Full-Scale Tests and Evaluation for Quality Assurance of Ductile Cast Iron Casks

T. Kusakawa[1], T. Kishi[2], H. Ohtsubo[2], S. Shiomi[3], H. Takaku[3], C. Ito[3], T. Saegusa[3]

[1]*Waseda University*
[2]*University of Tokyo*
[3]*CRIEPI, Japan*

INTRODUCTION

Ductile Cast Iron (DCI) has not been yet employed for Cask Material in Japan. This might be because there are insufficient material data on fracture toughness and because brittle failure acceptance criteria is not yet established for cask applications.

This paper describes the results of materials tests using six full-scale DCI cask bodies, a proposal of brittle failure acceptance criteria based on the fracture mechanics, and the results of its verification tests using a full-scale DCI cask.

THE QUALITY ASSURANCE COMMITTEE ON DCI CASKS

Organization and Research Program

In order to carry out the present research, Central Research Institute of Electric Power Industry (CRIEPI) organized "The Quality Assurance Committee on Cast Iron Casks (The QA Committee)", which is composed of about 100 members in total. Table 1 shows the members of the QA Committee.

The QA Committee is aiming to carry out research and developments that will confirm integrity of the DCI Casks. Fig. 1 shows the flow diagram of the major research by the QA Committee.

MATERIAL TESTS

Specimens and Test Items

The material tests were planned to use the specimens sampled from full-scale DCI cask bodies in order to grasp the real material data and its distribution in the cask bodies. Six Japanese foundries (Nippon Steel, NKK, Kawasaki Steel, Kobe Steel, Japan Steel Works, Kubota) casted six full-scale cast iron cask bodies by their own casting methods, individually. The wall thickness of the bodies varied from 350 to 500 mm. Fig. 2 shows one of the examples of sampling position for the material

Table 1 The QA Committee Members
As of June 1989

Name	Organization
T. Kusakawa*1	Waseda Univ.
S. Aoki *2	Tokyo Inst. of Technology
H. Ohtsubo *3	Univ. of Tokyo
T. Umeda	Univ. of Tokyo
T. Kishi *4	Univ. of Tokyo
K. Ikawa	Univ. of Tohoku
T. Kobayashi	Toyohashi Univ. of Technology
T. Yasunaka	National Research Inst. for Metal (STA)
K. Hirano	Mech. Eng. Lab. (MITI)
M. Adachi	JAERI
M. Nomura	JAERI
T. Ohtake	PNC
T. Hayashi	Tokyo Electric Power Co.
M. Yoneda	Kansai Electric Power Co.
I. Fukui	Chubu Electric Power Co.
T. Ohgami	Kyushu Electric Power Co.
M. Inoue	Japan Atomic Power Co.
M. Mizobuchi	Federation of Electric Power Co.
S. Fukuda *5	CRIEPI
H. Abe	CRIEPI
H. Ohnuma	CRIEPI
D. Sakurai	Nippon Steel
A. Itaya	NKK
H. Nagahama	Kobe Steel
R. Honma	Japan Steel Works
S. Nakamura	Kubota
S. Tanaka	Mitsubishi Metal
M. Hirose	Mitsui Engineering and Shipbuilding
K. Takeshita	TN Tokyo
S. Shiomi *6	CRIEPI
T. Saegusa	CRIEPI
C. Ito	CRIEPI
K. Shirai	CRIEPI
K. Shimazaki	CRIEPI
K. Tsuda	CRIEPI

*1 Chairman, *2 Advisor,
*3 WG-B Leader, *4 WG-A Leader
*5 Leader of Cask Design Committee
*6 WG-C Leader

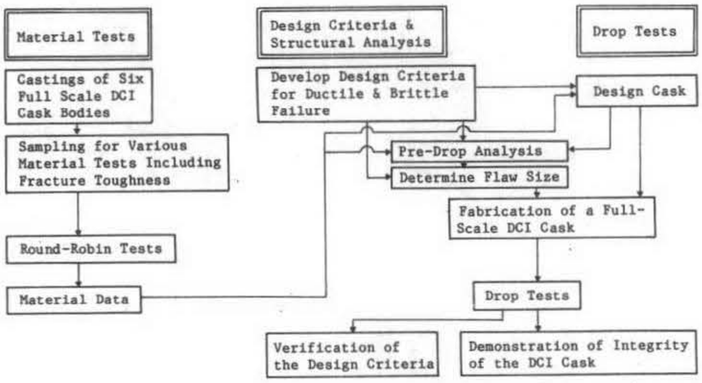


Figure 1. Flow Diagram of the Major Research by the QA Committee

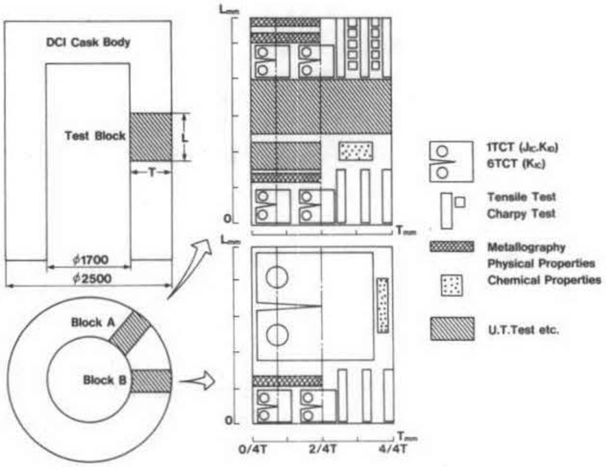


Figure 2. Example of Sampling Position for Material Testings

tests. In order to increase the reliability of the test results, the tests were conducted by more than two organizations (so called Round Robin Method was pursued).

Results and Discussions

Fig. 3 shows the results of the tensile tests with respect to the position in the wall thickness of the DCI cask bodies. The alphabetical letters A through E correspond to the individual DCI cask bodies casted by the six foundries. The variation of the tensile properties may be classified into the following three types of through-wall thickness distributions. 1) The properties are relatively low in the center of the wall thickness and higher near the wall surfaces. 2) The properties are relatively high near the inner wall and lower near the outer wall surface. 3) The properties are relatively high near the outer surface and lower near the inner wall surface. The other measurements "elongation at fracture" and "Young's modulus" also showed the similar trend of the through-wall thickness distribution.

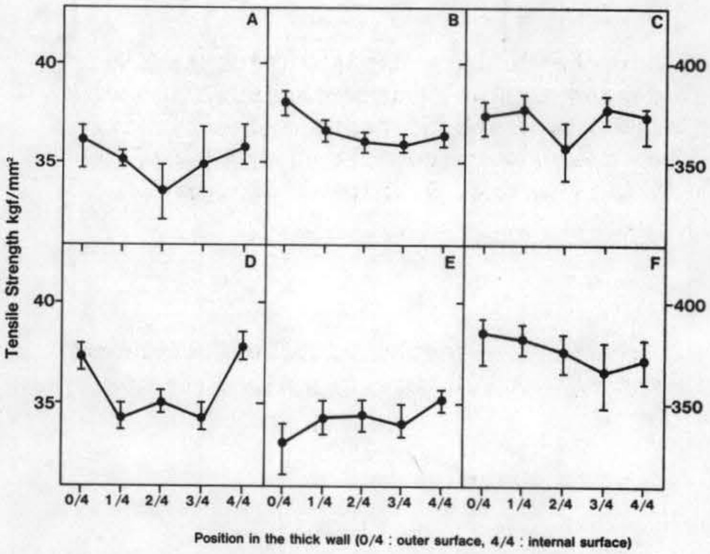


Figure 3. Tensile Strength of Different Positions in the wall of the DCI Cask Bodies

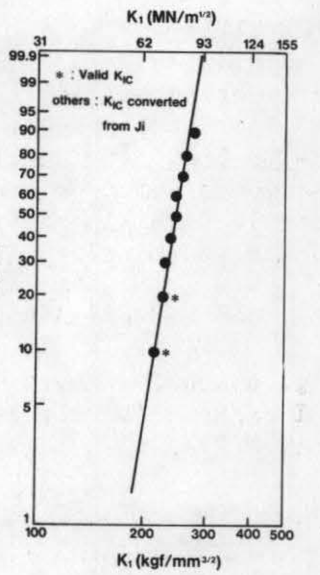


Figure 4. Weibull Plot of K_{IC}

Fig. 4 shows the fracture toughness K_{IC} test results plotted on the Weibull Probability chart. Correlation can be judged as very good as normal K_{IC} data.

Fig. 5 summarizes the results of the tensile tests and the fracture toughness tests. These values are relatively higher and favorable than those found in the literature.

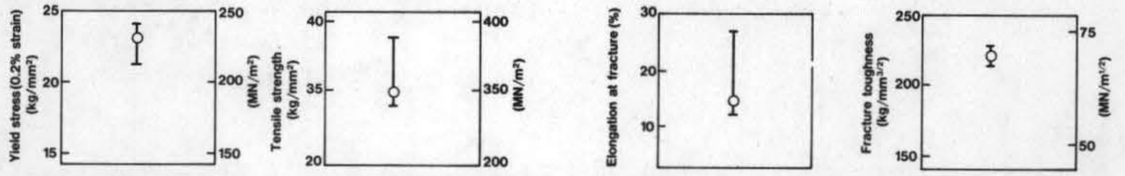


Figure 5. Summary of the Results of the Tensile Tests and Fracture Toughness Tests

BRITTLE FAILURE DESIGN CRITERIA

Based on the fracture mechanics and referring to the ASME Code Sec. III, Appendix G and Sec. XI, Appendix A, the QA Committee proposed a brittle failure design criteria of DCI casks as follows.

$$a_c = \frac{(K_{IR}^{*})^2 Q}{\pi \{1.1\, M_k\, (2\sigma_M + \sigma_m) + M_B(2\sigma_B + \sigma_b)\}^2} \quad \cdots\cdots\cdots\cdots \quad (1)$$

where the nomenclature is defined in the chart of Fig. 6.

The characteristics of Eq. (1) are that it includes a safety factor "2" in the denominator and that K_{IR}^{*} is introduced in substitution for the K_{IR} defined in the ASME Code.

DROP TESTS

In order to confirm the proposed brittle failure design criteria (Eq. (1)) and the integrity of the DCI cask against the mechanical impact, the QA Committee undertook the following steps of tests and evaluation including 9-m drop tests. The drop tests were conducted by CRIEPI jointly with Nippon Steel, Kubota, Mitsui Eng. & Shipbuilding and Mitsubishi Metal.

Chart of Tests and Evaluation

Fig. 6 shows a chart of tests and evaluation on the brittle failure of DCI casks. The blocks numbered from ① to ⑧ are described in the followings, respectively.

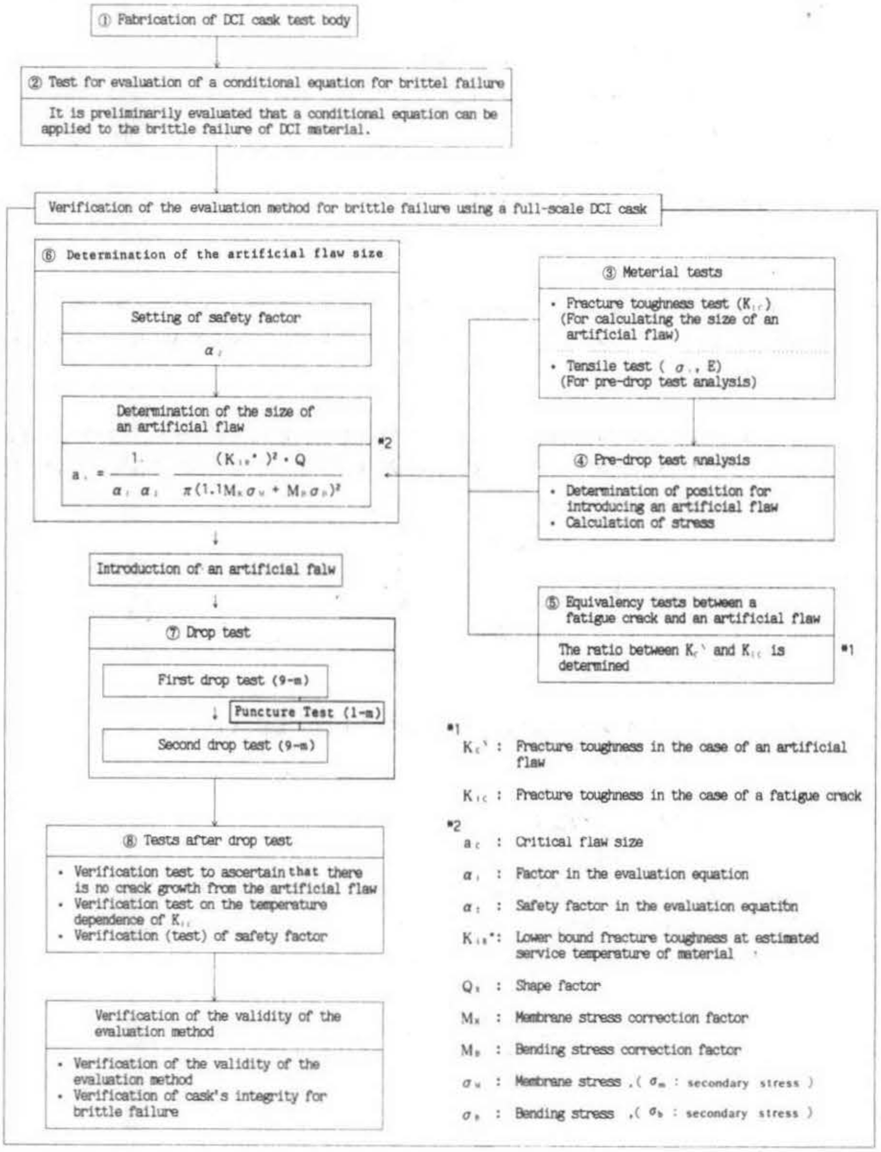
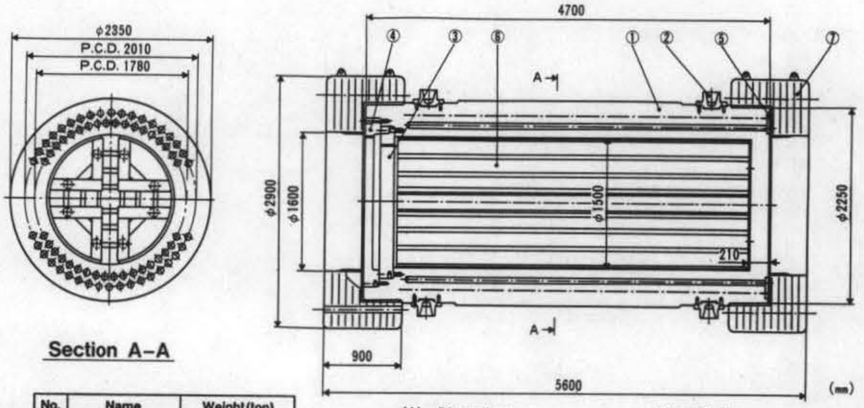


Figure 6. Chart of Tests and Evaluation on the Brittle Failure of DCI DCI Casks

Fabrication of DCI Cask Test Body (①)

The QA Committee developed a neutral design specification of a DCI cask for the test so that the test result of the DCI cask can be generally applied to DCI casks of various designs.

Fig. 7 shows the sectional view of the test body with dimension and weight.



No.	Name	Weight (ton)
①	Body	72
②	Trunnion	0.3
③	Primary lid	5.8
④	Secondary lid	
⑤	Bottom plate	
⑥	Dummy weight	25
⑦	Impact limiter	7

(1) Dimensions

Outside diameter : 2350 mm
Inside diameter : 1500 mm
Wall thickness : 425 mm
Height : 4700 mm

(2) Weight

Body : 72.0 tons
Lid : 5.8 tons
Dummy weight : 25.0 tons
Impact limiter : 7.0 tons
Trunnion : 0.3 tons

Total :110.1 tons

Figure 7. Sectional View of DCI Cask Test Body (Unit : mm)

Test for Evaluation of a Conditional Equation for Brittle Failure (②)

Linear fracture mechanics predicts that brittle failure will occur when

$$K_I = K_{IC} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (2)$$

where K_I is the stress intensity factor and K_{IC} is the fracture toughness of the material. The QA Committee examined if Eq. (2) can be applied to DCI by conducting fracture tests of large DCI plate specimens at brittle failure conditions. The results confirmed the applicability of Eq. (2) to the DCI material.

Material Tests (③)

Fracture toughness (K_{Id} at $\dot{K}_I \simeq 10^3 \text{kgf/mm}^{3/2} \cdot s$), yield point ($\sigma_y$), and Young's modulus (E) of the DCI cask were required for the pre-drop test analysis. The prolongation and the core materials sampled from the DCI cask body were used for the material tests. The following results were obtained:

$$\overline{K_{ID}} = 236 \text{ kgf/mm}^{3/2} (73.2 \text{ MN/m}^{3/2}), \quad \sigma_s = 18.9 \text{ kgf/mm}^{3/2} (5.86 \text{ MN/m}^{3/2})$$

σ_y = 37 kgf/mm^2 (363 MN/m^2), E = 16000 kgf/mm^2 (1.57 × 10^5 MN/m^2)
where $\overline{K_{Id}}$: average value of K_{Id} measurements, σ_s : standard deviation

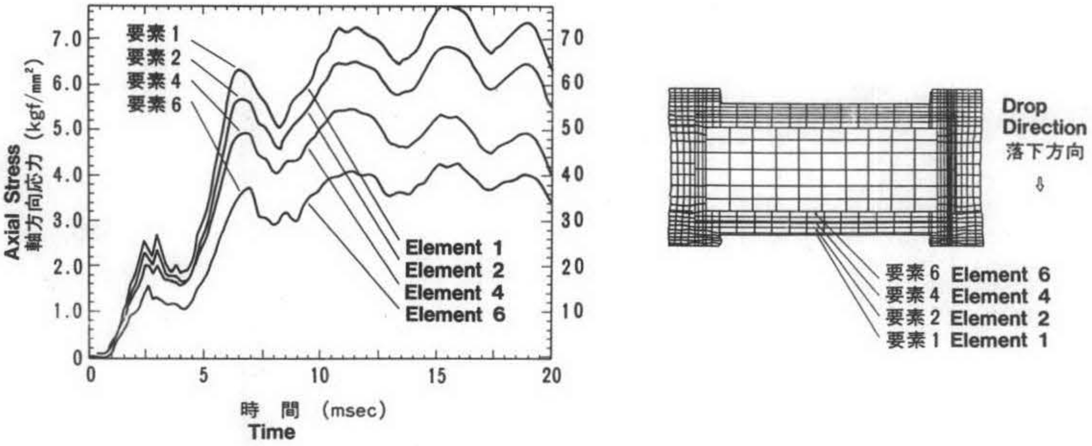


Figure 8. Stress Response Curve at 9-m Drop Test

Pre-Drop Test Analysis (④)

Using the DYNA-3D code, pre-drop test analysis of the DCI cask under the 9-m drop test condition and the 1-m puncture test condition were conducted for different drop directions, e.g. horizontal, vertical, and corner. As the results, it was found that the maximum tensile stress would be generated when the DCI cask were dropped horizontally. Fig. 8 shows the axial stress variation with time in the central lower section where the maximum tensile stress will be generated. The calculated result of the maximum stress was about 8 kgf/mm^2(80 MN/m^2).

Equivalency Tests between a Fatigue Crack and an Artificial Flaw (⑤)

The drop tests were planned for the DCI cask with a sharp flaw. The QA Committee decided to introduce an artificial flaw with a tip radius of 0.1-mm by the Electron Discharge Method. Fracture toughness tests of 6TCT specimens with a fatigue crack and those with an artificial flaw with a tip radius of 0.1-mm were conducted to confirm equivalency in their fracture toughness values.

Determination of the Artificial Flaw Size (⑥)

The QA Committee planned to conduct two 9-m drop tests as follows. The first 9-m drop test aimed to demonstrate the integrity of the DCI cask with an artificial flaw of 20-mm in depth that is more than twice as large as the flaw size detectable by the conventional Ultrasonic Test. The second 9-m drop test aimed to verify the proposed brittle failure design criteria by Eq. (1) that includes a safety factor of "2". At the second drop test, the artificial flaw was determined to be 83.5-mm that analitically corresponds to a condition of a safety factor of about

"1.5" against brittle failure at the 2nd 9-m drop test of the DCI cask. Fig. 9 shows the drawings of the two kinds of the artificial flaws introduced by the Electron Discharge Method at the position where the maximum tensile stress will be generated at the 9-m drop tests of the DCI cask.

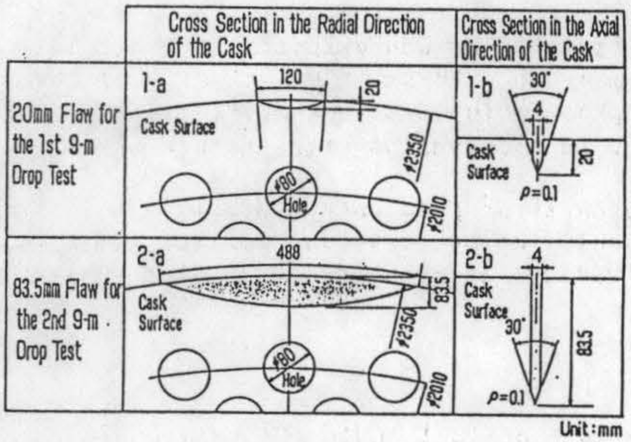


Figure 9. Semi-Elliptical Artificial Flaw on the DCI Cask Surface

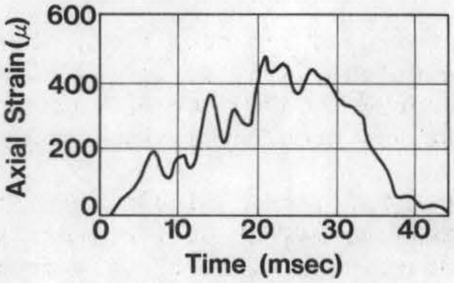


Figure 11. Dynamic Strain Measurements in the Vicinity of the Artificial Flaw at the 9-m Drop Tests

Drop Tests and Results (⑦)

Two 9-m drop tests as mentioned above and a 1-m puncture test were conducted using the full scale DCI cask. In these tests, the DCI cask body was cooled down to less than -40°C (233K) by the shower of vaporized liquid N_2. Prior to each test, a set of the conventional impact limiter of the atomospheric temperature was attached to the both ends of the DCI cask.

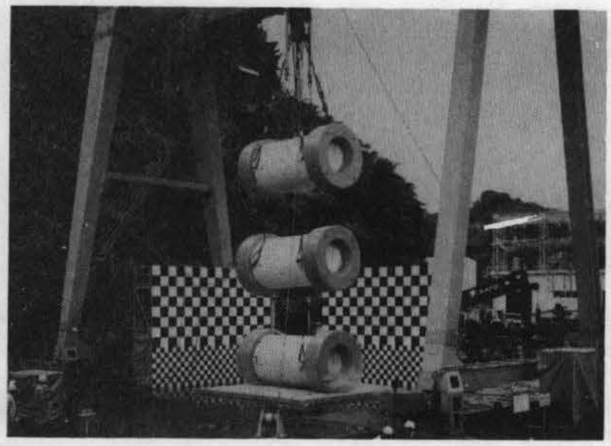


Figure 10. 9-m Drop Test of DCI Cask

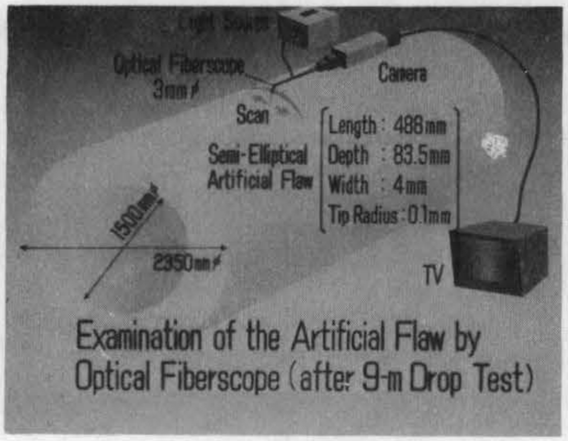


Figure 12.

Examination of the Artificial Flaw by Optical Fiberscope (after 9-m Drop Test)

Fig. 10 shows the 9-m drop test. The temperature of the DCI cask body was -43°C (230K) at the 1st drop test and -44°C (229K) at the 2nd drop test. Fig. 11 shows the dynamic strain measurements in the vicinity of the artificial flaw at the 9-m drop tests. The measurements match with the analytical results shown in Fig. 8 very well, taking account of the Young's modulus 16000 kgf/mm^2 (1.57×10^5 MN/m^2).

After each 9-m drop test, the artificial flaw was examined by a special technique using an optical fiberscope (Fig. 12). It was clear from the observation that there was no crack propagation from the aritificial flaw by the 9-m drop tests, by comparing to an observation of a fatigue crack.

Meanwhile, the DCI cask was horizontally dropped onto the mild steel pin from the height of 1-m. As the result, no penetration occurred and the integrity against brittle failure was evaluated using Eq. 2 with strain measurements, etc.

SUMMARY AND CONCLUSION

1. Sufficient fracture toughness data of full scale DCI cask bodies were obtained to evaluate brittle failure and for quality assurance.

2. A brittle failure design criteria of DCI casks was proposed.

3. Integrity of the DCI cask with an artificial flaw of 20-mm in depth that is more than twice as large as the flaw size detectable by the conventional Ultrasonic Test was demonstrated against brittle failure under the 9-m drop test condition at -43°C (230K).

4. Integrity of the DCI cask with a artificial flaw of 83.5-mm in depth was demonstrated against brittle failure under the 9-m drop test condition at -44°C (229K).

5. The proposed brittle failure design criteria was verified for cask applications.

6. Integrity of the DCI cask was demonstrated against penetration and evaluated to be sound against brittle failure under the 1-m puncture test condition at -43°C (230K).

REFERENCES

The Quality Assurance Committee on Ductile Cast Iron Casks *Research on Quality Assurance of Ductile Cast Iron Casks,* CRIEPI Report EL 87001 (1988), and Proc. BAM Seminar of Containers for Radioactive Materials Made from Nodular Cast Iron in Berlin (1987).