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Two Decades of Experience with more than 750 CASTORÒ and CONSTORÒ Transport and Storage Casks

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1. Introduction

In 1983 the world-wide first dual purpose transport and storage cask - a CASTOR® Ic-DIORIT - was loaded in Würenlingen/ Switzerland. Meanwhile CASTOR® casks are used at 24 sites on four continents. Spent fuel assemblies of PWR, BWR, VVER, RBMK, FBR, MTR and THTR as well as vitrified high active waste canisters are transported and/or stored in these kinds of monolithic metal casks. MOX spent fuel of PWR and BWR has been loaded, too.

Starting in the mid of the 90s, GNB developed the new CONSTOR® cask concept, which is based on a double liner technology with a layer of heavy concrete as shielding material inbetween. This CONSTOR® cask concept fulfils all design criteria for transport and for storage given by the IAEA recommendations and by national authorities.

Up to now, more than 750 CASTOR® and CONSTOR® casks have been used for transports or/and loaded for long-term interim storage. More than two decades of storage experience attest to the excellent behavior of the casks including the metallic gaskets and the tightness monitoring system.

Detailed measurements of temperatures and of gamma and neutron dose rates have shown in each case that the safety requirements have been fulfilled. These measurements allowed to reduce unnecessary safety margins to optimize the benefit for the user.

2. Cask technology

CASTOR® casks have been successfully developed, manufactured and delivered for transport and interim storage of spent fuel and high active waste (HAW). These casks fulfil both the requirements for type B packages according to IAEA regulations and the requirements covering different accident situations to be assumed at storage sites.

The cask body is made of ductile cast iron. To improve the neutron moderation, axial boreholes drilled into the cask wall are filled with moderator rods made of polyethylene. As protection against corrosion, the inside surface of the cask and the sealing surface is protected with a nickel coating. The outside surface is protected by a coat of epoxy-resin paint. The basket for spent fuel assemblies basically consists of tubes made partly of borated stainless steel or combinations of steel and aluminium. On the outside wall of the cask, cooling fins may be machined to improve the heat transfer from the cask to the environment. The cavity of the cask is closed by a primary lid and by a secondary lid. The space between the lids is filled with helium under overpressure; the control of this pressure delivers the required tightness during storage. Four trunnions are used for cask handling, fixing the cask in a transport frame. Shock absorbers are used during transport.

The new concept CONSTOR® cask was developed with particular consideration given to an economical and effective method of manufacture using conventional mechanical engineering technologies and common materials. Nevertheless, the CONSTOR® sandwich cask concept fulfils both the internationally valid IAEA criteria for transportation and the criteria for long-term interim storage.

The CONSTOR® concept is based on a sandwich design with outer and inner shells made of steel. The space between these shells is filled with heavy concrete for gamma and neutron shielding. The design does not rely on the concrete for structural integrity. In the concrete zone, heat conducting elements are arranged to improve heat transfer. The cask bottom has the same sandwich design as the wall. At the upper end, the shells are welded to a ring made of forged steel.

The lid system is designed as a multibarrier system. The bolted and sealed primary lid provides strength, shielding and temporary sealing functions. The sealing plate and the secondary lid are welded to the forged steel ring after loading of the cask. These two welded lids, together with the inner and outer shells, constitute the double-barrier system. Alternatively it is possible to bolt the lid system.

Table 1 summarises the main inventory parameters of some CASTOR® and CONSTOR® types.

Cask Type	License [year]	HM Mass [MT]	Heat Load [kW]	Enrichment [w%]	Burn up [GWd/MTU]	MOX F.A.
CASTOR® HAW20/28 CG	1995	38,4	45	-	-	-
CASTOR® HAW28M	2005	39,2	56	-	-	-
CASTOR® V/19	1995	10,6	39	4,45	65	4 of 19
CASTOR® V/52	1997	9,7	40	4,65	65	16 of 52
CASTOR® Va/21	2006	11,7	48	4,65	75	8 of 21
CASTOR® Vc	?	11,0	46	5,0	70	20 of 61
CONSTOR® V/32	?	15,2	32	5,0	60	-
CONSTOR® V/69	?	12,2	32	5,0	60	-

Table 1: Cask Inventory Parameters

3. Verification of cask analysis

More than 20 years of experience with CASTOR® casks is the basis for the methodology applied to the cask analysis. Extensive routine thermal and radiological measurements are performed on each loaded cask and provide a wealth of information about the cask performance. Additional data have been generated by dedicated experimental programs. Here some results of thermal and radiological measurements are presented and compared to predictions from the theoretical analysis.

Thermal analysis

To validate the heat dissipation analysis for the Gorleben storage facility temperature measurements have been performed on an array of 32 CASTOR® casks stored at the facility. The thermal power of the casks was mainly between 27 and 39 kW with a few casks of lower thermal power. Maximum surface temperatures of 60-70 °C were found by thermography, confirming the values predicted by heat transfer analysis, including 3d fluid-dynamics, to within 2 K. To derive the cask model for the heat transfer analysis, measurements were performed on a single CASTOR® V/19 standing under a vented concrete cover. From the fluid-dynamic analysis of these measurements, effective heat transfer coefficients for the finned cask surface were derived.

During transport CASTOR® casks are covered by a hood. The air flow through the hood and around the cask has been analysed by fluid-dynamic calculation and verified by measurements on a CASTOR® HAW 20/28 CG. Figure 1 shows the excellent agreement between calculated and measured temperatures of the air flow at different locations under the hood.

For more details of the thermal analysis verification see /1/.

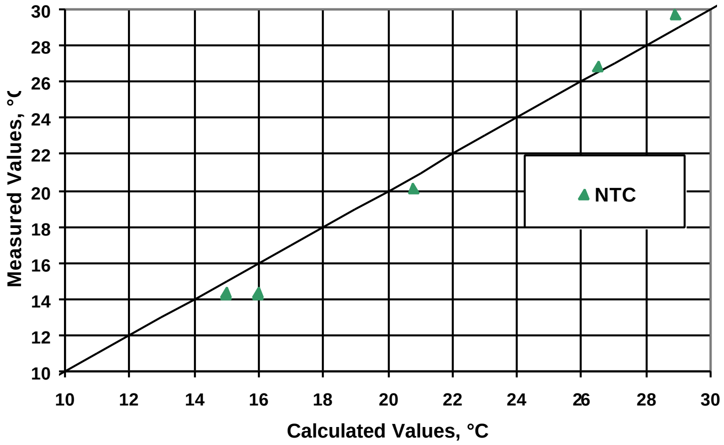

Figure 1: Air Temperatures for a CASTORâ HAW 20/28 CG with Hood

Shielding analysis

The shielding analysis verification applied to CASTOR® casks is demonstrated for the CASTOR® HAW 20/28 CG, which is employed to transport and store vitrified high level waste. Figure 2 shows the model employed for MCNP /2/ Monte Carlo shielding analysis together with measurements performed by BfS /3/, /4/ on a cask presently stored at the Gorleben facility.

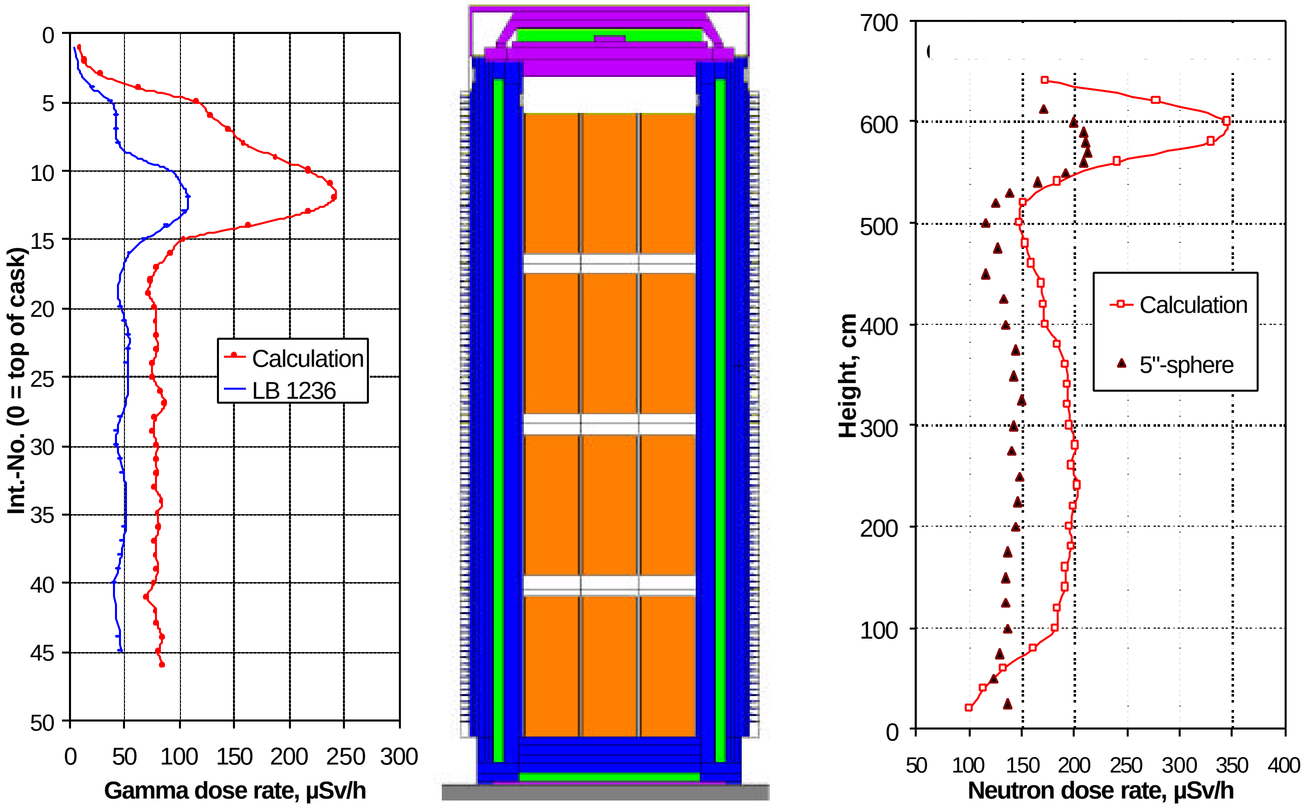

Figure 2: Axial Dose Rate Profile and MCNP Shielding Model for CASTORâ HAW 20/28 CG

On the basis of the activity inventory characteristics for this cask loading one finds a good general agreement between measured and calculated values, and even local details in the axial neutron and gamma dose rate profiles correlate very well. From comparison of the calculated and the measured data it is obvious, that the calculations overestimate the measurements significantly. Averaged over the cask surface one finds a ratio of c(alculated)/m(easured) = 1.4-1.6 for the neutron dose rate and c/m = 1.4 for the gamma dose rate, depending on the detector system employed. In this context neutron spectra have been measured by a Bonner sphere system to derive the effective neutron quality factor peculiar to the CASTOR® shielding design.

This has been observed as a general trend for all casks of this type employed so far. Figure 3 shows this trend for the neutron surface dose rates of the 18 CASTOR® HAW 20/28 CG casks most recently stored at the Gorleben facility. From Figure 3 one finds that the neutron c/m converges to 1.6. The decrease in the fluctuations in c/m corresponds to refined measurement protocols; the calculation model for the shielding analysis is in all cases identical (except for the variation of the activity inventory).

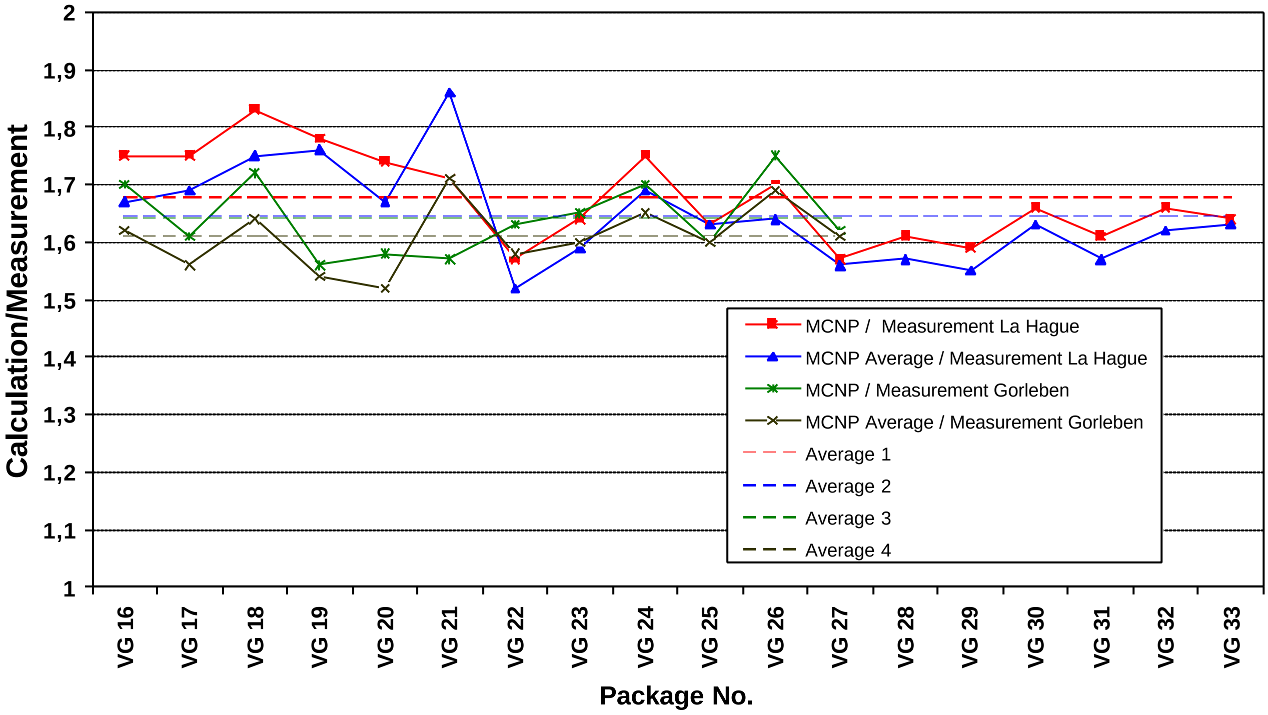

Figure 3: **c/m Ratio for Casks of Type CASTOR^{â} HAW 20/28 CG at Gorleben**

These experiences point to a systematic overestimation of the dose rate by the shielding analysis, from which empirical correction factors are derived to reduce some conservatism of the analysis.

4. Cask storage experience

Safe Confinement

Each storage cask is equipped with 5 metallic gaskets. Up to now, the sum of the number of gaskets multiplied by the storage times results in almost 24,000 gasket·years. In the two decades of dry storage in CASTOR® casks only one gasket with increased leakage rate has been found. It was at a secondary lid of a cask for PWR fuel assemblies. From these numbers a deficiency rate of $4 \cdot 10^{-5}$ a^{-1} can be concluded. Although the uncertainty of this value cannot be determined, it is a clear indication of the excellent performance of the lid system and especially of the metallic gaskets.

The required limiting value of the Helium leakage rate of a single gasket is 10^{-7} hPa·l/s (in USA and Lithuania 10^{-6} hPa·l/s). The measured leakage rates range from 10^{-10} to 10^{-7} hPa·l/s, cf. Figure 4. The overwhelming majority of measured values is concentrated around $2 \cdot 10^{-10}$ hPa·l/s. There are no real measuring values but the measurement has been terminated because the leakage rate values have been far away from the limit. It can be concluded that the design of the confinement system and the procedure for cask closure allow to meet the limits with respect to confinement of the radioactive inventory with large safety margins.

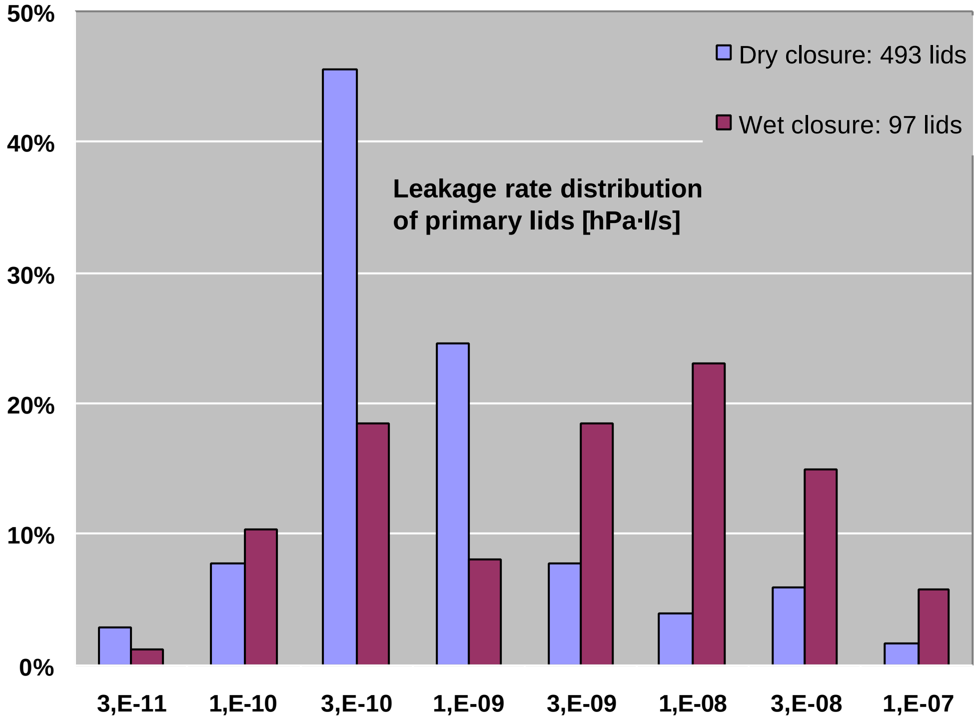

Figure 4: Cask Confinement Experience

Up to now, around 750 CASTOR® and CONSTOR® casks have been loaded for long-term interim storage. This results in around 4,800 cask·years, allowing to draw conclusions with respect to the safety of dry storage, especially for the safe confinement of the radioactive inventory. The storage experience shows the excellent behavior of the metallic gaskets and of the tightness control system.

Long term cladding behavior

An extended testing program related to cladding behavior during dry storage was carried out in Germany. Basket and cladding temperatures were measured, and the results from storage conditions within the cask on the cladding were examined. Similar investigations were performed by the Idaho National Engineering and Environmental Laboratories (INEEL) from 1985 to 1999. There was no evidence of degradation of cladding material.

5. Accident Testing

The CASTOR® and CONSTOR® casks have been thoroughly investigated by many experiments. There have been around 100 drop tests, a lot of them with full scale casks, fire tests, simulations of airplane crash, investigations with anti tank weapons, and an explosion of a railway tank with liquid gas beside a CASTOR® cask.

Apart from being used as effective public demonstrations of the safety margins, these experiments always served for the development of theoretical models. Furthermore, analyses of the behavior under extreme loads are currently in the process of being used for risk analyses to determine the residual risk.

Drop tests

In addition to drop tests within the framework of cask licensing, a range of drop tests was also performed from greater heights or under more severe conditions. These include among others:

- Drop test of an original CASTOR® Ic cask in side-on-orientation from 19.5 m height onto the foundation of a road suitable for heavy vehicles (1980)
- 9 m drop tests with CASTOR® Ia and Ic prototypes without shock absorbers in side-on-orientation onto the lifting trunnions, in some cases cooled down to –40 °C (1978 – 1985)
- 14 m drop tests with CASTOR® VHLW cask onto steel roller pedestals mounted on the unyielding surface; without shock absorbers, but with an artificially applied 120 mm deep notch in the highest-loaded area (1991).
- 9 m drop tests of a hollow-cylinder 1:2.5-scale CASTOR® V model onto steel roller pedestals, without shock absorbers but with large artificially applied faults in the highest-loaded area; no fracture despite several times increased loading compared with the use of shock absorbers (1988).

In all these experiments with increased mechanical load impacts going beyond IAEA design requirements the casks showed no loss of integrity.

Aircraft crash

The basis for the assessment of the safety margins of the casks to withstand the mechanical loads of an aircraft crash is formed by a number of experimental investigations performed between 1978 and 1980 at the German Federal Armed Forces' test site at Meppen. These experiments involved shortened CASTOR® casks of the types Ia and IIa, retaining their original cross-sections. In all experiments, a heavy hollow cylindrical projectile was fired from a special gun at near sonic velocity at the shell or lid side of the test cask. The results from these tests are proven integrity and sufficiently low residual leak rate.

Tank wagon explosion

In Germany the Bundesanstalt für Materialprüfung (BAM) performed a fire experiment involving a 45 m³ tank wagon filled with 10 m³ (5.1 t) of propane gas. This experiment was to provide insights for the assessment of the thermal behavior of liquid-gas tanks in an accident fire and yield indications as to which disaster control measures might be derived. The failure of a propane gas tank goes in hand with the consequential effects of a boiling liquid expanding vapor explosion, i. e. with an expanding fireball, blast wave and flying debris. Events like these involving the bursting of a tank holding flammable gases that have been liquefied under pressure belong to the most severe accidents in industrial history.

The test bed was composed of steel troughs filled with fuel oil, set up within a U-shaped sand embankment, to provide the fuel for the fire to engulf the tank wagon and the CASTOR® cask arranged at a right angle to it. The lid end was not, however, additionally protected by a shock absorber (as in the case of a road transport) nor by a cover plate (as used in storage configuration).

A few minutes after the ignition of the fire the propane gas tank burst with a subsequent abrupt release, expansion and ignition of the propane gas. The propane gas tank ruptured at first in the axial direction on the side not facing the CASTOR® cask. The abrupt gas release and explosion on the side not facing the CASTOR® cask caused a rocket-like acceleration of the entire tank wagon in the direction of the CASTOR cask. The long side of the tank wagon hit the upper half of the lid side of the CASTOR® cask. An inspection and leak test of the CASTOR® cask after it was dug out showed that the lid had suffered no lasting deformation and that the effectiveness of the lid bolts and the leaktightness remained unchanged.

In all these experiments mentioned here above with increased mechanical load impacts – which usually go beyond the test requirements of the IAEA regulations that already cover severe accidents – the casks showed no loss of integrity. It is therefore proven that CASTOR® casks provide a considerable safety margin beyond the licensing design limits.

6. Outlook on further development

The challenge for further development results from a higher technical specification, particularly in relation to fuel, reduction of cost and an increase in licensing requirements. The first two points are a clear consequence of the market conditions facing the utilities world-wide. The last point serves the need to keep design and proof of the design state-of-the-art.

Concerning technical specifications, increased enrichment and higher burn-up are the most challenging issues, along with disposal management of spent mixed plutonium-uranium oxide (MOX) assemblies in certain countries. As a consequence, higher heat loads and sophisticated shielding methods have to be considered. Apart from design and new materials, new methodologies have to be developed and applied. Examples are the application of burn-up credit or the optimised utilisation of the inventory self-shielding by using sophisticated fuel assembly arrangement algorithms .

In addition, disposal of defective fuel is increasingly being requested; this has a clear impact on design features, not only of the cask internals but also of handling equipment.

To reduce cost an increase in the number of fuel assemblies per cask as well as a cost optimised cask design are the most important approaches to be followed by the cask suppliers. Sophisticated and validated methodologies for the proof of the design during the licensing process remain important.

7. Conclusion

Transport and dry storage of spent fuel and HAW in GNB casks is a proven and extensively applied technology. More than two decades of experience over two decades with almost all types of fuel and HAW has been gained. GNB's CASTOR® and CONSTOR® type cask fulfil the highest safety requirements in terms of both transport and storage. Future challenges have been clearly identified and will be met by new designs for the next generation of GNB casks.

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