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A SURVEY ON 35 YEARS OF PACKAGING, TRANSPORT AND STORAGE OF RADIOACTIVE MATERIAL

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ABSTRACT

This will is a report from an expert working in this field since 1978, participating in PATRAM conferences since 1980. Exactly in that year 1978 the development and testing of the CASTOR casks started in Germany, with the intention to use these transport casks for interim storage of spent fuel. After involvement in the first full-scale drop tests of those large spent fuel casks for transport package design approval, the official assessment as storage cask started. At the beginning of that new decommissioning technology a series of storage demonstration programs were conducted; most interesting were cases where a cask was loaded in a NPP with fuel assemblies instrumented with thermocouples, equipped with a first lid penetrated by instrumentation cables, closed by a second lid, transported to a research institute and stored there for 2 years, with verification of maximum cladding temperatures and leak-tight closure. In 1982 the basis BAM expert reports for the licensing of CASTOR casks in away-from-reactor storage sites Gorleben and Ahaus were finished. The first cask loading for interim storage was performed in Switzerland in 1983; that CASTOR Ic-Diorit cask, 30 years of age, is the “grandfather” of all dual purpose casks. In 1984, a remarkable transport accident happened, the sinking of the “Mont-Louis” with 30 48-Y-UF_6 containers; BAM shortly before had issued the approval for a tank container that could be used for the recovery of some these UF_6 containers. The 90s saw the full-scale drop tests with the POLLUX multi-purpose cask design (for transport, interim storage, final disposal), drop test series with new transport packages for fresh fuel assemblies including the “French puncture drop”, finally a spectacular BLEVE blast onto a CASTOR cask. 2004 we were proud to host the PATRAM conference, the second time in Berlin. For the Technical Tours BAM performed drop tests with two full scale SNF casks (the largest ones tested world-wide) at our new 200 t drop test facility. In the meantime a lot of other assessment experience, e.g. in ductile iron brittle fracture, numerical calculations, radwaste disposal container testing etc. was stacked. Changes in safety assessment methodology over the last decades will briefly be addressed.

PACKAGE DESIGN DEVELOPMENT

<u>Dual Purpose Casks for Spent Nuclear Fuel (SNF)</u>

In 1978 the BAM testing of the German CASTOR® casks (designer GNS, Germany) started. After a series of drop tests with a 1:2 scale CASTOR Ia model, a full scale prototype of that design was drop tested [1]. The justification for requesting a full scale model was the impossibility of “scaling” the material properties of thick-walled ductile iron correctly. In 1980 the first dual purpose cask (DPC) versions of CASTOR IIa (1:2 scale model) and TN 1300 (1:3 scale model; designer Transnuklear, Germany) had been drop and fire tested.

In Germany very early the dry SNF storage in DPCs was chosen to serve as an alternative SNF decommissioning option. The design of these DPC is focused on a double lid closure system of a monolithic cask body made of ductile iron or forged steel. The two lid barriers are sealed with long-term resistant metal seals, and the interspace pressure between the lids is monitored by a pressure switch indicating a drop of overpressure [2]. BAM was not only involved in mechanical and thermal testing of the transport package design, but also had been contracted with the DPC safety assessment in the storage site licensing procedures [3, 4]. Between 1982 and 1984 a series of dry storage demonstration programs with different cask designs was performed [5], see Figure 1. The DPC development in Germany spread rapidly, and 1986 CASTOR V/21 casks were delivered to the USA (in use by VEPCO, Surry, Va.), and a demonstration program with one of that casks was performed at INL [6].

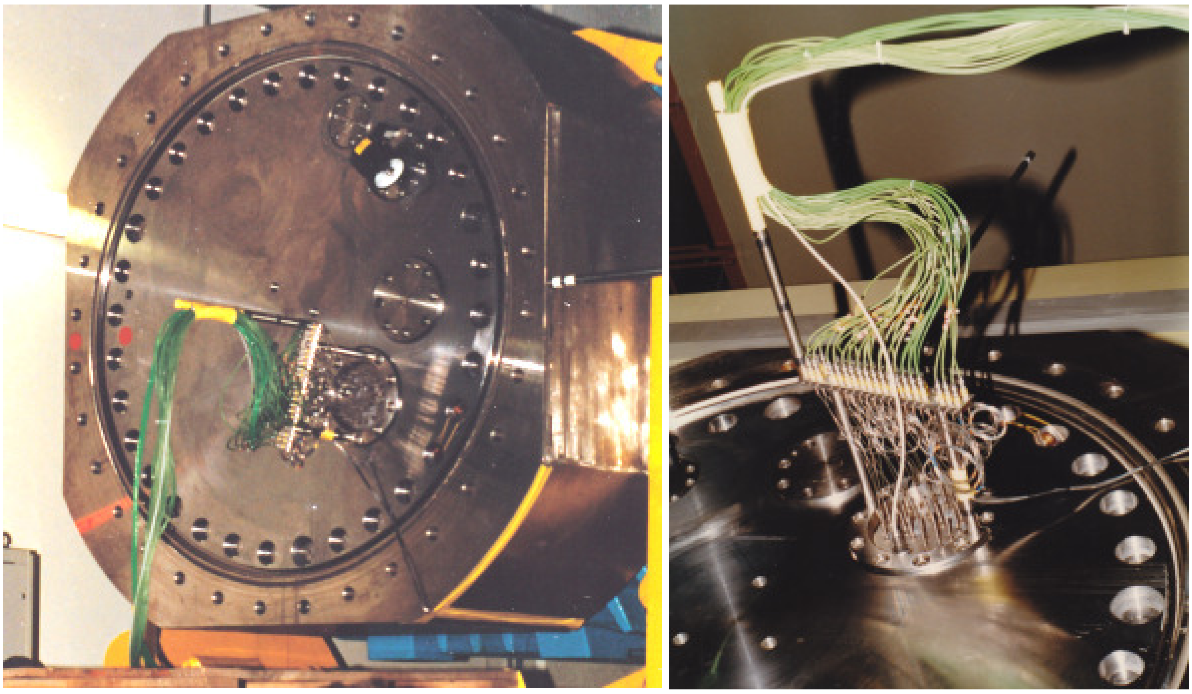

Figure 1. SNF dry storage demonstration program; CASTOR Ia cask with thermocouple penetration through the closure lid

There were numerous different CASTOR DPC designs developed for use in Germany and other countries. The first loading of a DPC took place 1983 at Paul-Scherrer-Institute in Switzerland. There the grandfather of all SNF DPCs, the CASTOR Ic-DIORIT is still in storage since 30 years (Figure 2).
A comprehensive overview representing the status of package designs that had been approved around 1995 is given in [7].
For decommissioning actually German NPPs CASTOR V/19 (for 19 PWR assemblies) and CASTOR V/52 (for 52 BWR assemblies) casks are used. These DPCs are stored since 2005 in storage sites located at the NPP sites (316 casks at the end of December 2012). Other important SNF DPCs are CASTOR 440/84 casks for decommissioning of the shut-down WWER 440 NPPs of the former German Democratic Republic and Czech Republic. 65 of these casks are stored in "Zwischenlager Nord (ZLN)" in Lubmin.
In Germany the Thorium-High-Temperature Reactor technology was developed, and for the transport and storage of these "pebble-bed balls" SNF the CASTOR THTR/AVR design was developed [8]. 305 of these casks with THTR SNF are stored in central storage site Ahaus, and 152 of these casks with AVR SNF at research center Juelich.

Figure 2. CASTOR Ic-DIORIT since 30 years in operation (Foto: Paul-Scherrer-Institute)

Figure 3. POLLUX cask for transport, storage and disposal of SNF; left: 5-m drop onto concrete, right: preparation for 9-m drop with lid corner onto unyielding target (BAM Lehre, 1994)

Around 1994 there was an interesting development of a multipurpose cask design, the POLLUX cask for transport, storage and disposal of SNF [9] from which a full scale prototype underwent a BAM drop test program including regulatory 9-m drop tests as well as on-site handling accidental drops from 5 m onto concrete (Figure 3).

Dual Purpose Casks for High Level Waste (HLW)

Based on the same principle as the DPCs for SNF, appropriate cask designs have been developed to transport and storage of vitrified HLW. Till 2005 most of the spent fuel from German NPPs went to reprocessing in La Hague, France, and a smaller part to Sellafield, UK. The HLW residues are vitrified and filled into stainless steel canisters. 28 of these canisters are loaded into one DPC, and in several transport campaigns the casks had been transported from France to central transport cask storage site Gorleben. Currently all HLW from France is stored there in 108 casks (1 TS 28 V, 74 CASTOR HAW 20/28 CG, 12 TN 85, 21 CASTOR HAW 28M). The transport of 21 CASTOR HAW 28M from Sellafield back to Germany is planned for near future.

In an interesting joint USA-Germany cooperation a CASTOR VHLW transport cask for a canister of vitrified HLW, provided by GNSI/DOE, had been tested in a series of regulatory drop tests (from 9 m, equipped with impact limiters) where Sandia accompanied with measurements BAM drop testing [35]. The cask was also investigated in a joint Sandia/BAM research project on safety of ductile iron casks; here the cask with a large machined artificial failure was dropped from heights up to 14 m onto steel rails to demonstrate safety margins.

Package Designs for LLW/MLW

Important for NPP decommissioning are also all those different waste packages designs. In Germany the ductile iron technology was also applied on compact thick-walled cylindrical waste containers (MOSAIK®casks, GNS, Germany). With the perspective of storage and disposal in a repository (which will be in Germany the finally licensed KONRAD site, a former iron ore mine), also cubically shaped containers (“Gußcontainer”) were developed. The assessment of these cubic ductile iron containers was concentrated on the complex structural analysis of flat bottom drops onto a target simulating a real underground, and the fire impact assessment for containers filled with ion exchange resins [10]

Transport Packages for fresh Fuel Assemblies

Around the year 2000 it was identified that some older designs of packages for fresh fuel assemblies had deficiencies, specifically concerning puncture resistance. This resulted in series of BAM drop tests with an existing package design [32], and with new developed package designs [33], see Figure 4.

Figure 4. Testing of packages for transport of fresh fuel assemblies; 1-m puncture bar drop with ANF-10 package (left); internals of opened RA-3D package after a drop test sequence

DEVELOPMENT OF PACKAGE ASSESSMENT METHODS

The structural analysis was at first very much concentrated on performance of drop tests. From the beginning in Germany large scale tests have been preferred to avoid problems in transfer of small scale model test results to real size packages. The older cask designs incorporated rather large margins of safety; they did not required large impact limiters, and had been tested sometimes without any impact limiter. With growing cask capacities, what increases cask weight and diameter, and with shrinking margins of safety, with consideration of more specific design criteria, like limitation of maximum allowable local strain, stress intensity factors for brittle fracture failure prevention etc., the character of mechanical assessment methods changed consequently (Figure 5). Also the available methods improved. Since about 10 years the Finite Element Analysis (FEA), even for dynamic impacts, is able to provide reliable results, if modeling is correctly done on basis of appropriate chosen material laws and contact parameters. For thermal analysis this method is used more or less solely a bit longer.

With respect to dynamic stress analysis, combined with brittle fracture safety analysis, and thermo-mechanical assessment, we on the other hand made the experience that the application of FEA is accompanied with a significant increase in physical testing. FEA of drop test impacts needs to be verified by experimental package drop tests; here is the only justified use of small scale models, besides containment leakage rate testing.

If the impact loads are close to the limits allowed, FEA needs to be done on basis of real material properties, to be estimated by physical testing at relevant strain rates and temperatures. <u>That concludes: The more you calculate, the more you have to test experimentally</u>.

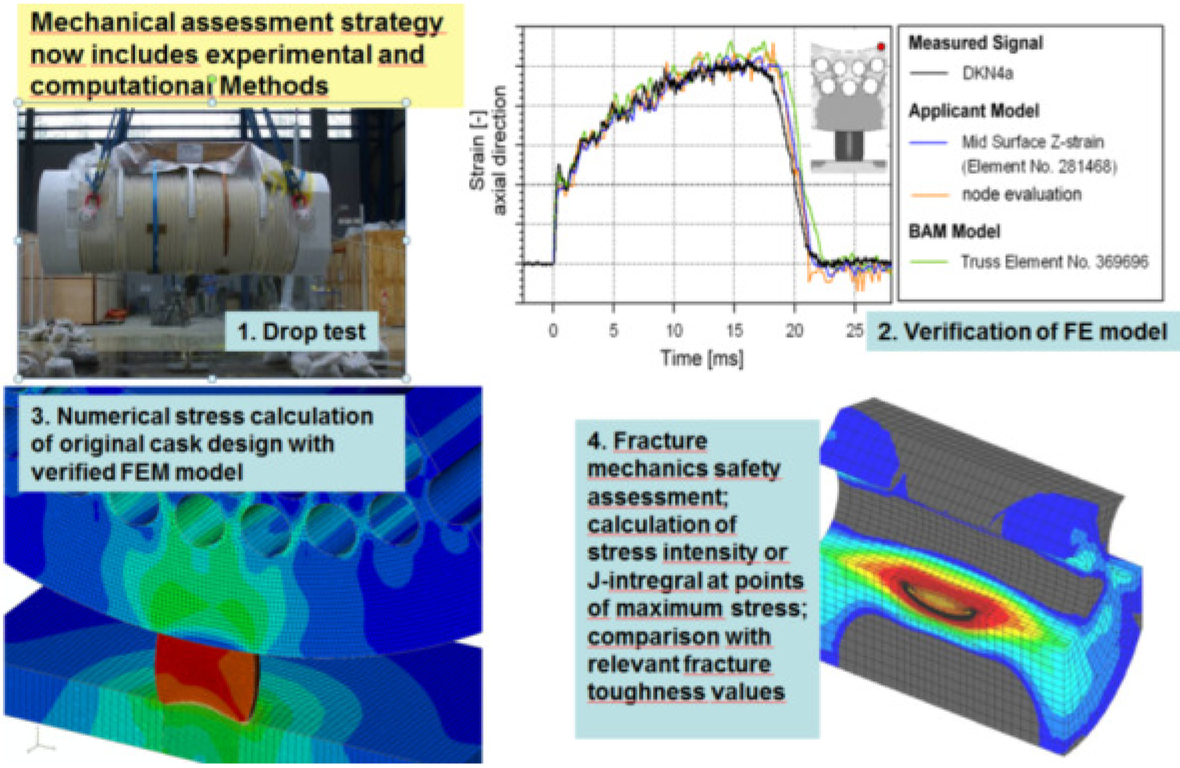

Figure 5. Actual mechanical safety assessment strategy

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Every test method needs continuous improvement or development of alternative means. When we got problems in running the well-known open fuel oil pool fire (because of restrictions to smoke emission), we developed an alternative fire test facility, fired by LPG [11].

We identified that drop tests of multi mass systems cause additional stresses due to internal collisions [12], what has to be considered in every structural analysis since then.

We evaluated appropriate leakage test methods and investigated low temperature behavior of elastomeric seals [13].

The long lasting involvement in assessing ductile iron casks, led to development of dynamic fracture mechanics assessment approaches [14].

The research in lid closure system behavior under mechanical impact [15] initiated the FEA analysis of bolted closure systems.

The behavior of packages under drop test slap-down conditions had been investigated carefully by experimental and numerical methods [16].

For drop testing, BAM did not only put into operation in 2004 a new large drop test facility where in its first year two full scale SNF DPCs of the newest generation have been tested [17] but also provided guidance for the correct performance of the 1 m puncture bar drop test on small scale package models [18]. Figure 6 shows the evolution of BAM`s outdoor drop test facilities in the past.

BAM had provided important input to the introduction of the new mechanical test, the “crush test” for light weight packages [19].

One of the most advanced drop test programs, containing new measurement techniques like projected fringes method, had been performed with a half scale model of the CASTOR HAW28M, the HLW cask of the last generation [10]. This design assessment case has shown that drop testing of a small scale model is to be combined with a lot more of numerical calculations and material investigations to allow the real package design approval [21].

Figure 6. BAM`s outdoor drop test facilities, Berlin-Grunewald (right, 1975-1980), Lehre (middle, 1978- 2005), BAM TTS (right, since 2004)

Specific attention has also been given to assess the mechanical behavior of high burn up spent fuel assemblies [22], and the containment function with respect to activity release calculation [23].
The performance of drop tests with waste disposal containers onto concrete targets was developed to a high level of confidence and quantitative test results which are important for advanced design development [24].
BAM research currently is concentrated on dynamic compression testing of impact limiting material, in combination with numerical calculations [25], and on metal seal investigations with regard to performance criteria and their dependence from time and temperature [26].
The experimental and the theoretical mechanical, thermal and containment assessment tools are continuously under development at BAM.
Besides regulatory tests, BAM often performed or assessed extra-regulatory test conditions, like drop tests from larger heights, extended fire tests, aircraft crash simulating tests or calculations, drop tests with specimen containing artificial failures, LPG tank wagon explosions etc. That kind of investigations has been summarized comprehensively in [27].

SPECIFIC ASPECTS

BAM as scientific and technical expert institution is involved not only in package design assessment, but also in all aspects of quality assurance in packaging manufacture and operation. For packages requiring competent authority design approval, BAM is responsible in depth for approval of the manufacturer`s management system till final and periodic inspection of each fabricated serial packaging [34].

BAM also supervises manufacturers of packagings for packages not requiring competent authority design approval [28]. Subject of testing and approval by BAM are also special form radioactive materials and sealed sources [29].

BAM as competent authority for approval of dangerous goods tank containers had in 1984 approved a special Tank container designed for the recovery of leaking UF_6 containers (as requested by German Federal State Authorities at UF_6 storage sites); this tank container could be used in the same year within the recovery action of 30 UF_6 48-Y containers from the sunken cargo vessel “Mont-Louis” at the coast of Belgium [36], see Figure 7.

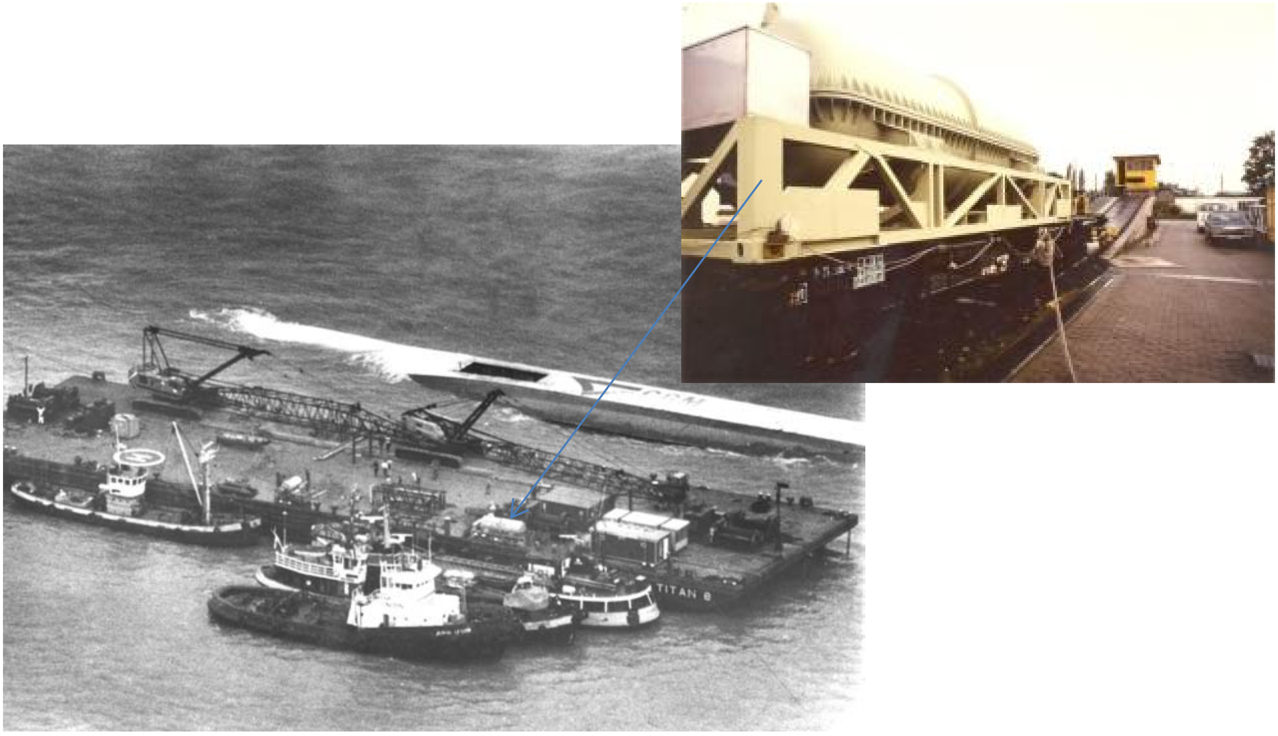

Figure 7. Sunken cargo vessel Mont-Louis 10 miles north of Ostende, Belgium, 1984; Tank container for recovery of damaged UF_6 Containers during prototype testing, approved by BAM (Fotos: NCS)

In 1987, one year after the Chernobyl NPP accident, a corruption scandal in Germany within radioactive waste decommissioning contracts with utilities occurred [37], which seriously eroded public acceptance, and led to a complete reorganization of the German nuclear waste management sector. Another event that caused further irritations was the detection of surface contamination of spent fuel transport casks in 1998, what caused a stop of transports in Germany for some years; after thorough investigations and introduction of consequent decontamination protection measures [38] the transportation activities proceeded without any complications.

Decommissioning of nuclear installations are accompanied with transportation of dismantled large components, where BAM is involved in mechanical safety assessment [30]. A very special involvement was the technical supervision of the dismantling activities of Russian nuclear submarines [31].

The problem currently receiving most attention is the appropriate consideration of ageing of technical components, safety cases, approval certificates, standards, regulations, knowledge, persons, institutions related to longer terminated storage of SNF and nuclear waste. Everyone involved in spent fuel and waste management has to ensure sufficient safety margins and associated regulatory framework, so that future operations, e.g. transport of SNF or HLW to currently unknown destinations for conditioning for final disposal can be performed in a safe way, based on then still existing full knowledge of the technical basis of safety. An important approach with respect to an integrated safety case guidance for SNF dual purpose casks was just finished in a first stage at the IAEA [36].

CONCLUSIONS

In Germany the development of packages for spent nuclear fuel and for high level waste during the past 35 years was dominated by transport casks that are used for storage in central sites as well as in at-reactor sites. In the meantime several hundreds of these dual purpose casks (DPC) have been manufactured under supervision of BAM, and are in operation. Their storage and safe transport in future requires appropriate ageing management and regulatory control, including transport package safety case and design approval update during their storage period.

The test methods, experimental as well as computational, have been improved continuously. Their improvement was always supported by BAM research and development activities on drop and fire test methodologies, containment investigations, structural analyses, safety criteria justification and quality assurance aspects. Experience has shown that assessment strategy has changed significantly towards the use of Finite Element Analyses with quantitative and in-depth analysis of high loaded structures, but that development requires back-up by more experimental testing for verification and exact material law justification.

A lot of package development took place in other sectors too, e.g. for new package designs for fresh fuel assemblies. A fast growing sector currently are containers for non-heat generating radioactive waste, to provide decommissioning options to NPPs, specifically for those which are going to be dismantled, and which have to comply with repository requirements. Decommissioning of shut-down NPP is associated with more transports of large components as “packages” of low specific activity or as surface contaminated objects.

35 years ago was more or less a time when developments associated with nuclear energy started; now we are more confronted with that remains that were generated during the last 35 years, and which have to be managed properly for today as well as for future generations.

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