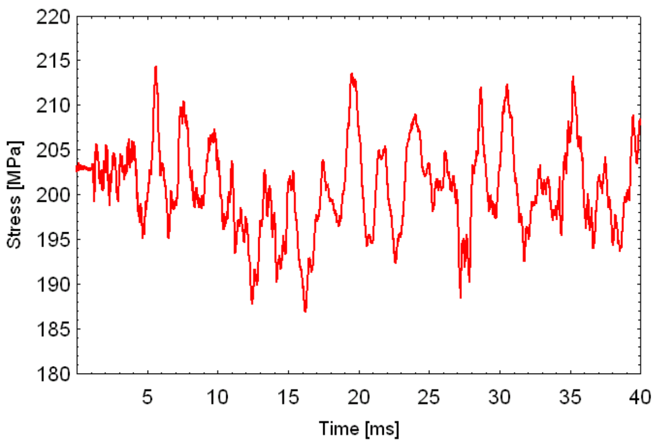



Fig. 5: Time dependence of the tensile stress component in the primary lid bolts

expect, however, that with an additional projectile test using e.g. the cask design under discussion a lower leakage rate than the current value could be proved thoroughly.

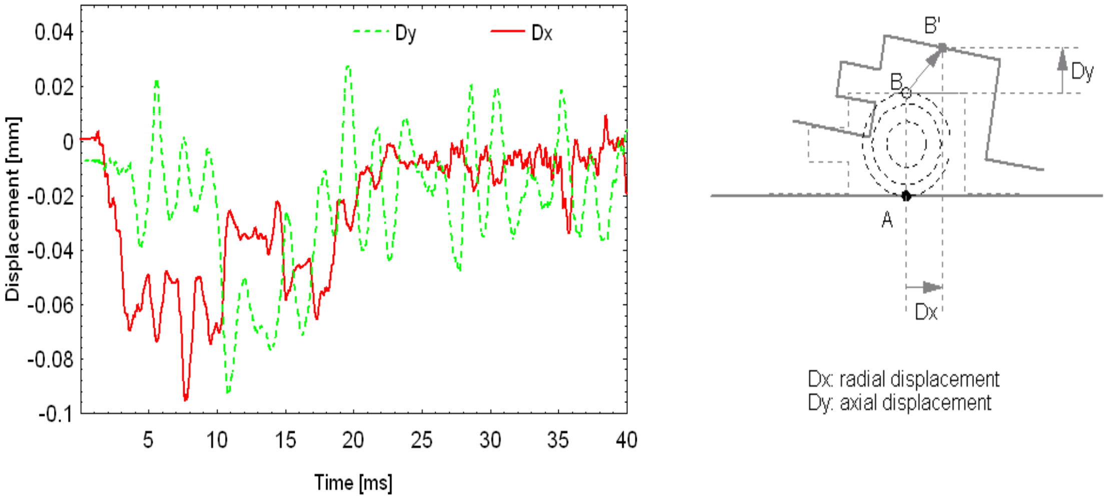



Fig. 6: Sliding (radial) and opening (axial) displacements at the groove of the large metallic seal of the primary lid

## 3 LATERAL IMPACT BY BUILDING OR AIRCRAFT FRAGMENTS

For the safety assessment of the cask in case of a lateral impact, the stressing of the lid seal system and the cask body can be compared with the results for similar Type B – test scenarios like the horizontal or slap down drop test. BAM investigations distinguished between the stressing of the cask due to the load function and subsequent loadings caused by cask collisions inside a storage site and/or when the cask finally hits the ground of the storage building. Because of the tremendous amount of possible final drop configurations there is a need for finding a conservative impact scenario. This was done in an effective way by analyzing the cask kinetics using rigid body substitutes for the cask. The mean results of these parameter studies are the amount of the rigid body acceleration or deceleration respectively and the exact cask position and movement (velocity and rotation) when hitting another cask or the ground of the storage building. The following two impact situations are distinguished between the impact with and without a cask collision. In the first case the boundary conditions, e.g. the friction between the cask and the storage building ground, are chosen in a manner to generate maximum values of rigid body decelerations. These decelerations cover also the subsequent loadings of clashed casks caused by the drop onto the ground of the storage building or the case of further cask collisions because the initial energy and impulse of the first hit cask are split into two parts and are additionally reduced by local plastic deformations and cask vibrations caused by the collision. The second scenario depends on the concrete cask allocation inside a storage building. Here, only the collision of two heavy casks of the same design and mass has been considered. But nevertheless very severe local loadings can occur if a relative light-weighting cask is accelerated to a high speed by the lateral impact and collides then with a heavy-weighting cask.

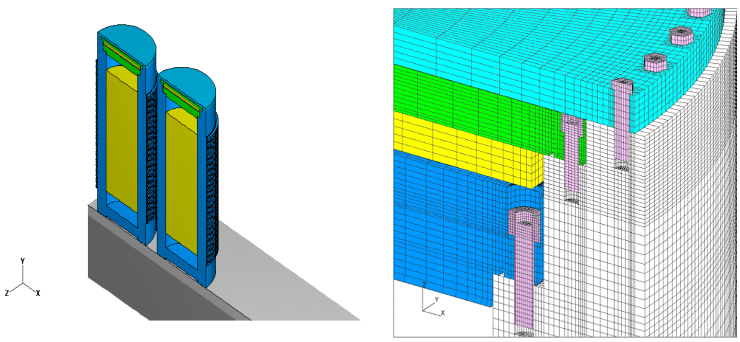


Fig. 7: a) FE-Model with the storage building ground (left)
b) Detail of the lid system with its bolts (right)

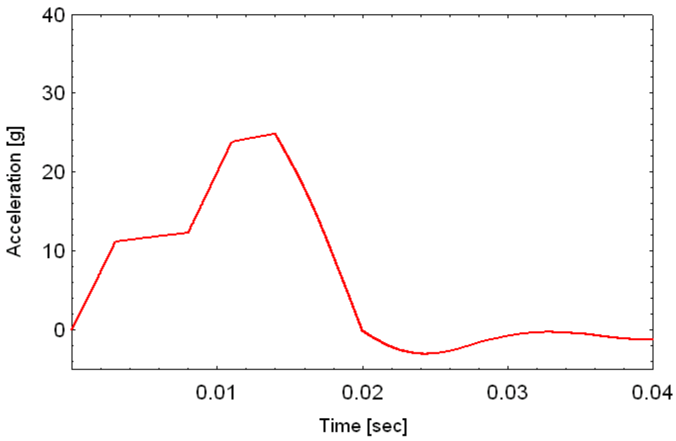
### 3.1 MODELLING OF THE LATERAL IMPACT ANALYSIS

In Fig. 7 the used 3-D finite element model is exemplified with the exception that the bolts in figure 7b in the executed simulations were modelled only with one-dimensional truss elements. By the way, the more detailed 3-D model (Fig. 7b) will be used for a further investigation. It is useful to model the cask fins not only because they reduce the maximum cask deceleration due to plastic deformations but also because they influence the cask movement in a positive manner as will be discussed later.

The Finite Element program code ABAQUS has the very important feature of changing a continuum cask FE model into a rigid body model easily. It is also possible to analyze rigid bodies and continuum FE submodels simultaneously. That is why the ground of the storage building has been built up as a half space (dry sand), supported by so-called elastic infinite elements and with an elastic-plastic concrete pad on top.
The constitutive material equations for the ground of the storage building are DRUCKER-PRAGER for the concrete with a minimum compression strength of 35 MPa and linear elastic for the sand (dynamic modulus of elasticity is 500 MPa). A parametric study has shown that a friction coefficient of 1 for all contact areas is conservative to estimate the stressing of colliding casks as well as to generate the most severe drop loadings.

### 3.2 DISCUSSION OF THE LOADING CASE -LATERAL IMPACT-

At first, for the analysis of the cask kinetics as mentioned already, the cask models were treated as rigid bodies (Fig. 8). The peak of the rigid body acceleration caused by the lateral impact according to the used load function (Fig. 8a) and/or during the drop of the cask onto the ground of the storage building (Fig. 8c) is sufficiently low compared with a similar Type B packages test condition. Whereas for the colliding casks unrealistic high decelerations are calculated (Fig. 8b) because e.g. the propagation speed of shock waves inside a rigid body is infinite.
For that reason, secondly, the cask clash was simulated by the use of elastic material properties for the casks, too. Fig. 9a shows a more realistic decelerations/accelerations curve for the elasticly modelled casks. Because of the influence of shock waves inside the cask structure, all Finite Element nodes oscillate too much to get a clear decel-



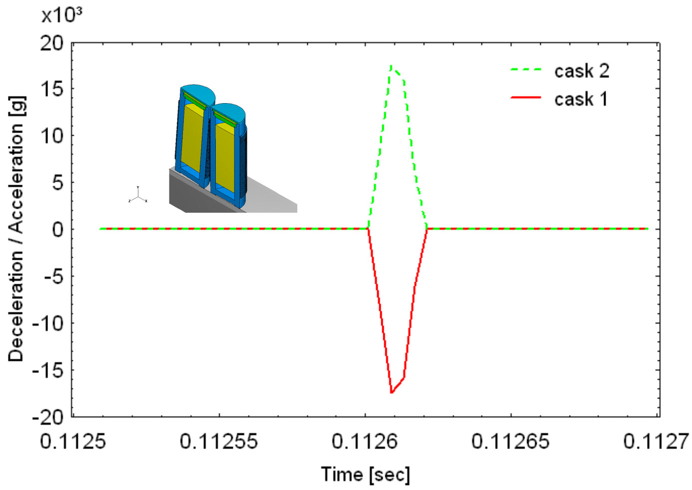
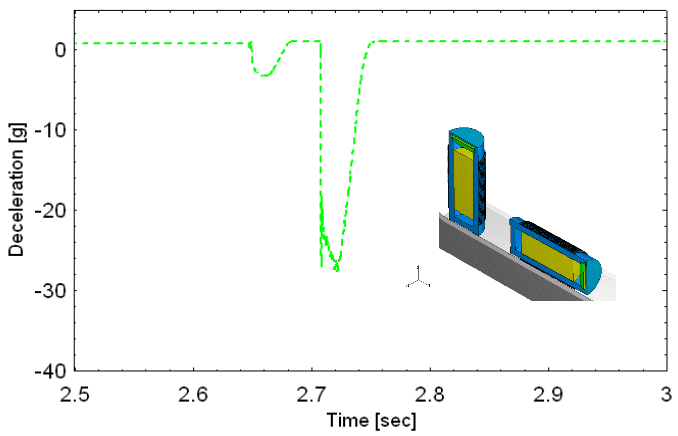
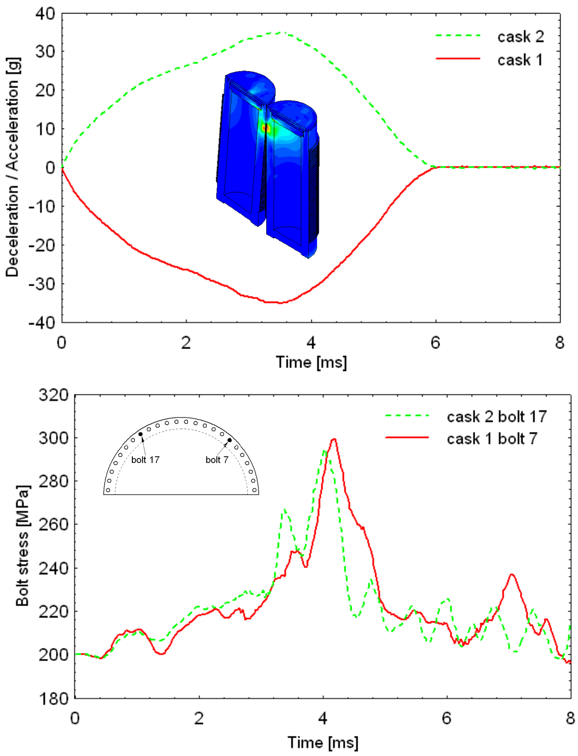




Fig. 8: Motion analysis of casks
a) Initial impact (above left),
b) Ridig body collision (above right),
c) Impact onto the ground of the storage building (below right).




erations/accelerations curve directly from the simulation. That is why the decelerations/accelerations were estimated by using the curve progression of the contact force. By the examination of the rigid body kinematics for the shown cask construction it turned out that because of the used impact function no ideal flat impact of the cask onto the ground of the storage building was possible. The cask touches the storage ground with the bottom fins first (first peak in Fig. 8c). The contact zone then "moves further" because of the angular momentum of the cask towards the head of the cask.

Finally, Fig. 9 shows some details of the stressing caused by the cask collision for the elastic simulation. The peak contact force reaches 40 MN, but the resulting stress inside the cask body is relatively low, except for the compression at the fins (Fig. 9b). The location and tension stress history of the highest stressed primary lid bolts are shown in Fig. 9c.



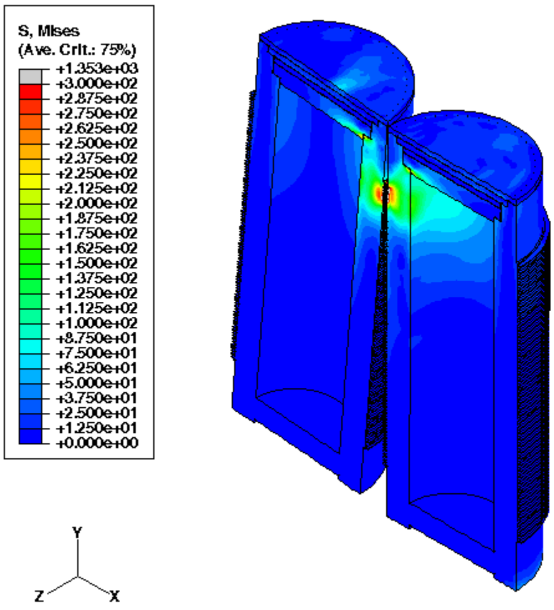




Fig.9: Results of the elastic calculation of the casks during the collision
a) De- and acceleration history in g (left above);
b) Stress field caused by the collision (right)
c) Bolt stress vs. time (left below)

## 4 SUMMARY

This paper describes methods to analyze the stressing of transport and storage casks for spent fuel in case of severe impact loads related to an aircraft crash and based upon that a conservative leakage rate for calculating the amount of radioactive release can be estimated. To do the latter, the relative displacements at the groove of the large primary lid seal must be calculated in connection with the determination of the maximum stressing of the primary lid bolts. If these bolts keep their pre-stressing then the leakage rate remains still very low, although relative displacements and stressing of the metallic seal may occur temporarily. The calculated relative displacements are compared with lab-examined [13, 14] or field test results [8] and based upon expertise in this field conservative leakage rates can be derived. At present, a quantitative relationship between the calculated deformations of the lid system and leakage rates is not possible. Because leak tightness is primarily influenced by the microscopic interaction of the involved material surfaces and their special conditions such a relationship will have to be confirmed experimentally.

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