



## **NUMERICAL SIMULATION OF 9 METER DROP OF A TRANSPORT AND STORAGE CASK WITH ALUMINIUM IMPACT LIMITER**

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### **ABSTRACT**

For the purpose of numerical simulation of 9 meter drop of a transport and storage cask with aluminium impact limiter, an elastic-incremental plastic material model with strain rate hardening acc. to Cowper-Symonds is used for the development of isothermal as well as adiabatic stress-strain relations of aluminium from the compression test at constant ambient temperature. After that, two different simulation strategies are compared. At first, the drop test is calculated fully coupled, i.e. with isothermal stress-strain relations and possible heat generation in the material. Then the drop test is recalculated in a very simplified manner with adiabatic stress-strain relations from the compression test in an isothermal simulation. Both calculation strategies show similar results in the investigated load scenario.

### **INTRODUCTION**

The 9 meter drop test onto an unyielding target is one of the important mechanical tests within the safety assessment of transport packages for radioactive material. In general the package is equipped with impact limiters to reduce the dynamic load on the cask by absorbing a major part of the kinetic energy. Some packages are equipped with aluminium rings as belt impact limiter around the cask body to absorb the kinetic energy in horizontal drop scenarios. In comparison to other materials, aluminium has a lot of favourable properties; it is homogeneous, relatively robust and has a high specific energy absorption capacity. During the drop test, there is high energy dissipation caused by large plastic deformation of the aluminium rings. Most of the dissipated energy is transformed to heat energy and lead to a temperature change inside areas of large deformation. That means, it is a coupled dynamic thermo-mechanical process. For simulation of such processes a suitable definition of thermo-mechanical conditions and an appropriate isothermal stress-strain relation of aluminium for different strain rates and different temperatures are needed. A suitable definition of thermo-mechanical conditions for the simulation of cask drop test is very difficult. Due to short impact time (milliseconds) an adiabatic approach as simplification for the thermo-mechanical condition can be applied for modelling in most cases. But even for such approach a suitable isothermal stress-strain relation of aluminium for different strain rates and for different relevant temperatures is needed. The stress-strain relation of aluminium needed for simulation shall be measured on appropriate specimens as a function of strain rate and temperature at isothermal conditions. Because of temperature change due to dissipated plastic energy at high strains, it is very difficult to get a suitable isothermal stress-strain relation under these conditions. Usually the specimen is measured only at constant ambient temperature with different strain rates. By this measurement the stress-

strain relation is isothermal at very low strain rates (quasi-static conditions) and adiabatic at very high strain rates (dynamic conditions).

In this study an elastic-incremental plastic material model with Cowper-Symonds parameters for strain rate depending material hardening is used for the evaluation of isothermal and adiabatic stress-strain relations of aluminium from specimens measured at constant ambient temperature. Hereafter two different simulation strategies are compared, on the one hand a fully coupled thermo-mechanical simulation with heat generation and on the other hand an isothermal simulation using adiabatic stress-strain relations without heat generation.

### **DROP TESTS OF PACKAGES WITH ALUMINIUM IMPACT LIMITER**

For transport and storage of vitrified High Level Waste from reprocessing a new cask design was developed by German company GNS Gesellschaft für Nuklear-Service mbH, Essen [1]. BAM as part of the competent authority system was responsible for mechanical safety assessment within the complete evaluation of the Safety Analysis Report. An extensive drop test program with an instrumented half-scale model cask was carried out [2].

Among other assessment goals the horizontal drop tests P01 (0.3m drop, 20°C) and P04 (9m drop, -40°C) were performed for testing jacket impact limiters made of aluminium. The test cask was equipped with several acceleration sensors and strain gauges. Figure 1 shows the test cask before these drop tests.



a)



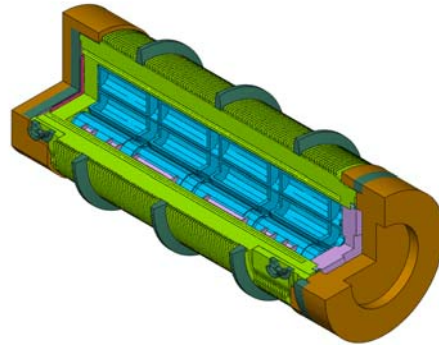
b)

**Figure 1. Scaled model cask before the test; a) P01 and b) P04**

### **FINITE ELEMENT MODEL**

For assessment purposes by competent authority, BAM developed a finite element (FE) model of the whole test scenario independently of the applicant. The FE model (Figure 2) of the drop test cask CASTOR<sup>®</sup> HAW/TB2 was built in a detailed manner to get reliable and accurate results for drop test simulations. The model consists of following main components:

- cask body made of ductile cast iron with moderator boreholes,
- primary lid and lid screws,
- trunnions,
- model canisters,
- model graphite columns,
- moderator plate on the cask bottom,
- closing plate on the cask bottom,
- bottom end and lid end impact limiter filled with wood and
- three jacket impact limiters made of aluminium.

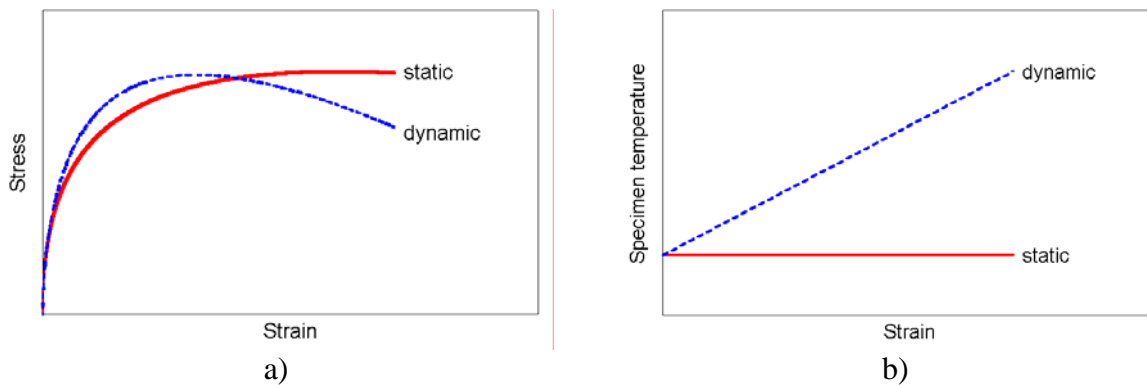


**Figure 2. FE Model of the drop test model CASTOR<sup>®</sup> HAW/TB2**

The gross weight is approximately 14.5 Mg. The complete FE model has about 300,000 elements and 400,000 nodes. It was built up with 3D solid elements of ABAQUS type C3D8R with linear interpolation and reduced integration for the dynamic simulation. All free surfaces (between cask body and canisters, cask body and primary lid, cask body and impact limiter as well as between impact limiter and foundation) were defined with ABAQUS option "general contact" without friction. For verification purposes of the FE model, an extra drop test of 0.3 m without impact limiter directly onto the IAEA foundation was carried out and successfully simulated [3]. After that the FE model with impact limiters and their connections to the cask body were developed to simulate the other drop tests with impact limiters, e.g. 9m drop tests P05 with lid impact limiter and P14 with bottom impact limiter [4].

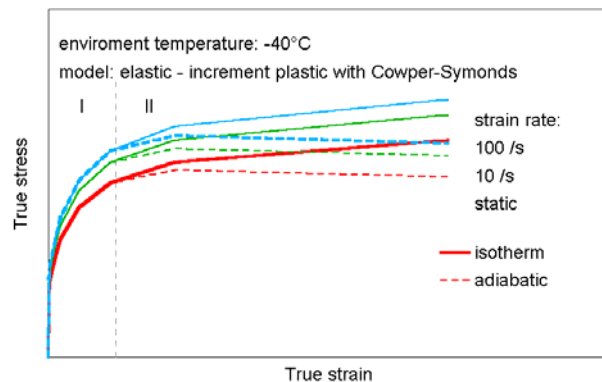
**MATERIAL MODEL OF ALUMINIUM**

The stress-strain curves of aluminium impact limiters used in the simulation are based on experimental investigations. The curves depend on temperature and strain rate. As in figure 3 presented, the measuring of isothermal stress-strain curves is difficult due to a significant temperature rise during large deformation along with high loading rates. The specimen behaviour is isothermal only for low strain rates (quasi-static case) and otherwise adiabatic even under laboratory test conditions.



**Figure 3. Characteristic behaviour of aluminium test specimen a) stress-strain curve and b) temperature-strain curve**

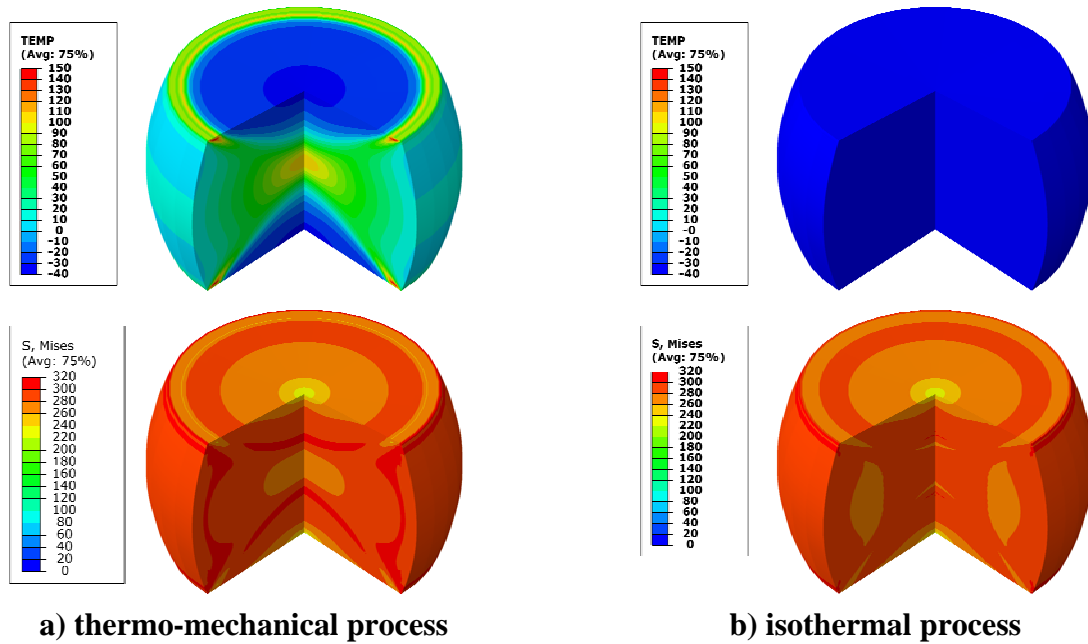
Johnson and Cook explain in their paper [5] that for a sufficient description of the material behaviour at high strain rates and for large deformation it must be distinguished between isothermal conditions and adiabatic conditions. In the present study, the isothermal behaviour of aluminium was derived from measurements at low strain rates (quasi-static case); the adiabatic behaviour was derived from measurements at high strain rates (dynamic case). The experimental findings were described by an elastic-incremental plastic material law with strain rate hardening according to Cowper and Symonds for different temperatures. The same Cowper-Symonds parameters were used for isothermal as well as adiabatic curves. Figure 4 shows the derived isothermal and adiabatic stress-strain curves depending on the strain rate at a temperature of  $-40^{\circ}\text{C}$ . They are divided into a small deformation area (area I) and a large deformation area (area II). The limit line between area I and area II is defined by the point where the stress difference between the measured quasi-static curve and measured dynamic curve (for the highest investigated strain rate) has its maximum. In area I there is no difference between isothermal and adiabatic behaviour, thus the Cowper-Symonds parameters can be taken from there. In area II the isothermal dynamic curves are constructed from the isothermal quasi-static stress-strain curve postulating the same dynamic hardening as in area I; the adiabatic dynamic curves in area II are calculated from the stress-strain curve measured at the highest strain rate and the Cowper-Symonds parameters from area I.



**Figure 4. Schematic isothermal and adiabatic stress-strain curves of aluminium**

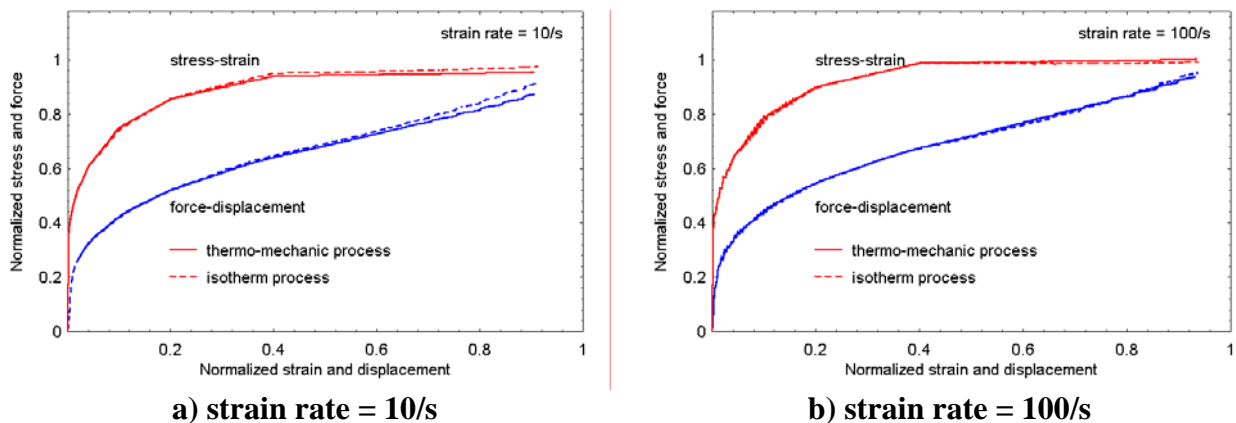
### **SIMULATION OF MATERIAL TESTING**

For purpose of verification of material parameters described in prior section, different compression tests of test specimen were simulated with the finite element method. A thrust plate is controlled with different loading velocities for quasi-static and dynamic tests. The material testing under different dynamic conditions (strain rate 10/s and 100/s resp.) was simulated using the material definitions explained in prior section. Two different strategies were applied: 1) coupled thermo-mechanical calculations under consideration of heat generation inside the specimen with given isothermal stress-strain relations depending on temperature; 2) isothermal calculations without consideration of a temperature change inside the specimen, where the adiabatic stress-strain relations for the initial temperature were used. In the latter case the influence of temperature change is included in the definition of the adiabatic stress-strain relations, see above. For the evaluation of the simulation results the global force-displacement curves were calculated and compared with experimental results.



**Figure 5. Illustration of compression testing of aluminium specimen**

Figure 5 shows the deformation of specimen from dynamic simulations (strain rate = 100/s) with corresponding temperature (Temp) and equivalent stress (S, Mises) distribution from coupled thermo-mechanical calculation (Figure 5a) as well as from isothermal calculations using adiabatic stress-strain relations (Figure 5b). The rise of temperature in the centre of the specimen in the thermo-mechanical simulation is higher than 100 K (Figure 5a). The differences in stress distribution between the two calculations are negligible small.



**Figure 6. Force-displacement and stress-strain curves of simulations with different strain rates**

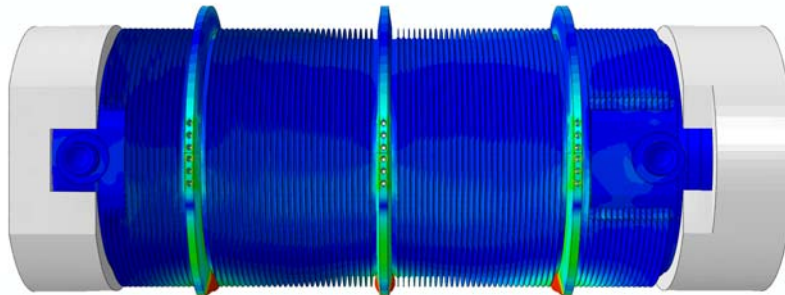
Figure 6 shows the calculation results for the global force-displacement curve derived from the thrust plate and the local stress-strain curve from the centre of the specimen at strain rates of 10/s (Figure 6a) and 100/s (Figure 6b) respectively. The real behaviour of an aluminium impact limiter caused by deformation during the 9 meter drop test is within these limit curves. The two different



strategies (thermo-mechanical and isothermal) show only very small deviations at medium strain rates for large deformation (Figure 6a, strain > 30%) and insignificant deviations at high strain rates (Figure 6b) at all.

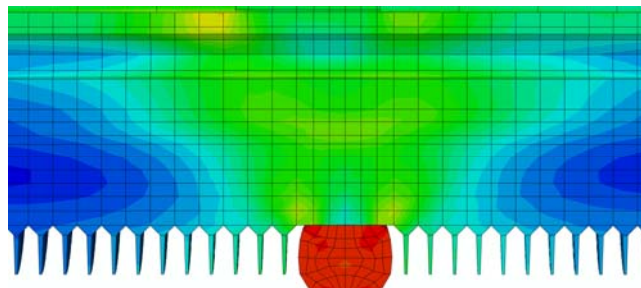
### **SIMULATION OF DROP TESTS**

The dynamic calculations of drop tests were carried out with ABAQUS/Explicit version 6.5 in 2007 (Figure 7). Simplified simulations were done without thermo-mechanical coupling at isothermal conditions using adiabatic stress-strain curves. More sophisticated simulations were carried out with thermo-mechanical coupling under consideration of heat generation inside the aluminium material using isothermal dynamic stress-strain curves. The simulation results for test P01 (0.3m drop) and test P04 (9m drop) were generated for the following cases: a) isothermal calculation with isothermal stress-strain curves (Iso), b) coupled thermo-mechanical calculation with isothermal stress-strain curves (Therm) and c) isothermal calculation with adiabatic stress-strain curves (Adia).



**Figure 7. Simulation result of the drop test with ABAQUS**

Figure 8 shows schematically the stresses of the cask body near aluminium impact limiters during a 9 m drop test onto the unyielding (rigid) target at a temperature of -40°C. The aluminium impact limiters absorbed the kinetic energy for the most part. The cask body remained undamaged as shown by the test. The simulation of a 9 m drop test with thermo-mechanical coupling shows a considerable temperature increase in the area of maximum stresses of the jacket impact limiters because of large plastic deformation.

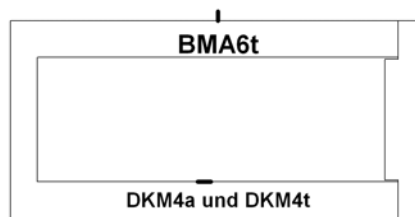


**Figure 8. Illustration of maximum stresses inside the cask body near an aluminium impact limiter (9 m drop)**

Table 1 shows the comparison of the normalized maximum cask body deceleration at the measuring point BMA6t (Figure 9) gained from different simulations (Iso, Therm and Adia) and from experiments (Exp). The calculated maximum decelerations of test P01 meet the measured value and do not differ because of only small deformation inside the aluminium impact limiters and hence no differences between the several approaches for the constitutive behaviour of aluminium as described above. For test P04 the isothermal calculation (Iso) gives the highest maximum deceleration because the material is modelled too hard in this approach compared to reality. The other two simulations – coupled thermo-mechanical calculation (Therm) and isothermal calculation with adiabatic stress-strain curves (Adia) – show similar but conservative results compared with the test result because of the more realistic description of material behaviour in these cases. Strains at measuring points DKM4a and DKM4t (Tab. 2) have the same trend as the deceleration signal.

**Table 1. Normalized maximum decelerations at measuring point BMA6t**

	<b>P01</b>	<b>P04</b>
<b>Exp</b>	0,2	0,75
<b>Iso</b>	0,2	0,85
<b>Therm</b>	0,2	0,78
<b>Adia</b>	0,2	0,79



**Figure 9. Chosen measuring points on the cask body used for comparison**

**Table 2. Normalized maximum strains at measuring points DKM4a and DKM4t**

	<b>P01</b>		<b>P04</b>	
	<b>DKM4a</b>	<b>DKM4t</b>	<b>DKM4a</b>	<b>DKM4t</b>
<b>Exp</b>	0,08	0,14	0,23	0,42
<b>Iso</b>	0,06	0,15	0,29	0,60
<b>Therm</b>	0,06	0,15	0,21	0,51
<b>Adia</b>	0,06	0,15	0,21	0,51

## CONCLUSIONS

This paper describes the numerical simulation of two drop tests (0.3 m and 9 m) performed within an extensive drop test programme with a half-scale model cask with jacket impact limiters made of aluminium. At first a detailed 3D finite element model was developed and verified by a drop test performed without impact limiters. After that the aluminium impact limiters and their connection to the cask body was taken into account. The commercial FE code ABAQUS™ has been used for all



calculations. The simulations were compared with results of the drop tests. A fitting strategy has been suggested for deriving isothermal and adiabatic stress-strain curves of aluminium depending on temperature and strain rate from dynamical experimental investigations of small specimens under constant ambient temperature. The derived stress-strain curves were verified by simulating unconfined compression tests. Hereafter dynamic simulations of drop tests were carried out under consideration of these stress-strain curves of aluminium. At first the simulations were done without thermo-mechanical coupling at isothermal conditions using adiabatic stress-strain curves. In the next step more sophisticated simulations were carried out with thermo-mechanical coupling under consideration of heat generation inside the aluminium material using isothermal dynamic stress-strain curves. The comparison of the calculation results shows that for the drop tests considered here both computational approaches lead to comparable results.

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