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MECHANICAL DESIGN ASSESSMENT APPROACHES OF ACTUAL SPENT FUEL AND HLW TRANSPORT PACKAGE DESIGNS

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ABSTRACT

In recent years BAM finalized the competent authority assessment of the mechanical and thermal package design in several German approval procedures of new spent fuel and HLW package designs. The combination of computational methods and experimental investigations in conjunction with materials and cask components testing is the most common approach to mechanical safety assessment. The methodology in the field of safety analysis, including associated assessment criteria and procedures, has evolved rapidly over the last years. New features relating to analysis aspects and assessment methodologies are summarized in this paper.

The design safety analysis must be based on a clear and comprehensive safety evaluation concept, including defined assessment criteria and constructional safety goals. In general, for new package designs the implementation of experimental package drop tests in the approval process should be obligatory. Additionally, pre- and post-test calculations as well as components or material testing could be important. The extent to which drop tests are necessary depends on the individual package construction, the materials used and identified safety margins in the design. Numerical calculations by means of the Finite-Element method are 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 dependency). The use of an appropriate small-scale or a full-scale test model determines the extent and depth of the correlated calculations. Exact calculations require an input of realistic material laws which often have to be generated by appropriate material testing.

This paper concentrates on the complex relationship between the chosen drop test program with a small scale model and related mechanical Finite-Element analysis for design verification. As an example this paper describes a specific new German dual purpose cask design developed for transport of vitrified high-level waste from France to interim storage in Germany.

INTRODUCTION

The Federal Institute for Materials Research and Testing (BAM) is the German authority which is involved in the testing of spent fuel and HLW transport package designs. The BAM's tasks associated with this, include the assessment of the mechanical and thermal design, the containment design and all aspects of quality assurance and surveillance regarding the 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]. BfS performs shielding and criticality safety assessment, and after receipt of BAM's safety evaluation report, it issues the package design approval certificate. The subsequent manufacture of each packaging is controlled by BAM to be certified in accordance with the approval certificate.

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 the necessary information in order to demonstrate compliance in a package design safety report. The new European PDSR-Guide [8] is intended to assist in the preparation of such a package design safety report in all European countries.

REQUIREMENTS FOR MECHANICAL DESIGN CONCEPT

BAM requires the applicant must present conclusive concepts for the safety analyses illustrating mechanical resistance in routine, normal and accident transport conditions [1]. This includes the selection of relevant drop test positions with defined goals for individual drop test sequences based upon pre-calculated results, 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 necessary to consider for Type B(U) package approvals the temperature range of -40°C up to the operating temperature, and stresses due to the thermal test have to be considered too [1]. The evaluation of (local) loads has to be carried out, e.g. with regard to plastic deformations at operating temperature or local stresses under the lowest temperature of -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-GGR 007 [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 and their manufacturing method need to be qualified sufficiently.

It is also important for all considerations (material investigations and/or calculations of stresses/strains) to identify correctly the existing dynamic loading rate due to the IAEA mechanical 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 should be carried out depending on the complexity of the individual construction with an analytical approach, numerical models or experimental testing. BAM attaches importance to 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 package design construction principles 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 analysis concept. For example, such an additional component test could enable an evaluation of the impact limiter behavior in the entire 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 [7] shows that the verification of validity of reduced-scale model drop tests is hard to obtain.

According to IAEA regulations [1] the possibility exists to use 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 achievable to the original design (geometry and loads, materials, lid system, leak tightness, seal and bolts behaviour etc.)
- Strategy for the transfer of reduced-scale 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 experimental test conditions.
- 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 difficulties with reduced-scale model 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 [7].

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 (CASTOR® HAW 28M) 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 goals of drop test sequences as well as the defined test parameters (temperature, drop positions, sequences etc.) were justified by the applicant and confirmed by BAM. The measurement results of deformations, strains and decelerations are mainly required for justification of acceptable stresses and deformations, 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 covering 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 described 17 drop tests with one specimen and was performed by BAM at the BAM Test Site Technical Safety (BAM TTS) in Horstwalde near Berlin. Experience with this specific case has shown that the number of drop tests should be reduced significantly by putting more effort into pre-test calculations and investigations. The mechanical tests of the half-scale model were carried out at vertical, horizontal and oblique drop orientations. 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 (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 puncture bar drop 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 stages of the 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 a 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 design to be approved. A detailed description of the drop test program, measurement techniques and results are given in [10].

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 recent package approval procedures the evaluation of impact limiter performance, including knowledge about energy absorption and plastic deformation under hypothetical accident conditions led to the performance of 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 (another one then described above) were performed in accordance with specific impact limiter deformation requirements specified by the regulatory tests 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 [5].

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.

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. Additionally, electrical measurement methods and optical measures are important to gain comprehensive knowledge about the actual figure of impact limiter deformation. 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).

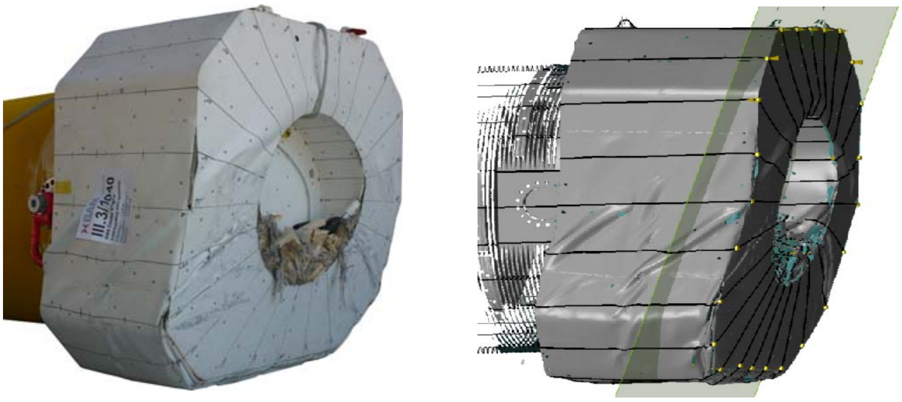

Fig. 2. Tested impact limiter after 13 m oblique drop compared with deformed impact limiter model from 3-D measuring digitization

NUMERICAL CALCULATIONS

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

- justify a drop test program outline,
- transfer drop test results with a reduced-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 which are different to applied 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 of the safety of the package the individual components of the numerical model need a partial verification, e.g. impact limiter, basket for the fuel assemblies etc.

BAM has defined basic conditions for the preparation, checking and evaluation of numerical calculations in Safety Analyses Report (SAR) in a guideline [3] mainly to assure the correct performance of numerical simulations according to the state-of-the-art technology and to optimize and to clarify the examination of these reports. The SAR itself has to fulfill formal requirements (layout) and must include all data essential for the understanding and checking of modeling (completeness) and the discussion of results. This includes the documentation of the software and input data used. The modeling (simplification of the technical problem, discretization, types of finite elements, material data, initial and boundary conditions, loads etc.) must be discussed in detail. Presentation (data processing, graphic and tabular presentation) and evaluation (checks, precision and discussion) of the results is also essential.
BAM owns the appropriate hardware and software to independently perform FEM calculations with skilled personal.

Example – Verification of 9m 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 occur when a long cylindrical cask is dropped horizontally with a distinct impact angle. At first, only one end of the cask hits the target in this loading scenario, representing 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 impact against 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.

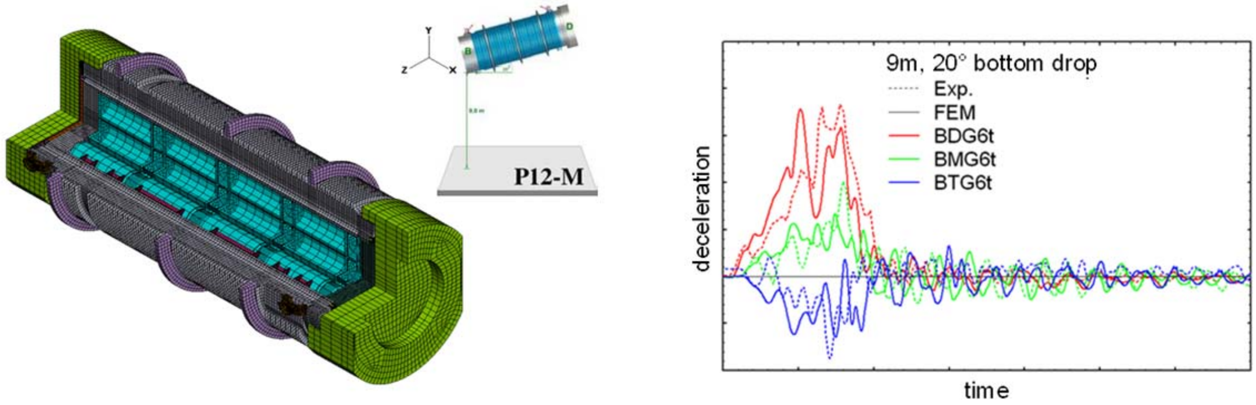

Fig. 3. Slap-down drop test with an impact angle of 20°

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, e.g. using a numerical simulation of the test scenario. Fig. 3 illustrates the Finite-Element model of a new HLW cask (CASTOR® HAW 28M) which is equipped with impact limiters at the bottom and lid side and additionally with three jacket impact limiters. The latter primarily softens the horizontal impact. The performance of the impact limiters was investigated utilizing both tests and calculations. Due to these results a design modification was carried out. The bottom side jacket impact limiter was moved toward the end 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 similarity of the curves can be assessed as sufficient for a full-scale test.

Example – Verification of 1m puncture bar drop test within licensing of a new HLW cask

Before experimental testing pre-computations are often performed for identification of most damaging 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 worst test conditions were sufficiently met and whether the experimental results are conservative enough 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 in reduced-scale model test conditions. The most damaging test situation 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 perfectly. Hence the worst case load can form the basis of the safety analysis within the licensing procedure without repetition of the test.

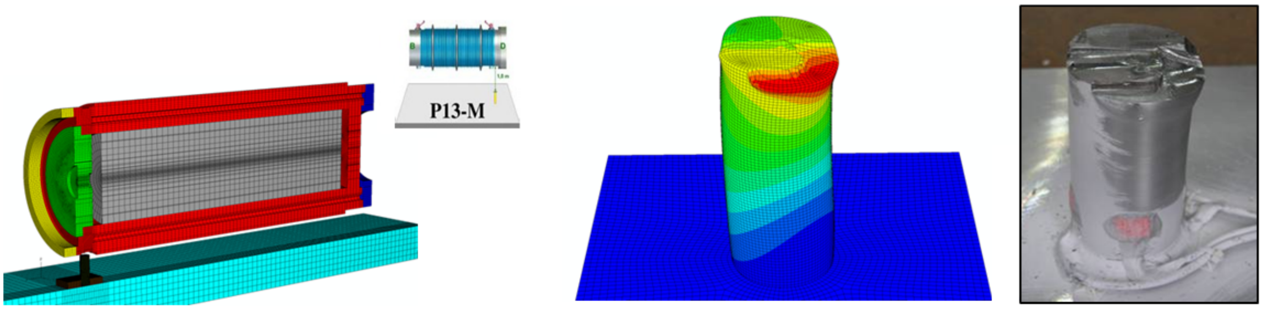

Fig. 4. Drop of cask lid area from 1 m height onto a puncture bar

MATERIAL INVESTIGATIONS

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. If the material or the manufacturing/assembling process used is not precisely standardized, 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. 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 has to investigate all relevant materials used in numerical analyses. An important point is the need to provide strain-rate dependent stress-strain curves for lower and upper specified values.

CONCLUSIONS

The IAEA package design test requirements are of a very basic character. The way to fulfill 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, such as the differences between a 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 the proof of applicability or verification. To achieve realistic modeling, accompanying material or component testing is required. Consideration of full-scale package drop testing can shorten the otherwise lengthy process of finalizing the safety case, because this approach reaches maximum approximation to reality.

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