

**Drop Tests and Numerical Impact Analyses of  
New Cask Designs for High Activity Waste (Haw) and Spent Fuel  
– Updated Bam Design Testing Experiences –**

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**ABSTRACT**

In Germany, several new cask designs by international vendors (Gesellschaft für Nuklear Service mbH (GNS), TN International (TNI), Mitsubishi Heavy Industries (MHI)) are under design testing and within official licensing procedures for transport and storage casks for spent fuel and high activity waste (HAW). BAM (the German Federal Institute for Materials Research and Testing) has been performing several extensive drop test series with prototype casks to evaluate the safety margins against mechanical test conditions. An important project is the new GNS cask design for HAW, the CASTOR<sup>®</sup> HAW 28M. Sixteen drop tests have been performed under transport conditions with a 1:2 scale cask model equipped with impact limiters and extensively instrumented with strain gauges and accelerometers. Additionally, the accident scenario inside a storage facility has been investigated by a cask drop without impact limiters onto a nearly unyielding target. This scenario is dominated by highly dynamic effects and interactions between the test object and the target.

Complete safety assessments for such mechanical accident scenarios and highly loaded cask structures require additional numerical investigations. They are done by complex finite element (FE) calculations that provide detailed dynamic stress and strain analyses all over the cask structure and at such points where sensors can't be applied. In addition, differences between the material property quantities of the prototype cask and the minimum material property requirements for the cask series production can be investigated as well as dimensional tolerances.

By example, the safety assessment method and some of its special aspects are illustrated by the cask drop without an impact limiter onto a hard foundation. The main aspects and challenges are to develop a sufficient computer model of the cask and foundation and to provide detailed interpretation of the large amount of measurement data for achieving good correlation between experimental and numerical results.

**INTRODUCTION**

As described in former publications [1, 2, 3, 4], BAM has established a completely new drop test facility to test transport and storage casks of a new cask generation with larger dimensions, higher total masses and, last but not least, higher internal stress levels. The new facility facilitates the development and safety evaluation of new spent fuel and HAW transport and storage cask designs with better cost-benefit ratios. Drop tower and foundation were designed to test ob-

jects up to 200 metric tons. The facility includes all necessary infrastructures such as the preparation building, handling equipment, measurement hardware and data recording equipment. The drop tower went into successful operation with the first drop tests during the PATRAM conference in September 2004.

### BAM DROP TESTING WITH NEW CASK DESIGNS

During the last two years, BAM has performed a series of drop tests with three different new cask designs from international vendors:

- The MSF 69 BG from Mitsubishi Heavy Industries (Japan), a 126 Mg (without impact limiters) transport and storage cask for 69 BWR spent fuel elements,
- The TN 85 (TN 81) cask manufactured by TN International (France) for 28 canisters of vitrified nuclear waste from reprocessing and
- The CASTOR<sup>®</sup> HAW 28M manufactured by GNS (Germany), which is a transport and storage cask for 28 canisters of vitrified nuclear waste from reprocessing.

Fig. 1 shows the scale or prototype casks in typical drop test orientations and with their masses and dimensions. For the MSF 69 BG, a full-scale test cask was used for five drop tests and a 1:2.5 reduced scale model was used for eight additional drop tests.



Fig. 1. BAM drop test series in 2004 - 2006 with new cask designs

Twelve drop tests were performed with the TN 85 (TN 81) 1:3 reduced scale cask model. Because of the smaller mass and dimensions of the test object, BAM was able to perform these tests at its smaller test facility at the main BAM location in Berlin and in parallel with the other test series at the new Horstwalde drop test facility.

Another extensive drop test series was performed with the 1:2 scale CASTOR<sup>®</sup> HAW 28M/TB2 model cask under various drop orientations (vertical, horizontal, angular). Fifteen tests were performed under transport conditions with the cask equipped with impact limiters, and one 0.3 m vertical drop test was performed without impact limiters onto the nearly rigid IAEA target at the test site. The latter test represented a handling accident on a real foundation inside the Gorleben interim storage facility.

In all cases, the test casks were equipped with a large number of strain gauges and accelerometers. The data were collected by a 64-channel high frequency data recording system that was aided by a data reduction computer system. Additional measurements include photogrammetry, high-speed video recording and helium leakage rate measurements of the cask lid closure systems. Most test series were usually performed with only one test cask. Because of different drop orientations and scenarios, e.g. horizontal drop, vertical drop, puncture test, etc., the test cask was subjected to maximum stresses in different areas, especially the impact zones. In most cases, there was negligible damage, and the cumulative cask exposure was acceptable and demonstrated additional safety margins. Publications [5, 6] contain more information about BAM measurement techniques.

## **SAFETY ASSESSMENT STRATEGY**

Safety assessments for new and complex cask designs for transport and/or storage licensing need challenging strategies by using different methods such as full-scale prototype tests, model tests of appropriate scale, calculations, and references to previous satisfactory demonstrations [9]. For the current BAM design test procedures the safety assessments for the mechanical IAEA test conditions or the storage site specific accident conditions start with preliminary finite element (FE) calculations (performed by the applicant and checked by BAM) primarily with the scaled test cask model for verification of the proposed test cask instrumentation and test plan. Based upon the finite element precalculation, extensive test cask instrumentation can be located appropriately and estimates of sensor levels provided. After installation of the instrumentation a series of drop tests consisting of different test sequences is performed. The results of the first test and subsequent test sequences are evaluated and reviewed to determine if adjustments of the test plan are necessary.

After completion of the drop tests, numerical post-test analyses are carried out by the use of the finite element method (FEM). These analyses provide a detailed assessment of the entire test cask structure. The evaluations focus on the quality of the correlations between test data and calculated data for all measurement points, over the impact history, and for the different drop test scenarios. These evaluations ensure that all relevant physical effects were considered by the cask analyses in an appropriate way to serve as a basis for the following safety assessments. Because of the complexity of the parameters that influence both analysis and testing, the validation of ex-

perimental boundaries including material properties and the numerical aspects is often a challenging task. For that reason, a detailed analysis of the drop test results is performed after the drop test. Because during the testing, the desired ideal boundary test conditions often cannot be met exactly in practice, post-test analyses are carried out under the real (actual) conditions of the test. At the successful completion of these steps, a validated finite element model results.

Frequently only one model is developed for all load cases to lower the total cost and effort for the modelling. Generally, such models are very complex with many material interactions. However, it can be more useful to develop separate reduced scale models to understand the physical correlations (boundary conditions, material behaviour etc.) and to show the individual aims of the safety analyses.

BAM develops its FE models independently of the applicant and uses alternative FE codes to analyse these models. In some cases, the material behaviour can be described with similar material models when equivalent models are missing in the material library of an alternative code. Also, the exact implementation of a complex material behaviour may differ. Through the use of different codes, possible errors in the numerical simulation may be found.

With the validated finite element model, ideal, i.e. worst case, boundary conditions can be scaled up to analyse the full-scale cask design and to verify scaling laws. The maximum stressed cask areas and components with respect to e.g. fracture mechanics, plastic deformations and leak-tightness of sealed lid systems can be identified and evaluated for the final safety assessments. It must be recognized especially that nonlinear effects cannot be scaled with simple rules. When scaling is not feasible, the investigations must be carried out directly with a full-scale model.

## **ANALYSES OF THE STORAGE SITE SPECIFIC ACCIDENT SCENARIO INVOLVING THE CASTOR<sup>®</sup> HAW 28 M/TB2**

In spite of the fact that drop test series are dominated by the requirements from the IAEA transport regulations that include subjecting the package to different drop orientations, BAM requires additional evaluation of storage site specific accident scenarios where casks are not equipped with impact limiters. These scenarios dedicate that a cask body may directly hit a very hard foundation, which leads to a totally different mechanical reaction and stress state as compared to the relatively smooth impact by a properly designed impact limiter. BAM has investigated such cask impacts without impact limiters during the last several years through a research project called EBER that is supported by the Federal Ministry of Education and Research (BMBF) under contract 02 S 8021 [7]. Amongst others, a procedure using FEM for the stress analysis of cubic ductile cast iron containers under mechanical accident conditions was developed and verified with experimental results. The analysis of the highly dynamic stresses was very successful using this procedure. However, it was obvious that impacts from small drop heights can induce highly dynamic stress waves with possible high maximum stresses and strain rates and that the contact conditions and properties of the foundation do significantly influence the cask reaction.

With that knowledge BAM took the opportunity to start an investigative program within the framework of the German atomic law licensing procedure for the CASTOR<sup>®</sup> HAW28M [8]

where BAM would perform cask design testing on behalf of BfS (Federal Office for Radiation Protection). In coordination with BfS and GNS an additional drop test including strain and deceleration measurements and high-speed video recording with the 1:2 scaled test cask (TB2) from 30 cm heights was performed at the BAM drop test facility. The selected test scenario considers one critical accident situation if the cask drops from the crane of the storage building during handling operation and hits the ground. The test provided the required test data, especially strain measurements, to validate the finite element model. Fig. 2 shows the drop test configuration and a photo sequence of the impact.

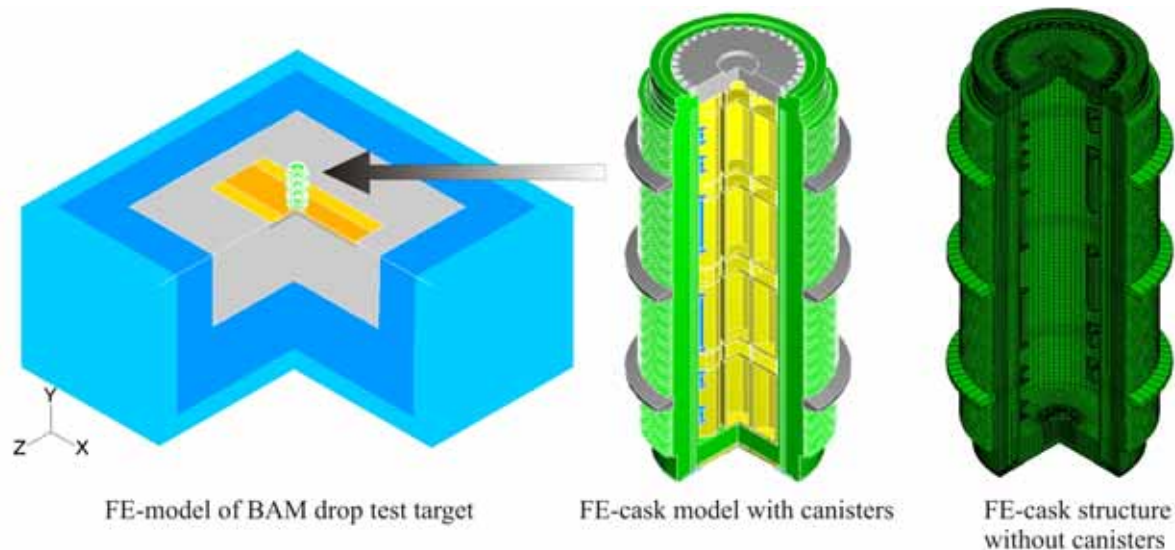


**Fig. 2. 0.3 m vertical drop test at BAM with CASTOR<sup>®</sup> HAW/TB2 onto the 2,600 Mg IAEA target**

Based on the interpretation of videos and measurement data as the impact sequence illustrates, the cask hits the ground in nearly a perfect orientation and only a very small angle  $< 0.1^\circ$  was observed between target and bottom of the cask. After the primary impact, the cask inclined visible (as shown in picture 3 of the sequence) and rebounded with additional slight rotation. The cask inclination during the secondary impact led to a concentrated load and a visible imprint on the steel plate of the target.

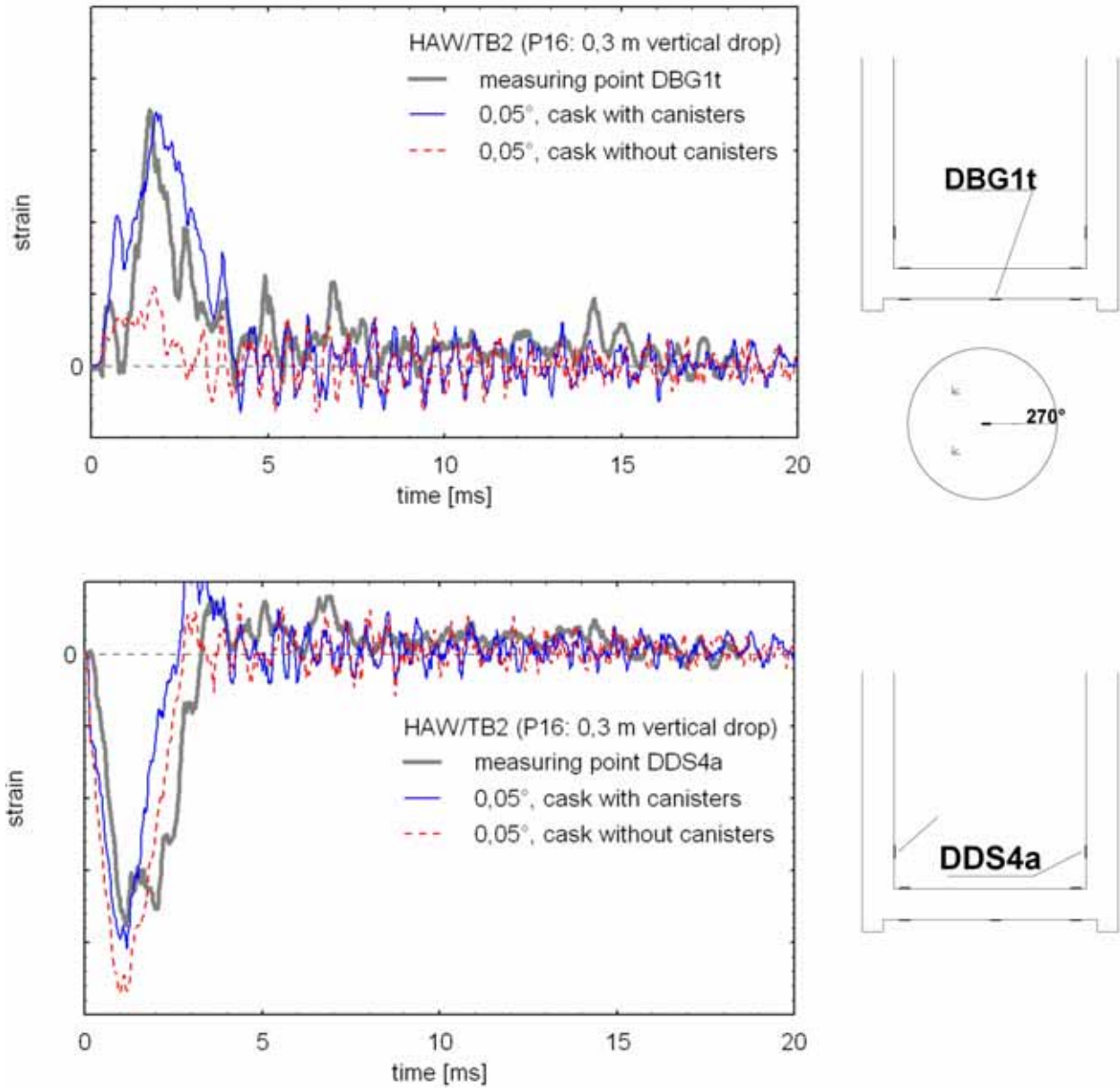
For reanalysis of the drop test, BAM developed a detailed finite element model of the test cask and its main components including the components inside of the cask as shown in Fig. 3. Because slight impact angles in combination with selected strain measurement points have to be considered during the evaluation process, it was essential to construct a complete three-dimensional cask model. A segment model using symmetry conditions was not able to capture the response of the unsymmetrical impact. The three-dimensional model, of course, results in a higher but necessary numerical effort. Additionally, not only the cask model was important to build but also the precise modeling of the IAEA foundation of the BAM drop test facility. The hard impact contact conditions between the cask and the foundation surface have a large influence on cask response. The impact stress waves generated by the cask that are induced into the foundation and their transmission and reflection are mainly influenced by structural transitions

between different materials or components. For that reason, it was necessary to build a detailed foundation model with dimensions large enough to avoid unrealistic reflections of stress waves and their possible influence on the cask reaction during the calculation time, see Fig. 3. It should be pointed out that such contact problems are mainly specific to hard impact scenarios without the use of additional impact limiters.



**Fig. 3. BAM finite element model of CASTOR<sup>®</sup> HAW/TB2**

The modeling and the following dynamic calculations were performed with the ABAQUS/Explicit finite element code which has been very successfully used at BAM for several years for physically similar analyses for various research projects. The main criteria for a sufficient correspondence between test and calculational results are the correlation of a set of representative measurement points over the cask structure and during the whole significant impact period. In this case, there were at first seven measurement points at the bottom area of the cask. The time period considered was 20 ms which is more than four times the duration of the primary impact. Fig. 4 shows two representative strain histories, one for the center of the cask bottom and one at the inner side wall. The evaluation considered very small impact angle of  $0.05^\circ$  that was observed during the evaluation of the video recordings. Additional analyses with different angles of  $0^\circ$ ,  $0.05^\circ$  and  $0.1^\circ$  showed a significant influence on the results. Another analytical verification performed includes the canisters inside of the cask. The differences between the dotted and the continuous line in Fig. 4 show that the canister responses are captured in a sufficient manner. The oscillations after 5 ms represent stress waves running through the cask body which are influenced by the interaction of the canisters amongst themselves and with the cask. Further verification evaluated finite element modelling of cask (e.g. FE mesh refinements), foundation and contact conditions.



**Fig. 4. Comparison of FE-calculation results and strain measurement data for CASTOR<sup>®</sup> HAW/TB2 (for confidential reason without strain dimension)**

The graphs represented by Fig. 4 show reasonable correspondence of test data and calculational results which means that the physical test response was sufficiently captured by the numerical model. With the last correlation, an appropriate basis for further strain and stress analyses of the whole cask structure under worst-case conditions without an impact angle has been demonstrated.

## **FURTHER INVESTIGATIVE STRATEGY INVOLVING THE CASTOR® HAW28M/TB2 SITE SPECIFIC DROP TEST**

After verifying the finite element calculation model as described above, stress-strain analyses over the entire cask structure and especially the top area with the lid system will be performed to determine the highest stressed areas. Based on past experience, the results for the 0° impact angle are the most critical. Off-angle impacts demonstrate very clearly that in case of such impact conditions, a single drop test may not be sufficient. However, with the help of the numerical simulation of the drop test scenario, the number of real tests may be reduced. But before doing that, the experimental boundary conditions must be well understood.

The most critical stress-strain levels and the material and component specific safety margins against failure modes like brittle fracture and plastic deformation have to be evaluated as the basis for checking the safety assessments given by the applicant GNS within the licensing procedure.

Additionally, the comparison of the analysis results (maximum stress levels, strain rates, stress and strain histories during and after the impact) with those of the vertical 9 m drop test onto the cask bottom equipped with an impact limiter will be helpful for final safety evaluation.

## **CONCLUSIONS**

The accident scenario inside a storage facility has been investigated by a cask drop without impact limiters onto an unyielding target. The test scenario and experimental results were shown. On one hand, a comprehensive computer model of the cask and the foundation was used to understand the experimental data, and on the other hand, this model was validated by means of the measured data. After scaling of this model to full-scale cask size, the numerical model can be used to calculate non-measured information such as stresses and strains in the entire cask structure as the basis for the complete safety assessment.

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