Transport and Storage Cask Safety Assessment
- Drop Tests and Numerical Calculations -

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ABSTRACT

BAM (the German Federal Institute for Materials Research and Testing) has been performing cask design testing for more than 30 years with a large number of prototype casks of original dimensions and of 1:2 or 1:3 scales. In 2004 a brand new drop test facility was built at the new BAM test facility at Horstwalde about 80 km to the south of Berlin. In September 2004 first demonstration tests with 2 different cask designs were performed in connection with the PATRAM 2004 conference held in Berlin. The dropped prototype casks had gross masses of 141 and 181 metric tons. Since that time BAM has been performing a lot of more drop tests with new cask designs developed by different international cask manufacturers for getting German Type B(U) transport licenses.

Current safety assessments especially for mechanical accident scenarios require a combination of experimental and analytical/numerical proofs commonly, because both methods offer specific options and advantages with respect to more and more detailed structural analyses. That again is a consequence of the permanent cask design optimisation for commercial reasons leading to higher stress levels in general. For that reason BAM also improves its numerical analyses capacities including the operation of different software codes. A general BAM guideline describing basic requirements for numerical safety assessment reports gives a good orientation for both applicants and inspectors. But different details of any cask design and safety assessment have to be taken into account and lead to specific questions, investigations and experiences.

This paper gives an overview about the new BAM drop test facility and the ongoing drop testing there and it presents current experiences and results of numerical cask analyses and the specific methods developed and used by BAM. In this context special attention is turned to the correlation between experimental and numerical results and an outlook to future developments is given.

INTRODUCTION
- BAM Transport and Storage Cask Design Testing Experiences -

The task of Type B package assessment activities for BAM arose from the necessity for transport and storage of spent fuel from German power reactors in the 1970s. First cask designs were developed and as an obvious method for demonstrating safety levels directly drop tests with prototype cask and model casks come up rapidly. For that reason BAM built a first big drop test facility at Lehre about 200 km west of Berlin for testing prototype casks with gross masses of up to 80 t in accordance with the IAEA regulations [1, 2].

After some first test series with French casks like TN 8/9 and TN 12 in the mid-1970s BAM started testing the new CASTOR® cask design developed by GNS (Gesellschaft für Nuklear-Service mbH) in 1978. In contrast to the TN cask design with steel-lead-steel walls the new CASTOR® casks were made of monolithic ductile cast iron.

The first six drop tests were performed with a 1:2 model of a CASTOR Ia (designed for carrying four PWR spent fuel elements) with a total mass of about 8 t. Because of the completely new material BAM required four additional drop tests with an original prototype cask with a gross mass of about 65 t. These were the first tests worldwide with such a big cask. They became mainly necessary because of the ductile cast iron quality depends on the wall thickness and the mass of the casting. In particular, a greater wall thickness leads to lower relevant material properties like fracture strength and fracture toughness. The test procedure for qualification of the new material required drop tests at the lowest temperature of -40°C to be considered for transport as well as additional investigations of material specimens from the prototype cask. The CASTOR® Ia was at first equipped with only one lid for transport. But with the development of transport and storage casks with long-term resistant two-lid systems with metallic seals, new drop tests became necessary. In this field the following drop tests with:

- a 1:2 model of a CASTOR® IIa for carrying 9 PWR spent fuel elements,
- an full-scale CASTOR® Ic prototype cask for carrying 16 BWR spent fuel elements,
- a 1:3 model of a TN 1300 for carrying 12 PWR spent fuel elements,
- an full-scale TN 900 prototype cask for carrying 21 BWR spent fuel elements, and
- a 1:3 model of a TS 28V for vitrified high active waste from reprocessing

were of great importance.

Additionally, BAM has performed several tests with smaller casks for non-heat-generating radioactive waste, e.g. of the GNS MOSAIK design, as well as a lot of extra-regulatory tests, e.g. to investigate existing safety margins against an accidental military aircraft crash. A good overview about extended mechanical tests with many different cask designs is given in [3]. All together BAM has experience from more than 70 drop tests with full-scale prototype and 1:2 to 1:3 model casks at the first drop test facility at Lehre.

BAM does also investigate thermal cask behaviour for operating conditions and accidental fire scenarios with fire tests and numerical calculations but this topic is not discussed here.

THE NEW BAM DROP TEST FACILITY FOR CASKS OF UP TO 200 TONS

With the ongoing development of transport and storage casks of a new generation with better cost-benefit relations and in consequence of that with larger dimensions, higher total masses and

-last but not least- with higher inner stress levels BAM decided to construct a new drop test facility for future demands. That facility should allow drop testing of full-scale spent fuel and HLW casks of the new generation. The new drop test facility (drop tower and foundation) was developed for test object masses of up to 200 tons including all necessary infrastructure like preparation building, handling equipment and measurement techniques including data recording equipment. The project was planned and realised in a really short time. The drop tower was put into successful operation with the first drop tests during the PATRAM conference in September 2004.

The new BAM drop test facility is constructed for test objects with masses of up to 200,000 kg and provides the capability for lifting and dropping in any desired orientation from a height of 9 m or more (Fig. 1.) [4]. The main construction features are:

- a 36 m high drop tower as steel pipe construction,
- a 200 ton hoist on top of the drop tower, with a maximum hook height of 30 m,
- a 24 m x 20 m closed test preparation building below the drop tower with moveable roof and rolling gates,
- a 80 ton overhead crane inside the test preparation building.

The unyielding target is realized by a reinforced concrete block with 14 m length, 14 m width and 5 m depth and a mass of 2,450,000 kg.
The impact pad consists of a center steel plate of 2.5 m x 10 m x 0.22 m and two side steel plates of 1.0 m x 10 m x 0.22 m, also embedded and fixed on the concrete block.

Various detaching devices developed by BAM are used to release packages, depending upon their weight. For packages up to 200,000 kg, a hydraulically operated system is in use (Fig. 1.). The technical principle is that the rupture of a steel bolt by a hydraulic mechanism with an electric controlling device releases the test object, causing it to drop moment free. The bolt is adapted to the test object's mass by varying the cracking pressure on the selected notched bolts diameter. Up to an object mass of 20,000 kg smaller release devices operate by electro-mechanical mechanism.

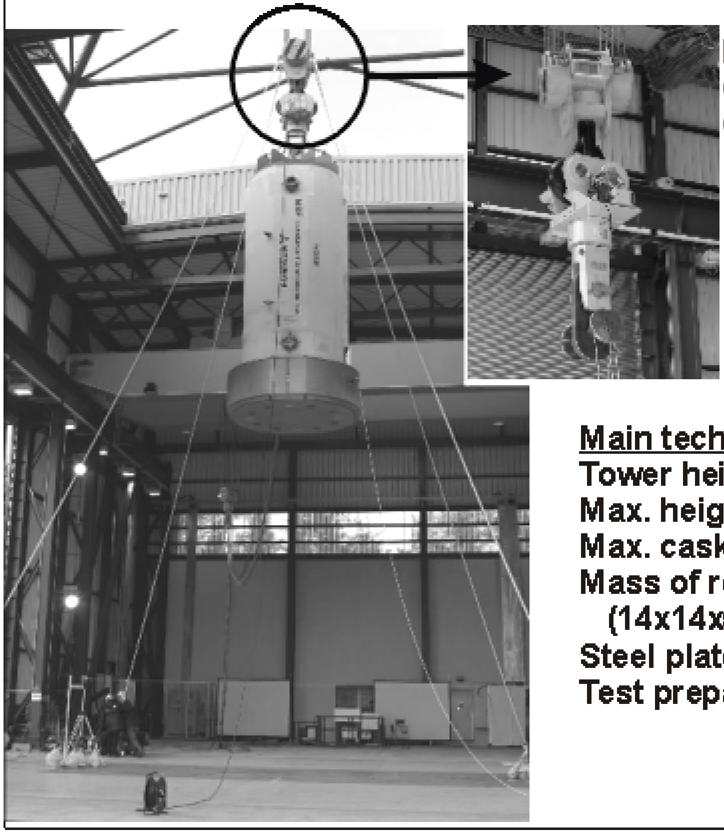
The first drop tests with two big spent fuel casks (a 141,000 kg Mitsubishi MSF-69 BG cask and a 181,000 kg GNS CONSTOR V/TC cask as shown in Fig. 2.) were performed in connection with technical tour events during the PATRAM 2004 conference and demonstrated the successful operation of the new facility. The 181 t CONSTOR cask was the heaviest spent fuel cask ever been tested worldwide. In the meantime (from Sept. 2004 to Dec. 2005) BAM has performed 3 more drop tests with the full scale MSF-69 BG cask, 7 drop tests with 1:2.5 scale MSF-69 BG model cask, 15 drop tests with the 1:2 scale CASTOR® HAW 28M/TB2 model cask (top picture of Fig. 2.) with various drop orientations (vertical, horizontal, angular). Publications [5 - 8] contain some more information about BAM measurement techniques, cask design features and first drop test results.

The bottom pictures and the diagram in Fig. 2. show a 9 m slap-down drop test with a full scale MSF 69 BG cask and the measured decelerations at the bottom and the lid side of the cask. That demonstrates the fact that the maximum decelerations of the secondary impact of the lid side are much higher (in this case about twice as high) as those of the primary impact and that also in the drop orientation case the lid side would touch the ground first. The velocity history in the diagram shows the additional acceleration of the lid side initiated by the primary impact. But despite the fact that the lid-seal-system and its leak-tightness function are stressed at most by this accelerated side impact, it has to be considered that correlations between decelerations and safety relevant dynamic material stresses have to be evaluated in detail for final safety assessment.

BAM test facility
(aerial view)

Drop tower
with closed test building

Vertical drop test configuration



Hydraulic detaching device

Main technical data:

Tower height: 36m
Max. height of stroke: 30m
Max. cask mass: 200,000 kg
Mass of reinforced concrete foundation (14x14x5 m^3): 2,450,000 kg
Steel plate impact area (10x4.5x0.22 m^3)
Test preparation area: 24m x 20m

Fig. 1. The new BAM drop test facility

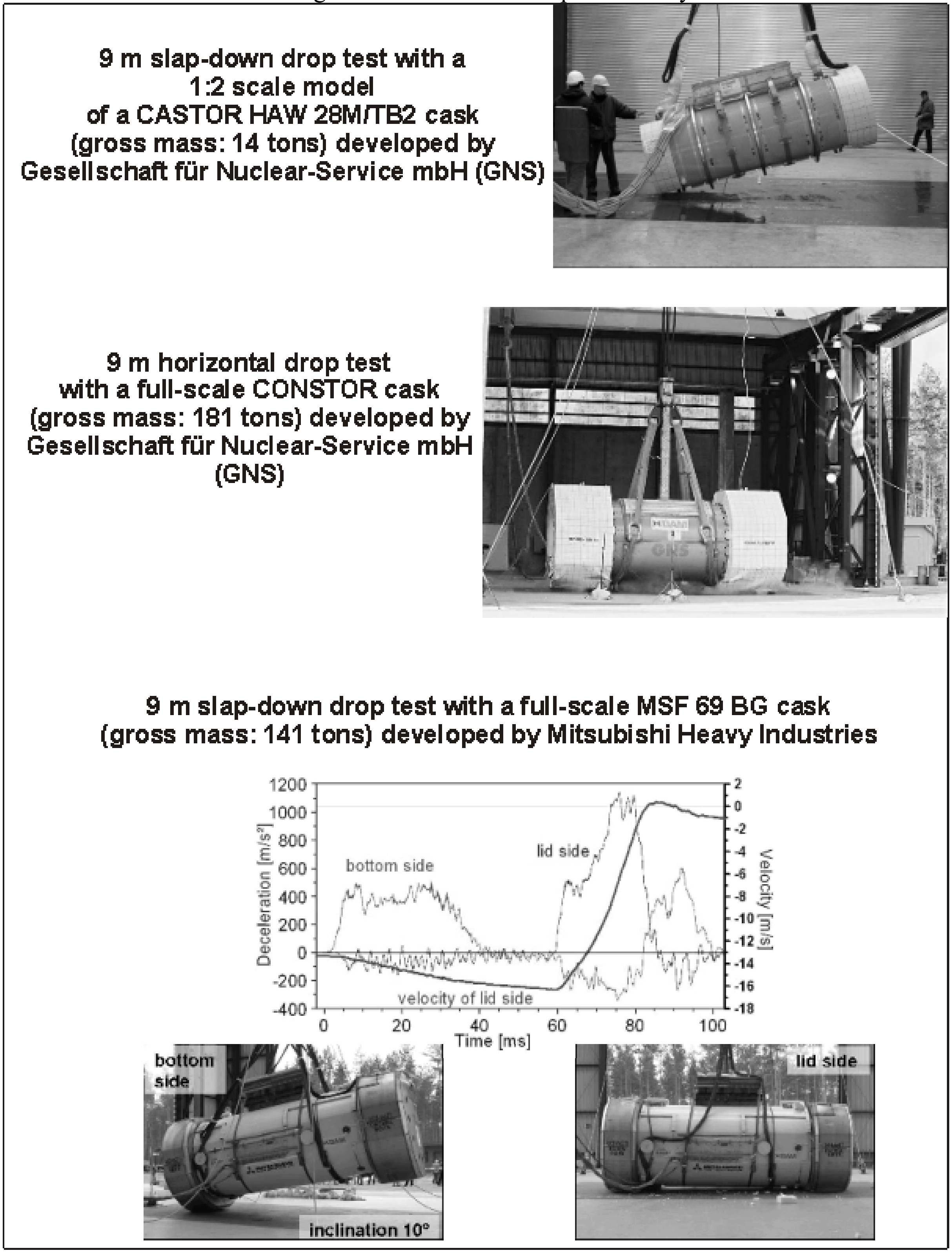


Fig. 2. Examples of recent BAM drop tests with new cask designs

REQUIREMENTS FOR NUMERICAL SAFETY ASSESSMENTS USING FINITE ELEMENT METHODS (FEM)

BAM has defined basic conditions for the preparation, checking and evaluation of safety analysis reports in a guideline [9, 10] mainly to assure the correct performance of numerical simulations according to the state of art and to optimise and to clarify the examination of these reports.

Obviously, the used finite element code has to be part of a quality assurances system and the personal must have enough expertise to do this kind of numerical analysis. If the work is carried out by a third party, the applicant must make sure that this party observed the guidelines, too.

Depending on the quality of the physical and geometrical modelling of a certain technical question BAM distinguishes between simple, but conservative design calculations, sensitivity studies, benchmark investigations and verification reports. Because of the complexity of Type B packages (cask body, basket with loading, lid system and impact limiter) it is very important to verify package components (finite element models of impact limiters, baskets or bolts) separately. Otherwise, to much conservative handicaps may have to be introduced and could finally lead to an unnecessary and unrealistic negative assessment result. On the other hand and despite the nowadays available computer power the use of two or more finite element models (global model and sub models) is also often necessary for a complete safety analysis of one test scenario.

The safety analyses report itself has to fulfil formal requirements (layout) and must include all data essential for the understanding and checking of the modelling (completeness) and the discussion of the results. This includes the documentation of the used software and input data. The modelling (simplification of the technical problem, discretisation, element types, material data, initial and boundary conditions, loads, etc.) must be discussed in detail.
Also very important are presentation (data processing, graphic and tabular presentation) and evaluation (checks, precision and discussion) of the results.

In the last part of the guideline the checking of the safety analyses report by BAM is shortly discussed. Finally, the guideline ends with the following statement:
Carrying out model or prototype tests may be especially necessary, when the results of FE calculations cannot be quantified with sufficient precision, due to a lack of sufficiently verified important input parameter (e.g. characteristic material values), or if the design model of the cask and/or the impact limiter strongly deviates from design models which already were the object of an expertise.

The following chapter contains an example for the productive and indispensable interaction between experimental testing and numerical investigation.

RELATIONSHIP BETWEEN EXPERIMENTAL AND NUMERICAL SAFETY ASSESSMENTS

Both experimental investigations and numerical calculations are used for the safety assessment of casks for radioactive material. The connection of both is the basis of the assessment and evaluation concept at the BAM in accordance to the present state of the art.

Numerical methods, e.g. finite element analysis (FEA) are used for the pre- and post-simulation of the IAEA drop tests [1, 2]. The drop tests are usually conducted at the BAM test facility. The general procedure with regard to the combination of experimental and numerical methods is shown in the following concept description:

Pre-Analysis and Experimental Investigations

In preparation of the experimental investigations both the design of the package construction as also the planning of the drop test program occurs with analytical and numeric tools. These consider the IAEA test conditions [1, 2]. The pre-calculations to be presented by the applicant are assessed by BAM and are used as a basis for the determination of an optimized drop test program. In addition the test cask measurement application with various devices (e.g. acceleration sensors, strain gauges) is planned on basis of the numeric pre-calculations. Special attention is put onto the application of the measurement equipment in highly loaded areas of the test cask. These areas are different between the individual drop tests. The assessment and evaluation of the finite element analysis is an excellent method for the optimized determination of the measurement arrangement.

As an example Fig. 3. shows the numerical pre-calculation for the 9m drop test to be carried out according to IAEA presented from an applicant. In this example it is the new cask design CASTOR® HAW 28M developed by GNS (Gesellschaft für Nuklear-Service mbH) for vitrified high active waste from reprocessing. In a first step pre-calculations and drop tests are performed with a 1:2 scale cask model as shown before in Fig. 2. With regard to certain questions of the integrity of the cask body the determination of the slap-down position as a critical drop test could be derived from the numeric analysis.

Experimental Investigations and Post-Analysis

After the drop tests numeric post-analyses are carried out. The analyses offer the possibility of a detailed calculation and assessment of the entire cask construction. Verified computational models (finite element models) are created on basis of the numeric pre-calculations and the results of the experimental drop tests.

The demands of BAM are in accordance to the state of the art [9]. Usually these analyses are the basis of the safety analysis report for the specific cask design. In this context the BAM creates own finite element models too. These have different aims depending on the various questions of the assessment. On the one hand this work is necessary for a compared calculation to the FEA in the safety analysis report of the applicant. On the other hand extensive sensitivity analyses with these models are carried out to the detection and assessment of influence parameters, as material properties or specific boundary conditions of the drop tests. For example Fig. 4. represents the finite element model for the assessment of geometrical deviations of a test cask (reduced scale model 1:2) in a carried out puncture drop test. In this case the sufficient knowledge of the dynamic local stress distribution and level in the puncture load entry area at the cask body wall with its inner bore holes for neutron shielding rods is a complex challenge. Maximum stresses can be found especially at the inner wall surface and between the bore holes caused by local wall bending.

The requirement of a connection of experiment and numeric pre- and/or post-analyses has always to be seen in the context of the overall concept of the proof chain. The question of the transferability of test results of scale models to the original cask design is to be seen exemplary here. At this point BAM demands precise clarification and verification of scaling laws and considerations of the similarity theory. Various questions of the similarity theory, e.g. strain rate dependence in view of the assessment of local strains, can be clarified with the finite element analysis.

In this connection it is important to point out that the FEA is used to calculate local stresses and strains, e.g. in the cask body. The stresses and deformations are assessed on basis of these calculations. This procedure presupposes, however, a computational model verified at experimental results [9]. Following proof steps, as for example fracture mechanical questions that are not verified by an experimental testing procedure, can evaluate with these calculations. In the field of fracture mechanics safety assessments for ductile cast iron BAM has elaborated guidelines for the use of appropriate methods [11], too.

In addition finite elements analyses are important in order to be able to estimate safety reserves during the assessment process. If only experimental tests are carried out, no statements can be found to that.

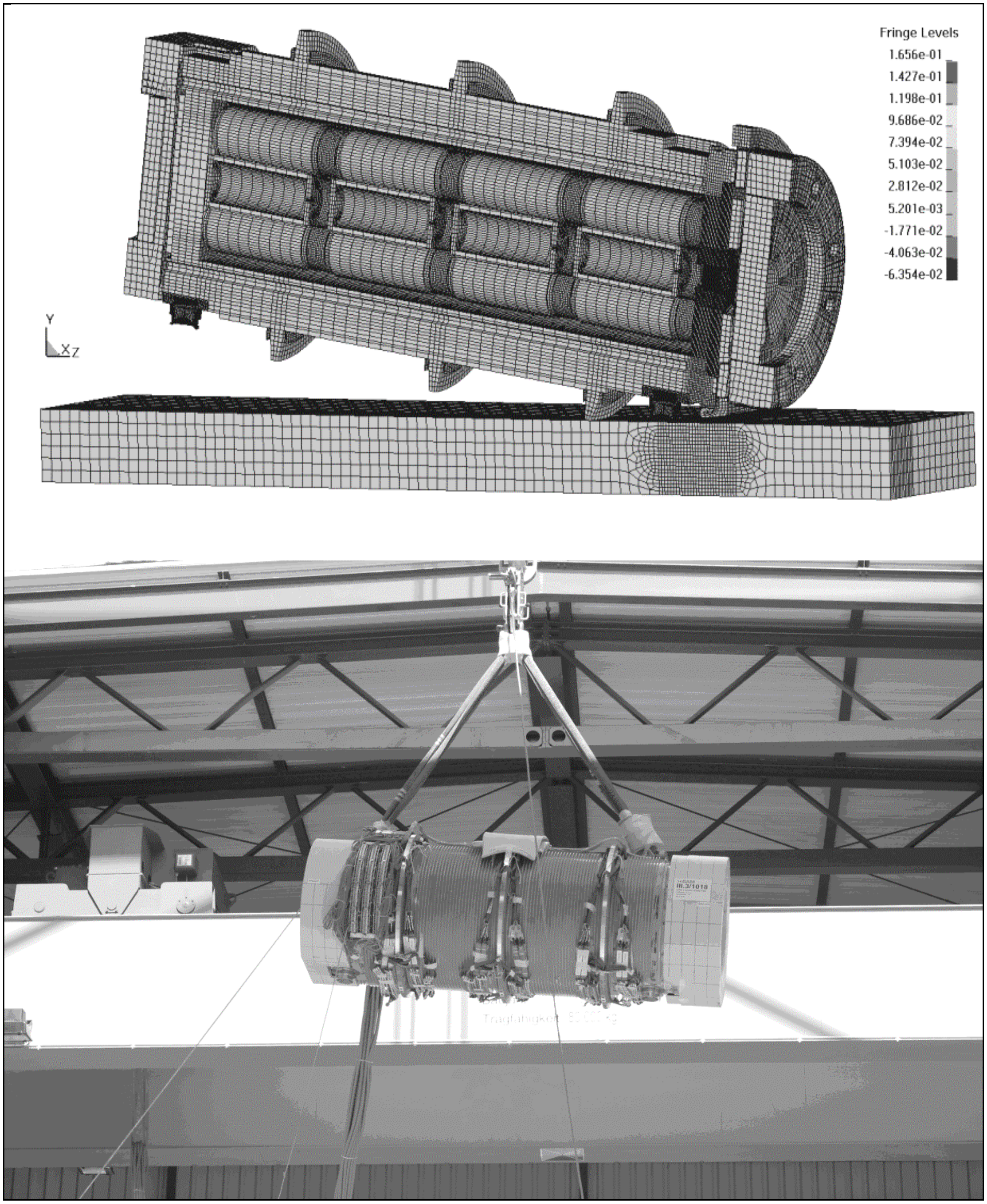
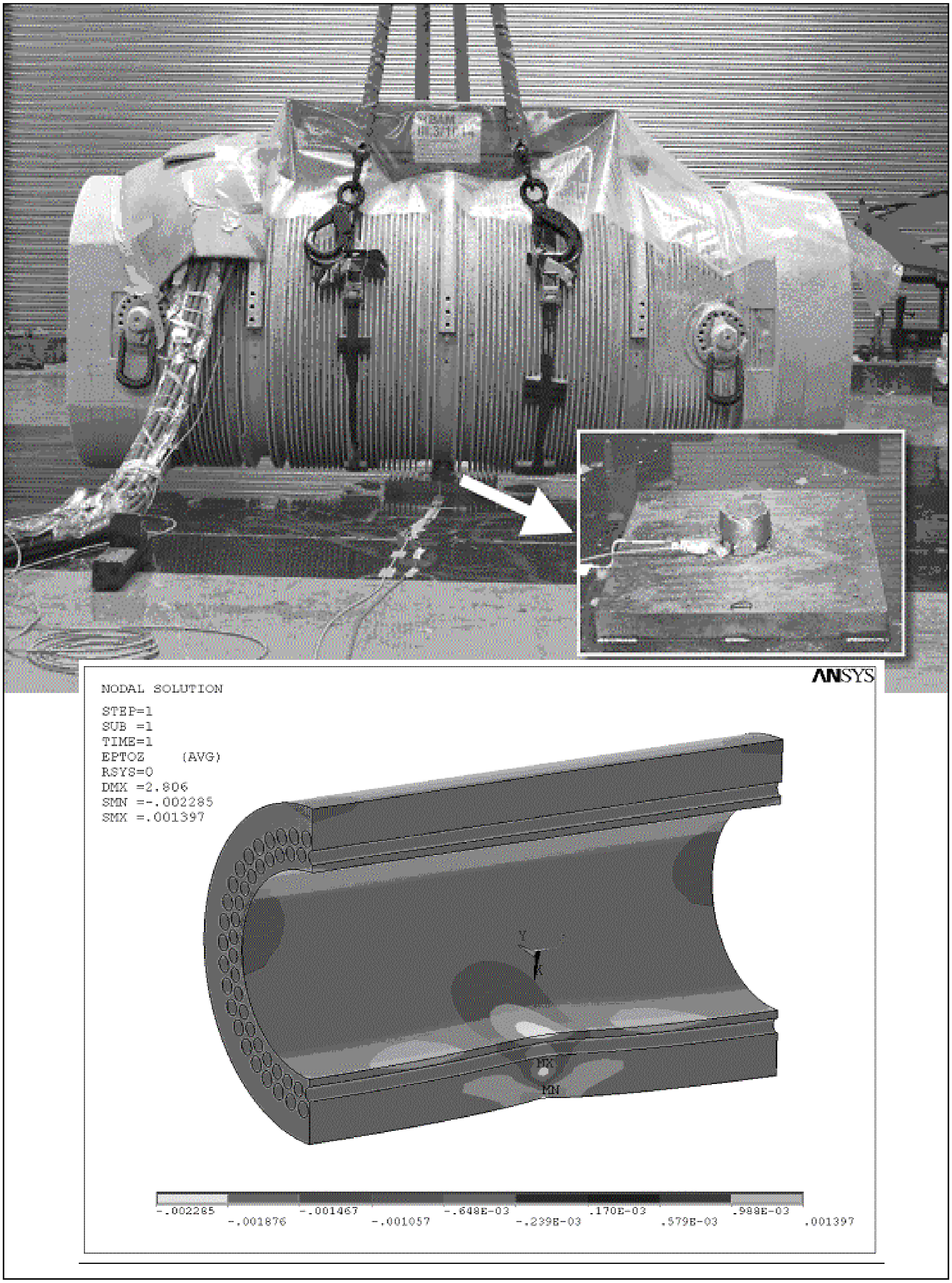


Fig. 3. 9 m slap-down drop test with a CASTOR® HAW 28M/TB2 (gross mass ≈ 14 tons; length ≈ 3.38 m; diameter ≈ 1.41 m)
- finite element analyses (GNS model) and experiment (BAM) -


ANSYS
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
EPTOZ (AVG)
RSYS=0
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Y
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MX
MN
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-.648E-03
-.239E-03
.170E-03
.579E-03
.988E-03
.001397

Fig. 4. BAM sensitivity analysis for a 1 m puncture drop test (CASTOR® HAW 28M/TB2)

CONCLUSIONS

BAM as the responsible German authority for transport and storage cask design testing has great experiences in experimental design testing, especially drop testing of full-scale and model-scale prototype casks for radioactive waste. The old 80 ton drop testing facility at Lehre was replaced by new 200 ton drop tower with additional modern technical infrastructure at the BAM test site Horstwalde in September 2004. More than 20 drop tests have been performing by BAM since beginning of operation including the biggest and heaviest cask ever tested, a CONSTOR® V//TC of 181 tons. Test and measurement data (e.g. accelerations, strains) are collected, documented and interpreted in a big scale and variety.

In addition to the experimental data very complex numerical analyses are performed increasingly by applicants for design optimisation goals as well as by checking authorities like BAM for development of adequate checking tools and methods. For standardisation and daily’s work assistance in this field BAM has developed technical guidelines which define basic standards as well as safety assessment options.

The correlation between experimental data and calculation results was discussed and explained by means of examples from the current CASTOR® HAW 28M/TB2 design testing procedure. Ongoing extensive drop test series also for other new cask designs in combination with pre- and post calculations will create an increasingly broadening base for better knowledge and understanding of safety relevant material stresses considering relations between model and full-scale test objects.

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