New generation of CASTOR® casks for high enriched, high burn-up fuel from German NPP

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1. Introduction

Requirements for new cask designs for transport and long-term dry storage of spent fuel assemblies (FA) from LWR-reactors are based on both increased source terms of the LWR FA including MOX FA, as well as the demand for economical optimisation of decommissioning costs by increased cask capacities.

For this, cask development is the challenge to create and establish cask designs that can accommodate more FA with higher source terms, each under fixed boundary conditions (i.e. transport requirements and limitations of the power plants as crane loads and/or fixed maximum dimensions).

This task has been elaborated by working simultaneously on different development actions each focussed to improve the cask performance. In the following a brief summary will be presented to give an overview which developments and investigations have been and are still will be performed for development and safety analyses of the new CASTOR®-designs under the main subjects: material investigation and qualification, component tests and verifications, detailed design analysis and not at least design verification.

2. Material Investigation and Qualification

The main topics for improvement of material characteristics could be derived directly from the sophisticated content of the new CASTOR®-designs. Higher enrichment per FA and/or MOX-content per cask, increased burn-up per FA and increased cask capacity require material concepts which allow compact basket designs and stable and reliable properties at high temperature levels.

One approach is to combine the tasks for safety of components, e.g. of the cask basket from different materials to a minimised number of materials. This approach led to investigations of different solutions for borated aluminum. This material composition was chosen due to its potential to be useful for neutron absorption for criticality control, heat conduction for limitation of the temperature of the nuclear content and mechanic strength of basket components. GNB selected and investigated different Al/B-material alloys, both of melting as well as of powder metallurgic origin with varying production lines and alloy compositions. Each alloy was tested for verification of the relevant properties as there are: Boron content and distribution, mechanical properties at low, ambient and maximum temperature levels, thermal and physical properties, neutron absorption behaviour, resistance to radiation and corrosion, to mention some of the most relevant. Figure 1 shows as an example the investigation of homogenity of distribution of B_4C-particles in a matrix of Al-powder of material-plates after prototype manufacturing.

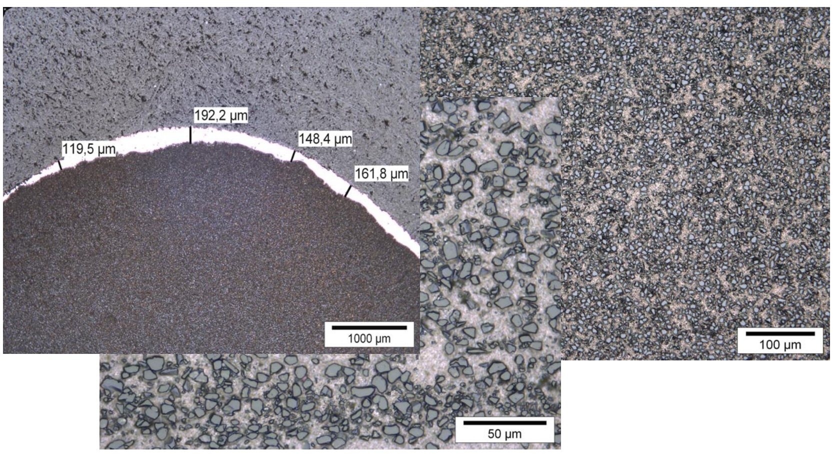

Figure 1 Homogenity of Powder Metal Al/B_4C Material Composition

As another main field, due to increased neutron sources, both per FA and per cask the development and qualification of moderator materials with enriched hydrogen content should be mentioned. Different compositions as polyethylene and polypropylene have been investigated. Test programs have been initiated under special consideration of long-term stability, optimal behaviour under temperature and mechanic loads, long-term radiation and temperatures beyond the level, which can be realised in cask designs.

3. Component Tests and Verifications

Beside analytical predictions, tests on single components have been performed on a wide range of applications and components for the new CASTOR®-designs. These component tests have been shown to be extremely useful prior to any design freeze. Conceptual safety avoids cost- and time-expensive loops within the development project. Due to this, e.g. further investigations of the sealing system for quantification of the leak-tightness behaviour under extreme mechanical loads and prototype manufacturing and assembly of new basket solutions have been performed. Furthermore, in case of new materials such as borated aluminum components, test productions in comparable size and with comparable manufacturing parameters were started. Other component tests were not performed with a focus on later hardware production, but for qualification of sophisticated finite-element tools e.g. for mechanical safety analyses. Fig. 2 shows real deformation and for comparison the result of the explicit finite-element calculation of the load case.

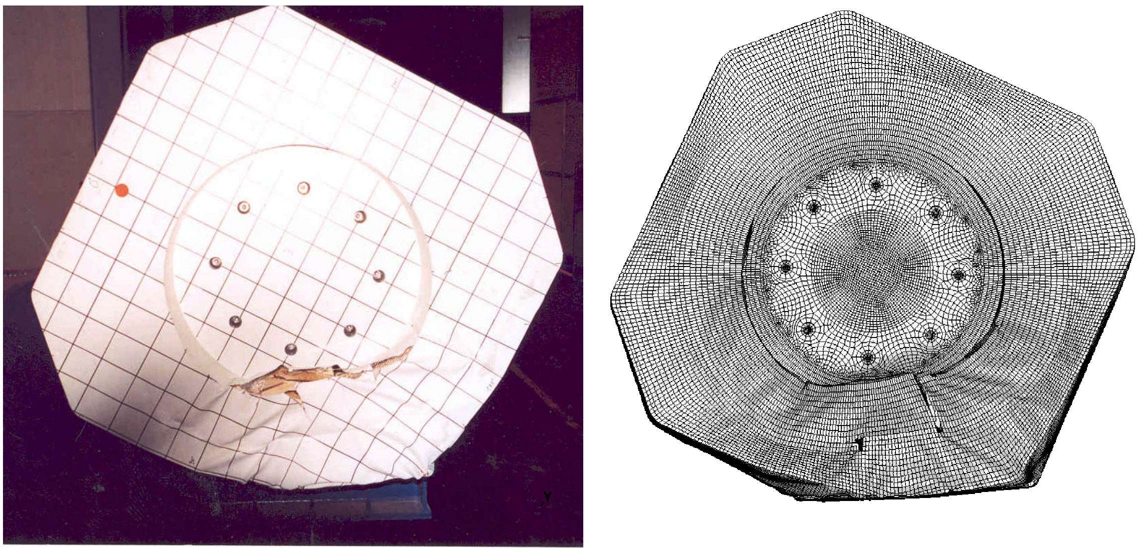

Figure 2 Test of 1:2-scaled, Shock Absorber Design vs. Result of FEM-Calculation

In this case the 1:2-scaled model cask CONSTOR®-VB2 was equipped with shock absorbers which have been predicted by the mechanical experts of GNB and partners to be progressive regarding deformation and deceleration behaviour under type B-accident loads. The test series with drops from 0.3 as well as from 9 m onto unyielding targets under different drop orientations confirmed both the prediction, as well as the detailed FEM-simulation. This is positive for the reliability of sophisticated analytical safety proofs.

4. Detailed Design Analysis

The analyses of shielding and thermal behaviour as well as of cask strength according to IAEA Type B test-requirements (9m drop, 1m pin drop, 800 °C fire test) were carried out by means of qualified calculation methods and programmes The mechanical analysis under hypothetical accident conditions for different loading cases (drop in different impact orientations of the cask) were performed with numerical methods, like Finite-Element-calculations (FEM) with ANSYS. The used calculation model consists of lower bound material properties, 3-dimensional simulation of the cask geometry, reasonable assumptions and clearly defined boundary conditions. As a result of the calculations the local distribution of all stress tensors inside the cask body is known (see example in Figure 3).

In the framework of the safety assessment, stress limitation criteria were defined in order to assure a sufficient margin against plastic deformation and brittle failure. These criteria consider the behavior of ductile cast iron as well as the applied method for stress calculation. The strength analysis has shown that the mechanical stresses under both normal operational and test/accidental conditions are below the respective allowable stresses.

Furthermore mechanical design calculations under consideration of dynamical behaviour with the code LS-DYNA have been performed for numerous drop-orientations and have been integrated in the safety analysis report of the casks. In combination with the above mentioned stress limitation criteria, the integrity after drop test series could be shown.

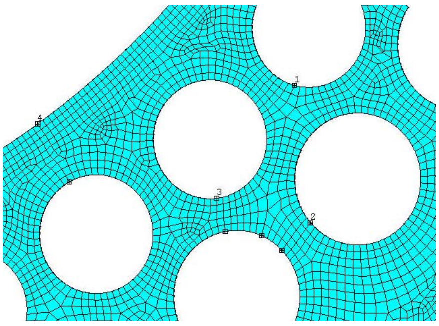
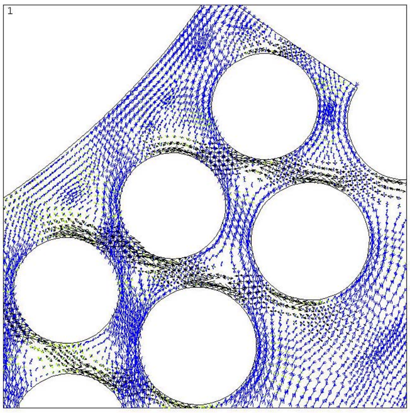
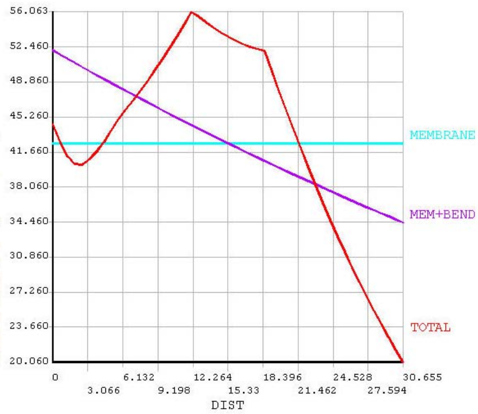

Figure 3 Model, Load and Stress in the DCI-Cask Wall

The thermal behaviour of the cask and inventory was analysed for the normal transport conditions and for the IAEA fire test conditions as well as for storage conditions. The respective analyses were performed by means of composed numerical-analytical methods (steady-state thermal conditions) and numerical non-steady state methods (cask under fire conditions) using the finite element code ANSYS.

The three-dimensional Monte Carlo code KENO was selected for performing the criticality analysis because it has been extensively used and validated by others and has all the necessary features for this analysis. The criticality calculations were performed with the SCALE program system.

The shielding analyses were performed with MCNP, which is a Monte Carlo transport code that offers a three-dimensional combinatorial geometry modelling capability including complex surfaces. For normal transport conditions the cask was modelled with the impact limiters and the transport hood. The hypothetical accident conditions assume the absence of the transport hood, the impact limiters and the neutron moderator. The shielding analysis covers the hypothetical accident conditions in the related regulation in a conservative manner, because in reality the impact limiters remain on the cask and the total loss of the neutron moderator is not possible. Moderator regions in the shielding model are replaced by air.

5. Design Verification

The results of the safety analysis after drop tests according to IAEA-regulations will be confirmed by means of a drop test program using a scaled model. The tests will be performed under supervision of competent authorities and independent experts, such as BAM and German TÜV. For preparation of the drop tests, detailed calculations of the dynamical behaviour with the code LS-DYNA will be performed prior to the test series both with the most unfavourable values of properties of the material specifications as well as with actual values of the test cask. Integrity checks and verification of the leak-tightness of the test cask will be a main objective of the test program. Fig. 4 shows the main steps and time schedule of the test program.

6. Summary and Conclusion

The development of the new CASTOR®-designs has been the challenge to create and establish cask designs that can accommodate more FA with higher source terms per FA under fixed boundary conditions.

This task has been solved by development, qualification and implementation of advanced material solutions. Optimisation could be reached by component tests and verifications which give safety under the aspect of coming hardware to be manufactured. Detailed design analysis incl. design verification with state-of-the-art FEM-systems and Monte-Carlo-Codes has been integrated in the safety analysis of the cask designs. Furthermore, for the new CASTOR® designs drop test series incl. pre- and post calculation as well as leak-tightness and integrity verifications will be performed under supervision of the Federal Institute of Material Research and Testing (BAM).

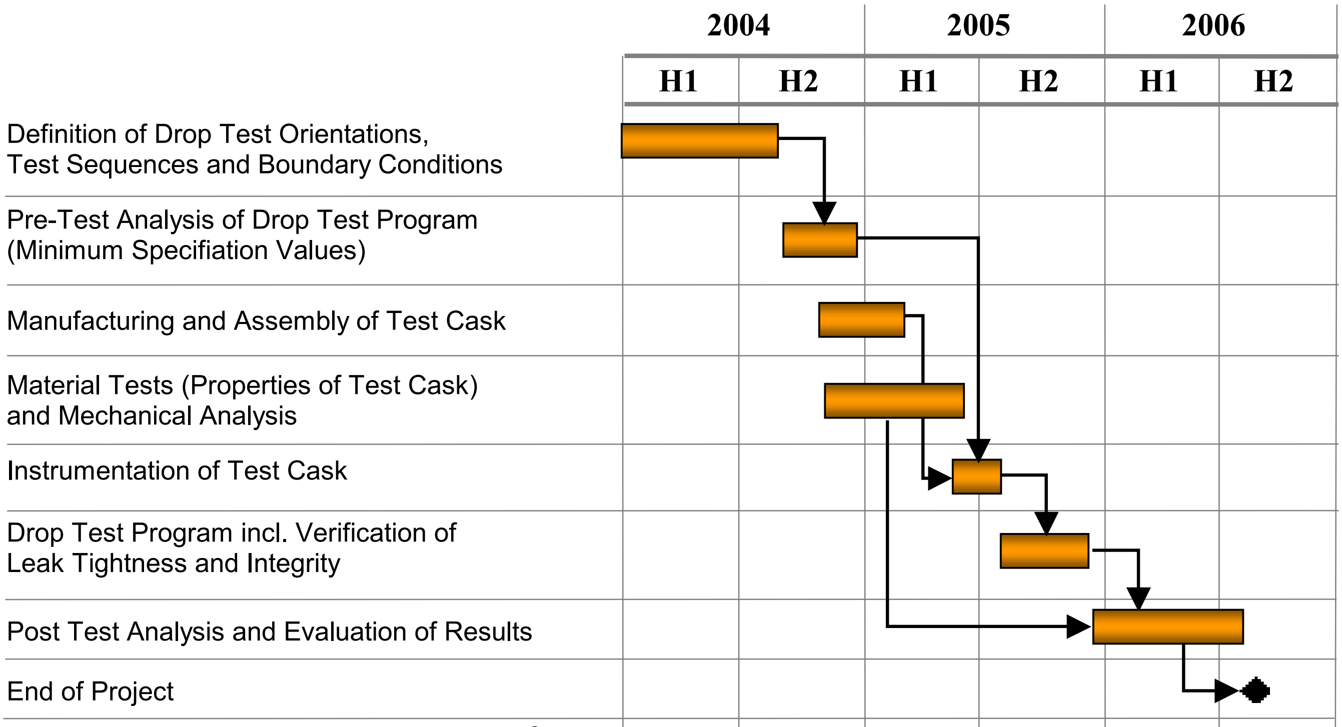

Fig. 4 Time Schedule for CASTOR®-Test Cask V/TB1a

The licensing procedure for the cask designs CASTOR® Va/21 (PWR-FA type 16x16 and 18x18) and CASTOR® Vb/24 (PWR-FA type 15x15) has already started. Development of the CASTOR® Vc-design for BWR-FA will be finished within the next months and safety analyses will be performed under consideration of the aspects described in this paper.