Extended Brittle Fracture Safety Demonstrations of Cubic Ductile Cast Iron Containers

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INTRODUCTION

In Germany cubic monolithic ductile cast iron (DCI) casks are provided for transport, interim storage, and final disposal of non-heat-generating radioactive waste. The approval of such multipurpose casks has to consider the requirements from three different fields of operation. These are the IAEA IP-2, -3, Type A or B package requirements for transportation, as well as the requirements from the specific conditions of the interim storage facility and from the repository.

The mechanical design requirements for Type B transport packages are defined in the IAEA Safety Series No. 6 for normal conditions (such as mass dependent drop test, stacking test with five times the mass of the actual package, penetration test) and for accident conditions (9 m drop test onto an unyielding target, 1 m drop onto a solid mild steel bar). In consequence of these tests, different limitations of activity release and dose rates must not be exceeded. The requirements for German storage facilities are very similar, with few different requirements for normal conditions (impact test with a velocity of 4 m/s, stacking test with a min. height of 6 m), accident conditions (5 m drop onto the real ground of the facility), and in consequence of these tests, limitations of tightness, integrity, and activity release. The covering requirements, especially the most critical accident scenarios, are the basis for the design performance tests by BAM.

This paper presents the current results of BAM design tests with a cubic DCI container of the "Type VI-15," which is manufactured by Gesellschaft für Nuklear-Service (GNS). The geometry of such containers (see figure 1) with a structural net mass of approximately 18.3 Mg and a maximum gross mass of 20.0 Mg is prescribed by the preliminary conditions for final disposal of radioactive waste in the former iron ore mine, Konrad, in Lower Saxony.

THE GERMAN BRITTLE FRACTURE SAFETY DESIGN CONCEPT FOR DUCTILE CAST IRON (DCI) CASKS

The use of ductile cast iron as a proper material for shipping and storage casks for radioactive materials is closely associated with the prevention of brittle failure also under the most critical Type-B accident conditions especially at temperatures down to –40°C. The current German safety assessment concept was established in the 1980s by BAM (Wieser et al. 1985, Aurich et al. 1987) and is mainly based upon approval design tests with large cylindrical CASTOR and TN casks equipped with impact limiters. This concept needs only a reduced fracture mechanics analysis because of stress limitation to approximately 50% of the material yield strength and appropriate quality assurance measures, which ensure only tolerable crack-like defects within the cask structure in connection with guaranteed fracture toughness down to –40°C.

But generally, if one or more of the above-mentioned limitations are not met, a specific fracture mechanics safety analysis becomes necessary. Such situations occur more and more because cask design optimization leads to smaller wall thicknesses and new cask designs such as cubically shaped multipurpose casks lead to extreme dynamic behavior of the cask structure (Völzke et al. 1994, 1995). Basis for any brittle fracture safety assessment concept must be a well-balanced proportion between material stress, material properties, and quality assurance measures. The actual draft of Appendix IX of the IAEA Safety Series 37 (IAEA-TECDOC-717) represents the international status of engineering and research in this field. But a complete fracture mechanics safety assessment for higher stress levels (elastic-plastic fracture mechanics) and highly dynamic cask impact needs additional investigations of elastic-plastic and dynamic fracture mechanics behavior of DCI. Alternatively, a drop test at the lowest temperature with a precracked prototype cask in the most critical drop orientation represents also a fracture mechanics safety assessment (Völzke et al. 1995). In this case, the material quality of the prototype cask defines the limitations of the representative material properties for the series cask production.

IDENTIFICATION OF THE MOST CRITICAL ACCIDENT SCENARIOS AND RESULTS FROM STRESS ANALYSIS FOR "TYPE VI" CONTAINERS

Extensive investigations by BAM have demonstrated that a 5 m drop flat onto the real ground of the Konrad repository is the most critical accident scenario for the integrity and tightness of "Type VI-15" containers, which have to fullfil the stronger Konrad class II requirements (integrity, tightness) for containers with higher activity limits. Because no shock absorbers can be used inside the KONRAD repository, the 5 m drop normally leads to higher deceleration and impact stresses of the container's structure compared to the IAEA test scenario for shipping casks equipped with well-designed impact limiters. The drop tests were performed by BAM at its test site at Lehre. There the real ground of the repository was simulated by a concrete plate positioned onto the unyielding IAEA target with a layer of wet sand in between.

The results of strain and deceleration measurements of two extensive drop test series in 1991 and 1993 (see table 1) gave detailed and reproducible information about time-dependent stress intensities and their locations about the container walls (Droste et al. 1992, 1994). The first test series was performed with a complete, maximum-loaded container. The second test series was performed with an empty container without protection plate. For compensation of the lower impact energy in this case, the drop height was increased to 5.59 m. The duration of the primary impact was about 5 ms, and the measured decelerations reached up to 1300 g. The target was damaged very little with impressions of only a few mm on the concrete plate including some small cracks within the impact area. The maximum tensile stresses of the container structure (bending stresses because of container wall vibrations in the center of the flat walls and at the inner edges between the walls) reached little plastic deformations, but greater deformations or damages never occurred. The maximum dynamic strain rates reached 7/s.

Table 1. Results from Drop Tests with 'Type VI-15' Containers

Drop height and orientation	max. deceleration; primary impact duration	max. tensile strain (location)	leakage rate; max. strain rate
5 m; container bottom	≈ 1260 g ≈ 4.5 ms	≈ 1050 µm/m (center of a smaller side wall)	leakage rate after the impact $<1.2 \cdot 10^{-8}$ Pa·m³/s.
5 m; smaller side wall	≈ 1210 g ≈ 5.0 ms	≈ 1200 µm/m (center of a smaller side wall and inner edge)	leakage rate after the impact $<6.3 \cdot 10^{-9}$ Pa·m³/s.
5 m; short edge	≈ 250 g ≈ 15 ms	≈ 380 µm/m (inner edge)	leakage rate after the impact $<5.0 \cdot 10^{-7}$ Pa·m³/s.
5.59 m; container bottom	≈ 1300 g ≈ 5.0 ms	≈ 2200 µm/m (inner edge between two side walls)	max. strain rate ≈ 7/s
5.59 m; container bottom	≈ 1250 g ≈ 5.0 ms	≈ 2600 µm/m (inner edge between two side walls)	max. strain rate ≈ 2/s

These drop tests represent the extensive experimental stress analysis for the most critical accident scenario, which has been complemented by a holographic vibration analysis of the original prototype container performed by GNS. The results of the stress analysis have shown high dynamic strain rates with maximum stress levels up to the material yield strength. Because the limitations of the current BAM brittle fracture safety design concept are exceeded, and a dynamic fracture mechanics safety concept has not been established up to now BAM decided to perform a final prototype drop test with a precracked "Type VI" container at the minimum temperature for brittle fracture safety assessment.

CONDITIONS FOR THE DROP TEST WITH A PRECRACKED "TYPE VI" CONTAINER

The selection of a test container from a total of nearly 50 sand-form casted containers was determined by the material quality that was analyzed for each container from six bore-hole specimens from the thermal center of the side walls in connection with a licensed quality assurance program for "Type VI" containers as industrial packages. The results of the structural and mechanical material tests are summarized in table 2. The chosen test container with series No. 5008 is on a low but acceptable level of material quality with the lowest tensile fracture elongation of all fabricated containers.

Table 2. Material Properties of the Test Container No. 5008

	Min.-max.-values of ser.-no. 5008	Mean value of ser.-no. 5008	Mean value of all fabricated containers
Ultimate Tensile Strength (R_m)	392 - 439 N/mm^2	411 N/mm^2	394 N/mm^2
Yield Strength ($R_{p0,2}$)	264 - 274 N/mm^2	270 N/mm^2	257 N/mm^2
Elongation	6,0 - 16,5 %	9,2 %	20,0 %
Perlite Content	----	12 %	3,6 %

The selected test container was prepared with five artificial flaw-like defects (figure 2) at the highest stressed areas during the impact (figure 1). The dimensions of the defects depend on the sensitivity of the applicable nondestructive testing methods, e.g., ultrasonic, to find flaw-like defects. The tip radius of the flaw-like defects must be lower than 0.1 mm for representing a real flaw (IAEA-TECDOC-717). For measuring of the crack opening displacements, three different methods were selected: a strain gauge measuring beam, an optical sensor, and a static distance measurement before and after the drop test. For verification of the real stress state during the impact, numerous strain gauges were attached to the container walls as shown in figure 3. Additionally, accelerometers were attached at the top of the container, some screws of the lid were prepared also with strain gauges, and temperature measurements were performed in the areas near the flaw-like defects. The drop test height was 5.59 m, because the test was performed with an empty container without the protection plate. The additional drop height of 59 cm represents the additional energy of the maximum gross mass of the loaded container.

Figure 1. Container Geometry and Positions of the Flaw-like Defects

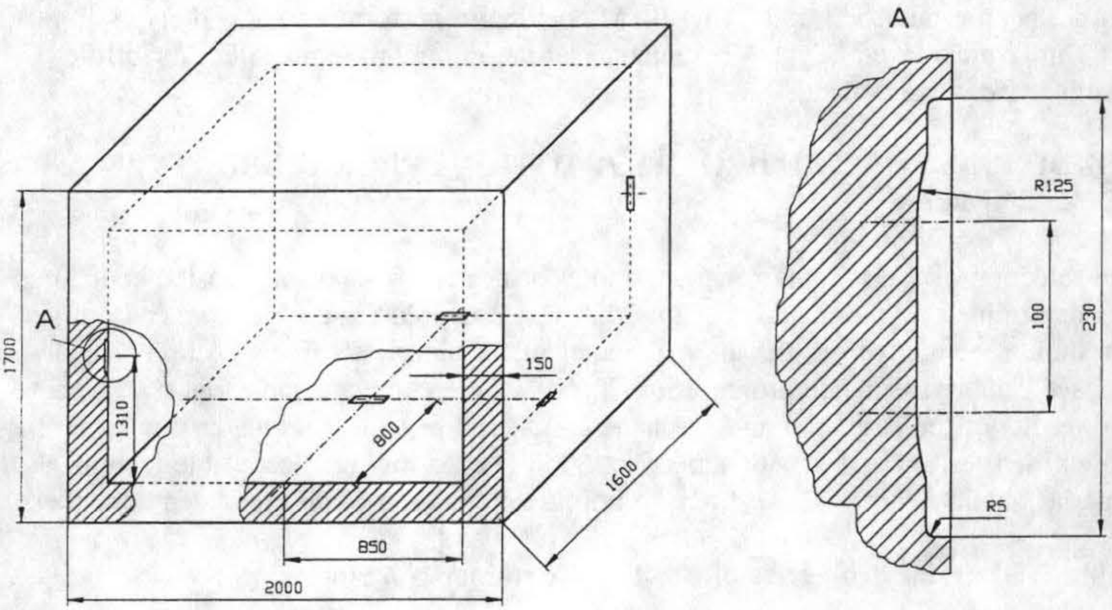
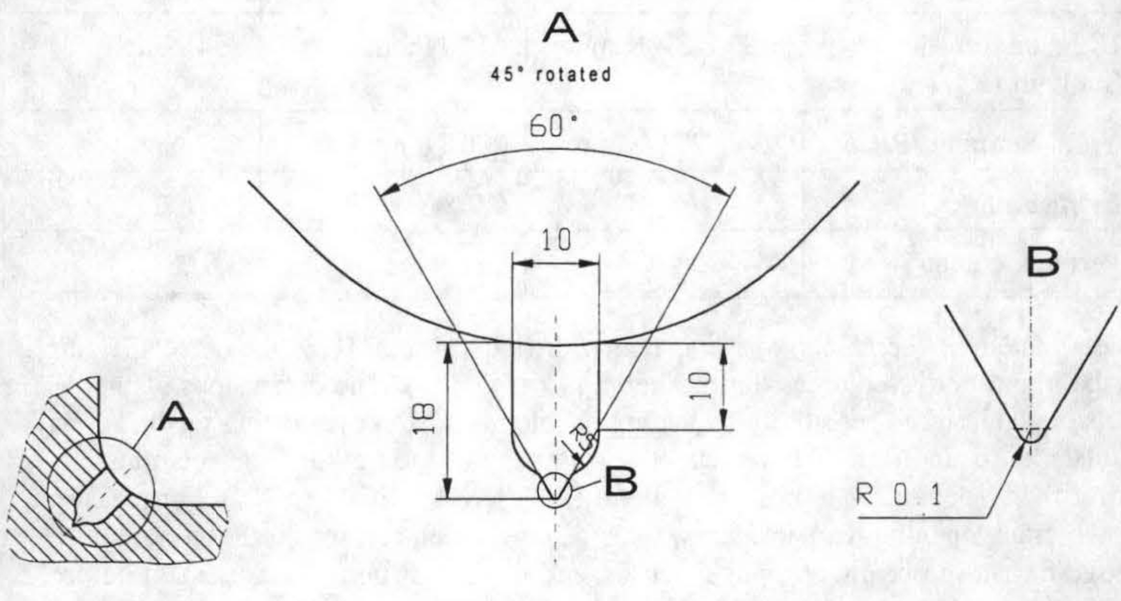
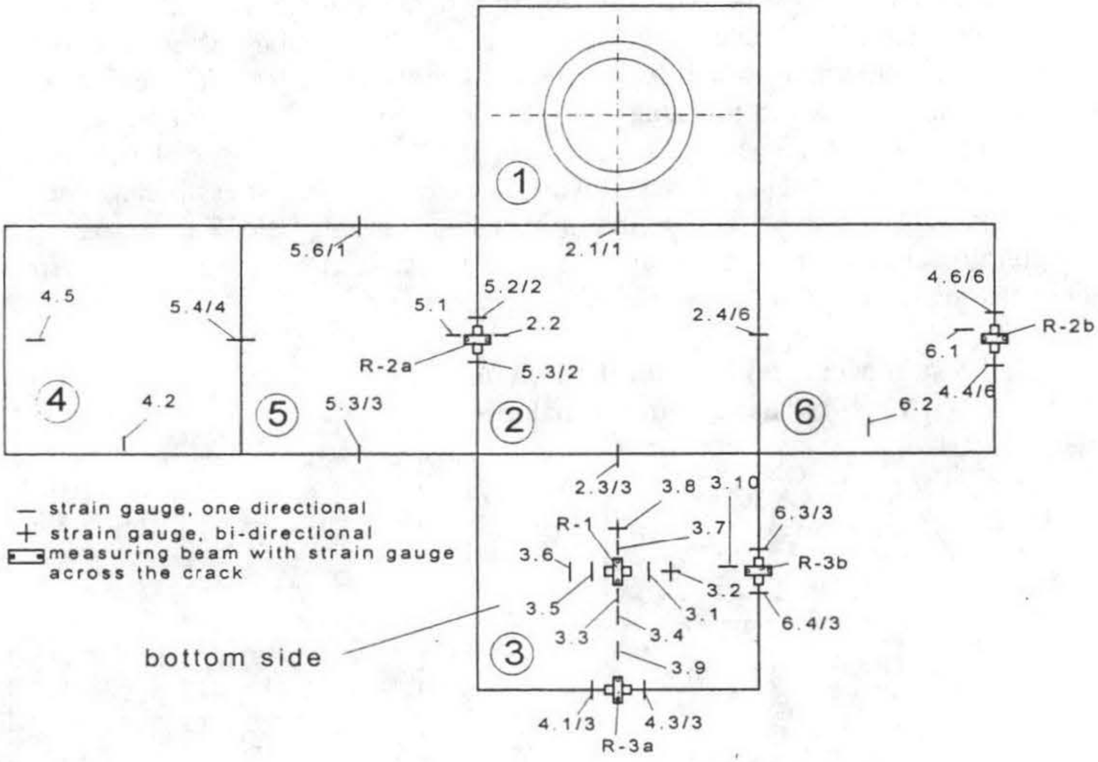


Figure 2. Geometry of the Artificial Flaw-Like Defects



The test temperature was chosen to be ≤–20°C in the area of the artificial flaw-like defects because this is the minimum temperature to be considered for the Konrad repository. The container was cooled down by liquid nitrogen inside a wooden cool box. The real temperatures during the drop differed between –15°C and –21°C at the container outside and between –22°C and –27°C at the inner sides of the container walls near the artificial flaw-like defects.

Figure 3. Instrumentation Plan of the Container Inside



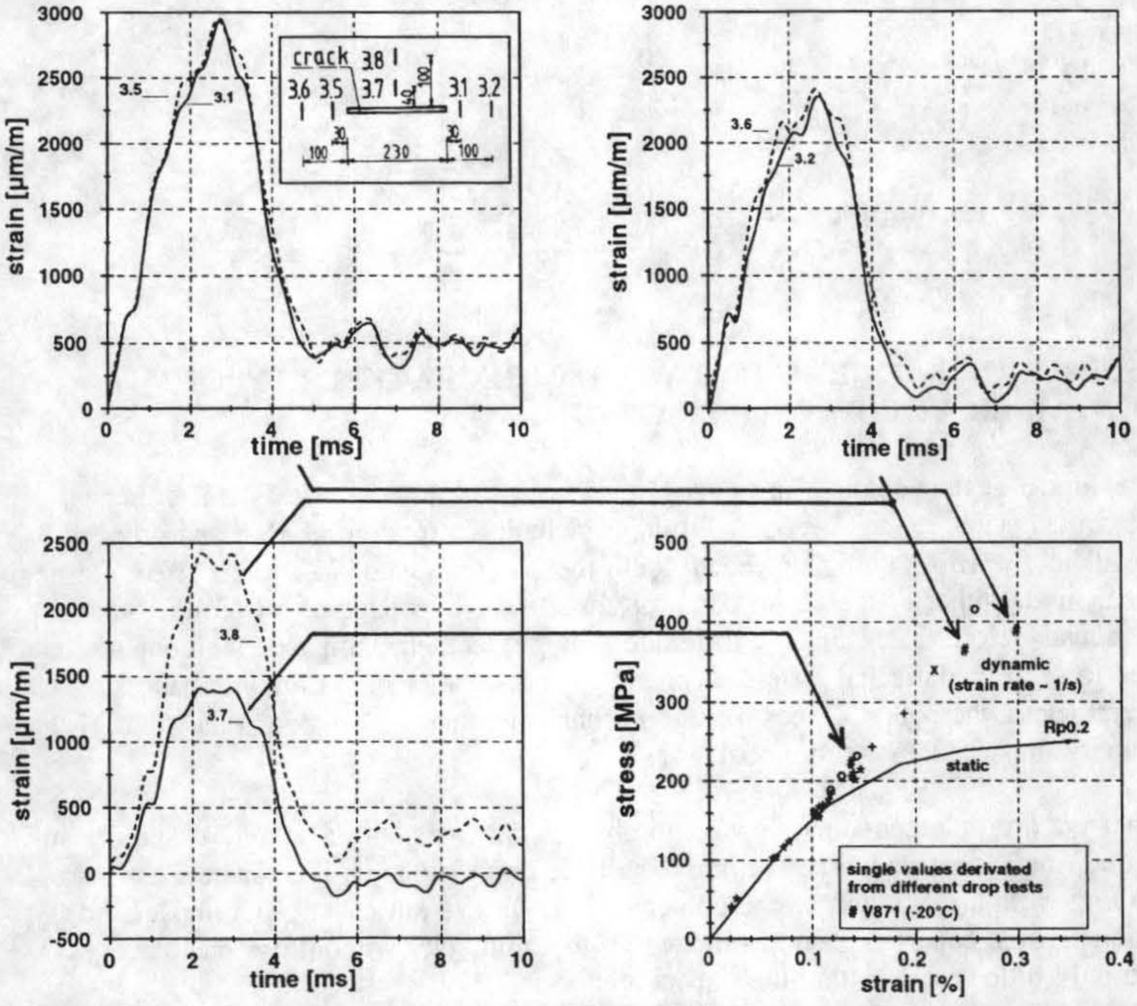
RESULTS OF THE DROP TEST WITH A PRECRACKED "TYPE VI" CONTAINER AT LOW TEMPERATURE

The course of the container drop was rather surprising because after the first impact the container rebounded nearly 1.0 m high including a rotation of 180° and dropped down finally with its top side exactly onto the concrete plate again. This effect did not occur in any other of the performed drop tests, but we realized also from the other drop tests before that very little differences in the geometric impact conditions will lead to such fundamental different container motions after the primary impact. But, nevertheless, the consequences for the mechanical container behavior as a result of the primary impact are not substantial.

After the drop the container showed no obvious damages but only little plastic pressure deformations at the corner fittings. The little impressions on the concrete plate are varying, with a maximum at one corner as a result of a not exactly flat impact. Additionally, the concrete plate has moved on the sand layer without obvious damages and only little cracks within the impact area.

The strain and deceleration data registration was realized by two 36-channel measurement devices in connection with a high-speed memory system. Because of a technical defect in one of the two measurement devices, only the data from 36 recorded channels (mainly strain measurements of the container walls) are applicable for evaluation, which is still running now. Exemplary results of the strain measurements on the container bottom side are shown in figure 4. The primary impact duration is about 5 ms and the maximum strains depend on their distance to the artificial flaw-like defect. Their extrapolation to the center of the inner bottom side lead to a maximum tensile strain of about 3700 µm/m, which is obviously above the static material yield strength and higher than measured in the comparable former drop tests. The dynamic strain-rates reached up to 1.4/s. The last diagram in figure 4 shows the elastic-plastic stress-strain behavior of the container material with an increasing yield stress because of higher strain rates corresponding to other investigations in this field. This means, that 3700 µm/m maximum strain at a strain-rate of 1.4/s results in only little plastic deformations without reaching the dynamic 0.2% yield strength.

Figure 4. Strain Measurements on the Container Bottom Side and Elastic-Plastic Material Behavior



A first evaluation of the measured crack opening displacements (max. values of about 100 µm) under simplistic assumptions (e.g., lin.-elastic, plane strain state) resulted in a maximum stress intensity factor K_I of about 2600 N/mm$^{3/2}$. An estimation of K_I from the maximum tensile stress ($K_I = \sigma \cdot f \cdot (\pi \cdot a)^{1/2}$, $\sigma_{max.} \approx 410 N/mm^2 \cdot (75mm - 18mm)/75mm$, form-factor $f \approx 1.1$, $a = 18mm$) leads nearly to the same K_I-value but, nevertheless, more precise investigations considering the dynamic and elastic-plastic effects are proposed.

For further determination of the material properties and microstructure, especially in the areas of the artificial flaw-like defects, several specimens are prepared from the test container. A first visual inspection has shown no significant flaw extension, which means material fracture toughness has not been reached during the container impact.

CONCLUSIONS

The assessment of the brittle fracture safe design for transport and storage casks made of ductile cast iron under consideration of the most critical accident scenarios is essential for an extended use of this material. With dropping a cubic DCI 'Konrad'-Type VI container from 5.59 m height onto a representative disposal facility target, including a low material quality level (e.g., perlit content 12%; elongation 9.2%), extreme dynamic stress states, artificial flaw-like defects in the highest stressed areas at a temperature of −20°C, BAM performed the brittle fracture safety assessment during the running licensing process. The drop test demonstrated the integrity of the cask design without crack extension also under such extreme conditions. Additional investigations of the test container's material structure and properties and a fracture mechanics analysis under consideration of dynamic and elastic-plastic material behavior will lead to an extended and more general brittle fracture safety assessment concept for the German licensing procedures in the sense of the IAEA-TECDOC-717.

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