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Design Assessment by BAM of a New Package Design for the Transport of SNF from a German Research Reactor

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Abstract

For disposal of the German research reactor of the Technical University Munich FRM II a new transport and storage cask design was under approval assessment by the German authorities. The Bundesanstalt für Materialforschung und -prüfung (BAM) assessed the mechanical and thermal package safety and performed drop tests. The activity release approaches and subjects of quality assurance and surveillance for manufacturing and operation of the package were assessed by BAM as well.

The cask body is made of ductile cast iron and closed by two bolted lid systems with metal seals. The material of the lids is stainless steel. On each end of the cask a wood-filled impact limiter is installed to reduce impact loads to the cask under drop test conditions. In the cavity of the cask a basket for five spent fuel assemblies is arranged.

For the safety case a combination of experimental testing and analytical/numerical calculations were applied. In total, four drop tests were carried out at the BAM large drop test facility. Two tests were carried out as a full IAEA drop test sequence consisting of a 9m drop test onto an unyielding target and a 1m puncture bar drop test. The other two drop test were performed as single 9m drop tests and completed by additional analyses for considering the effects of an IAEA drop test sequence.

The main objectives of the drop tests were the investigation of the integrity of the package and its safety against release of radioactive material as well as the test of the fastening system of the impact limiters. Furthermore, the acceleration and strain signals measured during the tests were used for the verification of Finite-Element-Analysis (FEA) used for the safety analysis of the package design.

The finite-element models incorporated in the package design safety report include the cask body, the lid system, the inventory and the impact limiters with the fastening system. In this context special attention was paid to the modeling of the encapsulated wood-filled impact limiters.

Additional calculations using the verified numerical models were done by the applicant and assessed by BAM to investigate e.g. the brittle fracture of the cask body made of ductile cask iron within the package design approval procedure.

This paper describes the package design assessment from the view of the competent authority BAM including the applied assessment strategy, the conducted drop tests and the additional calculations by using numerical and analytical methods.

Introduction

Within the German transport package approval procedure for the new dual purpose cask CASTOR® MTR3, the applicant Gesellschaft für Nuklear-Service mbH (GNS) provided the safety analyses report (SAR) for a Type B(U) package containing fissile material [1].

The transport approval procedure of such packages in Germany are regulated in the German guideline R003 [5]. BAM is responsible for the mechanical and thermal assessment, the assessment of the activity release and the assessment of the quality assurance measures as well. The Federal Office for the Safety of Nuclear Waste Management (BfE) is responsible for the assessment of radioactive inventory, the criticality, the shielding and is issuing the package design approval certificate.

For the safety case a combination of experimental testing and analytical/numerical calculations is applied, caused by BAM's requirement that drop tests have to be carried out. The corresponding test program with a full-scale model was discussed and agreed between the applicant and BAM. The drop tests were carried out by BAM.

SAR provided by the applicant was structured according to the European Guideline "Package Design Safety Reports for the Transport of Radioactive Material" [3].

Package Design

The cask body with a wall thickness of 355 mm is made of ductile cast iron. The length of the package (including impact limiters) is 2969 mm and the diameter is 2400 mm. In total the package has a weight of about 23 metric tons.

The cask is closed by two bolted lid systems with metal seals. The material of the lids is stainless steel. On each end of the cask an impact limiter is installed to reduce impact loads to the cask under drop test conditions.

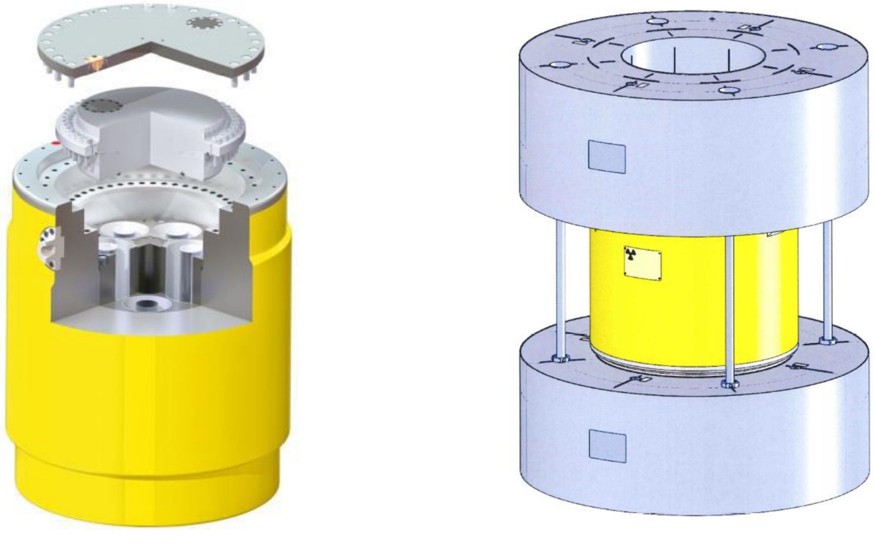

Figure 1 CASTOR® MTR3 by Gesellschaft für Nuklear-Service (GNS) [4]

Two impact limiters consist of spruce wood, which is encapsulated in a steel structure, and are attached to the cask body by using of four fastening bars.

In the cavity of the cask a basket for five spent fuel assemblies is arranged.

The containment system of the package consists of the cask body and either the primary or secondary lid with small lids closing the orifices as well as with the metal seals and the screws of each lid.

On the lid side of the cask body two trunnions for handling operations are diametral-oppositely arranged.

Assessment Strategy

In the safety case a combination of experimental testing and analytical/numerical calculations is applied for demonstrating the design safety under normal and accident conditions of transport. Two tests were carried out as a full IAEA drop test sequence consisting of a 9m-drop test onto an unyielding target and a 1m puncture bar drop test. The other two drop tests were performed as single 9m drop tests and completed by additional analyses in order to consider the effects of an IAEA drop test sequence.

The safety analyses discussed and agreed between the applicant and BAM can be divided into the following steps:

- Numerical calculations under IAEA drop test conditions. The results of these calculations were used to determine the most damaging positions for experimental drop tests (e.g. drop test orientation, test specimen temperature). Based on these numerical calculations, necessary constructive adaptions or modifications of the test specimen were defined. Furthermore, needed instrumentations of the test specimen were defined (strain gauges, accelerometers).
- Drop tests by using a full-scale cask model. The main objectives of the drop tests were the direct proof of the integrity of the package and its safety against release of radioactive material as well as the proof of the fastening system of the impact limiters.
- Recalculations of the drop tests and verification of the developed numerical models used for the safety analysis report.
- Adjustment or calibration of the numerical models (if necessary after the verification process) and additional calculations for all regulatory test conditions as well as relevant parameter combinations of the package design.

Assuming the use of verified or covering calculation models, the above-mentioned approach of the safety demonstration fulfills the requirements of the IAEA-Regulations [1]. Based on the assessment of the pre-calculation results and the intensive discussions of the experimental program, BAM confirmed that the drop tests discussed in the following chapter are appropriate for the assessment objectives.

Drop Test Program and Test Specimen

The program of the mechanical testing within the transport approval procedure included four drop tests.

Two tests were conducted as a full IAEA-drop test sequence consisting of a 9m horizontal drop test onto an unyielding target and a 1m puncture bar drop test. The diameter of the puncture bar is defined by the IAEA [1], but the length of the bar must be determined concerning different boundary conditions and shall have a minimal length of 200mm. The length must be adapted to the shape of the package to maximize damage in the package components and to prevent contact with the surrounding surface before maximum puncture load is applied. In addition, the drop orientation and possible pre-damages of the package resulting from a previous 9m drop test must be considered as well. The length of the bar, made of mild steel, was determined analytically in advance and is described in [10].

Furthermore, a 9m vertical and a 9m oblique (edge) drop test, each onto the lid sided impact limiter, were conducted. The test specimen was equipped with a new impact limiter system for each single drop test and sequence. The metal seals and the screws of the entire lid system were also renewed.

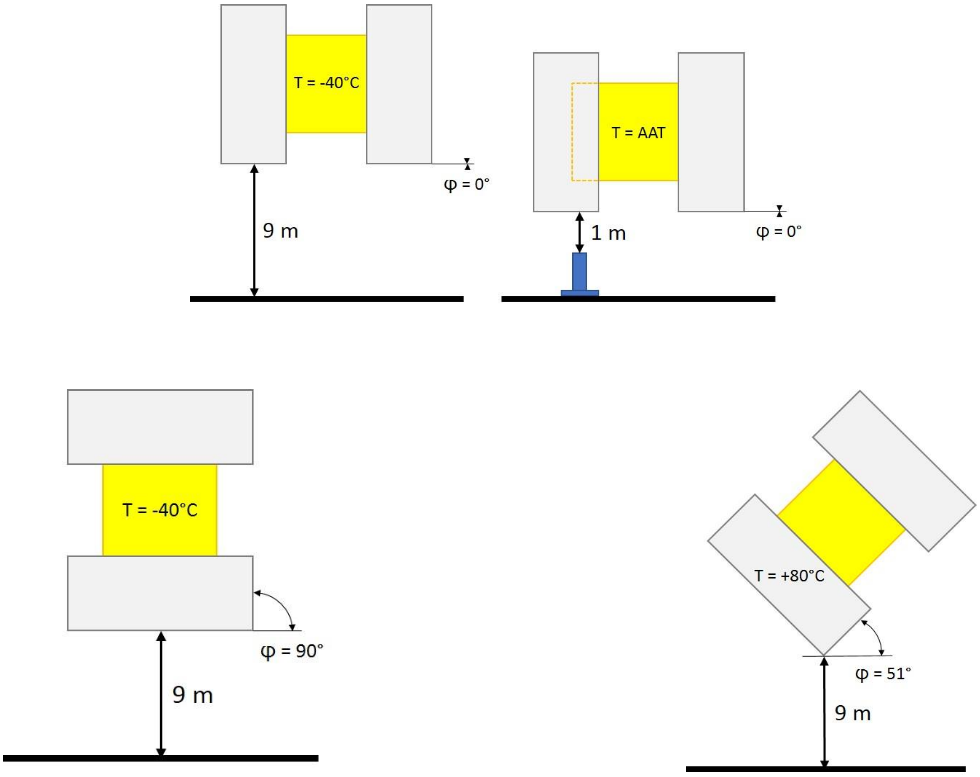

Figure 2 CASTOR® MTR3 drop tests orientations [2]

The drop test program and the applied measurements/instrumentations has been detailed described in the PATRAM 2019 paper [2].

The main objectives of the drop tests were the investigation of the integrity of the package and its safety against release of radioactive material as well as the test of the fastening system of the impact limiters. Furthermore, the acceleration and strain signals measured during the tests were used for the verification of FE-Models used for the safety analysis of the package design.

The test specimen corresponds to the original design and is almost identical in terms of its dimensions, mass and materials. In the frame of the assessment strategy, the following constructive adjustments were made on the test specimen [2]:

- Adjusting the constructive maximum radial gap between the primary and secondary lid and the cask body to guarantee the maximum lateral displacement of the primary and secondary lid.
- Adjusting the constructive maximum axial gap between the inner side of the primary lid and the basket, in order to reflect the maximum loads on the lid system caused by the internal impact of the basket onto the primary lid during the 9m vertical drop test onto the lid side impact limiter.

The interaction between lid system and content of the package during mechanical drop testing is of decisive matter to evaluate impact loads and the design safety. In case of a movable content its impact onto the inner side of the lid can cause additional load peaks on the lid and its screws [8]. The covered boundary conditions regarding the maximum gap shall consider this effect in the test specimen.

Figure 3 CASTOR® MTR3 oblique test

Another difference to the original cask design was the installation of the lid screws. There is a considerable scatter in the screw preload because of the dispersion of friction conditions at the threads and under the screw heads as well as imprecisions in the screw tightening technique. According to the assessment strategy, the lid screws of both closure systems should be tightened with the minimum allowable preload, except of two instrumented screws per primary and secondary lids, which should be tightened with the maximum value. The combination of minimum preload of the screws and maximum lateral gaps between the lids and the cask body are favourable for the lateral displacements of the lids during the 9m horizontal drop test as well as for their axial displacements during the 9m vertical drop test. These displacements in turn lead to increasing the potential damage of the metal seal and maximizing the loads on the instrumented screws with a maximum preload. In this way, a covering load situation for all components of lid system can be simulated in the drop test.

In order to provide an accurate and reliable preload state of the lid screws, a force-controlled tightening method [9] was used for the assembly of the test specimen, in contrast to a torque-controlled tightening for the assembly of the original cask. The force-controlled tightening method is based on an ultrasonic system which sends an ultrasonic impulse longitudinally through the screw during the tightening procedure.

Numerical Analysis

As mentioned above the drop testing of the package was supported by additional analyses mainly using the finite element codes LS-DYNA (explicit) and ANSYS (implicit). Depending on the question at hand, different FE-models from the full package to separate components were created by the applicant GNS.

The models and the input files were submitted to BAM for examination. In the preliminary step, BAM checked the geometric and physical simplifications and assumptions in the models for plausibility and evaluated the quality of the FE meshes. BAM performed its own calculations on selected FE models to confirm the consistency between the specified input files and the results presented. Possible influences of the software version used were analyzed in these calculations as well.

Furthermore, BAM performed calculations with modified applicant's FE models to investigate the potential impact of various parameters which were not proved by the applicant or were not obvious (e.g. some friction coefficients, gaps between components). These parameter studies were necessary to understand and interpret ambiguous results or numerical effects. In some cases, BAM has also created its own FE models and performed additional calculations to check the results of the applicant.

As a result of these examinations, BAM has confirmed the acceptability of the assumptions and simplifications made by the applicant in the modeling. Nevertheless, the extended verification analysis was required to assess the reliability of calculation results and the accuracy with which the mechanical behavior of the package under drop test conditions is simulated by the FE models created. The strain gauges and accelerometer signals as well as the displacements measured in the drop tests provided the basis for this verification.

For the recalculation of the drop tests, the applicant has appropriately modified the FE models of the package. The modifications were necessary, e.g. for the masses of the package components and for constructive gaps adjusted on the test cask. Furthermore, the verification models include the accelerometers simulated as rigid bodies and the strain gauges reproduced as rod elements. The size and location of the sensors considered are in line with the instrumentation plan of the test package. For this, the mesh of the design models is slightly changed. Another modification of the FE models in the verification concerns the preload in the bolts of the primary and secondary lids (see foregoing chapter).

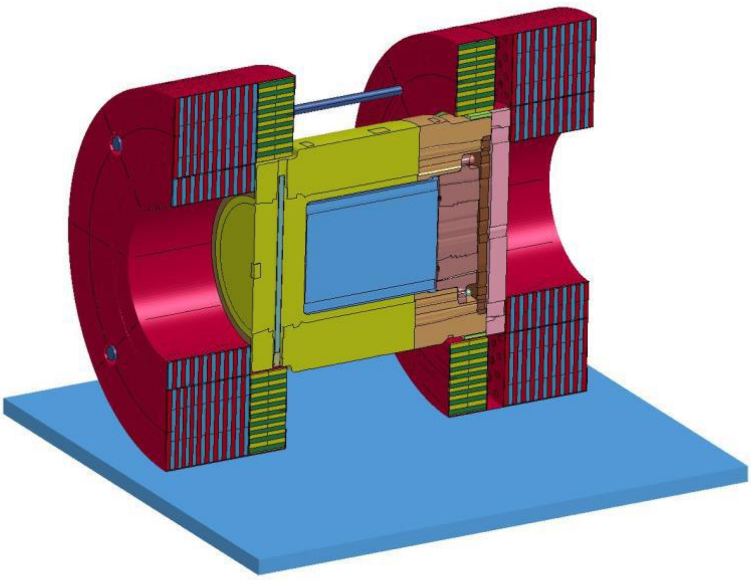

Figure 4 Example of CASTOR® MTR3 numerical model used in SAR

The FE models submitted by the applicant and the associated post-processing tools were used for the BAM own parameter studies to investigate the physical correctness of the verification results and their sensitivity to parameter changes. The verification analysis performed by applicant showed different quality of the correlation between the numerical and experimental results for different drop orientations. BAM has accepted the applicant's FE models as an adequate tool within the design assessment strategy of CASTOR® MTR3. This conclusion considers the positive results of the drop tests and results of the BAM own calculations as well.

Fracture Mechanics

For the cask body of CASTOR® MTR3, made of ductile cast iron, the fracture mechanical considerations were part of SAR. The stress distribution in the cask body is determined by using the verified global finite element models (see chapter *"Numerical Analysis"*). The specification of artificial flaw positions follows the German guideline BAM-GGR 007 [6]. Positions at which the maximum principal stress exceeds half the yield strength are considered as relevant. For Type B(U) packages, the yield strength has to be considered for a lowest temperature of -40 °C [1] which is assumed to be a lower bound temperature. This is a regulatory conservative assumption which does not take into account the possible warming of the container by the nuclear material inside.

The global analysis is carried out for structures without artificial flaws. The crack driving force is then determined by sub-models containing these. The information transferred from the global to the sub-model is the displacement of the nodes at the outer nodes of the sub-model where it is inserted into the global model. It is important, in that context, that the sub-model has to be large enough such that the local influence of the crack on the stress-strain field is subsided at its boundary. In order to guarantee this, sub-models of different size should be calculated. The requirement is fulfilled by sub-models which result in identical J-integral or K values. In order to perform a safety assessment this crack driving force has still to be compared with the dynamic fracture toughness of the material [7].

Thermal Assessment

The package is equipped with wood-filled impact limiters to reduce the impact loads onto its components during the drop tests. To fulfill the IAEA requirements [1], it is needed to consider the cumulative effect of mechanical and thermal tests. Thus, the damage resulting from the mechanical tests is to be considered as an initial condition for the thermal test.

Drop testing might cause significant damage of the impact limiter steel sheets and might enable sufficient oxygen supply to the impact limiter during the fire test to ignite the wood filling. The boundary conditions of the fire test are precisely described in the IAEA regulations. During the test the impact limiter will be subjected to a 30 minute enduring fully engulfing 800 °C fire phase. Subsequent to the fire phase any burning of the specimen has to extinguish naturally and no artificial cooling is allowed. Up to now fire propagation inside impact limiters is not yet considered in impact limiter design. This understanding is based on the assumption that because of the steel sheet encapsulation the oxygen supply in non-damaged condition is completely prevented. Recent resumption of the possible impact limiter burning topic and preceding tests show that in consequence of recently conducted mechanical drop tests damage in the steel encapsulation occur, which might realise sufficient oxygen supply for a smouldering fire inside the impact limiter.

BAM conducted some small-scale fire tests [11, 12] and one large-scale fire test [13] with a real size impact limiter to investigate the burning behavior of wood filled impact limiters in steel sheet encapsulation.

In frame of the package license procedure of the package design CASTOR® MTR3 this effect was considered by the applicant and assessed and accepted by BAM.

Conclusions

BAM assessed the new dual purpose package CASTOR® MTR3 in view to the mechanical and thermal safety analyses including drop tests, the activity release approaches and subjects of quality assurance and surveillance for manufacturing and operation of the package.

A combination of experimental testing and analytical/numerical calculations were used by applicant for safety analysis. In total, four drop tests were carried out at the BAM large drop test facility to investigate the integrity of the package and its safety against release of radioactive material as well as to test the effectiveness of the impact limiters and their fastening system.

The acceleration and strain signals measured during the drop tests were used to verify the FE models needed for the subsequent mechanical analysis of the design. The additional calculations by using these models were done by the applicant and assessed by BAM to investigate, e.g. the range of parameters not directly simulated in the drop tests or to evaluate the brittle fracture issues for the cask body made of ductile cask iron.

As a result of the design assessment BAM confirmed that the package CASTOR® MTR3 complies with the requirements of the IAEA-regulations [1]. The package design approval certificate was issued by BfE in January 2019. A first transport with this type of package is planned for 2020.

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