MECHANICAL AND THERMAL SAFETY ANALYSES AND DEMONSTRATIONS FOR CUBIC DCI MULTIPURPOSE CONTAINERS

H. Völkze, G. Wieser, U. Zencker and B. Droste
Bundesanstalt für Materialforschung und -prüfung (BAM)
Unter den Eichen 87, D-12205 Berlin, Germany

Abstract — A cubic multipurpose container made of ferritic ductile cast iron (DCI) is investigated for the most critical container accident scenarios, a drop from 5 m height flat onto the ground of the German Konrad repository without additional impact limiters and a one hour fire with an average temperature of 800°C. For the mechanical drop test analysis BAM has developed special finite element modelling for numerical calculation of container stresses as the result of such a violent impact. The calculation results are compared with representative strain measurement data from several drop tests with an original prototype container. Referring to the fire test scenario the results from thermal tests by BAM with an original prototype container loaded with representative but inactive ion exchanger resin are presented and discussed.

INTRODUCTION

The cubic container design for transport, interim storage and final disposal of non-heat-generating nuclear waste may be advantageous because of the maximum utilisation of the available space in the storage and disposal facilities. Depending on the level of radioactivity of the waste products different requirements are defined for the packages, which have to be fulfilled under normal and accident conditions. The requirements from the three fields of operation are defined by the IAEA regulations for transport, by the technical acceptance criteria for the German interim storage facilities and by the preliminary requirements for the German Konrad repository, a former iron ore mine which is currently going through the licensing process.

Current results are presented of BAM design tests and safety analysis for the cubic ferritic ductile cast iron (DCI) container of the Konrad Type VI with outer dimensions of 2.0 m × 1.7 m × 1.6 m, 150 mm wall thickness, a structural net mass of approximately 18.3 Mg and a maximum gross weight of 20 Mg (Figure 1) which is manufactured by Gesellschaft für Nuklear-Service (GNS).

The most critical container accident scenarios are a drop from 5 m height onto the ground of the Konrad repository without additional impact limiters and a one hour fire with an average temperature of 800°C.

Several drop tests with a fully instrumented prototype container have shown a highly dynamic behaviour of the cask structure with maximum stresses up to the yield stress.

For more detailed and precise drop test analysis BAM has developed special finite element modelling (FEM), for numerical calculation of container stresses as a result of the violent impact. The calculation results are compared with representative strain measurement data from drop tests using an original prototype container. These numerical calculations are carried out in a research programme (sponsor Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, BMBF) where the use of DCI containers made of contaminated scrap metal from the decommissioning of nuclear installations is investigated. The decrease of mechanical properties due to scrap metal additions needs a more detailed stress analysis where appropriate FEM has to be used.

Further tests and investigations are related to the most critical fire accident scenario inside the repository in comparison with the IAEA Type B fire test conditions. Because of different fire conditions in both scenarios BAM decided to perform a fire test with an original prototype container loaded with representative but inactive ion exchanger resin. The temperatures of the fire, the container structure and inside the container and the inner pressure were measured during and after the fire test.

DROP TESTS

Extensive investigations by BAM have demonstrated that a 5 m drop flat onto the real ground of the Konrad repository represents the most critical accident scenario concerning integrity and tightness of such Type VI containers, if they have to fulfill the stronger Konrad Class II requirements for containers with higher activity limits. Because no shock absorbers are provided inside the Konrad repository, the 5 m drop normally leads to higher decelerations and impact stresses of the container structure compared to the IAEA test scenario for shipping casks equipped with well designed impact limiters. The drop tests were performed at the BAM test site in Lehre. The real ground of the repository was simulated by a concrete plate put onto the 1000 t IAEA target with a layer of wet sand in between (Figure 1).

The results of strain and deceleration measurements of two extensive drop test series in 1991 and 1993 gave detailed and reproducible information about time-dependent stress intensities and their locations about the con-
The first test series was performed with a complete, maximum-loaded container. The second test series was performed with an empty container without a protection lid. 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 always about 5 ms, and the decelerations reached up to 1300 g (1 g = 9.81 m s⁻²). The target was damaged very little with a penetration of only a few mm into the concrete plate and some small cracks within the impact area. The maximum stresses of the container structure caused slight plastic deformation, but greater deformation or damage never occurred. The maximum dynamic strain rates reached 7 s⁻¹.

Finally a drop test was performed at a material temperature of −20°C with a prototype container prepared with artificial flaw-like defects in the highest stressed areas. Also under such extreme conditions preservation of integrity and tightness was generally demonstrated but additional visual inspection after the drop test showed, in some cases, limited crack extension at the tips of the artificial flaw-like defects; this has to be evaluated carefully giving consideration to material properties.

**NUMERICAL ANALYSIS**

While strain gauge measurements are only possible at discrete positions, a numerical simulation shows all stress and strain components including their rate of change all over the cask structure. The precise modeling of the target is as important as an adequate modeling of the container structure: both are of great influence on the calculation results. For verification of the results from such numerical calculations a comparison with representative test data is essential. Finally, the results from both the experimental and the numerical investigations can lead to a complete understanding of the very complex mechanical container behaviour.

The drop test configuration is shown in Figure 1. Figure 2 shows a finite element model of a quarter segment of the test configuration. Effects from the lid system are negligible in this case. The container, the concrete target, the wet sand layer and the IAEA unyielding target consist of solid 8-node elements with reduced integration and hour-glass control. They are connected by interface elements without friction. For the container material an elastic material model is used (Young’s modulus E = 162 500 MPa, Poisson’s ratio ν = 0.29, mass density ρ = 7000 kg m⁻³). The initial velocity of
the cask is defined by the drop height (5.59 m). All
dynamic calculations were done using ABAQUS/
Explicit (5).
At first, the flat drop of the container onto an unyield-
ing target was investigated. Therefore, contrary to Fig-
ure 2, the target was modelled with only two-dimen-
sional rigid surface elements. The accuracy and
convergence of the container model was analysed by
varying the number of elements over the wall thickness.
It was found that at least three elements over the wall
thickness should be used to describe the plate bending
for the purpose of this study. Calculated and measured
strain history curves from the middle of the bottom plate
(inside surface) are shown in Figure 3(a). These graphs
represent bending strains superimposed by high fre-
quency stress wave effects. The measured impact dur-
ation of approximately 5 ms is not contained in the cal-
culated curve. Because the unyielding target model is
different from the real impact situation the amplitudes
of the calculated strains are much higher than the meas-
ured ones.
A half space meshed with solid elements surrounded
by infinite elements is a more realistic representation of
the real ground. The concrete material model uses the
linear Drucker-Prager criterion (5):
\[
F = \sigma_e - p \tan(\beta) - c = 0
\]
where
\[
\sigma_e = \sqrt{(1.5 \; s_{ij} \; s_{ij})}
\]
is the Mises equivalent stress, \( s_{ij} = \sigma_{ij} + p \; \delta_{ij} \)
is the deviatoric stress and \( p = -\sigma_{kk}/3 \) is the equivalent
pressure stress. The cohesion of the material
\[
c = (1 - \tan(\beta)/3)\sigma_e
\]
is related to the uniaxial compression yield stress \( \sigma_c = 45 \; \text{MPa} \) and the friction angle \( \beta = 66^\circ \). The elasticity in
conjunction with this model is defined by the parameters
\( E = 37 \; 000 \; \text{MPa} \) and \( \nu = 0.21 \) (6) and the mass density is
2340 kg.m\(^{-3}\). Figure 3(b) shows the corresponding strain
history curves which are significantly smoother with
lower amplitudes than in Figure 3(a) because of the tar-
gent deformation. The impact energy was partially trans-
mitted into the foundation. Inelastic effects were found
only in the vicinity of contact surfaces (far away from
infinite elements). However, the characteristic curve
shape of the measured data is also not represented by
this calculation model.
It was thus obvious that modelling of the drop test
target has to consider more realistic structural and
material data. In the complete model (Figure 2) the con-
crete foundation is a plate which has the same material
properties as given above. The steel plate of the IAEA
target is considered as an elastic half space modelled
with infinite elements again (\( E = 210 \; 000 \; \text{MPa} \), \( \nu = 0.3 \),
\( \rho = 8000 \; \text{kg.m}^{-3} \)). Between concrete plate and IAEA tar-
get there is a layer of wet sand (\( \rho = 2000 \; \text{kg.m}^{-3} \) con-
obtained in a steel frame. In separate compression experiments (Odometer experiments) its stiffness modulus $E_s$ of 106 MPa was measured, which can be expressed by a modulus of elasticity of 79 MPa for an assumed Poisson’s ratio of 0.3. By using this structural and material data our calculated strain history curves (Figure 3(c)) show good agreement with the measured impact duration of nearly 5 ms, but the magnitude of the oscillations is still too high. The beginning of the experimental graph depends on an initial angle ($\theta_0$) between container bottom plate and target because the drop test was not ideally flat. The calculated irreversible penetration of about 0.3 mm into the concrete plate and the maximum vertical elastic displacement of the container bottom plate of about 10 mm are confirmed by deceleration measurements and visual inspection from the drop tests.

Until now the material damping of the ductile cast iron was neglected which can be included by an additional ‘damping stress’

$$\sigma_d = \beta_R \dot{\varepsilon}$$

(4)

proportional to the total strain rate $\dot{\varepsilon}$ with the material’s current elastic stiffness $D^{\prime}$. The damping factor

$$\beta_R = 2 \frac{\xi}{\omega_i}$$

(5)

can be expressed in terms of a fraction $\xi$ of critical damping for a particular frequency $\omega_i$ of vibration. Because the same damping factor is effectively applied to all the modes in an element, a chosen value of $\beta_R = 10^{-5} s/\pi$ reduces frequencies of 1 kHz by 1% and frequencies of 10 kHz by 10%. In this case the measured strains are in general good agreement with the experimental results (Figure 3(d)).

Our investigations into the numerical simulation of such strong and highly dynamic impact scenarios demonstrated that only realistic modelling of the real structural and material characteristics will lead to sufficient agreement with results from real drop tests.

THERMAL TESTS

According to the preliminary requirements for the German Konrad repository the container conservatively has to withstand an IAEA fire over one hour. The leakage rate must be $\leq 1.0 \times 10^{-5} \text{Pa.m}^{-3}.\text{s}^{-1}$ before and $\leq 1.0 \times 10^{-4} \text{Pa.m}^{-3}.\text{s}^{-1}$ after the thermal test. During the fire the pressure inside the container has to be measured and no unsteadiness of the pressure curve is permitted.

A description of the BAM open-fire propane-burning test facility and the method to verify the fire conditions is described elsewhere. A 1:1 container model was used, made of welded steel sheets and filled with water to find essential parameters for the burner configuration and a

![Figure 4. Fire temperature during DCI container fire test. The fire temperatures are measured at 10 cm from the container walls. Heavy line, average of all six fire temperatures.](image)
SAFETY ANALYSES FOR DCI CONTAINERS

necessary propane consumption rate. The test container was made of ductile cast iron (GGG40). It was filled with the spherical ion exchanger ‘LEWATIT S100 KR/H-chlorfrei’ from Bayer with around 50% moisture content.

For measuring pressure and temperatures of the ion exchanger and seals inside the container the measuring cables of the pressure gauges and thermocouples were led out through an additional opening in one side wall. The cables were protected against the fire using an isolated pipe. The opening was closed by a flange which was sealed with a metallic gasket. Most of the thermocouples inside the container were fixed on a steel rack at the three symmetric axes of the container. The measuring points of container wall, lid and fire temperature are positioned on the same axes.

Figure 4 shows the fire temperature and demonstrates that the test conditions fulfilled the requirements. It is also a good example of an IAEA fire with an average fire temperature of about 800°C and a heat transfer of \( \approx 75 \text{ kW.m}^{-2} \). The total leakage rate of the lid system was \( \approx 10^{-8} \text{ Pa.m}^3\text{s}^{-1} \) before and \( \approx 3.0 \times 10^{-6} \text{ Pa.m}^3\text{s}^{-1} \) after the fire test. During the fire the inner pressure increased but reached its maximum of 0.93 MPa after 5 h. No discontinuity of the pressure curve occurred. After four days the internal pressure decreased to about 0.43 MPa. The maximum inner wall temperature inside the container reached 392°C after 73 min. The maximum seal temperatures reached 238°C for the main seal after 2.6 h and 210°C for the cover plate seal after 5 h. Figure 5 shows the temperature distribution inside the ion exchanger along a horizontal symmetric axis. It shows a delayed heat transfer and a big influence of the temperature distribution by mass transfer, see, for example, the thermocouple at 215 mm distance from the container wall where the temperature increased in a very short time to about 100°C. The maximum temperatures of ion exchanger resin will be at the edges and corners of the cubic container and were estimated to be more than 400°C.

CONCLUSIONS

The complex mechanical and thermal behaviour under the most critical accident scenarios of cubic ferritic ductile cast iron containers for transport, storage and disposal of non-heat-generating radioactive waste has been investigated by BAM.

The development of detailed and precise numerical drop test analyses needs special finite element modelling of container and foundation for accurate numerical calculation of container stresses as a result of the violent impact of containers without impact limiters. For the investigated test configuration different simplified target models (rigid surface, elastic-plastic half space) were tested, but only a realistic modelling of the real struc-

![Figure 5. Temperature distribution during DCI container fire test. Temperature of the ion exchanger resin: (Δ) 50 mm from inner wall; (□) 215 mm from inner wall; (○) centre, 650/850 mm from inner wall.](image-url)
tural and material characteristics leads to sufficient agreement with results from real drop tests.

Thermal tests with a DCI Type VI container filled with representative ion exchanger resin in a one hour 800°C IAEA fire have demonstrated that development of inner temperatures and pressure are a complex matter not only during the fire but also during the cooling down phase. The effects of water content and thermal resistance of the resin and the heat transfer mechanisms are of great importance for the thermal safety assessment.

REFERENCES


ACKNOWLEDGEMENTS

The numerical calculations of the DCI container drops are supported by the German Federal Ministry of Education, Science, Research and Technology under contract No 02 S 7584 (Stillegung und Rückbau kerntechnischer Einrichtungen).