Ductile Cast Iron (DCI)—Progress on Research Activities on Fracture Mechanics

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Introduction

Designing systems for transporting radioactive material (RAM) has gained increasing importance as the need for transporting and storage of RAM has increased. As a result, significant applied research efforts are underway to develop new generation transportation casks which are more efficient than past designs and maintain the same or higher levels of safety. Many of these efforts focused on qualifying Ductile Cast Iron (DCI) as a suitable material for use as the containment boundary in transportation and storage casks.

In Western Europe, the acceptance and licensing of DCI has been attained and DCI transport casks are in use throughout Europe. The basis of the acceptance rests on numerous proof tests by BAM which have demonstrated the material integrity. Totally, 44 9 m-drop tests with DCI-prototypes up to 90 t were performed according to the IAEA test conditions. The ability to transfer results obtained from the drop tests of prototypes to the serial casks is ensured by combining a number of quality and compliance assurance measures.

The transportation community outside of Western Europe has been slower to adopt DCI. The principal issue is the establishing of a general adopted fracture mechanics approach. This issue is being investigated extensively mainly in the Federal Republic of Germany, Japan, and USA.

Status of International Research Activities on DCI

With respect to a fracture mechanics assessment of DCI, Japan, the USA, and FRG currently have test programs underway. Their status can be summarized briefly as follows:

- **Japan:** Research on DCI has been specified in Japan by the Nuclear Safety Commission. Its Central Research Institute of Power Industry CRIEPI organized a "Quality Assurance (QA) Committee on DCI Casks". Six thick walled cask bodies of full scale dimension were available for extensive and systematic material measurements. Besides, results derived from static tensile tests (yield strength, ultimate strength, ductility), metallographic and compositional appraisals, the measurements also provided fracture toughness values according to ASTM E 399 and ASTM E 813, respectively. Their results at -40 °C were between 70 MPa $m^{1/2}$ and 86 MPa $m^{1/2}$. These values are greater than the values of a "Lower Bound Curve" reported in the literature (R. Helms and J. Ziebs 1987).

  Instrumented precracked Charpy specimens were also tested to provide estimates of dynamic fracture toughness. The range of measured values was approximately 53 - 56 MPa $m^{1/2}$ at a temperature of -40 °C. All results are enclosed in the CRIEPI Report: *Research on Quality Assurance of Ductile Cast Iron,* April 1988.

A further essential part of the Japanese research program is the performance of several drop tests using full scale DCI prototype casks with artificial flaws. One 9 m drop test was carried out in June 1988. The location and dimensions of the machined artificial flaw met all requirements with regard to crack initiation in the most conservative sense. As far as known till now, metallographic studies in the flaw area did not indicate any cracking much less brittle fracture. A second drop test with a similiar cask was announced for April 1989.

- **USA:** In 1985, the U.S. Department of Energy (DOE) and the FRG Bundesminister für Forschung und Technologie (BMFT) entered into a three-year technology transfer agreement. The technical program plan was administered by Sandia National Laboratories SNL for DOE and BAM for BMFT.

  The agreement identified nine technical and administrative categories. A large part of the research efforts for the overall program centered on the category "Cask material behaviour" under exclusive considerations of the material DCI.

  Much of the materials testing at SNL has been associated with measuring static fracture toughness. SNL worked on establishing a correlation between fracture toughness and an easily measurable material property. The SNL demonstrated a strong correlation between static fracture toughness and graphite nodule spacing. This correlation should prove useful from a QA standpoint. SNL has been working on developing single specimen dynamic fracture toughness tests. Current test techniques do not necessarily produce reasonable results. The effort is one of several independent programs underway in the USA to develop an acceptable test technique.

  Beyond that, SNL and the Electric Power Research Institute (EPRI) sponsored an effort to draft a material specification for DCI. The effort resulted in a draft ASTM Specification, ASTM A874, "Ferritic Ductile Iron Castings for Nuclear Material Transport Containers Suitable for Low Temperature Service". A material specification which assures that DCI with a baseline of material properties is being provided is a necessary component within the overall QA system.

- **FRG:** Based on the requirements of the transport regulations and the national atomic energy act, BAM developed a special DCI evaluation concept. It is reported in the literature (Wieser, K. E. et. a. 1985) in detail and was presented to the public several times. Under the specific accident loads, failure due to brittle fracture can be precluded by a combination of performance tests and QA measures.

  Because developed fracture mechanics methodologies could provide the basis for the successful adoption of DCI in the international cask communities, BAM concentrated research activities on this matter. This was done in the frame of the bilateral research program mentioned earlier. Three points of main effort should be emphasized in particular:

  - Comprehensive material investigations on test specimens from prototype casks which survived successfully Type B(U) drop tests as well as from several hundred serial casks. The way of taking samples of both is by boring straight out of the cask wall by means of a special core boring machine. With this technique characteristic material values could be obtained representing the actual properties in the cask.

  - Drop tests of two test objects with induced artificial flaws in the cask wall. One of the test objects was instrumented in such a way that the crack opening displacement (COD) could be analyzed experimentally during impact. The COD gives information about the really interesting stress intensity in the notch. Both parameters are in a functional relationship.

- Destructive material analyses of test objects with artificial flaws after the drop test series. This included either metallographic investigations in the vicinity of the flaw or the determination of static fracture toughness at different temperatures according to ASTM E 399 standard.

Experimental Results of FRG Research

- **Material measurements:** In FRG, several hundred DCI serial casks are in service at present. In the frame of quality control, the material properties of each serial casting have to be determined by taking samples out of the cask's wall. Prototypes which were subjected performance tests in an approval procedure have been investigated much more extensive. This procedure provided a large data base which permits evaluations even under statistical aspects. As a result it can be stated that the level of ductility for example (as one of the main requirements in BAM's evaluation concept for DCI), tends to a continual improvement. In 1980 we started with 3 % ductility as a mean value in terms of elongation. Today, the mean value amounts to approximately 15 %, even for a wall thickness of more than 200 mm. Our material measurements on fracture mechanics corroborated a "lower bound curve" (see R. Helms and J. Ziebs) in which all available static fracture toughness data K_{Ic} are brought together as function of K_{Ic} vs. temperature. All measured valid K_{Ic} values of serial and prototype casks were far beyond this lower limit. The Japanese investigations confirmed this value as well. Therefore, it is a reliable and conservative assumption at present, to proceed from a K_{Ic} value 50 MPA $m^{1/2}$ at -40 °C. However, the knowledge of a lower limit value is only one part of the total problem. The other one is connected with QA. Material testing must be performed on the serial samples. Small Disc Compact Test (DCT) specimens would be the only possibility to control the real fracture toughness properties of each serial cask. BAM has a comprehensive test program underway to solve this problem, that means to ascertain the necessary relationship between large specimens (representing the wall thickness of a cask) and DCT specimens. Fig. 1 shows the proceeding in principle:

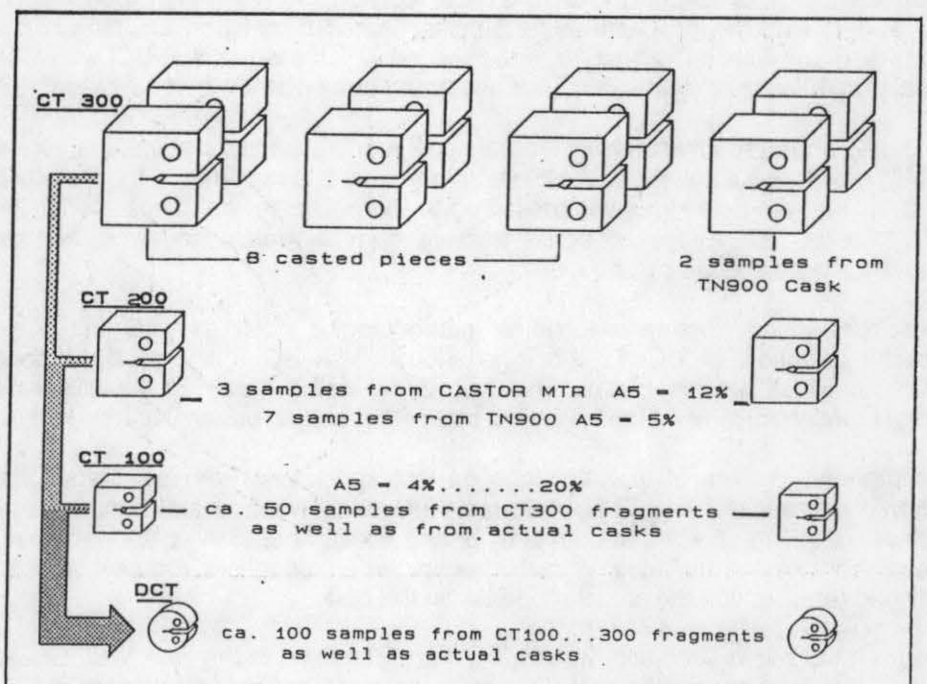

Fig. 1. BAM Test Programme to ascertain a relationship between (large) CT specimen and (small) DCT specimen

a) According to the elongation scatter of all serial casks manufactured till now, 10 CT 300 specimens were produced. These specimens will be subjected to "plane strane fracture toughness tests" according to ASTM E 399. The test temperature will be -40 °C.
b) The same procedure is valid on 10 CT 200 specimens, derived from two actual casks of corresponding wall thickness.
c) Then, approximately 50 CT 100 samples shall be produced. They are derived from CT 300 fragments as well as actual casks.
d) Finally, approximately 100 DCT samples shall be measured (from fragments CT 300, CT 200, CT 100).

Drop Tests with Test Objects Having Artificial Flaws

Test object I: In order to analyze a well defined defect under impact conditions, a simple geometrical test object was produced (see Fig. 2). Possible influences of other fracture conditions (fins, change in diameter etc.) was excluded by this simple shape. Concerning its main dimensions (length, diameter, wall thickness), it corresponded to 1 : 2,5-scale model of an actual cask.

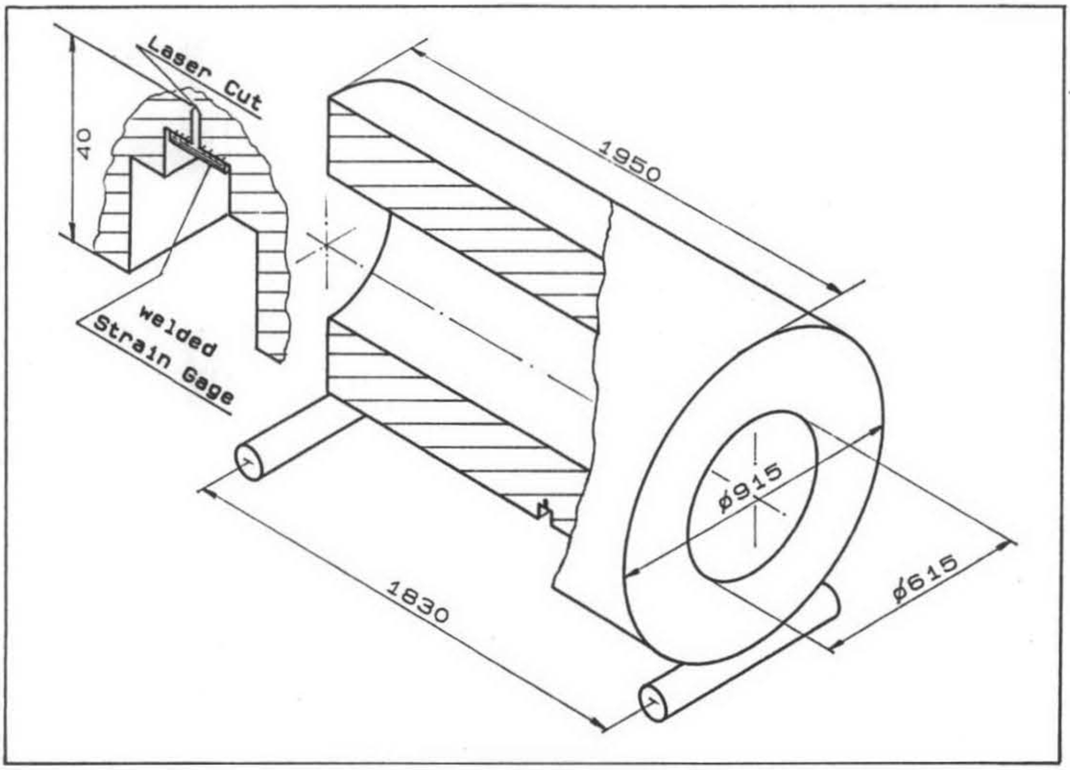

Fig. 2. DCI test object with artificial flaw of simple shape (mass: 5 to);
Welded strain gauges to measure COD

The flaw size was estimated under the assumption that stresses in the magnitude of 200 MPa (yield strength of the material) are acting on the object as a bending moment. This leads to a flaw depth of 40 mm, taking into account simultaneously a conservative fracture toughness value K_{Ic} = 63 MPa $m^{1/2}$ at room temperature. The tip radius was machined by a laser cut.

For the experimental determination of the COD during impact, a special kind of strain gauges was used. They were attached over the flaw by welding. The whole measurement equipment (including the strain gauges) was calibrated prior to the tests by means of clip gauges as they are used in static fracture toughness measurements.

In total, four drop tests from different hights (0,5 m, 1 m, 5 m, 9 m) were performed at room temperature. As an example shows Fig. 3 the measured COD as well as the occuring stress intensity K_I. Approximately 37 MPa $m^{1/2}$ were measured. That means: Even if the lowest dynamic fracture toughness of the material at -40 °C of the Japanese investigations is taken as a basis for an assessment, the measured stress intensity is far beyond a critical state. Consequently, metallographic investigations in the vicinity of the flaw tip did not indicate any crack initiation.

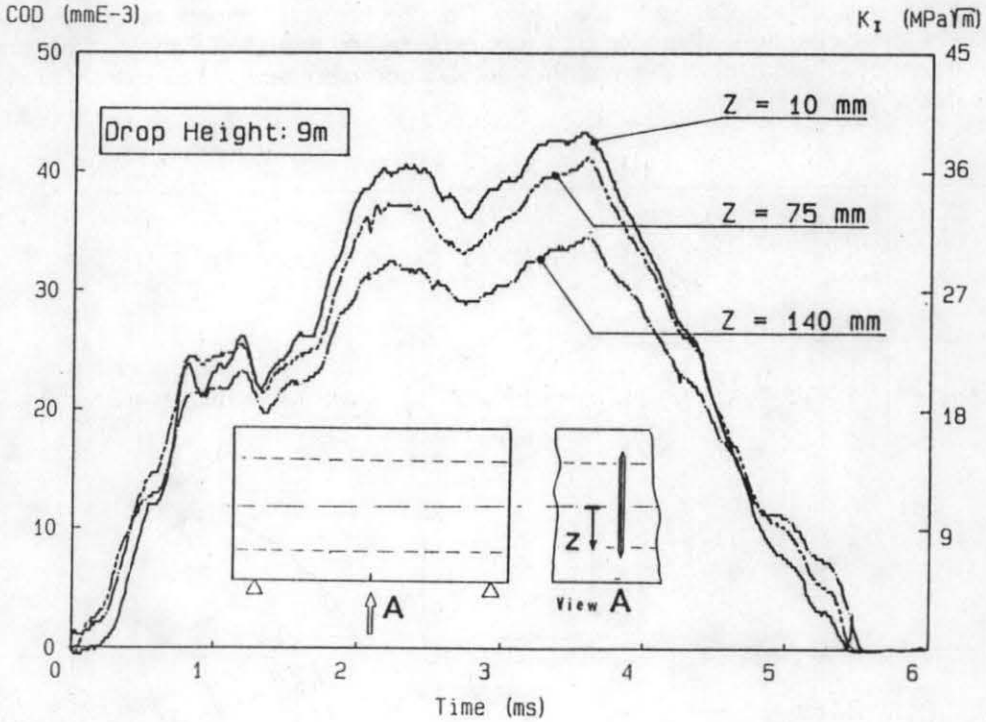

Fig. 3. Measured COD during the impact phase in a 9 m drop (Test object I)

Test object II: The second object which was dropped with an artifical flaw (see Fig. 4), was an actual cask design (12 to CASTOR MTR). With respect to the present wall thickness (340 mm) as well as the worst orientation in a 9 m drop, the critical size of the flaw was determined (depth: 80 mm). The static fracture toughness K_{Ic} at -40 °C was also measured according to ASTM E399.

Two drop tests were performed: one 9 m side on drop onto an unyielding target at -38 °C; one 1 m drop test on a punch at -30 °C (same orientation as above, however, 180° rotated around the center axis). The cask was instrumented with strain gauges and accelerameters. Results are not discussed here. They are enclosed in the *BAM Test Report No. 2527*. More interesting are the results derived from metallographic inspections after dropping. Fig. 5 shows the polished sections of two locations. Crack propagation is arrested after 0.4 mm as a maximum (wall thickness 340 mm). A second specimen shows crack arresting in a graphite nodul next to the notch.

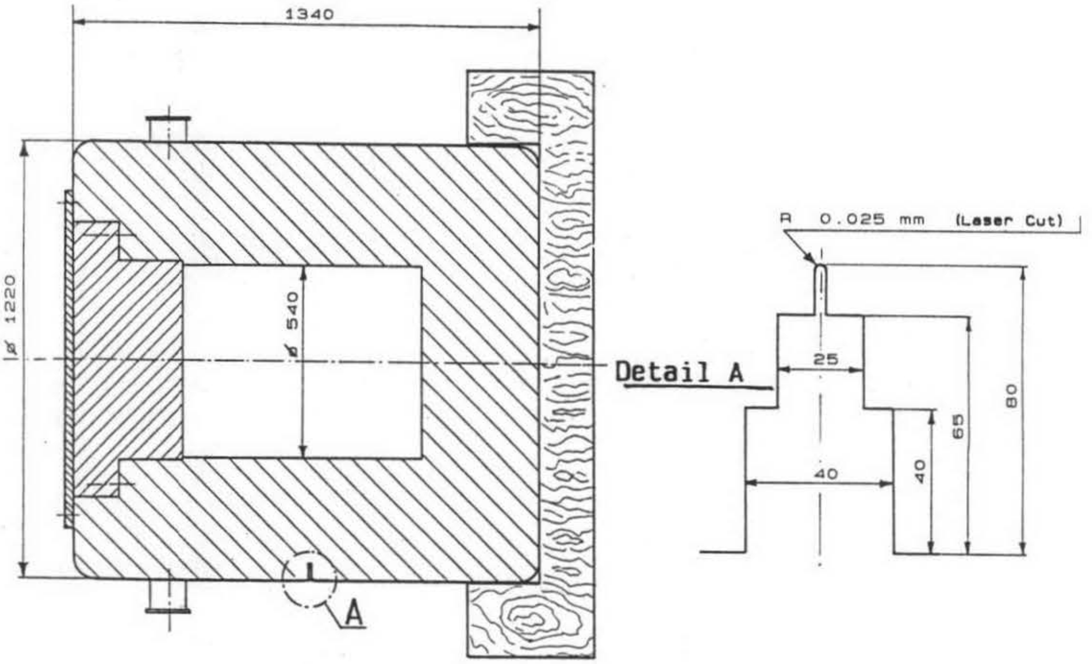

Fig. 4. Package design CASTOR MTR (mass: 12 to) with artificial flaw of critical size

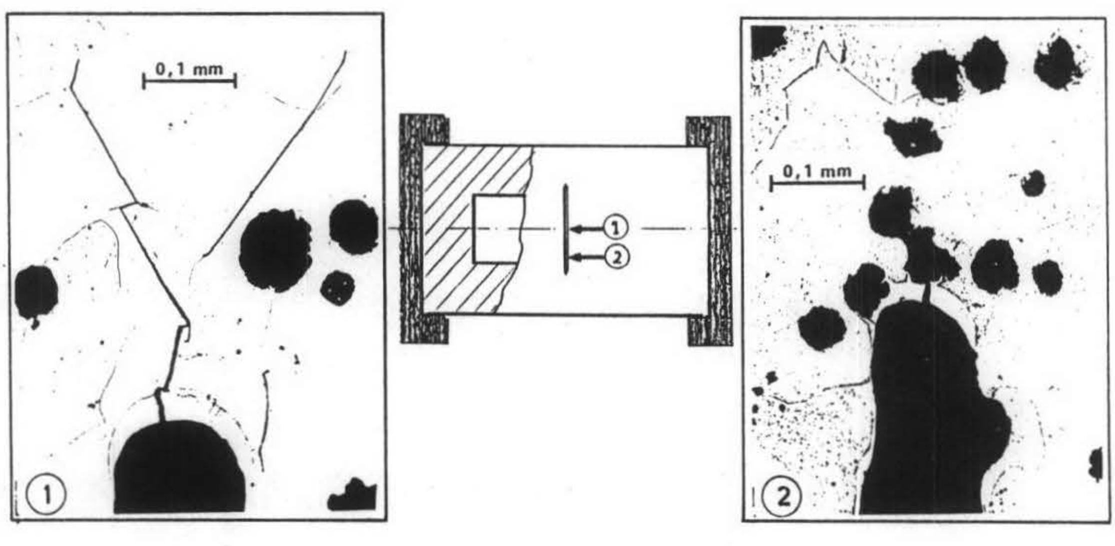

Fig. 5. Metallographic inspections in the flaw vicinity of CASTOR MTR after two drop tests (9 m; 1 m punch) at low temperature

Conclusions

Research efforts, especially by FRG (BAM), Japan (CRIEPI), USA (SNL) and other organizations have been performed to characterize DCI as a material for transport and storage casks. Results did give clear indications:

- of what physical parameters in DCI are good for or ditrimental to the resistance of brittle fracture (good graphite nodualarity, limitations of pearlite and tramp elements etc.),

- about the magnitude of the occuring stress intensity which must be excepted in a Type B performance test, taking into account a flaw of critical size in the worst drop orientation. Measured stress intensities in this connection were far beyond published static or dynamic fracture toughness values,

- about the behaviour of the material in the vicinity of the flaw. Metallographic inspections after Type B performance drop tests (9 m, 1 m punch, -40 °C) did not show any failure due to brittle fracture.

Established UT methods are sensitive and reliable enough to detect flaws of critical size. The mechanical testing to assure minimum fracture toughness properties coupled with UT inspection to assure soundness, provides the confidence that production casting will survive as severe an environment as proof-tested prototypes casks.

On the basis of all available results it ought to be possible to establish a general adopted fracture mechanics approach.

References

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