Testing of type B packages in Germany to environments beyond regulatory test standards

B. Droste*

For >30 years at BAM, type B packages have been tested to non-regulatory test environments in different research and regulatory assessment projects. The aims of these projects were the identification of package safety margins beyond regulatory standards, and the consideration of accident scenarios that are not covered by the IAEA transport regulations. The present paper will address the following BAM experiments and computations: drop tests of type B packages from a height of 200 m, including a 1 : 2 scale model of a TN 8/9 spent fuel cask; 19·5 m drop test of a full scale spent fuel cask, the CASTOR Ic, onto a highway target; 13 m drop test of the CASTOR Ic cask onto a HEXCEL shock absorber; 14 m drop test of a CASTOR VHLW cask with artificial flaw onto steel rails; BLEVE impact involving a CASTOR THTR/AVR cask; aircraft crash tests and FEM calculations; prolonged fire test (3 h, 10 min) with a Pu nitrate package after 200 m drop test; FEM calculations of external pressure from TNT explosions at a distance of 25 m. Briefly addressed will be other tests performed in Germany (GNS drop tests of waste packages from 800 m in height; and a 1 : 3·4 scale model of a former GDR spent fuel cask C 30 dropped from 25·5 m onto a concrete building structure).

Keywords: Type B packages, Drop testing, Large height drop tests, Explosion impacts, Extended fire test, Real target drop calculation, Aircraft crash simulation

Drop tests with packages from larger heights

Within the research project 'Classification and Safety Margins of Radioactive Materials Packages'[1] a series of drops from a height of $\sim$200 m have been performed by BAM with different type B packages that had been in use in 1977. The test results presented here in the next three sections are taken from the BAM test report written by B. Schulz-Forberg and H. W. Hübner.[1]

Drop (200 m) tests with half scale spent fuel cask TN 8/9

One test specimen used in the BAM research project was a 1 : 2 scale model of the spent fuel flask 'TN 8/9' that has been tested according to the IAEA transport regulations before it was lifted by, and dropped from a helicopter (Fig. 1*a*). This package was a typical representative of the group of 'massive' structured 'heavy weight' packages. This TN 8/9 model consisted essentially of a cylindrical cavity, made of 12·5 mm thick steel sheets, and the gamma shielding is formed by a 100 mm lead layer between outer steel sheets. Heat was conducted through the cask to the cooling fins that transferred the heat by natural convection. At both ends of the cask, there were circumferential impact limiters filled with balsa wood. Additional shock absorbers were fitted for transport, protecting the lid and bottom area, including the piping connections for the containment. Hollow trunnions were attached. The spaces between the cooling fins had been half filled with a mixture of concrete and resin as neutron shielding. The main dimensions of the cask were: $\sim$240 mm in inner diameter; $\sim$850 mm in maximum outer diameter; $\sim$2500 mm in overall length without shock absorbers; $\sim$200 mm in thickness of the impact limiters; $\sim$4125 kg in total weight including dummy weight (a steel tube of 75 kg). As target a concrete covered area of 20×80 m was selected. The target structure consisted of 60 cm layer of pit gravel (with a cubic compression resistance of 50 N mm^{-2}, 20 cm concrete (DIN, Bn 50), 20 cm concrete (DIN, Bn 350) reinforced by steel mats (DIN, Q 377). Before the package hit this relatively hard target, it was dropped three times missing the target. The fourth drop was successful, i.e. the concrete target was hit. The model struck the target in an inclined, nearly horizontal position, penetrated the upper concrete layer and caused a crater of $\sim$75 cm deep, 3 m long and 1 m wide (Fig. 1*b*). The respective drop times was measured as 6·35 s. This corresponds to an impact velocity of $\sim$225 km h^{-1}. Figure 1*c* shows the TN 8/9 model when it was lifted out of the penetrated concrete target. As a result of this impact, the following observations were made:

Federal Institute for Materials Research and Testing (BAM), 12200 Berlin, Germany

*Corresponding author, email bernhard.droste@bam.de

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a

b

c

1 200 m drop test of 1:2 scale model TN 8/9 spent fuel cask *a* helicopter and package before drop test; *b* package after drop from 200 m, penetrated into the concrete layer; *c* package after lifting off the concrete ground

(i) both shock absorbers sheared off as well as all clamping bolts. The lid shock absorber was nearly completely flattened
(ii) pressing of the cavity's closure and compressing of the respective screws, the lock could only be removed by machine
(iii) complete flattening of the cooling fins in the impact area, destruction and loss of the concrete–resin mixture
(iv) no loss of integrity of containment components
(v) no leaks could be detected by bubble testing, i.e. no leakage $>10^{-3}$ mbar L s^{-1} occurred.

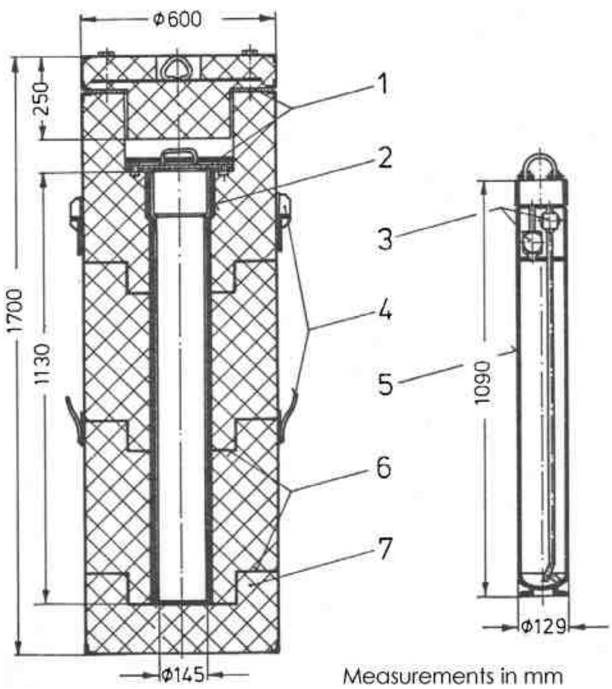
Drop (200 m) tests with spent fuel cask 'BRECO KR 100/200'

This cask consisted essentially of four cylinders fitted into each other. The outer double walled steel container had a mineral gravel insulation ('Fosselit') with impact limiters integrated at both ends. Inside the steel container was a lead container consisting of indented rings, bolted by tie rods. Inside this lead container was a second lead container, in which a stainless steel cylinder was placed, forming the actual containment vessel. After two drops into sandy soil, the third drop hit the concrete target. The cask penetrated the upper layer of concrete and caused a crater 30 cm deep (Fig. 2). As a result of that test the cask showed only minor overall deformations, two stiffening fins at the impact area were bent, a 15 mm gap at the impact area of the outer lid occurred, but no leak could be detected by bubble testing of the containment flask.

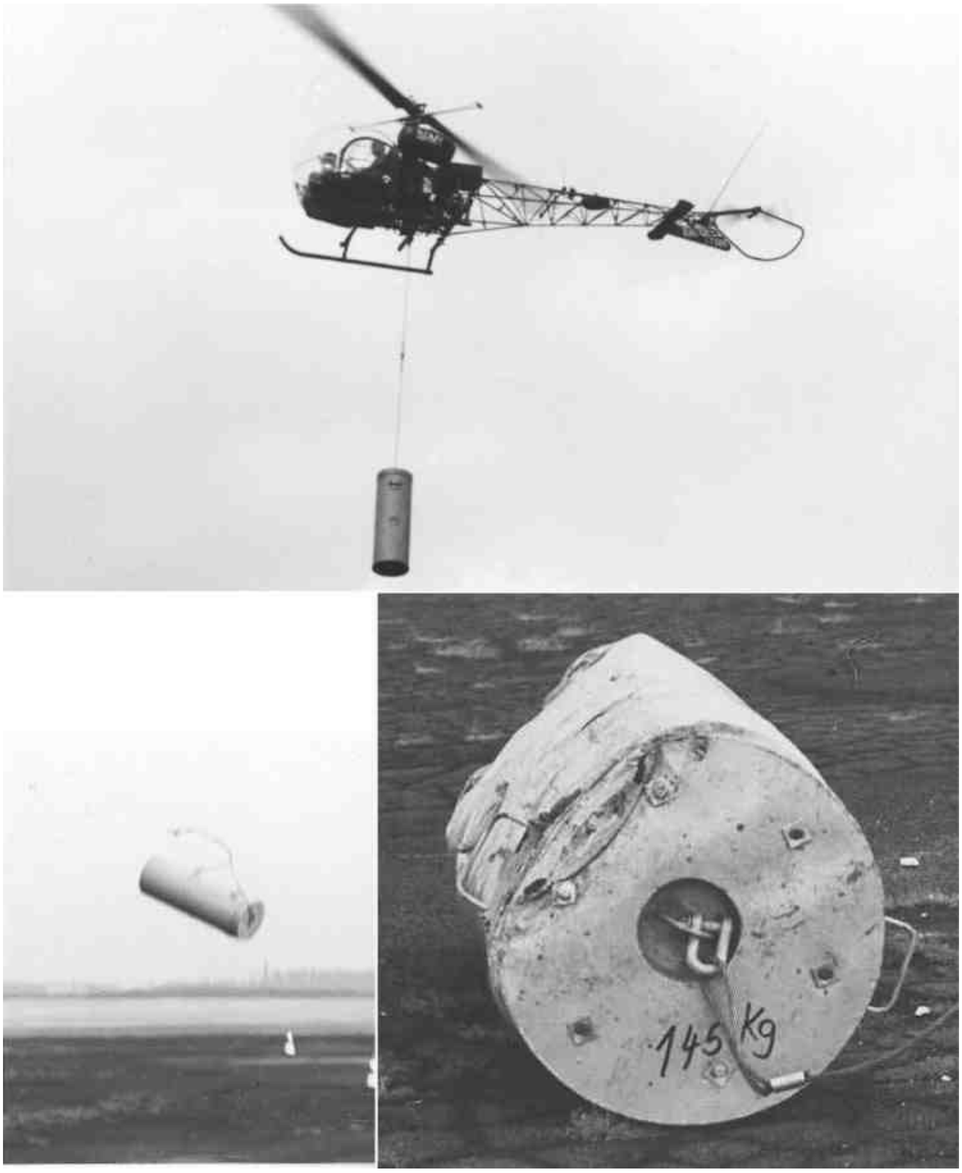
2 BRECO KR 100/200 package after drop from 200 m onto concrete pad

Drop (200 m) tests with Pu nitrate package '18 B'

Another test object for a 200 m drop test was the '18 B package', an approved package for the transport of 10 L Pu nitrate solution [$Pu(NO_3)_4$ aqueous solution in nitric acid from 3 to 10 mol L^{-1}] representing a heat source



3 Design of Pu nitrate package '18 B' (1 asbestos gasket; 2 asbestos casing; 3 valves; 4 steel handles; 5 titanium flask; 6 perforated steel sheets; 7 phenolic foam insulation)



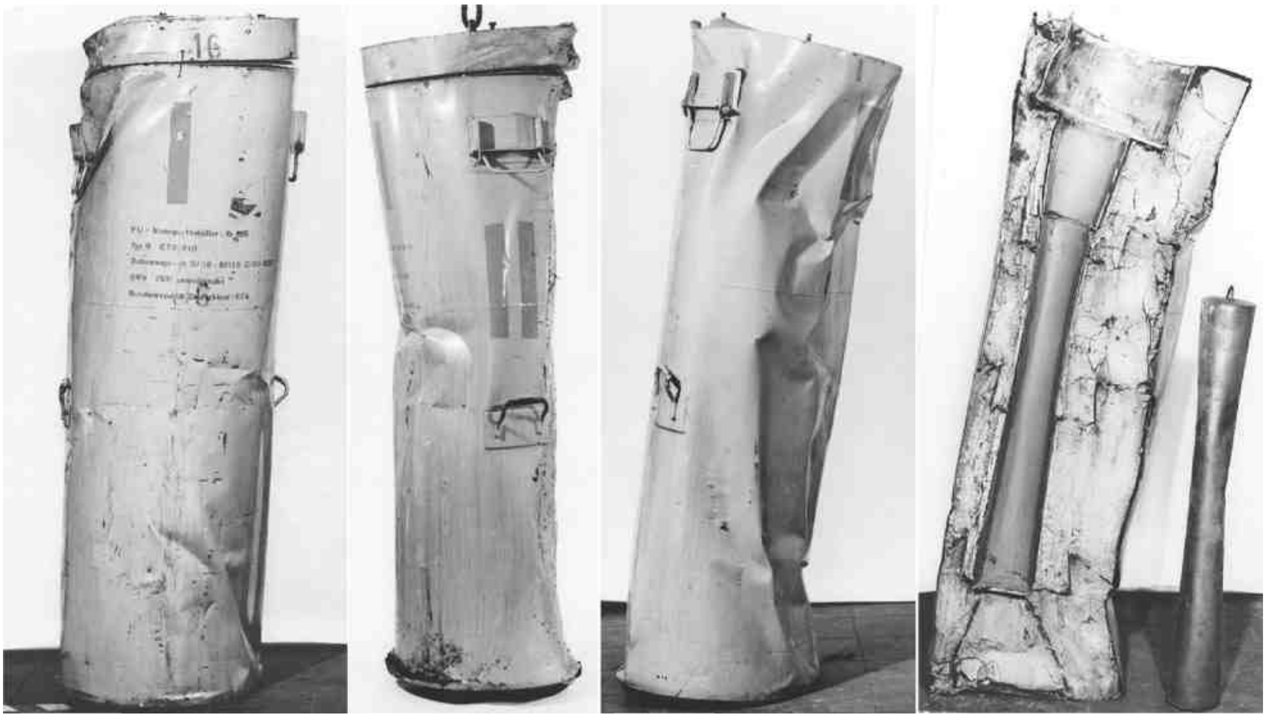
a b c

4 200 m drop test of Pu nitrate package '18 B' *a* package lifted by helicopter; *b* package immediately before hitting the ground; *c* package after drop

$>$6 W and $\leqslant$30 W. Figure 3 shows the construction of this package that represented a typical 'lightweight' package; a package category for which later the 'crush test' instead of the 9 m drop 'crash' test was implemented in the regulations. The container consisted essentially of two steel pipes closed on both ends, separated by radial and axial spacers and a phenolic foam insulation. In case of fire, the phenolic foam chars and emits combustion gases.

The fixed inner tube which functioned as the containment vessel, was made of titanium and filled with plutonium nitrate solution (water as test dummy). Metal siphon valves close discharge and filling pipes hermetically. Contamination is prevented by special couplings during piping.

Three helicopter drop tests with 18 B packages were performed from drop heights of 100, 185 and 200 m; Fig. 4 shows the test images. The 18 B packages after these tests are shown in Fig. 5. The 18 B packages had been dropped onto frozen hard soil with no significant penetration of the specimen into the soil. After all drops the long side of the package was crushed for $\sim$150 mm completely; after the 100 m drop (Fig. 5*a*) the inner lids and the titanium flask could be removed, and no water leakage was detected. The 18 B package from the 200 m drop (Fig. 5*b*) was cut through the cross-section to investigate the damage in detail (Fig. 5*d*). Although the titanium bottles had been deformed significantly after the 185 and 200 m drop, no water leakage was detected. The specimen from the 185 m drop (Fig. 5*c*) was retained in non-changed condition to be used for prolonged fire test (see the following section on enhanced fire tests). A modified design of an 18 B package (stiffer spacers) was later (12 May 1979) tested by Sandia National Laboratories in a high speed impact test (horizontal impact velocity of 129 m s^{-1}, onto an unyielding target), where the loss of containment integrity occurred.[2] These investigations have shown that for this type B package large margins of safety beyond the 9 m regulatory drop test existed, but 'type C package quality' was not provided. An enhanced crush test was also applied onto this package by BAM for the



a b c d

5 Pu nitrate packages '18 B' after drop tests from elevated heights *a* after 100 m drop; *b* after 185 m drop; *c* after 200 m drop; *d* cross-cut of 200 m drop test package with titanium flask beside

first time (9 m drop of a 2 tons, 1 × 1 m steel plate onto the package), which caused more severe damage than a 200 m drop test; this was one of the initiatives leading to the 'crush test' as a mechanical test for 'lightweight' packages, instead of the 9 m drop test.

Drop (800 m) tests with 'Mosaik' waste packages

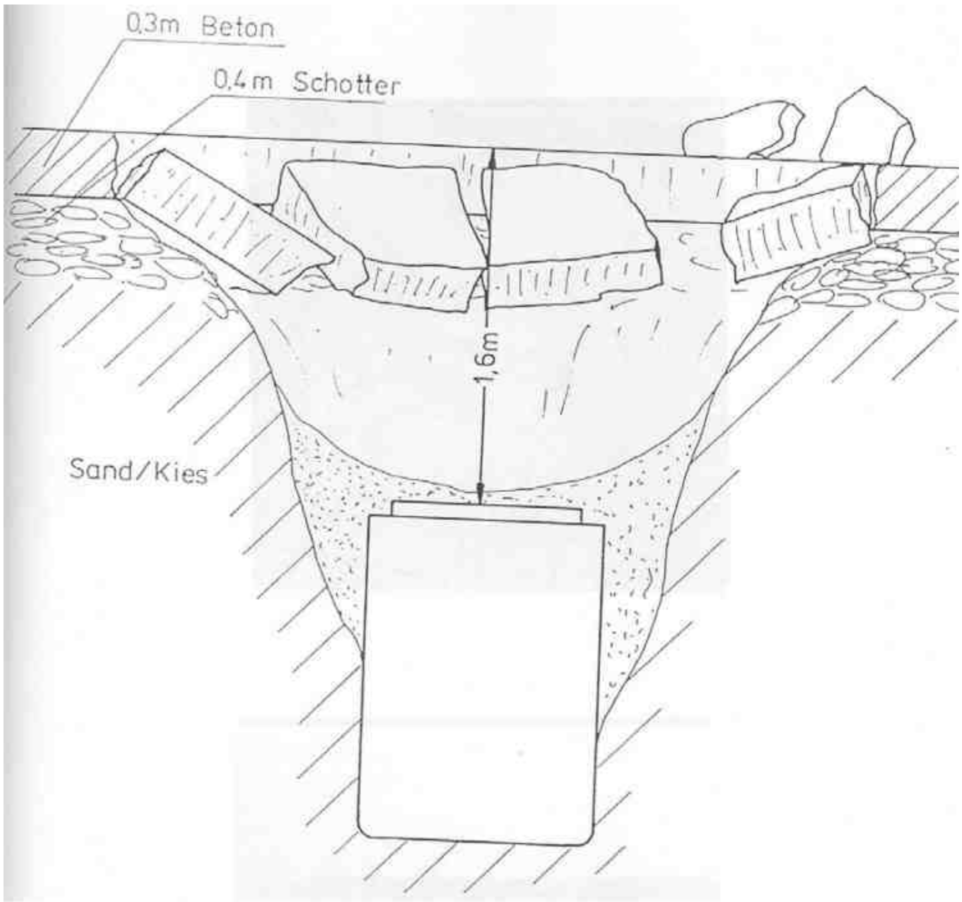
Another remarkable series of drop tests was performed by the German manufacturer GNS in 1982.[3,4] Within this investigation programme usual packages for transport and disposal of low and medium level radioactive wastes have been dropped by helicopter from heights of ~800 m onto an ground (compressed sand) covered by 40 cm gravel and 30 cm concrete. The aim of these tests was to investigate the results of accidental drops of those packages inside the shaft of a deep geological repository (e.g. Konrad, Germany). Test objects were different LSA I, LSA II, type A and type B packages. The type B package group was represented by three 'Mosaik' type packages, cylindrical, thick walled ductile iron casks (900–1000 mm in outer diameter; 1150–1500 mm in cylinder length; 3350–5780 kg in weight empty; 120–150 mm in DI wall thickness, with variable additional lead shielding inside). Figure 6*a* shows the penetration crater caused by the lid-down impact of a MOSAIK II cask (6070 kg in total mass, 1·06 m in diameter, 1·5 m in length) onto the concrete covered area; in the case of the same drop onto soil (beside the concrete target) the penetration depth (with the same cask position) was 0·9 m larger. Figure 6*b* shows the situation after a side on drop with a MOSAIK III-12 cask. The post-test investigations of the ductile cast iron casks showed that cask integrity was preserved and a significantly increased but still quantified leakage rate was given.

Drop (19·5 m) of full scale spent fuel cask onto 'heavy truck road' target

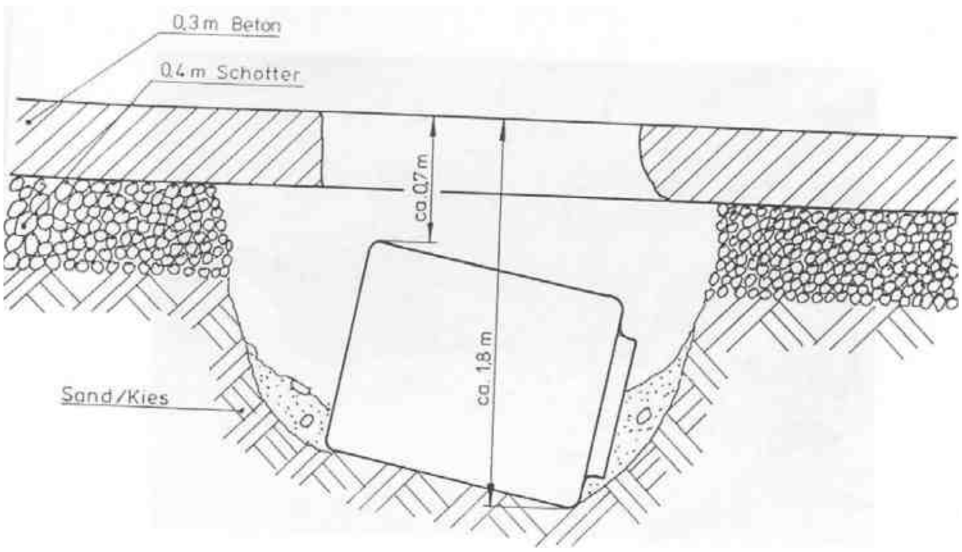
Around 1982 the question concerning the drop of spent fuel casks from a reactor building crane, where lifting heights up to 25 m have to be considered, came up. To investigate this question, BAM performed a drop test from a height of 19·5 m (the maximum height between test object and target that could be obtained at the BAM drop test site Lehre) onto a target layer simulating a typical heavy truck road. The results from this test have been published by Wieser *et al.*[5] Figure 7*a* shows the target set-up, as it was constructed above the 1000 t unyielding target of the test facility. The cask used was the full scale spent fuel transport and storage cask CASTOR Ic (83 tonnes in total mass, 5·455 m length, 1·73 × 1·73 m in cross-section, without impact limiters). Figure 7*b* shows the test facility and the cask at a height of 19·5 m above the target surface; Fig. 7*c* shows the cask after the horizontal drop (equivalent to the position during lifting at a reactor); it penetrated into the target for ~0·55 m. Measured deceleration values (60 or 70 g resp.) indicated that the impact force from this 19·5 m drop was less than about half of those values measured in a regulatory 9 m drop of a similar cask design.

Drop (13 m) test with full scale 'CASTOR Ic' cask onto aluminium honeycomb shock absorber

To test the behaviour of 'HEXCEL' shock absorbers, the full scale prototype CASTOR Ic was dropped from 13 m onto a layered target consisting of nine aluminium honeycomb layers (each 200 mm thick and each covered by 15 mm thick steel plate) and three steel plates (45, 45 and 30 mm thick) on the surface. The total thickness of the target was 2 m; the square dimensions were 3 × 3 m and 1·9 × 1·9 m at the base and top respectively. The CASTOR Ic cask was dropped with the corner lid over



(a)



(b)

6 Monolithic ductile iron packages of 'Mosaik' type after 800 m drop tests onto concrete covered ground (from GNS report/4/) *a* Mosaik II package ground penetration (lid side down impact); *b* Mosaik III-12 package ground penetration (inclined, nearly horizontal impact)

centre of gravity onto this target. The cask penetrated 0·96 m into the HEXCEL shock absorber (*see* Fig. 8), resulting in much lower deceleration values than in a regulatory 9 m drop test condition.

Drop (25·5 m) of 1 : 3·4 scale model of spent fuel cask 'C 30'

In 1986 the 'Brennstoffinstitut Freiberg' spent fuel transport cask design 'C 30' was assessed according to the IAEA transport regulations. The C 30 cask design was developed and approved and some six serial casks were manufactured in the 'German Democratic Republic (GDR)' for use in Eastern European countries for the shipment of spent fuel from WWER-440 reactors. An accident analysis for the NPP Greifswald had shown that a drop from a height of nearly 30 m onto a concrete building structure (rail track corridor) has to be considered as the most severe mechanical handling accident. To investigate this case, a 1 : 3·4 small scale model of the C 30 cask (*see* Fig. 9*a*) was dropped from a height of 25·5 m (Fig. 9*b* and *c*) onto a representative concrete building. Weiss and Diersch[6]

a

b

c

7 19.5 m drop of full scale spent fuel cask CASTOR Ic horizontally onto highway target *a* real target layer above the unyielding BAM drop test facility target (Lehre); *b* CASTOR Ic cask in 19.5 m height above target surface; *c* CASTOR Ic after drop and penetration into highway target surface

have reported this test. The horizontal roof part of this concrete target (1·9 × 2·3 × 0·14 m in dimensions) was supported by two outer ceilings (1·22 m in height, 0·1 m in thickness) and a middle ceiling (1·22 min height, 0·15 m in thickness). This concrete model was stiffened by crosswise beams, and mounted upon a reinforced

8 HEXCEL honeycomb impact limiting sandwich structure after 13 m lid corner over centre of gravity drop of full scale CASTOR Ic cask

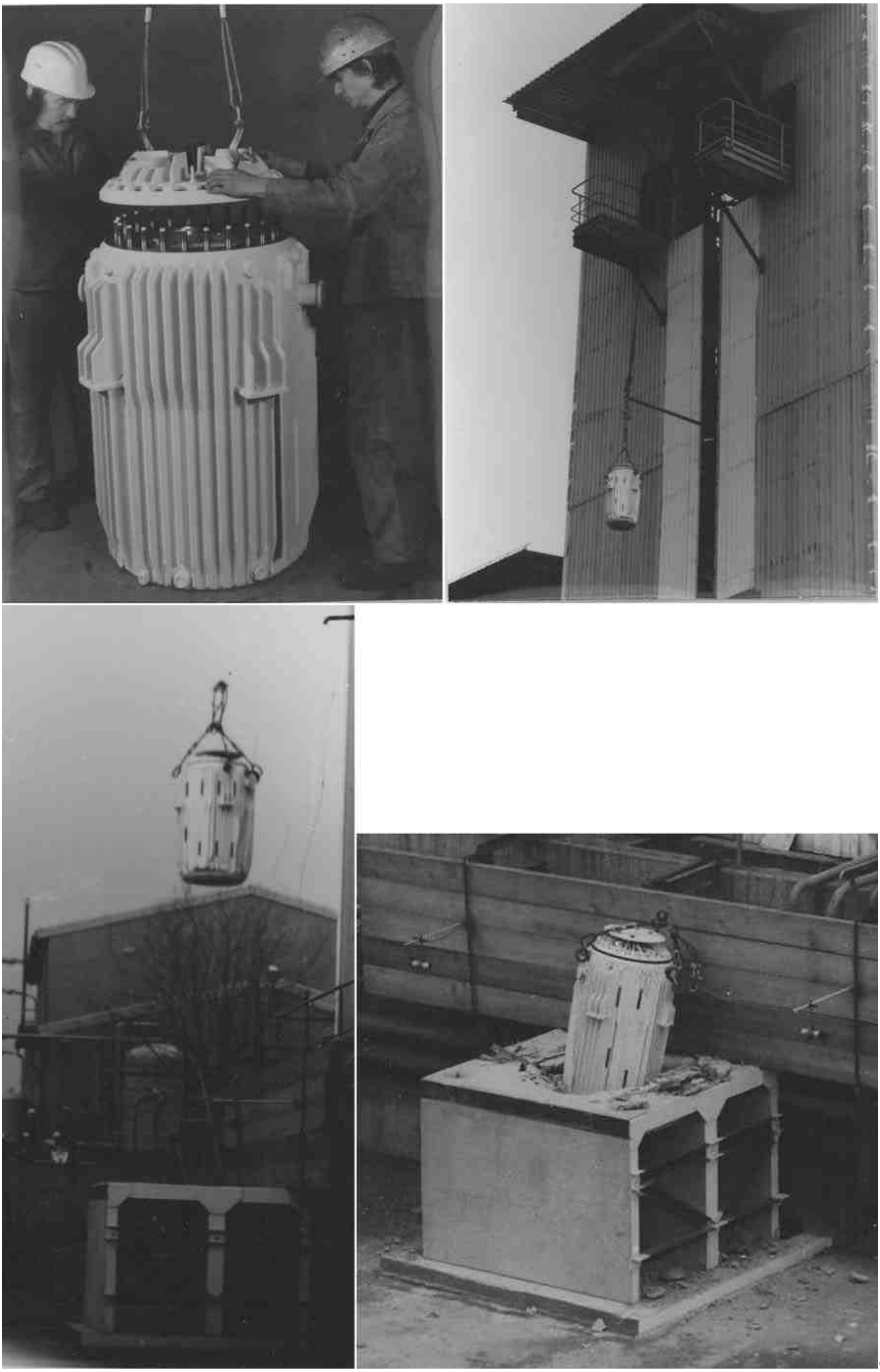
concrete base. Figure 9*d* shows the cask model penetrated 0·44 m into the concrete object. The measured deceleration was 340 g, the equivalent of 100 g for the cask (if rigid body deceleration is applicable). This indicated a remarkable margin of safety, because from the 9 m regulatory drop test a deceleration of 250 g for the full scale cask was obtained. The reason for this high safety margin is that the C 30 cask belongs to the category of casks with 'hard' integrated shock absorbers (cooling fins on the cylinder wall and on top of the lid, with only a small, compact impact limiting ring-like structure on the bottom side). The regulatory 9 m drop test of those cask designs onto an unyielding target results in high deceleration and impact forces.

Extended drop tests of ductile iron casks with artificial failures

Two research programmes on casks with large artificial failures in the cask body wall have been performed by BAM[7] to demonstrate the safety of packages made of this ductile cast iron. The first test object was a thick walled ductile iron hollow cylinder, with a geometry equivalent to a 1 : 2·5 small scale cask body wall section of the actual German CASTOR V dual purpose cask design. It was dropped with a 40 mm deep saw cut in the 150 mm wall onto steel rails placed upon an unyielding target, and the model retained its integrity without any crack propagation.

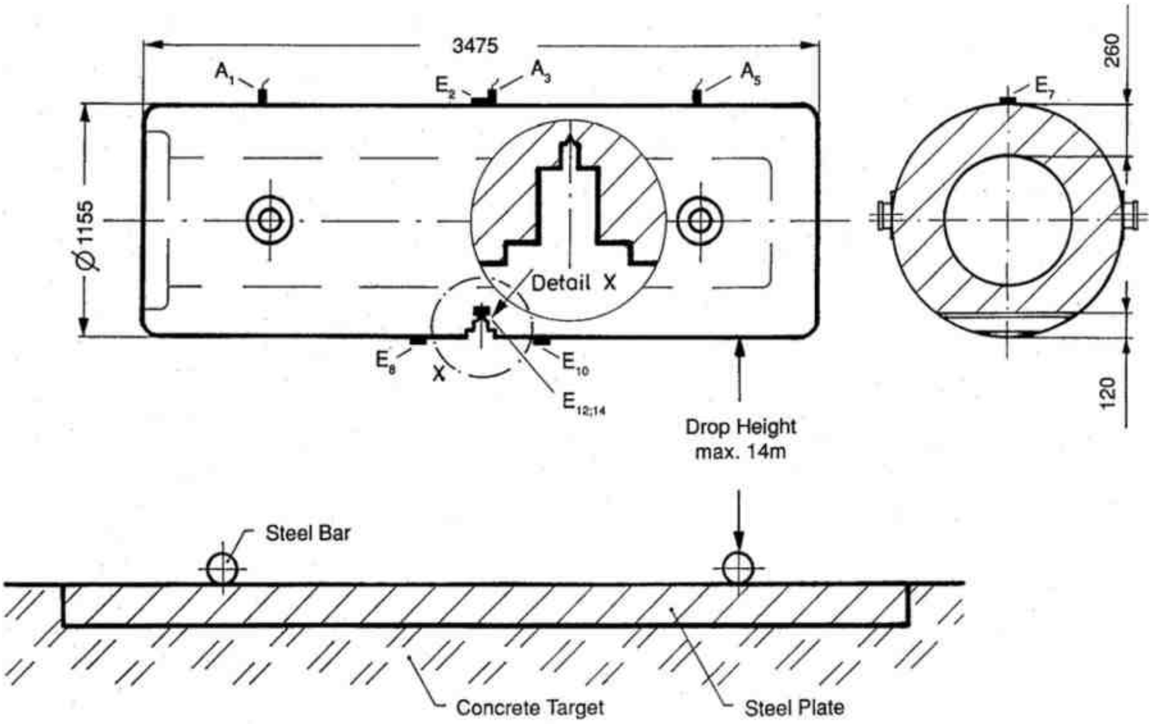
As a second test object, a full scale CASTOR VHLW cask was tested. The CASTOR VHLW was designed for transport of a single canister with vitrified high level waste (VHLW). After several 9 m drop tests within an approval procedure,[8] this specimen was tested with an artificial 120 mm deep cut in the 260 mm thick wall. The configuration of the specimen and the drop test is shown in Fig. 10*a*. With increasing drop heights (up to 14 m) and stress intensity factors (probably close to material fracture toughness), this object was dropped also onto 'rails' (steel cylinders placed upon the unyielding target) to investigate the failure region in the maximum bending stress zone (Fig. 10*b*). In Fig. 11 the measured dependence of the deceleration from the drop height is shown for this test series.

There was no crack propagation in the area of the artificial cut and no brittle failure occurred, although in the 14 m drop test the impact deceleration was 6·5 times

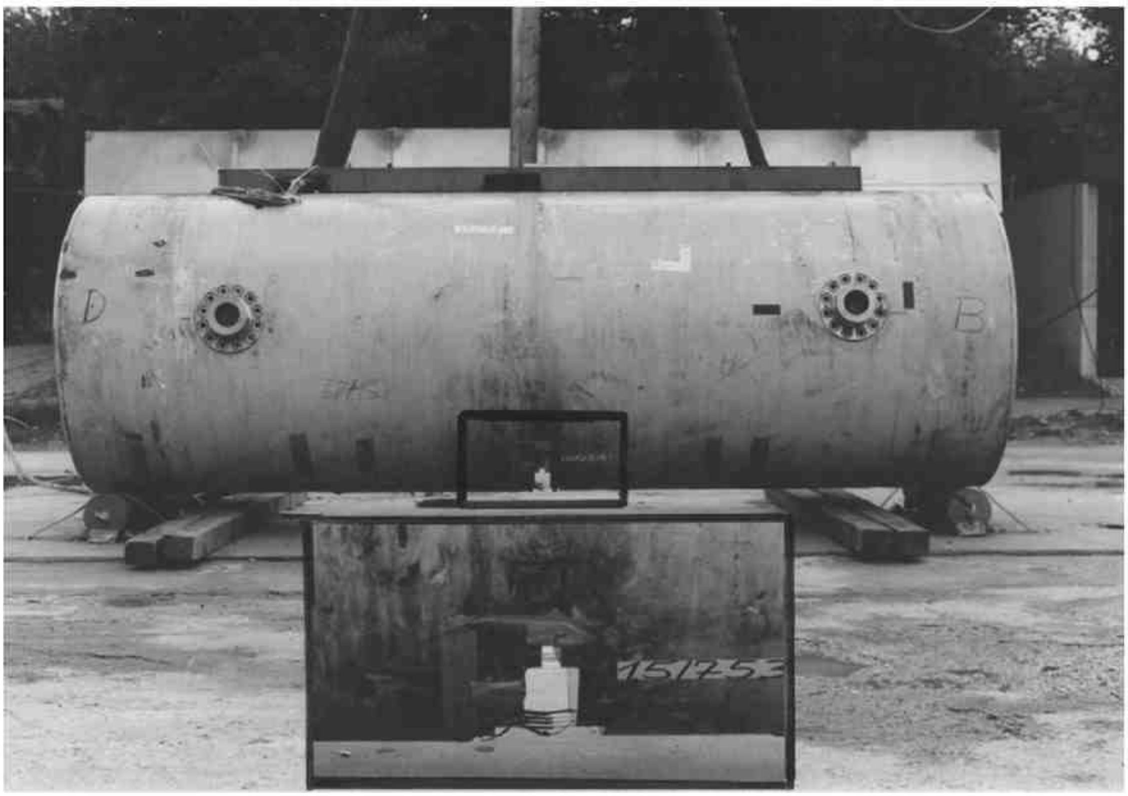


a b c d

9 25.5 m drop of 1:3.4 scale model of C 30 spent fuel cask onto concrete building structure cask model assembly *a* cask model in drop test position; *b* cask model dropping; *c* cask model after impact and penetration into concrete building (Brennstoffinstitut Freiberg test centre)



(a)



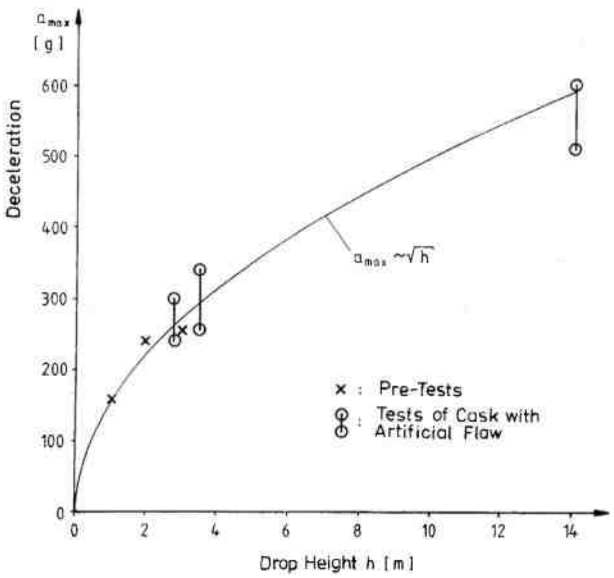
(b)

10 14 m drop of CASTOR VHLW cask with large artificial failure *a* cask and failure; dimensions, test set-up; *b* cask specimen and failure area in cask body; cask before drop test, resting on steel rails

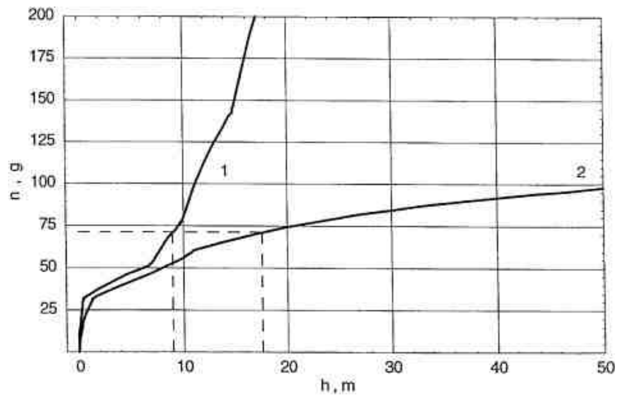
higher than that measured in the regulatory 9 m drop test (where the cask has impact limiters) as shown in Fig. 12. More details concerning the test geometry, cask properties and measured data are given in the literature.[7]

Real target drop test calculations

Within a study prepared for the European Commission,[9,10] the calculation of impacts of casks (type B packages) onto real targets was investigated by different approaches of the project participants: BAM, Ove Arup/UK and GNB/Germany. One part of the study was a comprehensive survey and review of literature, including some non-published reports on non-regulatory mechanical tests that had been performed in (or before) 1998. BAM developed a simplified analytical method based on spring mass models and assessed the parameter influences with a finite element analysis (FEA, with ABAQUS Explicit) of real target responses to cask impact and penetration. Ove Arup made FEA calculations (with LS-Dyna) for real target



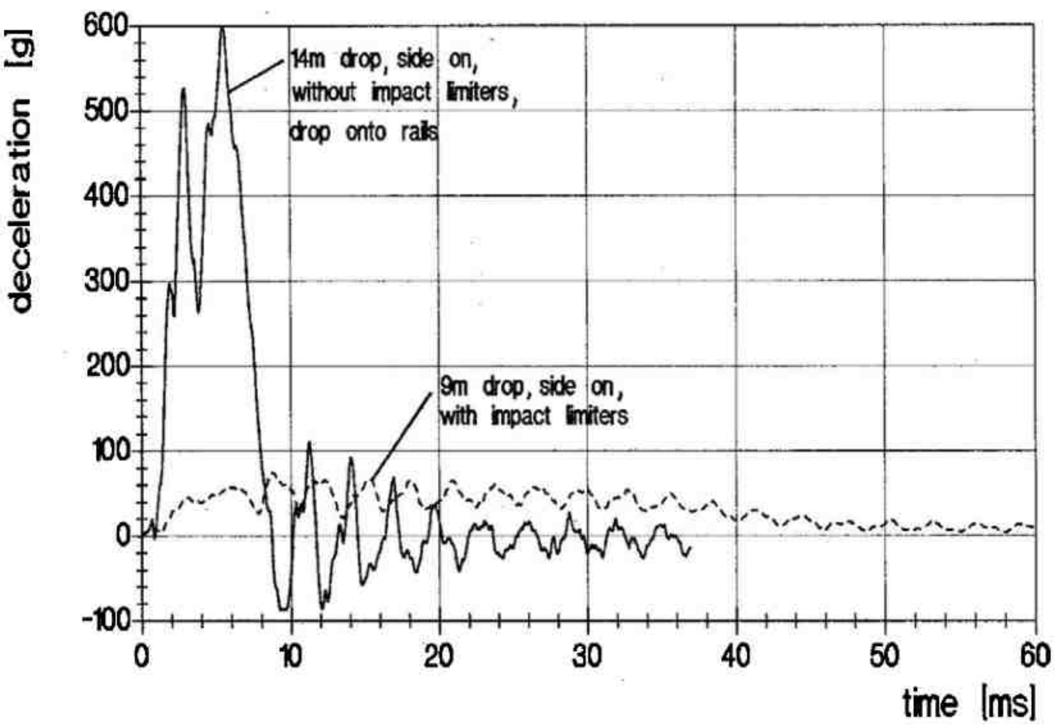
11 Relationship between drop height and maximum deceleration values measured for CASTOR VHLW horizontal drops onto rails



13 Calculated dependency of rigid body deceleration of reference cask with wooden impact limiters from drop height (1 for drop onto unyielding target; 2 for drop onto drift marly soil)

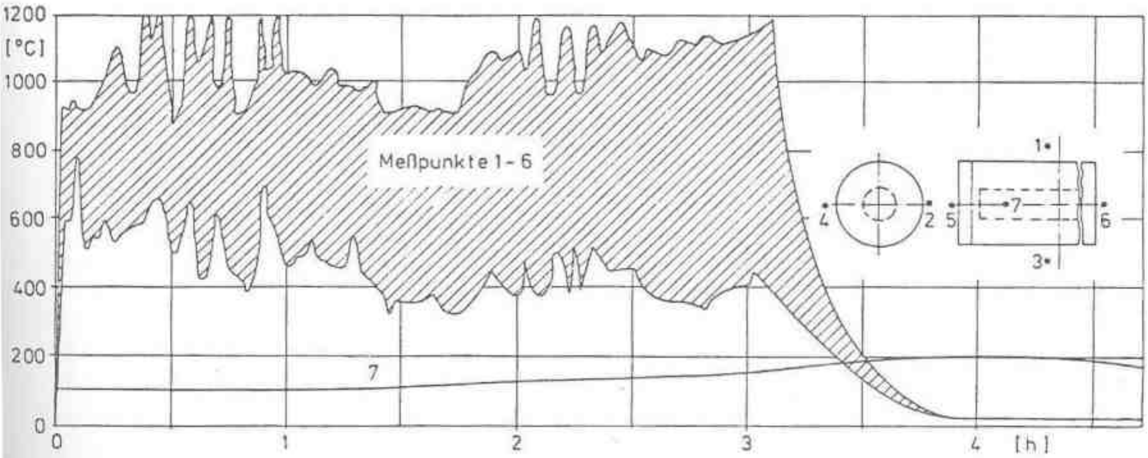
drops of the TK-6 cask, a cask with hard integrated shock absorbers, similar to the C 30 cask shown before; they showed that those casks can withstand rather high drop heights onto real targets, e.g. a concrete highway, loading to decelerations equivalent to a 9 m drop onto an unyielding target. GNB investigated the dropping of Mosaik flasks with and without impact limiters onto real targets with Dyna 3D FE code.

With the simplified analytical method noted above, BAM performed parameter studies to investigate the influence of target hardness as well as package impact limiter stiffness on the relation between 9 m regulatory drop and equivalent real target drop heights. The results showed clearly that the equivalent height for drops onto real targets, which do not produce inadequate loads of the cask, increases with the hardness of the impact limiters. On the contrary, this means that for soft impact limiters the margin of safety decreases; for a drop of a package with a large, soft impact limiter, the impact even onto a relative soft target is dominated more by the compression of the impact limiter than by the penetration into the ground. The calculation made by BAM also showed that the margin of safety decreases also with increasing dimensions of the impact contact area. For a reference cask [with a mass of 134 500 kg, a cask diameter of 2·25 m, an impact limiter diameter of 3 m and an impact limiter (spruce wood) thickness of 0·45 m], the deceleration resulting from a vertical drop onto an unyielding target (curve 1 in Fig. 13) and onto a real target (drift marly soil with a volumetric density of 22 kN m^{-3}, a friction angle of 0°, a cohesion of



12 Decelerations from horizontal 14 m CASTOR VHLW cask drop onto rails in relation to horizontal 9 m drop (onto unyielding target) of same package equipped with impact limiters

(a)



(b)

14 Enhanced fire test with '18 B' package dropped before from height of 185 m *a* package after 190 min pool fire test; *b* flame (1-6) and flask content temperatures during and after fire test

0·7 MPa and a dynamic factor of 2·0; curve 2 in Fig. 13) was calculated. For such a large diameter reference cask the drop from a height of 17·5 m onto a relative soft real target leads to an equivalent impact force like a 9 m drop onto an unyielding target. Here the fact is demonstrated that casks with large deformable impact limiting structures in combination with large dimensions do not have such high margins of safety as those of casks with hard integrated impact limiters. In those cases, it is necessary to investigate in more detail the safety margins of the construction beyond the 9 m regulatory drop test design limit, as shown in the literature.[11]

Fire and explosion impacts

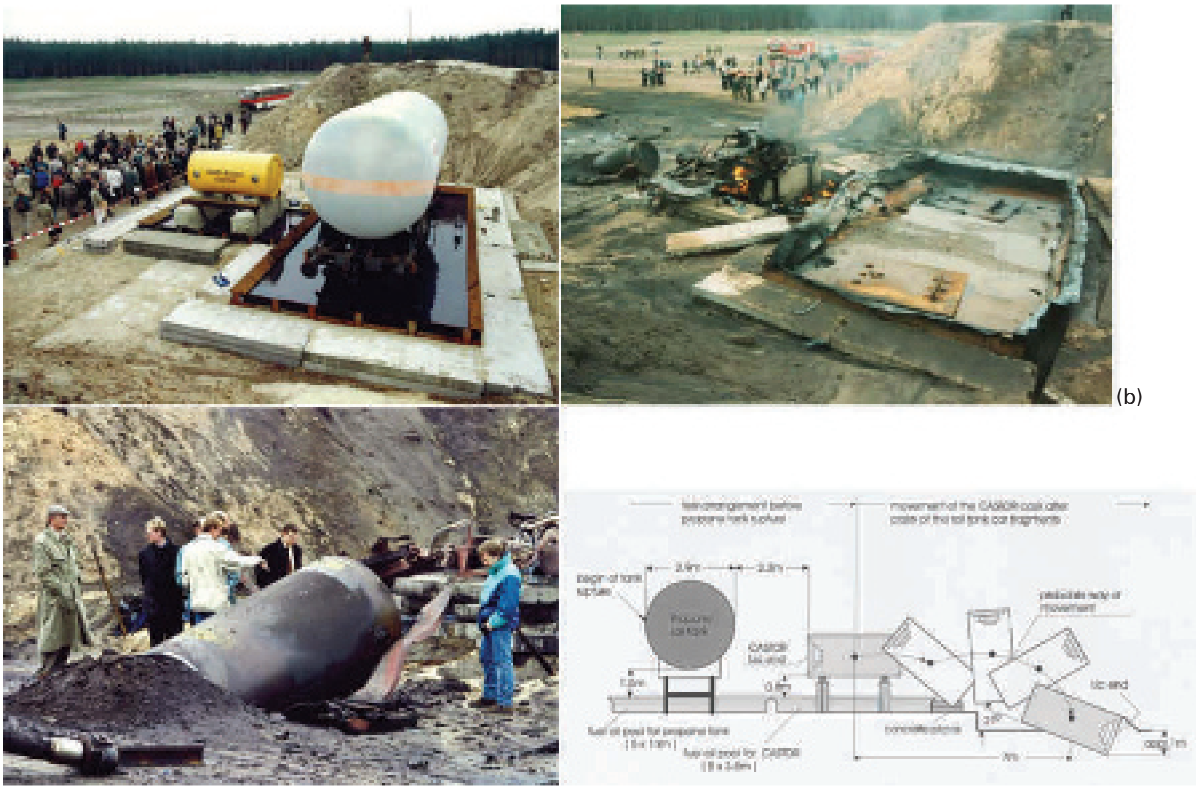
Besides, mechanical impacts enhanced fire tests or very specific investigations concerning explosion events beside type B packages, in most cases of spent fuel flasks, can also be reported.

Enhanced fire test with Pu nitrate package '18 B'

With the 18 B package impacted by a drop from 185 m (*see* Fig. 5*b*), a subsequent test in a long duration fire of 190 min was performed (Fig. 14*a*). The package was positioned above the open fuel oil pool (3×5 m) so that the flattened package side was down, directly exposed to the flames. The dummy load of 10 L water was preheated by a soldered heating coil to 130°C (maximum operation temperature) and maintained even during the fire test. Figure 14*b* shows the measured flame temperature spectrum and the temperature of the water filling, which reached a maximum of 203°C. The significant increase in content temperature was caused by the complete charring of the phenolic foam inside the deformed package part. Owing to a failure of the heating coil soldering tightness was lost, but from the evaluation of the temperature increase and the inspection of package components after the test, it could be concluded that a loss of tightness would not have occurred before a fire period of 75 min.[1]

LPG vessel explosion beside 'CASTOR THTR/AVR' spent fuel cask

On 27 April 1999, a fire test was performed by BAM with a 45 m^3 LPG tank wagon, partially filled with 10 m^3 pressurised liquid propane.[12] A CASTOR THTR/AVR cask (22 450 kg in mass; 2·785 m in length; 1·38 m in diameter; monolithic ductile iron body with 370 mm thick walls; double lid closure with inner 250 mm thick steel lid and outer 70 mm thick steel lid) was positioned above the fuel oil pool, beside the propane tank to suffer maximum damage from any explosion (Fig. 15*a*). The propane tank ruptured at 17 min after the fire ignition.



(a) (b) (c) (d)

15 Fire and explosion test with CASTOR THTR/AVR cask placed beside LPG tank wagon *a* situation before test; *b* situation after explosion (BLEVE); *c* cask thrown out of pre-test position, and penetrated into ground; *d* movement of cask after LPG tank explosion and tank wagon debris impact onto cask

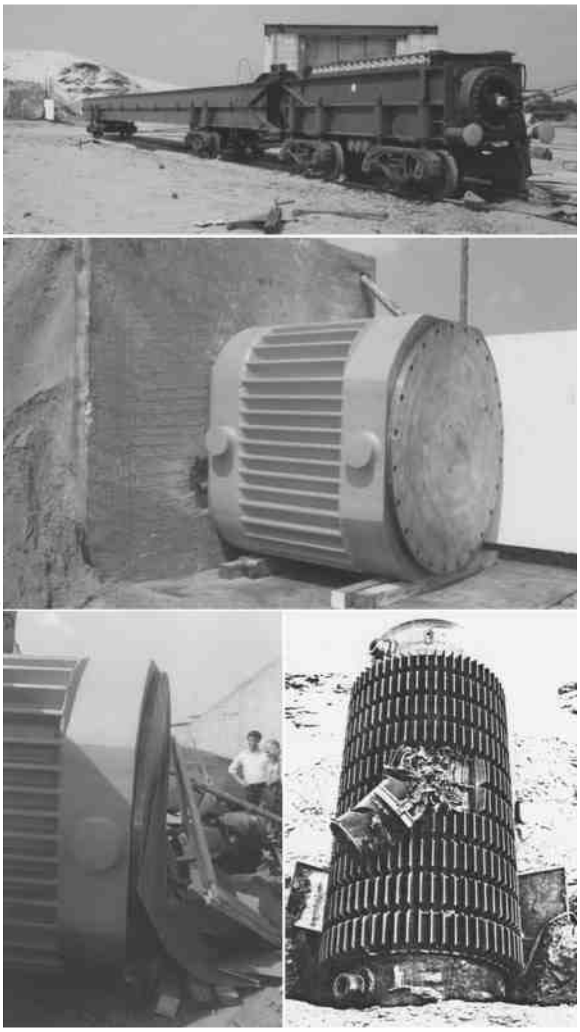
This resulted in a boiling liquid expanding vapour explosion (BLEVE) with an expanding fire ball (~100 m in diameter), heat radiation, explosive blast wave and the most severe impact onto the cask, i.e. tank fragments were blown towards the cask lid end. Figure 15*b* shows the completely destroyed test assembly. The shockwave and shrapnel acting directly on the CASTOR cask moved it (centre of gravity) ~7 m away from its original position. The accelerated tank fragments that crashed onto the upper part of the cask lid induced a rotation of the cask with the lid end travelling 10 m before it crashed into the ground (Fig. 15*c*). The cask movement is shown in Fig. 15*d*. Although the non-protected closure lid was exposed to fire, and hit severely by tank wagon fragments, post-test investigations demonstrated that no loss of leak tightness occurred. For more details see the literature.[12]

Finite element analysis of spent fuel cask subjected to blast loading

In a research for the evaluation of potential hazards in which spent fuel packages might be in close proximity with other dangerous goods in trains,[13] the hypothetical detonation blast wave from a wagon with explosives (21 t equivalent weight of TNT) at a distance of 25 m between the centre of the explosion and the cask front end was investigated. The characteristics of the blast wave were calculated according to standard literature (for details see Ref. 13). For spent fuel flasks (with a mass from 80 to 140 t, and diameters from 2 to 3 m) the upper limit of the velocity, to which a cask is accelerated after such an explosion, was estimated to be ~4·5 m s^{-1}. This value is much lower than that in a 9 m drop, and comparable to that in a 1 m drop, indicating that this effect of the explosion is covered by the regulatory test conditions. The maximum incident pressure acting on the side wall of a cask was calculated to be 2 MPa, equal to the static pressure of the 200 m water immersion test. Nevertheless the dynamic effects of the explosion on the cask wall, lid and lid bolts stresses had also been calculated by a FEA. To estimate the effect on leak tightness, the radial (sliding) and axial (opening) displacements of the lids at the gasket locations had been calculated. As a result of all evaluations it could be concluded that a typical spent fuel flask design is robust enough to withstand even such a severe detonation safely.

Aircraft crash simulating tests and calculations

The dual purpose casks used in Germany for transport and interim storage of spent fuel and HLW have to be assessed to determine how they respond to a military aircraft crash. This requirement comes from the German Atomic Energy Act, which requires this assessment for sensitive nuclear installations. For that reason from the beginning of the development of dual purpose casks for dry interim spent fuel storage in Germany such an impact has been tested. Between 1978 and 1982 six full scale tests at the Bundeswehr Test Site in Meppen, Germany, were performed.[14–16] In these tests, steel pipe projectiles (5 m in length, 0·6 m in outer diameter, in the core of a 3·2 m long hard steel pipe, crosswise steel stiffenings, 1000 kg in total mass) were shot by a 30 m long ‘canon’ (*see* Fig. 16*a*) accelerated to a velocity of 300 m s^{-1} onto different cask specimens. In the first test the bottom part of a CASTOR Ia cask was struck. In the



a b c d

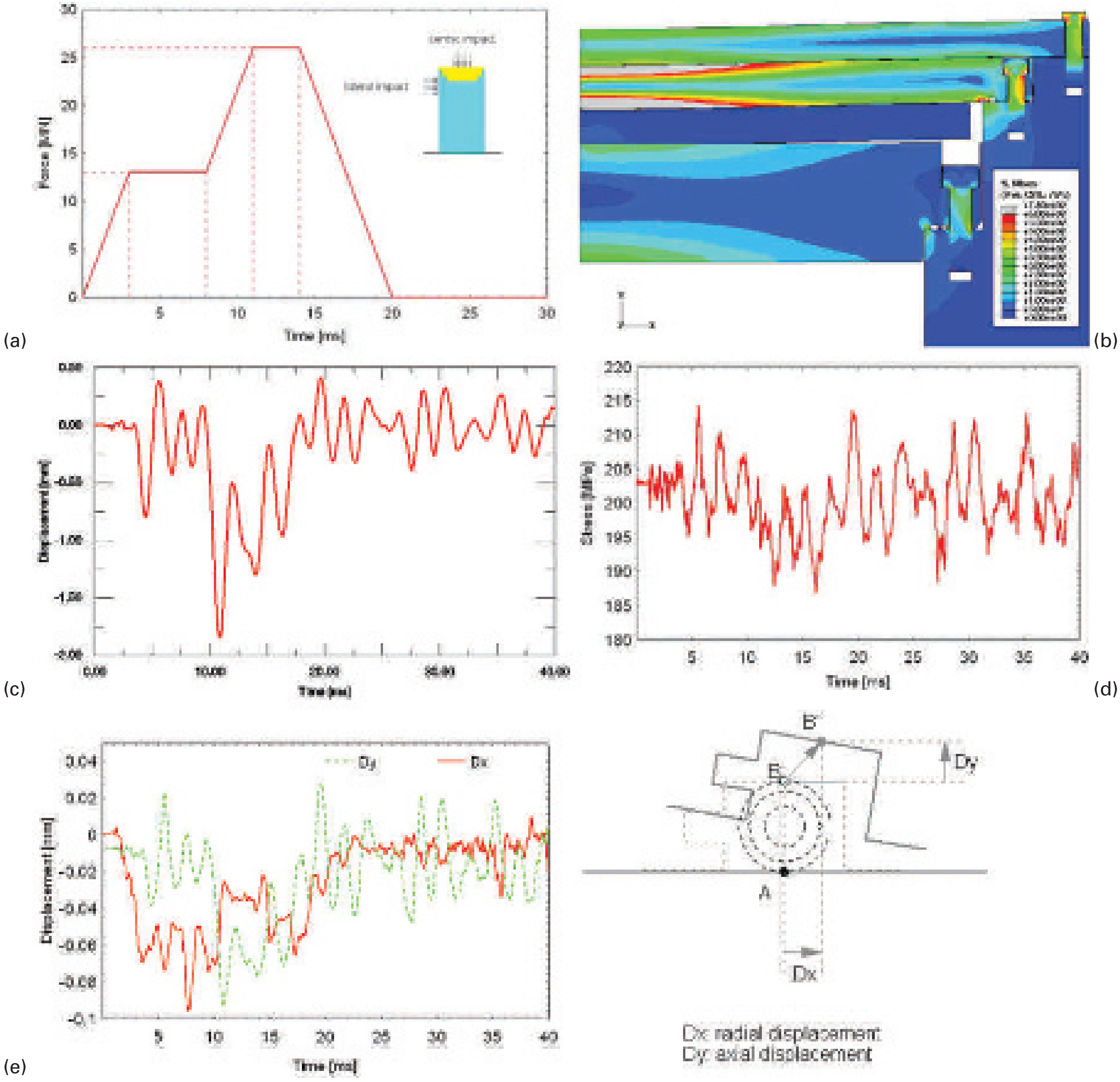
16 Aircraft crash simulating tests with dual purpose spent fuel casks *a* missile canon, Bundeswehr test site Meppen; at back, placed before concrete plate before hill, CASTOR IIa cask specimen; *b* CASTOR IIa cask specimen (with shortened length and full scale diameter) before test; *c* lid side of CASTOR IIa cask specimen after test (with test stand debris); *d* TN 1300 full scale spent fuel cask after missile impact onto cask wall

second test a cask lid was struck at an angel of 30°. The third test showed an axial impact on the centre of a CASTOR IIa double lid closure system, as it is still in use for actual German dual purpose cask designs (Fig. 16*a*–*c*). The test specimen was a 'shortened' version of a full scale diameter CASTOR IIa cask (Fig. 16*b*). The perpendicular impact of the projectile resulted in the deformation of the outer parts of the lid system (permanent deformation of the protection plate and the secondary lid); the inside primary lid was not deformed and had significantly lowered, but a quantifiable leak tightness still existed. Three other aircraft impact tests were performed on a large TN 1300 full scale spent fuel cask. Two shots were made perpendicular onto the centre of the lid system that was effectively protected by a massive protection lid which absorbed nearly all the impact energy. Another shot was made perpendicular onto the cask wall (Fig. 16*d*), where it could clearly be demonstrated that such an impact does not do any damage to massive cask structures.

After the terrorist attacks of September 11, 2001 the assessment of aircraft crash impacts was re-examined. Now the assessment issue was spread to the effects of large civil aircraft crashes. Immediately after September 11 BAM and GRS investigated this issue in a joint research project[15] to determine the level of high safety margins of the spent fuel and HLW casks in severe mechanical and thermal accident scenarios. Further detailed assessments have been carried out by a group of expert institutions (TÜV Hannover, GRS, Stangenberg und Partner, BAM) contracted by BfS (Federal Office for Radiation Protection) requested by the Competent Authority for licensing of the at reactor spent fuel storage facilities in Germany. BAM had the task to investigate the resulting mechanical impacts from aircraft engine crash loads (represented by calculated force–time relationships after penetration of an aircraft through building structures), building debris dropping onto standing casks, and finally the thermal impacts from kerosene fires. The detailed assessment reports are confidential, but the assessment methodology that was developed by BAM was presented in publications.[16–19] The calculations concentrated on cask wall, lids and lid bolts stresses, gasket temperatures and flange (axial and radial) displacements at gasket locations to verify the components integrity and to evaluate the influences on potential leakage rates. As an example for the methodology a reference calculation presented by G. Wieser *et al.*[17] is presented briefly. Figure 17*a* shows a published reference case load–time function (known as the Meppen test projectile characteristic) acting on the centre of the upright cask. Figure 17*b* shows the finite element stress analysis of the double lid system (with additional outer protection plate) for the moment of maximum primary lid displacement (Fig. 17*c*); Fig. 17*d* shows the tensile stress component in the primary lid bolts; Fig. 17*e* shows the calculated sliding and opening displacements at the groove of the large metallic seal of the primary lid. The displayed stresses and displacements are within limits where the safety of the cask function is preserved.

Conclusions

The tests and calculations of test scenarios that are reported underline significant margins of safety of massive type B packages. The investigated type B package designs, representing those packages that have been widely used in Germany for fissile radioactive materials transportation, show high safety margins, as it was confirmed also in similar accident testing in other countries (US, UK, Japan). A general transfer of positive test results to other package designs should not be assumed because every scenario and every cask design needs specific consideration. From real target drop calculations, e.g. it could be concluded that new generation casks with large soft impact limiting structures need specific studies concerning their effectively existing margins of safety beyond regulatory test conditions. In the case of other severe accident impacts, which could be quite different from regulatory tests, it could be demonstrated that massive type B package designs represent a safe confinement category, even in explosion and aircraft crash incidents.



17 **Calculations of centric aircraft crash impact onto lid system of reference cask *a* load-time function of missile (Meppen test projectile); *b* FE stress analysis of lid area at t=11 ms; *c* primary lid deflection history; *d* tensile stress component in primary lid bolts; *e* sliding (radial) and opening (axial) displacement of large metallic seal groove in primary lid**

References

1. B. Schulz-Forberg and H. W. Hübner: 'Klassifizierung und Sicherheitsreserven von Transportbehältern für radioaktive Stoffe', BAM-Research Report 230, 2. actualized edition, BAM, Berlin, April 2000, Wirtschaftsverlag NW, Bremerhaven.
2. H. R. Yoshimura, R. B. Pope, H. W. Hübner and B. Schulz-Forberg: 'Extended testing of an approved shipping container for plutonium components', Non-published report Sand 79-1404 C TTC/0019, SNL, USA, 1979.
3. K. Janberg: Proc. Int. Ductile Iron Progress Meet., Summary, Appendix S, US Department of Energy, Arlington, VA, USA, 1991.
4. Gesellschaft für Nuklear-Service mbH (GNS): 'Untersuchung zu mechanischen Lasteinträgen bei Endlagerbehältern', Non-published report, Bericht-Nr.: GNS B 40/82 (Rev. 1), Essen, Germany, December 1983.
5. K. E. Wieser, M. Jais and V. Holzlöhner: Proc. 7th PATRAM Conf., New Orleans, LA, USA, May 1983, Vol. 2, 879–885.
6. R. Diersch and M. Weiß: 'Störfallanalyse für den innerbetrieblichen Transport von abgebrannten Kernbrennstoffkassetten mit dem Container C 30', Non-published report, BI-E-Brennstoffinstitut Freiberg, GDR, Oktober 1985, 302–430.
7. B. Droste, B. Gogolin, H. Völzke, T. Quercetti and B. Günther: *RAMTRANS*, 1995, **6**, (2/3), 177–182.
8. K. G. Golliher, C. R. Witt and K. E. Wieser: Proc. 10th PATRAM Conf., Yokohama, Japan, September 1992, Science and Technology Agency, Ministry of Transport, 1123–1128.
9. B. Droste, V. Ballheimer, A. Probst, P. Zeisler, C. F. Tso, P. Donelan, M. Farina, R. Hüggenberg and W. Völzer: 'Evaluation of safety of casks impacting different kind of targets', Final Report of Project EC- DG XVII/C/3, Contract No. B4-1020/D/96-17 for the Commission of the European Communities, BAM, Berlin, Germany, 1998.
10. B. Droste *et al.*: Proc. of 12th PATRAM Conf., Paris, France, May 1998, PATRAM, 1343–1351.
11. V. Ballheimer, A. Probst and B. Droste: *RAMTRANS*, 2000, **11**, (1–2), 45–51.
12. B. Droste, U. Probst and W. Heller: *RAMTRANS*, 1999, **10**, (4), 231–240.
13. V. Ballheimer, B. Droste, G. Wieser and L. Qiao: *RAMTRANS*, 2004, **15**, (3–4), 239–245.
14. F. Glaser: Proc. 6th PATRAM Conf., Berlin, Germany, November 1980, PATRAM, 1338–1346.
15. F. Lange, H. J. Fett, E. Hörmann, E. Schrödl, G. Schwarz, B. Droste, H. Völzke, G. Wieser and L. Qiao: 'Safety margins of transport and storage casks for spent fuel assemblies and HAW canisters under extreme accident loads and effects from external events', Report within the framework of Project SR 2415, GRS, Cologne, BAM, Berlin, Germany, April 2002.
16. B. Droste, H. Völzke, G. Wieser and L. Qiao: *RAMTRANS*, 2002, **13**, (3–4), 313–316.
17. G. Wieser, L. Qiao, H. Völzke, D. Wolff and B. Droste: *RAMTRANS*, 2004, **15**, (2), 141–147.
18. G. Wieser, L. Qiao, A. Eberle and H. Völzke: *RAMTRANS*, 2004, **15**, (3), 223–230.
19. G. Wieser and L. Qiao: Proc. PVP 2006-ICPVT-11, 2006 ASME Pressure Vessels and Piping Division Conf., Vancouver, BC, Canada, July 2006, ASME, Paper PVP 2006-ICPVT11-93393.