DROP AND FIRE TESTING OF SPENT FUEL AND HLW TRANSPORT CASKS AT "BAM TEST SITE TECHNICAL SAFETY" - 10079

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ABSTRACT

BAM as competent German government institute for the mechanical and thermal testing of radioactive material transport and storage containers, operates unique drop and fire test facilities for experimental investigations on the open-air BAM Test Site Technical Safety (TTS).
To be able to perform even drop tests with full-scale spent fuel or HAW casks (i. e. the German CASTOR cask designs) BAM constructed in 2004 a large drop test facility capable to handle 200 tons test objects, and to drop them onto a steel plate covered unyielding target with a mass of nearly 2600 tons. Drop test campaigns of the 181 ton GNS CONSTOR V/TC, the 129 ton MHI MSF-69BG and a 1:2 scale model of the GNS CASTOR HAW28M (CASTOR HAW/TB2) have been performed since then. The experimental BAM drop testing activities can be supported also by drop testing of smaller packages (up to 2 tons) in an in-house test facility, and by dynamic, guided impact testing of package components and material specimen inside a new drop test machine. In May 2008 a new modern fire test facility was put into operation. The facility provides two test stands fired with liquid Propane. Testing in every case has to be completed by computational investigations where BAM operates appropriate finite element modelling on appropriate computer codes, e. g. ABAQUS, LS-DYNA, ANSYS and other analytical tools.

INTRODUCTION

In worldwide comparison the largest amount of casks for the transportation and subsequent interim storage of spent fuel and of high level radioactive waste (HLW) is designed, tested, approved, manufactured and operated in Germany. This is a matter of fact since 1978 when the political decision for nuclear power plant decommissioning by alternative means of dry interim storage in dual purpose metal casks was taken. In that year the development of the "CASTOR" casks began, and BAM, as part of the German competent authority system being responsible for mechanical and thermal package design assessment, started with drop testing of half-scale as well as of full-scale CASTOR casks. Also different TN dual purpose cask designs have been tested. Currently several hundred dual purpose casks are in use in Germany and in other countries. The development of HLW and spent fuel cask designs progressed rapidly. From first generation casks weighting about 70 tons, the development spread over to second and third generation cask designs with about 140 tons cask weight. The development of these high-capacity casks is correlated with serious problems in the assessment of the mechanical safety. For these high-capacity casks with contents masses of up to 30 tons, and with cavity diameters of up to 2 m, the impact forces acting onto structural parts of the containment boundary have to be limited by sophisticated constructions including impact limiters, and the assessment of the closure system become essential with respect to ensure integrity and leak tightness of flange/bolts/gaskets/lid connections.
Testing in the sense of the IAEA Regulations for the Safe Transport of Radioactive Materials means: "Assessment of package safety performance under all relevant regulatory requirements, using experimental testing (of small-scale or full-scale) package specimens, reference to satisfactory previous tests of similar nature, and conservative calculations, or a combination of all methods".
The design safety assessment has to consider all combinations and technical variations/interdependencies of

- the requirements (e.g. mechanical drop test positions and sequences to meet the most-damaging-criteria for all safety relevant package components, maximum and minimum temperatures etc.),

- the actual test package specimen properties (its existent geometry, material properties, component characteristics, scaling factor etc.) and/or the FE model boundary conditions (e.g. material laws, contact conditions etc.),
- the design to be approved (tolerances in geometry, material properties, characteristics; real contents influence, etc.).

The fact that any experimental test represents only a "spot" in that multi-dimensional assessment matrix requires an assessment strategy including the application of sophisticated measurement and calculation methods. Sometimes it is very much recommendable that the transfer process or the calculation verification has to be supported by additional material and/or component testing.

A complete safety proof consequently is a mixture of all methods: experimental testing on basis of pre-calculations, and finally – even in case of incorporating experimental full-scale cask testing – post-test calculations to justify the design to be approved for all requirements. For the new generation cask designs BAM required and performed again extensive drop test programs, in connection with associated material tests and calculations based on dynamic finite element methods.

DEVELOPMENT OF TEST FACILITIES FOR DROP TESTING OF FULL-SCALE SPENT FUEL CASKS

BAM is the competent German government institute for radioactive material transport packages mechanical and thermal safety assessment and quality assurance issues. Since the 1970's BAM has performed nearly all relevant drop and fire tests with packages designed and approved in Germany. In 1978 BAM started the extensive drop test series with CASTOR casks, a "design family" of spent fuel transport and storage casks (manufacturer GNS, Essen).

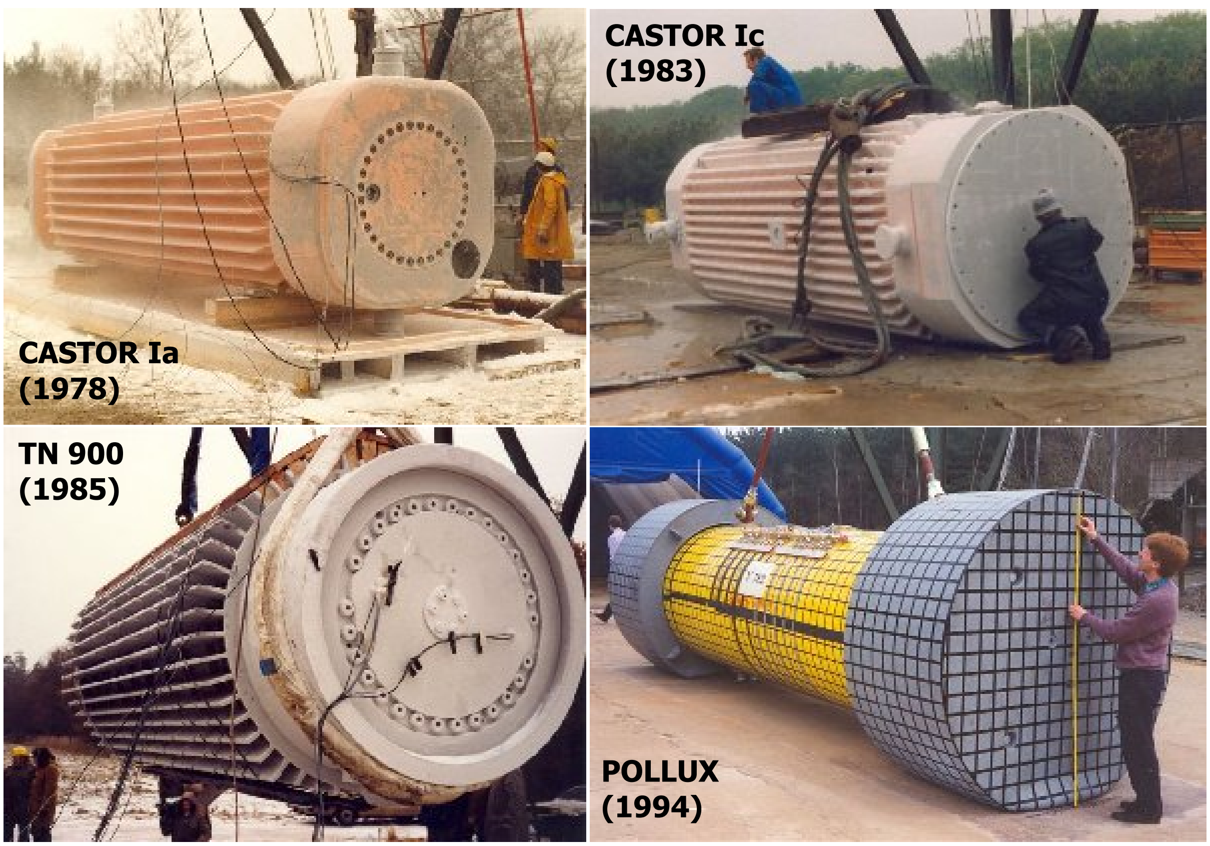

Fig. 1. Full-scale spent fuel casks tested at the former BAM Drop Test Facility in Lehre

After a series of 9 m drop tests with a CASTOR Ia 1:2 scale model, BAM requested the applicant to provide a full-scale prototype, because at that time it was impossible to model the material properties of the monolithic cask body made of ductile cast iron correctly. Safety relevant material properties like elongation at fracture or fracture toughness at that time were smaller in a thick-walled structure of a full-scale cask due to slower solidification of the thick-walled casting. In the meantime the casting technology has improved significantly due to active or passive mould cooling methods, and the material property scaling is not that much relevant anymore. Since that world-wide first full-scale drop testing of a large spent fuel cask (CASTOR Ia prototype with appr. 65 tons) on the BAM drop test facility in Lehre, BAM has performed further full-scale drop testing with three other spent fuel transport and storage cask designs, with the CASTOR Ic, the TN 900 and the POLLUX /1, 2/. Figure 1 shows the four large full-scale casks tested by BAM on the old drop test facility in Lehre between 1978 and 1994. It is remarkable that the first three cask designs have partially been tested at -40 °C, without being equipped with additional impact limiters.
After this "first generation" of casks (masses up to 80 tons) designed to serve as dual-purpose casks, a "second generation" of similar designs (masses up to 110 tons) have been tested in full-scale in Japan at the CRIEPI test centre /3/.

THE BAM DROP TEST FACILITY FOR LARGE FULL-SCALE CASKS

With the development of the "third generation" of spent fuel transport and storage casks (in USA so – called "rail casks", in Europe and Japan dual purpose casks for long-term interim storage with masses up to 140 tons), the need for full-scale cask testing of these objects from technical as well as from public acceptance point of view came up. In a study performed for the European Commission /4/, the impact of casks onto real targets was investigated. We could conclude that with increasing size of casks and their "soft" impact limiters, the safety margins decrease in relation between real target drops and the regulatory 9-m-onto-unyielding-target drop. Also for that reason and because of calculation validation reasons, the experimental testing and quantitative stress analysis of these new cask designs becomes more and more important. In the USA a study of the National Academies strongly endorse the application of full-scale testing of spent fuel or HLW casks /5/. BAM could start at the end of 2003 with detailed planning of a new drop testing facility on the "BAM Test Site Technical Safety" in Horstwalde, 50 km south of Berlin. At the begin of 2004 the contracts for the construction of the new test site were signed, and in April 2004 construction started. The new facility (Fig. 2) consists of a steel pipe construction drop tower with a height of 36 m; at the top of this tower is a small cabin with the 200 ton hoist; maximum hook height is 30 m. Below this drop tower is an integrated test hall (24 m x 20 m; steel frame construction independent from the drop tower) with a 80 t portal crane and a roof that can be removed if a cask is connected to the hoist. The impact pad is constructed as an unyielding target what is realized by a reinforced concrete block with the dimension 14 m x 14 m x 5 m depth. The impact pad is made of steel plates (10 m x 4.5 m x 0.22 m thickness) that are fixed to the reinforced concrete block by anchor boltings. The proof of the "unyieldingness" of the target was derived from measurements made at the target during drop tests /6/. The connection between hook and a cask is provided by special cask detachment devices that were designed by BAM to ensure a momentum-free release of the specimen (Fig. 3). Their construction is based on hydraulic mechanism rupturing a steel bolt, or by electro-mechanical means. The construction of the facility was finished in August 2004 with the static overload test of the whole lifting equipment (lifted weight 250 tons for the tower, the hoist and detachment device). Figure 2 shows the completed drop test facility. Considering the value and uniqueness of test results and the purpose of quantitative stress and deformation analysis in the safety case and for calculation bench-marking, an extensive coverage with strain gauges, accelerometers according to a sophisticated instrumentation plan is necessary for those tests /7/. Before and after the test designated measurement techniques, e.g. to quantify leakage rates by Helium leakage test, and to document position or deformations changes by bolt torque forces measurement, 3 D geometry testing, close range photogrammetry or optical surface digitalization /8/ are used by BAM.

Fig. 2. The large 200 t BAM Drop Test Facility

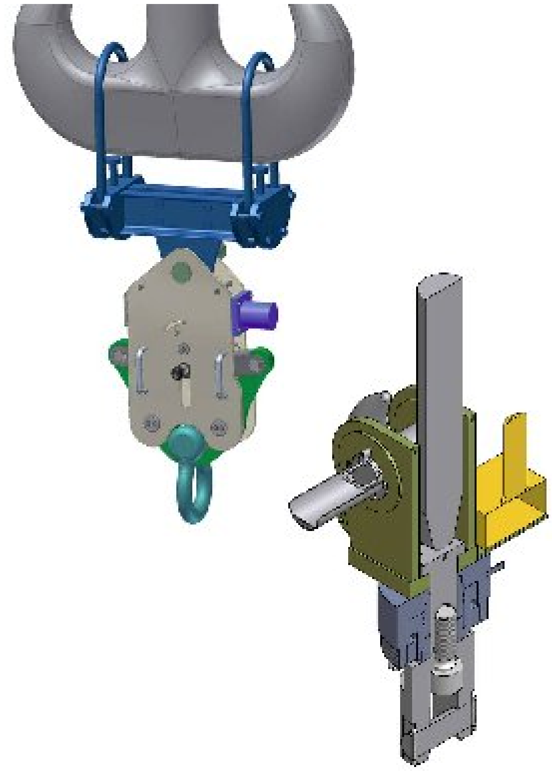

Fig. 3. Release systems

ACTUAL DROP TEST CAMPAIGNS OF SPENT FUEL AND HLW TRANSPORT CASKS

Just before the "14^{th} International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM 2004)" took place in Berlin, Germany, the new drop test facility was ready and could start operation with the first drop test on a technical tour of PATRAM 2004. At September 21, 2004 the heaviest cask ever tested world-wide was dropped horizontally from 9 m (see Figure 4). The CONSTOR V/TC (manufacturer GNS) is a steel-sandwich cask. The cask body has an outer and an inner liner made of steel. At the upper end, the liners are welded to a forged steel ring. The space between the two liners is filled with heavy concrete named CONSTORIT (iron aggregate frame and hardened cement paste). The transport version of this dual purpose cask is equipped with a puncture-resistant jacket (made of two parts of a massive steel shell) and two impact limiters; its weight was 181 tons. The test prototype was filled with a dummy representing the fuel assemblies and the basket. More details of the cask are given in /9/. The drop test was successful for the test facility which provided all necessary operations, for the instrumentation and measurements system which recorded properly all relevant strain and acceleration data, and for the cask design which demonstrated all relevant safety functions. From the cask structure only the impact limiters where deformed according to their function, and the Helium leakage rates of the closure lid where measured for seal no. 1 with $< 2.4 \cdot 10^{-10}$ Pam^3s^{-1}, for seal no. 2 with $8.7 \cdot 10^{-9}$ Pam^3s^{-1}. Test results are presented in more detail in /10/.

Fig. 4. 9 m horizontal drop test with the full-scale prototype of CONSTOR V/TC

At the end of the first operation week of the new drop test facility a second large full-scale dual-purpose cask was tested on September 24, 2004 within PATRAM 2004 technical tour no. 2 (see Figure 5). This test was performed with a full-scale prototype MSF-69BG (manufacturer MHI, Japan). This cask consists of a monolithic steel body with a double-barrier closure lid system. The cask body is on the outside covered with epoxy resin as neutron shielding material enclosed by an external shell. The two lids are screwed to the cask body and sealed with metallic O-rings. The cask weight was 127 tons. This test went successfully too, with respect to the facility operation, instrumentation and measurement performance. Since this drop test, some other four drop tests with this full-scale model have been performed (1m puncture test horizontally with impact onto the upper cask body/secondary lid area; 9 m vertical with lids downwards; 0.3 m oblique drop followed by a 9 m slap-down drop). More experimental drop tests had been performed with a 1:2.5 scale model cask of the same design. Test results are presented in /11/.

Fig. 5. 9 m slap-down drop test of the full-scale spent fuel cask design MSF-69BG

Within the package design approval process of a new CASTOR HAW28M cask for transport and dry interim storage of 28 canisters of vitrified high level waste, a series of 18 drop tests with a 1:2 scale model CASTOR HAW/TB2 have been performed. Sixteen 9 m or 1 m puncture drop tests according to the transport regulations, and two 0.3 m drop (one with, and one without impact limiter) were carried out. Although the test specimen (see Figure 6) remained intact and sufficiently leak-tight after these tests, the original cask design qualification needed a lot more of dynamic FEM calculations to transfer the test results with the 1:2 scale model to the 1:1 cask design, considering all relevant border conditions, like maximum and minimum temperatures, material properties and other design characteristics (e.g. bolt torque forces) variations. In September 2009 the Type B(U)F package design approval certificate for this cask has been issued by the German Competent Authority. Besides spent fuel and HLW casks, a lot of drop testing is performed with packages intended to be used for the disposal of non-heat-generating radioactive waste. A very impressive drop test program with a Japanese radioactive waste container design from Kobe Steel is presented in /12/.

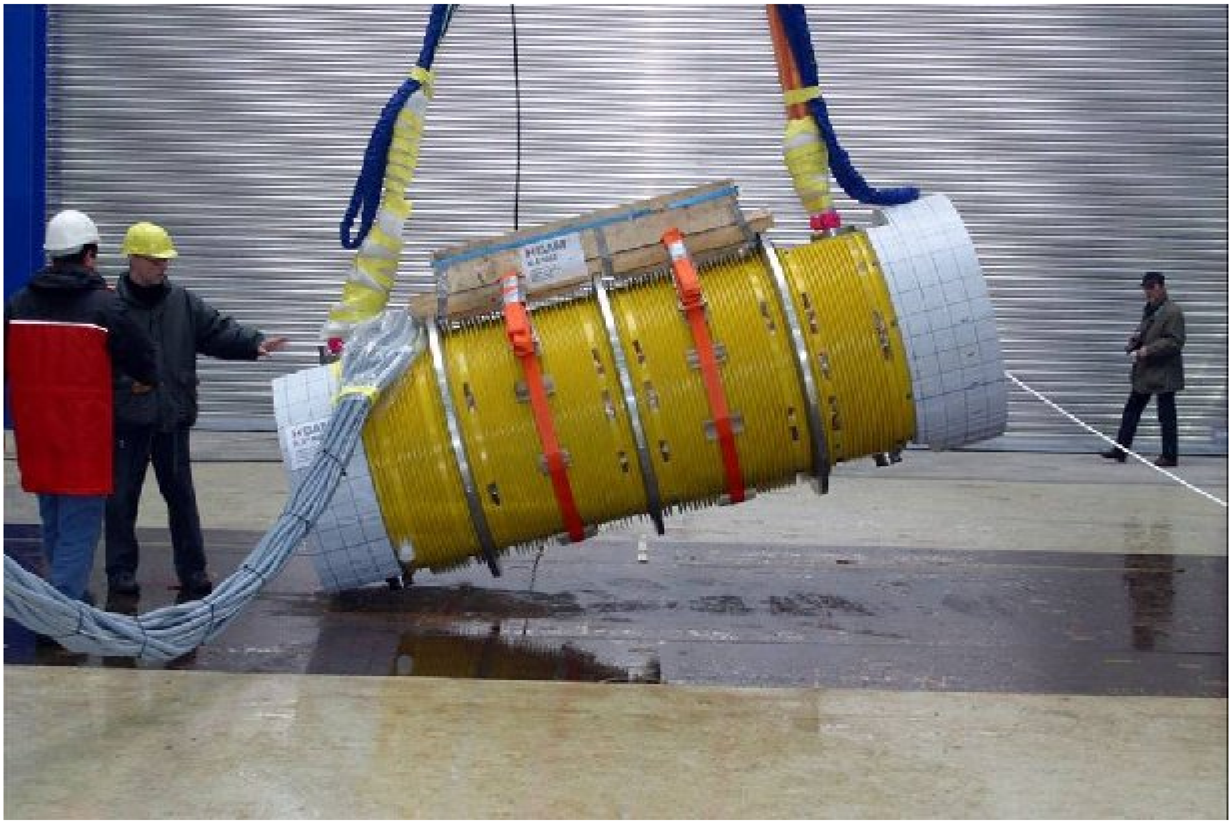

Fig. 6. 1:2 scale model CASTOR HAW/TB2

DROP TEST MACHINE

In addition to BAM's free drop test facility for testing of containers a unique drop test machine was constructed to investigate specific energy absorption of materials and structures under impact loading conditions. This fully instrumented drop test machine for maximum input energy of 118 kJ can be configured for many applications. Defined component loading allows impact, bending, compression as well as crash and crush tests. The facility can be used for testing or simulating: impact resistance and crash-worthiness of materials and structures, impact on structures, pipes, composites etc by spanners, crash protection and stability, developing materials models for FE. The drop test machine for guided drop tests consists of a 14-metre high steel frame structure with a maximum load capacity of 1000 kgs, a large impact area and 18000-kgs rigid foundation, see Figure 7.

The foundation consists of a steel-reinforced concrete block with an anchored steel plate. This steel impact pad (2000 mm x 150 mm) is equipped with a T-slot system to realize variable test setups, such as steel impact target, test bolts, clamping assistance. load cell, etc.

A vertical sliding carriage consisting of four high-speed runner blocks is guided on rails using low friction ball bearings. The maximum dropt height provided by the height adjustable frame of the test stand is 12 meters, and sled velocities at impact, can be up to 15 m/s. The slide rails serve for the support of test objects or drop weight. They are designed, dependent on the size of the test object, to allow variable widths, so that objects with a width up to 1600 mm can be tested. The drop objects are pulled up to the required drop height by a cable, guide rollers and an electric driven cable winch. An exact drop orientation of the specimen or drop weight is realised by a momentum free electro-mechanic release system. A tempering chamber is provided for the realization of test temperatures between -50 °C and +150 °C. The drop test machine is equipped with a makrolon-glassed steel fence and a safety interlock for the protection of persons and devices.

Fig. 7. 118-kJ Drop Test Machine

First operation and measurement experiences with this drop test machine are presented in /13/.

BAM FIRE TEST FACILITIES

On a large open area BAM operates since May 2009 two fire fest facilities where large containments for dangerous goods can be exposed to any kind of fire scenario. The heat energy is provided by liquid Propane pumped from a 60 m³ storage tank to the test facility where the liquid gas is released from nozzles in ring burner systems. The fire exposed test facility areas are 12 m x 8 m; test facility B is for fire testing of containers which may burst during testing (Fig. 8); test facility A (Figure 9) is designed for heavy test objects up to 200 tons, and can be used e.g. for full-scale spent fuel cask fire testing. On test facility A fire tests with calorimeters of various sizes have been conducted to verify the absorbed heat fluxes under the chosen test arrangements; the results of these tests will be published in near future, and shall demonstrate that the regulatory fire test conditions are met.

Fig. 8. BAM Fire Test Facility B

Fig. 9. BAM Fire Test Facility A

TESTING BY CALCULATIONS

For completion of safety assessments appropriate calculations have to be applied. BAM provides relevant hard- and software equipment for quasi-static or dynamic structural analysis of casks, e.g. by Finite Element Method (ABAQUS, ANSYS, LS-DYNA). Figure 10 shows the finite element model of a casks lid system as it has to be developed for investigating the response to mechanical or thermal impacts /14/. Those calculation methods are used not only for final package design verification based on experimental benchmarks /15, 16/, but are also essential for the investigation of hypothetical accident scenarios that are highly improbable to be examined by experiments, e.g. explosion blast waves /17/ or aircraft crash impacts /18/.

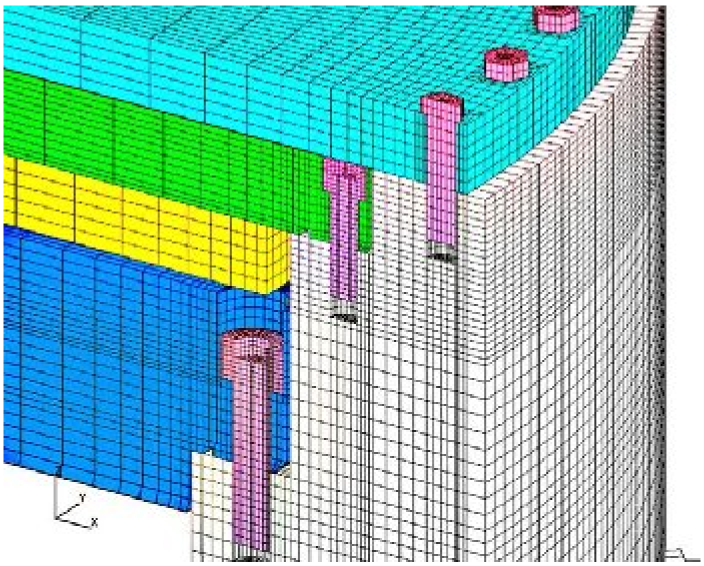

Fig. 10. Finite element model of the lid system of a spent fuel cask /13/

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