Recent experiences in mechanical design assessment of spent fuel and HLW casks by Competent Authority in Germany - 10093

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ABSTRACT

In the approval procedure of transport packages for radioactive materials, the competent authority mechanical and thermal safety assessment is carried out in Germany by BAM.

In recent years BAM was involved in several licensing procedures of new spent fuel and HLW package designs. The combination of computational methods and experimental investigation in conjunction with materials and cask components testing is the most common approach of mechanical safety assessment. The methodology in the field of safety analysis including associated assessment criteria and procedures has evolved rapidly during last years. New aspects relating to analysis aspects and assessment methodologies are summarized in this paper.

Without exception BAM requires clear and detailed description of the safety evaluation concept and the goals for the primary mechanical and thermal demonstrations for the package design testing procedure. The concept significantly influences the depth of an experimental or calculation proof. All relevant boundary conditions with respect to regulations must be taken into account, e.g. the assessment of stresses, strains and fracture mechanical considerations from -40°C until maximum operating and thermal accident temperature.

In general for new package designs the implementation of experimental drop tests in the approval process is necessary. Additionally, component tests could be important depending on the safety analysis concept. It depends on the individual construction of the packaging, the materials used and identified safety margins in the package design, whether and to what extend drop tests are necessary. The procedure needs to be sufficiently justified by the applicant in the safety analysis concept.

Numerical calculations by means of the Finite-Element method are currently part of safety analysis concepts of different package design approvals. The calculations are carried out statically or dynamically depending on the particular loading situation (static load or impact) and material behavior (e.g. strain rate dependence). The use of an appropriate small-scale or a full-scale test model determines the extent and depth of the correlated calculations.

Not in every case it is possible to obtain appropriate values or laws for material behavior from literature for the needed temperature or strain rate range. If non-standard materials are used experimental investigations for identification of mechanical properties are essential for a complete mechanical evaluation concept.

The safety analysis of the basket structure (for supporting of fuel assemblies or HLW canisters) with regard to the definition of the geometrical input conditions for the criticality analysis is to be

carried out depending on the complexity of the individual construction with an analytical approach, numerical models or experimental testing. BAM attaches importance to a sufficient verification of the models used in connection with sensitivity analysis. The chosen approaches need to be justified.

This paper shows the complex relation between the chosen drop test program with a small scale model and related Finite-Element analyses for design verification of a specific new German HLW package design.

INTRODUCTION

The Federal Institute for Materials Research and Testing (BAM) is the German authority which is involved in design testing of spent fuel and HLW transport packages. The BAM's tasks associated with this, contain the assessment of the mechanical and thermal design, the containment design and all aspects of quality assurance and surveillance regarding of manufacturing, the use and the maintenance of the package.

BAM executes the above assessments on the basis of the recommendations of the International Atomic Energy Agency (IAEA) TS-R-1 [1] and the appropriate conversions in national and international (e.g. European) regulations for the transport of radioactive material. All BAM tasks are performed in close cooperation with the official German Competent Authority, the Federal Office for Radiation Protection (BfS) as defined in the German guideline for the package design approval [2].

For each design of a package for the transport of radioactive material, it is necessary to demonstrate compliance with national and international transport regulations as applicable. It is recommended to combine all information necessary to demonstrate compliance in a package design safety report. The new European PDSR-Guide [9] is intended to assist in the preparation of such a package design safety report in all European countries. The development of this guide has been initiated and supported by the European Commission (EC) to improve harmonisation in this field in Europe. The guide is based on the IAEA TS-R-1 [1] Regulations which are generally consistent with the regulations for the road, rail, sea, inland waterways and air modes of transport, namely, ADR, RID, IMDG code, ADN and ICAO respectively, which have to be applied in European countries.

BAM has recently finished several design assessment procedures of packages for the transport of spent fuel and vitrified HLW. The mechanical design assessment for these packages designs required the performance of extensive drop test program in accordance with complex numerical modelling in combination with investigations of components and materials used.

In the following the experiences and requirements for the mechanical package design assessment is described from the view of the responsible authority.

REQUIREMENTS FOR MECHANICAL DESIGN CONCEPT

The BAM requires from the applicant presenting conclusive concepts for the safety analyses illustrating mechanical resistance in routine, normal and accident transport conditions [1]. This include the selection of relevant drop test positions with defined goals for individual drop test sequences based on pre-calculated justification, the comprehensive and reasonable instrumentation and measurement program for a drop test model with suitable measuring processing, the verification of suitable Finite-Element models up to the final comprehensive evaluation of the original package design behavior by specified evaluation criteria.

With regard to accident transport conditions it is typically necessary to consider for Type B(U) approvals the temperature range of -40°C until operating temperature [1]. This is used for both the evaluation of local loads, e.g. with regard to plastic deformations at operating temperature or local stresses under the lowest temperature at -40°C in regard to fracture mechanical behavior. Appropriate evaluation criteria have to be defined depending on the materials used. For example if ductile cast iron is used, BAM expects the correct application of the guideline BAM-GGR007 [4].

Not in every case it is possible to obtain appropriate values for material properties (e.g. strain rate depending stress-strain-curves) from literature. If non-standard materials are used experimental investigations for identification of mechanical properties (e.g. yield stress, fracture toughness etc.) are essential for a complete mechanical evaluation concept. These materials need to be qualified sufficiently. For example, the characteristics of boron-treated materials and the effects on the material properties, e.g. on the ultimate strain, have to be demonstrated.

It is also important for all considerations (material investigations and/or calculations of loads) to identify correctly the existing dynamic loading rate due to the IAEA test conditions (9m drop, 1m puncture bar drop test).

The safety analysis of the inner basket structure with regard to the definition of the geometrical input conditions for the criticality analysis is to be carried out depending on the complexity of the individual construction with an analytical approach, numerical models or experimental testing. BAM attaches importance to a sufficient verification of the models used in connection with sensitivity analysis. The chosen approaches need to be justified.

DROP TESTS AND COMPONENT TESTS

In general for new construction principles of package design the implementation of experimental tests in the approval process, for example of drop tests concerning the IAEA test conditions under normal and accident transport conditions, is necessary. Additionally, component tests could be important depending on the safety analyses concept. For example, such an additional component test could enable an evaluation of the impact limiter behavior in the whole temperature range.

Whether and to what extent drop tests are necessary, depends on the individual construction of the packaging, the materials used and implemented and identified safety margins in the package design. The procedure needs to be sufficiently justified by the applicant in the safety analysis concept. BAM experience in the comparison of full-scale and reduced-scale drop tests with a spent fuel cask design [8] shows that the verification of validity of reduced-scale model drop tests is hard to obtain.

According to IAEA regulations [1] the possibility exists for using reduced-scale models. If the drop tests with such models are carried out, attention needs to be paid to following fundamental aspects:

- Guarantee of the transferability of the test results of the reduced-scale model as far as possible to the original design (geometry and loads, materials, lid system, leak tightness, seal behavior etc.)

- Strategy for the transfer of model drop test results to the package design to be approved, e.g. by appropriate calculations considering all variations of test conditions and package properties which cannot be covered by the experimental condition.
- IAEA consistent realization of the drop tests under observation of the special properties of scale models, for example taking into account drop height corrections [6].

Considering the problems with reduced-scale drop testing it is recommended to base the package design assessment at least to some extent on full-scale drop testing.

In Germany the package drop tests in an approval process are performed by BAM where a 200 t drop test facility enables even full-scale drop tests of large spent fuel and HLW casks.

Example – Drop Test Program with a small-scale model for a new HLW cask design

Within the approval procedure of a new HLW cask design an extensive drop test program was performed. Fig. 1 shows the half-scale model used. The test model consisted of a cask body made of ductile cast iron, a primary lid with an integrated cover plate, 28 model canisters representing the inventory mass of HLW loading, three aluminium shock absorber rings around the cask body and two impact limiters at the upper and the lower end of the package. The drop test model had a weight of approximately 15,000 kg, a length of approximately 3,400 mm and an external diameter with impact limiters of approximately 1,400 mm.

The test goals of the drop sequences as well as the defined test parameters (temperatures etc.) were justified by the applicant and confirmed by BAM. The measurement results of deformation, strain and deceleration are mainly required for the verification of 3-D Finite-Element analyses within the mechanical safety assessment under normal and mechanical accident conditions of transport of the package design to be approved. The drop test program includes the necessary instrumentation plan, test procedure plan and handling procedure plan for the entire testing campaign.

The instrumentation plan contains the position, orientation and number of sensors all over the drop test model. BAM evaluated the instrumentation plan in context with the proposed mechanical safety assessment strategy for the package design approval. The main focus of instrumentation of the test model was the recording of strain and deceleration data. Therefore the specimen was assembled with 131 tri-axial strain gauges, 16 uni-axial strain gauges, 23 accelerometers and 5 temperature sensors. Accelerometers and strain gauges are instrumented in several positions over the cask body and primary lid.

The drop test program arranged 17 drop tests with one specimen and was performed by BAM at the BAM Test Site Technical Safety (BAM TTS) in Horstwalde near Berlin. The mechanical tests of the half-scale model were carried out at vertical, horizontal and oblique drop orientations. Drop heights were 9 m and 1 m for the punch test. The target was unyielding. The drop tests were carried out at different temperatures depending on goals of the single drop by -40°C, ambient temperature or 100°C (max. operating temperature).

The test procedure plan comprised the work scope of every single test step approved and performed during the drop test campaign. For example the drop height, temperature and measurement chain after every test as well as the realization of the leakage test (before and after drop test sequence), optical 3-D deformation measurement, visual inspection, normal video and high-speed recordings were checked. However it also included the complete geometrical measurement of the drop test model to identify deformation and displacement in the impact area.

Fig. 1. Preparation of 1m punch test at -40°C (check of test parameters)

The handling procedure plan included the steps for positioning and orientation of the tested half-scale model.

All steps of checks are based on the quality assurance plan which contains specifications for reviewing the test model. The detailed results are presented in data record sheets, protocols of inspection record and/or test certificate. Finally the drop test report includes all results of drop test sequences which are important for the safety design assessment of the package to be approved.

Example – Component Tests for investigation of behaviour of wooden filled impact limiter

Within the assessment of package safety performance mechanical testing of components could be useful for detailed analysis related to stress-strain behavior as well as permanent deformations of package impact limiters.

In a recent package approval procedure the evaluation of impact limiter performance including knowledge about energy absorption and plastic deformation under hypothetical accident conditions lead to perform component tests with wooden filled impact limiters. The impact limiters had an octagonal outer shape and were different from known geometry and constructional design of existing package designs.

Three drop tests with a half-scale model were performed according to specific impact limiter deformation caused by regulatory test requirements for accident conditions of transport. The results could be used for verification and benchmarking of a simplified analysis approach and a numerical tool used by the applicant. Assessment tools developed by BAM could be validated by the test results as well.

Different impact positions of the test model were considered. The drop orientations were: 9 m horizontal drop, 13 m oblique drop (Center of Gravity of the package over the impact corner) and 13 m horizontal drop at -40°C.

Generally, the rate of permanent deformation of impact limiters indicates possible sufficient protection of the cask body and the closure system of the package. The 13 m drop test (impact velocity approximately 16 m/s) was more severe than the regulatory (13.4 m/s) impact onto the unyielding target but was chosen in regard to the expected deformation grade of the impact limiter of the package design to be approved.

Strain and deceleration measurements during the experimental drop tests were performed focusing on rigid body impact response as well as structural impact response. Beside electrical measurement methods optical measures are important to get comprehensive knowledge about actual figure of impact limiter deformation as well. Compared with common dimensional inspection tools the use of an all around optical 3-D digitization of impact limiter after package drop testing gives a complete 3-D shaped component figure for quantitative damage analysis and model data for further calculations (Fig. 2).

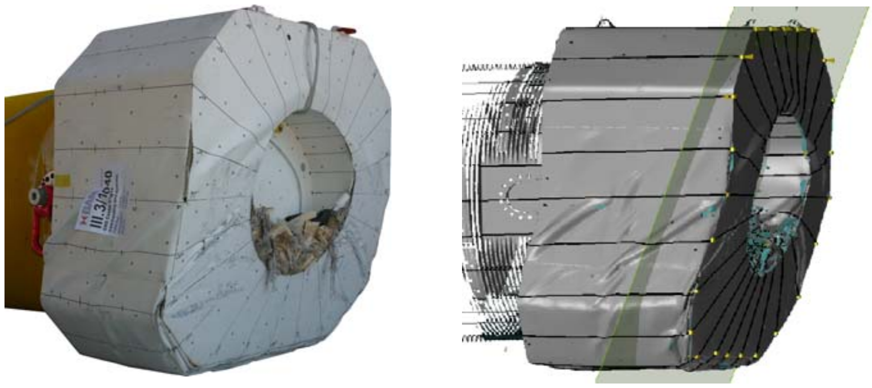


Fig. 2. Tested impact limiter after 13 m oblique drop compared with deformed impact limiter model from 3-D measuring digitization

NUMERICAL CALCULATIONS

Numerical calculations by means of the Finite-Element method are currently part of safety analysis concepts of different package design approvals in Germany. The calculations can be carried out according to the particular loading situation (e.g. strain rate dependent) statically or dynamically.

Detailed Finite-Element analyses may be necessary to:

- justify a drop test program outline
- transfer drop test results with a scale model to the original package, for example with design modifications or changed material properties,
- calculate local stresses and strains that are inaccessible for a direct measurement as for example of notches or areas within the cask body wall,
- analyse drop test scenarios at other boundary conditions that are different to the test conditions. For example at a temperature of -40°C or at maximum operating temperature.

The verification of the numerical calculations is essential. Depending on the influence to the safety of the package the individual components of the numerical model need a partial verification, e.g. impact limiter, basket for the fuel elements etc.

BAM has defined basic conditions for the preparation, checking and evaluation of numerical calculations in SAR in a guideline [3] mainly to assure the correct performance of numerical simulations according to the state-of-the-art and to optimise and to clarify the examination of these reports.

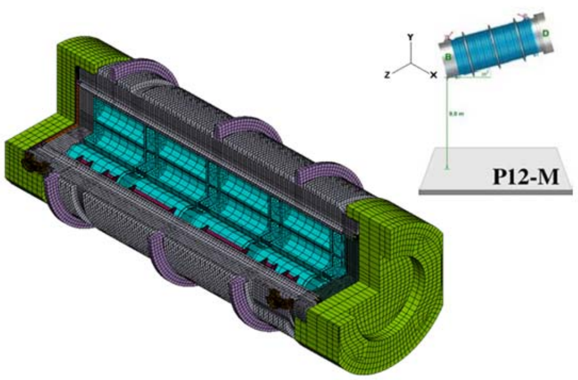
The SAR itself has to fulfil formal requirements (layout) and must include all data essential for the understanding and checking of modelling (completeness) and the discussion of results. This includes the documentation of the software and input data used. The modelling (simplification of the technical problem, discretization, types of finite elements, material data, initial and boundary conditions, loads etc.) must be discussed in detail.

Essential are also presentation (data processing, graphic and tabular presentation) and evaluation (checks, precision and discussion) of the results [3].

BAM owns the relevant hardware and software to perform independently FEM calculations with skilled personal.

Example – Verification of slap-down drop test within licensing of a new HLW cask design

A package has to be assessed under the most damaging test conditions according to the IAEA regulations [1]. First of all it must be investigated which loading conditions lead to a maximum damage of the package. For instance a slap-down effect can appear at a long cylindrical cask during a horizontal drop with a distinct impact angle. At first only one end of the cask hits the target in this loading scenario. This is the primary impact. As a result the cask gets an additional rotation which accelerates the other end of the cask. Therefore the secondary impact may lead to a higher load of the cask structure than the primary impact. This effect appears only at certain impact angles and is discernible particularly with a large ratio of cask length to diameter. The complete package under accident transport conditions must be considered to investigate this effect. If the cask is equipped with impact limiters, then these components must also be taken into account. Impact limiters at both ends of the cask usually prevent a slap-down if the impact angle is small (some degrees) because the cask sinks into the soft impact limiters. Therefore the critical impact angle is calculated before a test using a numerical simulation of the test scenario. Fig. 3 illustrates the Finite-Element model of a new HLW cask which is equipped with impact limiters at the bottom and lid side and additionally with three jacket impact limiters. The latter shall primarily soften the horizontal impact. The performance of the impact limiters was investigated by tests and calculations. Due to these results a design modification was carried out. The jacket impact limiters have been moved towards the ends of the cask. Fig. 3 compares the experimental and computational results from the re-examination of the cask design for the primary drop onto the bottom side of the cask with an impact angle of 20°. The reached similarity of the curves can be assessed as sufficient for a full-scale test.



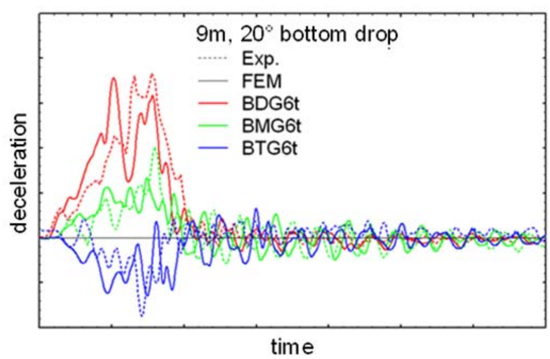


Fig. 3. Slap-down drop test with an impact angle of 20°

Example – Verification of puncture bar drop test within licensing of a new HLW cask

Before testing pre-computations are often performed for ideal test conditions. Then the experimental test is carried out. After the test the measurement results are compared with the pre-analyses. On the one hand it is assessed by means of calculation results whether the ideal test conditions were sufficiently met and the experimental results are conservative for the investigated scenario. On the other hand the measurements allow a verification of the numerical calculation model. The measurement results can often be understood better in detail by means of a numerical post-analysis if differences between the results of the pre-computation and the experimental data occur. If the cask has not hit the target in an ideal manner, a safety factor can be determined. Fig. 4 shows the Finite-Element model for a drop of the cask lid area from 1 m height onto a puncture bar. It is a half-scale test. The cask and the puncture bar were scaled under consideration of similarity aspects [6]. The visual inspection of the puncture bar and the evaluation of the measurement results indicate that the cask has not hit the puncture bar centrally. Unfortunately such very small deviations are always possible at reduced-scale test conditions. The most unfavourable test situation with maximum damage of the cask and highest stresses in the cask structure can be found by an exact post-analysis of the test and a re-calculation under ideal test conditions even if the test did not met these conditions. Hence the worst case load can form the basis of the safety analysis within the licensing procedure without repeat of the test.

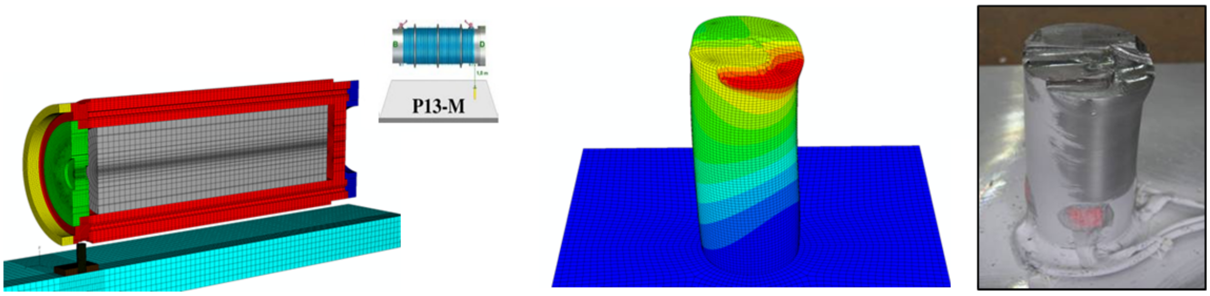


Fig. 4. Drop of the cask lid area from 1 m height onto a puncture bar

MATERIAL INVESTIGATION AND QUALIFICATION

Within the package design assessment all materials used, need to be qualified with regard to the relevant mechanical, thermal and chemical properties for the design and the manufacturing process. For the manufacturing process BAM requires for each safety relevant component a data sheet for the specification of the material (e.g. mechanical and thermal properties) and a data sheet of testing to meet these properties during manufacturing.

The proofs of the properties can occur either through references or through reports by the applicant to their own qualification procedures. The property values of standard materials can be justified on basis by references.

But if the material or the manufacturing/assembling process used is not standard or if the IAEA conditions exceed the boundary conditions which are defined in standards (e.g. operating temperature) then additional material investigations and/or comprehensive qualification procedures are necessary. The BAM cooperates closely with the TÜV Rheinland Group (as contracted expert institution) to ensure appropriate material and manufacture qualification processes and their correct practical realization as well as over matters of quality assurance.

Complex mechanical safety analysis strategies were used within recent licensing procedures of spent fuel and HLW cask designs by applicants. Applied dynamical Finite-Element analyses need a couple of more values for description of material properties than former simple analytical approaches of calculation.

For this reason the applicant investigated all relevant materials used in numerical analyses. A very important point is the need to provide strain-rate dependent strength curves.

ASSESSMENT OF THE CONTAINMENT SYSTEM

The analysis of the containment system (closure system, seals etc.) under the relevant IAEA transport conditions can be carried out by drop tests or by separate additional experiments on the mechanical design of the lid system. Similarity considerations including validated calculations on basis of these experimental data can be applied.

The use of experimental tests on full-scale or reduced-scale models or by component tests has to illustrate the ability of the containment system to meet the leakage-rate-criterion under deformation or axial or radial movement of the lid. Concerning this matter BAM developed quality assurance and assessment criteria. The criteria include the qualification of the manufacturer, the fabrication of test seals, a full qualification program for the mechanical, thermal and long-term behavior of the seals, quality assurance during fabrication of original seals, arrangements after assembling and after loading the cask as well as recurrent inspections of the seals and sealing surfaces during their usual operation.

The regulations, e.g. TS-R-1 [1], specify the different transport scenarios, termed as routine, normal and accident conditions of transport, and define limits for the loss of radioactive content (e.g. in [1], §657) under these transport conditions. BAM checks the loadings to the containment system which result from the defined transport conditions in the safety analyses. According to the German guideline for quality assurance and quality control of packagings for transport of radioactive materials (TRV 006 [7]) components of the containment are classified in the highest safety level.

Before a metallic or elastomeric seal can be used in series casks BAM assesses the qualification of the manufacturing process regarding stability and the compliance of specific design values of the seals which are derived from experimental tests, by component tests or from practical investigations with loading and unloading conditions of the cask.

CONCLUSIONS

The IAEA package design test requirements are of very basic character. The way to fulfil them seems to be simple, but this is not the case. It needs at first a carefully justified safety assessment strategy which links all required actions, like pre-test calculations, package tests, material and/or component tests, post-test calculations to integrate them into the safety case. The safety case is a multi-dimensional problem because every requirement has to be justified considering various parameters, like differences between test or calculation model and package design, package dimension and property variations.

Consequently every safety case needs a combination of all regulatory methodologies, like experimental and computational methods for structural analysis completion. Within the different methodologies careful planning, accuracy and documentation are required. Experiments have to be carried out with sophisticated measurement techniques. Calculations need stringent verification. For approaching realistic modelling, accompanying material or component testing is required. Consideration of full-scale package drop testing can shorten the long way to a finalisation of the safety case, because this approach reaches maximum approximation to reality.

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