Draft ASME Code Case on Ductile Cast Iron for Transport Packaging

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1. Introduction

The current Rules for Construction of “Containment Systems for Storage and Transport Packagings of Spent Nuclear Fuel and High Level Radioactive Material and Waste” of Division 3 in Section III of ASME Code (2001 Edition) does not include ductile cast iron in its list of materials permitted for use. The Rules specify required fracture toughness values of ferritic steel material for nominal wall thickness 5/8 to 12 inches (16 to 305 mm). New rule for ductile cast iron for transport packaging of which wall thickness is greater than 12 inches (305mm) is required.

2. Essence of Proposed Rule

Name of draft code case is “Use of Ductile Cast Iron Conforming to ASTM A 874/A 874M-98 or JIS G 5504-1992 for Transport Containments, Section III, Division 3”. The draft code case is to permit to use ductile cast iron with a wall thickness greater than 12 inches (300 mm) but less than 21 inches (530 mm) conforming to ASTM A 874/A 874M-98 or JIS G 5504-1192, for the construction of transport containments in Section III, Division 3 provided that the following additional requirements are met:

(1) The containment body shall be cast by a single pouring controlled by a casting plan to ensure reproducibility. The casting plan shall be agreed upon between the manufacturer and purchaser.
(2) Design stress intensity values, S_m are listed in Table 1.
(3) Yield strength values, S_y are listed in Table 2 (omitted in this paper).
(4) Ultimate tensile strength values, S_T are listed in Table 3 (omitted in this paper).
(5) For Young’s modulus, use Table 4 (omitted in this paper).
(6) For coefficients of thermal expansion, use Table 5 (omitted in this paper).
(7) For external pressure design, use Figure 1 (omitted in this paper).
(8) For fatigue design, use Figure (omitted in this paper)2.
(9) For Poisson’s ratio, use Table 7 (omitted in this paper).
(10) For thermal conductivity, use Table 6 (omitted in this paper).
(11) For specific heat, use Table 7 (omitted in this paper).
(12) Tensile test specimens shall be taken from each casting and the location shall be representative for the minimum properties.
(13) For fracture toughness requirements, toughness test specimens shall be taken from each containment casting or its excess length part that has the same or equivalent solidification property.
(14) Rapid-load fracture toughness tests shall be performed in accordance with WB-2321.3, except that ASTM E-1820-01 shall be used. A test shall consist of at least four test specimens. The test shall be performed at the lowest service temperature. The lowest service temperature shall not be below -40 ºF [-40 ºC]. The rapid-load fracture toughness value shall satisfy the following inequality at -40 ºF [-40ºC].

(average) $K_{IC,R} - 3\sigma_{SD} \geq 46$ ksi-in$^{1/2}$ [50 MPa-m$^{1/2}$]

where $K_{IC,R}$: Rapid fracture toughness (ksi-in$^{1/2}$ [MPa-m$^{1/2}$])

σ_{SD} : standard deviation (ksi-in$^{1/2}$ [MPa-m$^{1/2}$])

The average value and standard deviation shall be estimated assuming Weibull distribution of the measurements.

(15) For examination of the containment casting, the rule of WB-2571 “Required Examination” is to read as follows: Cast products shall be examined by ultrasonic method. In addition, all cast products shall be examined on all external surfaces and all accessible internal surfaces by either the magnetic and particle or liquid

penetrant method. Machined surfaces, except threaded surfaces, of a cast product shall be examined by either the liquid penetrant or magnetic method after machining.
The rule of WB-2572 “Time of Nondestructive Examination - (a) Ultrasonic Examination” is to read as follows: “Ultrasonic examination shall be performed after machining.”
The rules of WB-2574 “Ultrasonic Examination of Ferritic Steel Castings” shall be also applied.

(16)Castings shall not be repaired by plugging, welding, brazing, impregnation, or any other means.
(17)All other requirements of Section III, Division 3 are met.
(18)This code case number shall be listed in the Design Specification and the Data Report Form for this material.

TABLE 1 DESIGN STRESS INTENSITY VALUES S_m

Minimum Values At Room Temp.		Design Stress Intensity Values, ksi [MPa] Temperature, ºF [ºC]							
S_y ksi [MPa]	S_T ksi [MPa]	-20 to 100 [-29 to 38]	150 [65]	200 [95]	300 [150]	400 [205]	500 [260]	600 [315]	650 [345]
29.0 [200]	43.5 [300]	11.0 [74]	11.0 [74]	10.5 [72]	10.1 [69]	9.9 [68]	9.8 [68]	9.5 [65]	9.2 [63]

S_m: Stress Intensity Value, ksi [MPa]
S_y: minimum yield strength at room temperature, ksi [MPa]
S_T: minimum tensile strength at room temperature, ksi [MPa]
Note: For lower temperature than -20 ºF [-29 ºC], use the values at -20 to 100 ºF [-29 to 38 ºC].

3. Basis of the Proposed Rule

3.1 Design Stress Intensity Values for Ductile Cast Iron

3.1.1 Current ASME Code [1]

a. Ductile cast iron

Ductile cast iron for containment system is not included in the permitted materials specifications of WB-2121 that permits material given in Section II, Part D for Division 1, Class 1 or Division 3 Class TP construction.

b. Code Case N-205

The Code Case N-205, in 1981, permits use of Ductile iron SA-395 (Specification for Ferritic Ductile Iron Pressure-Retaining Castings for Use at Elevated Temperatures) for Class 3 pipe and fittings, conforming to the requirements of Section III, Division 1. The design rule is Design by Formula.

The allowable stress, S, was 12 ksi, where the tensile strength, S_T , and the yield strength, Sy , of the Ductile iron SA 395 was 60 ksi and 40 ksi, respectively. It means that a safety factor of 5 for the tensile strength was used (12 ksi = 60/5 ksi).

For the selection of a proper safety factor, following differences have to be considered:

i) SA-395 allows to take samples from a separate test coupon which could lead to better properties than those from directly taken from casting as required in the present code case.
ii) SA-395 does not require any fracture toughness evaluation as in the present code case.
iii) SA-395 is applicable for Class 3 component, whereas in the present code case Ductile cast iron is used for Class 1 component.

3.1.2 Options in the proposed rule

The design rule of the containment system for packaging for storage and transport of spent fuel is Design by Analysis, as Class 1 components of Section III. The design stress intensity value, Sm, is used for design. The safety factor shall be determined by its class and material of the product as specified in Appendix 1 (for Class 3) and Appendix 2 (for Class 1) in Part D of Section II of the ASME Code, as shown in Table 3.2.1.

Table 3.1.1 Criteria for Establishing Design Stress Intensity Values

Product Material	Class 1	Class 3
Wrought or cast, ferrous and nonferrous	The lowest of 1/3 St or 2/3Sy, etc.	The lowest of 1/3.5 St or 2/3Sy, etc.

Sm: Stress Intensity Value, ksi [MPa]
Sy: specified minimum yield strength at room temperature, ksi [MPa]
St: specified minimum tensile strength at room temperature, ksi [MPa]

There are some options for the design stress intensity values, as follows.

1) Option 1 (safety factor 3): This option complies with the criteria for Class 1.
2) Option 2 (safety factor 3.75): These values of Sm are the lowest of 1/3.75 St or 2/3.75 Sy, based on application of an additional safety factor (1.25) multiplied to the safety factor of 4 for Class 3 pipe and fittings.
3) **Option 3 (safety factor 4): These values of Sm are the lowest of 1/4 St or 2/3 Sy.**
US NRC has already approved this requirement for the storage license of CASTOR V/21 at Surry power station in 1985. This option is proposed for the new rule.
4) Option 4 (safety factor 5): This option complies with the criteria for class 3, but is most unlikely for the proposed rule.

3.2 Fracture Toughness of Ductile Cast Iron with Safety Margin

3.2.1 Fracture toughness requirements in the current ASME Code [1]

Fracture toughness requirements in WB-2300 specify "Required LST-RT_{NDT} Values for Ferritic Steel Material for Containment Vessel Material (Table WB-2331.2-1, for nominal wall thickness 5/8 to 12 inches(16 to 305mm))" and "Required Fracture Toughness Values for Ferritic Steel Material for Containment Vessels Having A Specified Yield Strength of 50 ksi (345 000kPa) or less at 100 F (38C) (Table WB-2331.2-2, for nominal wall thickness of 5/8 to 4 inches (16 to 102mm)).

The above requirements are not applicable to Ductile Cast Iron with a wall thickness greater than 12 and less than 21 inches.

3.2.2 Proposal on fracture toughness

In order to demonstrate the compliance of a packaging made of Ductile Cast iron with the transport regulation (10CFR Part 71, etc.), regulatory drop tests using a full-scale packaging were performed [2].

a. Drop test

A 9-m drop tests of a full scale prototype packaging for shipping spent fuel was performed at -40F (-40C). The full scale prototype packaging had artificial flaw at a location where the maximum tensile stress was expected. The size of the artificial flaw was 3.3 inches (83.5 mm) deep and 20 inches (510 mm) long semi-ellipse shape. The stress intensity factor of the test packaging, K_I was 35.0 ksi-in$^{1/2}$ [38.5 MPa-m$^{1/2}$].

The proposed code case is based on the results of the 9-m drop tests of the full scale prototype packaging for shipping spent fuel at -40 ºF (-40 ºC).

b. Fracture toughness

The Code Case requires fracture toughness that is larger than that of the prototype packaging. The fracture toughness of the test packaging was measured under a stress intensity factor rate being 273 ksi-in$^{1/2}$-s^{-1} [300 MPa-m$^{1/2}$-s^{-1}] that was calculated from the loading rate on the artificial flaw in the packaging at the drop test.

Results are as shown in Table 3.2.1.
The average and standard deviation of the fracture toughness of the prototype packaging are estimated assuming two-parameter Weibull distribution function of the measurements with median rank method to obtain accumulated distribution probabilities as follows.

Table 3.2.1 Fracture Toughness of Prototype Packaging at -40 ºF (-40 ºC)

Fracture toughness, $K_{IC, R}$ ksi-in$^{1/2}$ [MPa-m$^{1/2}$]
89.7 [81.5]
78.8 [71.6]
75.7 [68.8]
77.1 [70.1]

Weibull parameter α=12.3, β=68.0 ksi-in$^{1/2}$ [74.8 MPa-m$^{1/2}$]

(average) $K_{IC, R}$ = 65.2 ksi-in$^{1/2}$ [71.7 MPa-m$^{1/2}$] , σ_{SD} = 6.45 ksi-in$^{1/2}$ [7.09 MPa-m$^{1/2}$]

(average) $K_{IC, R} - 3\sigma_{SD}$ = 45.8 ksi-in$^{1/2}$ [50.4 MPa-m$^{1/2}$] ---------------Eq. 1

Thus, the Code Case requires that ductile cast iron shall satisfy the following inequality.

(average) $K_{IC, R} - 3\sigma_{SD} \geq$ 46 ksi-in$^{1/2}$ [50 MPa-m$^{1/2}$]

A reference fracture toughness of ductile cast iron as a function of temperature is found in literature [3] as shown in Fig. 3.3.1 and below. The reference fracture toughness was obtained by measurements from 12 different castings of ductile cast iron.

For temperature at 32 ºF [0ºC] or under

$K_{IR} = 18.2 + 1.22\, e^{0.0145\,(T_F+256)}$ ksi-in$^{1/2}$ $= 20.0 + 1.34\, e^{0.0261(T_C+160)}$ MPa-m$^{1/2}$ --------------Eq. 2

For temperature above 32 ºF [0ºC]
K_{IR} =98.3 ksi-in$^{1/2}$ [108 MPa-m$^{1/2}$]
where K_{IR} : Reference fracture toughness (ksi-in$^{1/2}$ [MPa-m$^{1/2}$])
T_F: Material temperature during service (ºF)
T_C: Material temperature during service (ºC)

The prototype packaging was intended to be and successfully manufactured so that the fracture toughness of the prototype packaging is equal to the reference fracture toughness, K_{IR}, at -40 ºF (-40 ºC).

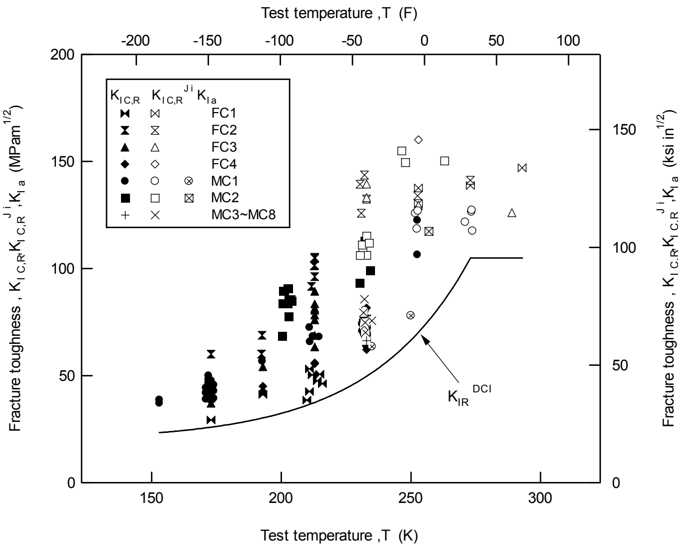

Fig.3.2.1 Fracture toughness of DCI [3]

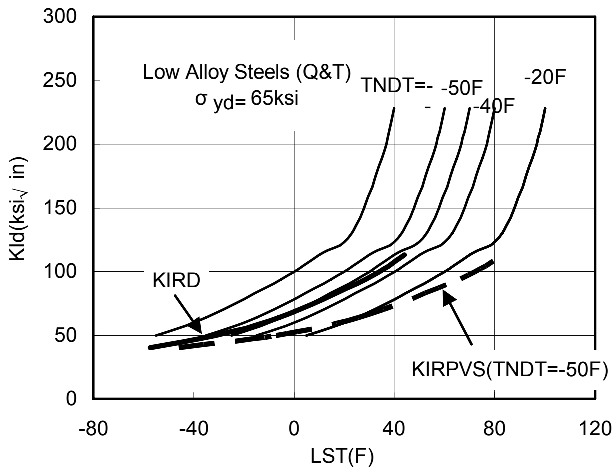

Fig. 3.2.2 Fracture toughness of DCI and those of quenched and tempered low alloy steels [3]

The fracture toughness of Ductile Cast Iron is higher than those of the pressure vessel steels (SA-533 or SA-508 steels) and is equivalent to those of quenched and tempered low alloy steels with T_{NDT} = -50F (227K).

c. Flaw size

The new rule proposes allowable flaw size shall be less than that introduced in the prototype packaging. In order to be consistent with current ASME Code, the new rule proposes to follow the same requirement as specified by WB-2570 (or NB-2571) "Examination and Repair of Statically and Centrifugally Cast Products".
The acceptance standards are as shown below:
Quality Level 4 for thickness greater than 4 in. (102 mm).
Quality Level 1 shall apply for the volume of castings within 1 in. (25 mm) of the surface regardless of the overall thickness.

UT Quality Level	Longest Dimension of Area
1	1.5 in. (38 mm)
4	3.0 in. (76 mm)

The prototype cask had an artificial flaw of 3.2 in. (83.5 mm) deep and 19.2 in. (488 mm) wide on the external surface of the cask.

d. Quality Assurance

The new rule proposes to take tensile test specimen from each cast product that represents the minimum property of the cast product. The new rule also proposes to take fracture toughness test specimen from each cast product or its excess length part having the same or equivalent solidification property as the containment vessel. (WB-2227 and WB-2322.1)

e. Safety Margin

e-1 Flaw size

As demonstrated in the next section, the Fracture Mechanics is applicable to the ductile cast iron. On this basis, the fracture toughness is proportional to (flaw size)$^{1/2}$. The prototype cask had an artificial flaw of 3.2 in. (83.5 mm) deep, whereas every product cask is examined by ultrasonic test so that there is no flaw deeper than 1 in.(25.4 mm). This means that ductile cast iron casks accepted by this code case has a safety margin of $(3.2/1)^{1/2}$ =1.8 in the fracture toughness property against fracture by the regulatory 9 m drop test condition.

e-2 Fracture toughness

As demonstrated in the next section, fracture occurs when the applied stress intensity factor becomes equal to the average value of the fracture toughness of the materials. This means the proposed fracture toughness obtained by Eq. 1 has a safety margin of 71.7/50.4=1.42

e-3 Overall safety margin

From the above discussions, the overall safety margin will be 3.2 X 1.4 = 2.5 against applied stress intensity factor at fracture.

3.3 Applicability of Fracture Mechanics to Ductile Cast Iron

Fracture tests of reduced scale cylindrical models made of ductile cast iron were conducted in order to demonstrate applicability of fracture mechanics to DCI [4]. The, stress intensity factors of the cylindrical models were compared with fracture toughness values obtained from the prolongation of the cylindrical models.

a. Reduced scale model

Nine reduced scale models were cast. Fig. 3.3.1 shows shape and dimensions of the cylindrical models. These models are about one fourth of 100 tone class cask in dimensions. Six of them were used as cast (DCI A). Three of them (DCI B) were subjected to heat treated to obtain lower toughness level than K_{IR}^{DCI}. Then, artificial semi-elliptical surface flaw was machined by arc-machining at the mid of outer surface of each model.

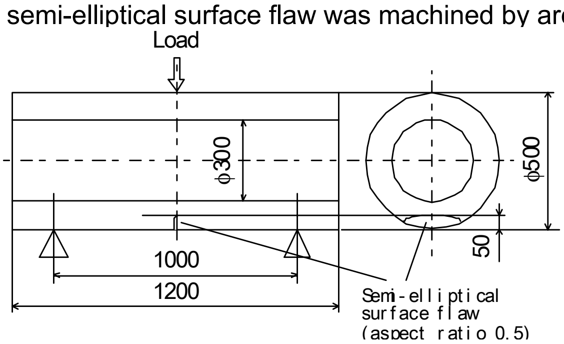

Fig. 3.3.1 Dimensions of reduced scale models (mm)

Table 3.3.1 Results of dynamic fracture toughness tests at 233 K

Material	Weibull parameters α	Weibull parameters β (MPam$^{0.5}$)	Average value $K_{Id,ave}$ (MPam$^{0.5}$)	Standard deviation σ_{SD} (MPam$^{0.5}$)	Lower bound confidential value $K_{Id,ave}-3\sigma_{SD}$ (MPam$^{0.5}$)
DCI A	6.8	126.9	118.5	20.5	57.0
DCI B	13.1	58.6	56.3	5.2	40.7

b. Dynamic fracture toughness

Two inch thick compact tension (2TCT) specimens were extracted from the prolongation of the reduced scale models. Results of the fracture toughness test was summarized and statistical analyzes were performed for the data set obtained at 233 K for each material as shown in Table 3.3.1.

c. Fracture test of reduced scale model

Fracture tests of the reduced scale models were performed by three points bending with loading span 1000 mm. Results the fracture tests were summarized and statistical analyses were performed for the data sets for each model as shown in Table 3.3.2.

Table 3.3.2 Results of fracture tests of reduced scale model at 233 K

Model	Weibull parameters α	Weibull parameters β (MPam$^{0.5}$)	Average value $K_{IF,ave}$ (MPam$^{0.5}$)	Standard deviation σ_{SD} (MPam$^{0.5}$)
DCI A	11.6	118.7	113.6	11.9
DCI B	8.1	62.2	58.6	8.6

d. Comparison of stress intensity factor and fracture toughness

Distribution of the stress intensity factor, K_{IF} , was compared with that of the fracture toughness, K_{Id} , in order to evaluate the applicability of the fracture mechanics to DCI. In both materials, the average values of $K_{IF, ave}$ were approximately equal to those of $K_{Id, ave}$, although the differences were observed in standard deviations.

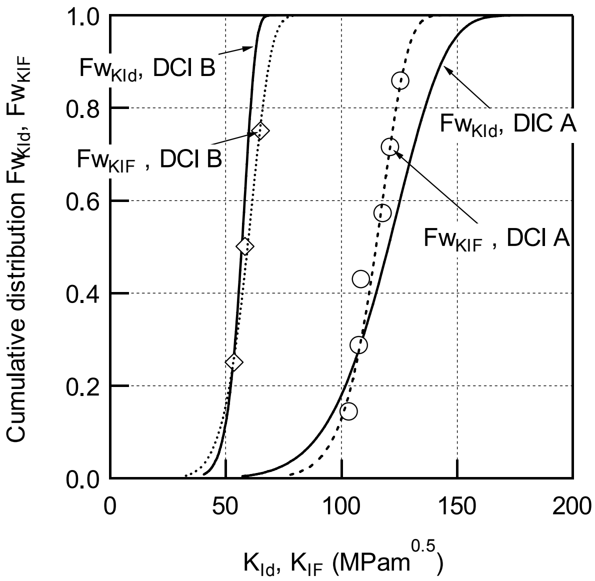

Fig. 3.3.2 Cumulative distributions of fracture toughness, K_{Id}, obtained by 2TCT specimens and the stress intensity factor at fracture, K_{IF}, of reduced scale models

3.4 Reproducibility and Quality Assurance of Ductile Cast Iron Cask

Reproducibility of Ductile Cast Iron is ensured by fixing the casting plan which includes parameters for solidification speed (mold design, etc.) and those for quality control (amount of nodulating agent, inoculating agent, temperature of molten iron, etc.). The casting plan is specified between manufacturer and purchaser. Examples of items of Quality Control executed by a German company and accepted by competent authorities of USA, Germany, etc. are shown below.

Fabrication and accompanying Quality Control

(1) Controlled Fabrication Process
  a. Casting
  b. Cool down
(2) Chemical Analysis during Casting
(3) Pre-machining for smooth surfaces
(4) Extended Visual Examination
(5) Ultra-Sonic Testing
  a.100 % of the cast Volume
  b. different sonic orientations
(6) Samples taken from Bore Holes
  a. Samples taken from region with expected worst properties at the middle of the wall
  b. Chemical Analysis
  c. Mechanical Properties
  d. Metallographic Examination

It was demonstrated in the literature that the minimum properties of the DCI cask were obtained from the middle of the wall thickness in the thickness direction and from the excess length part in the longitudinal direction of the cylinder [5].

3.5 Applicability of Ultrasonic Testing to Detect Defect in Ductile Cast Iron

3.6.1 Applicability
According to the literature [6], attenuation of ultrasonic velocity in cast irons depends on the frequency of the ultrasonic wave, types of graphite, etc. Ultrasonic velocity attenuates at larger frequency in gray cast irons. As the graphite becomes more flake-like, the attenuation increases. At a frequency of 5 MHz, the attenuation ranges from 2 to 22 dB/in for gray iron, whereas the attenuation is negligible for ductile cast iron. The ultrasonic examination (ASME SA-609/SA-609M : STANDARD PRACTICE FOR CASTINGS, CARBON, LOW-ALLOY, AND MARTENSITIC STAINLES STEEL, ULTRASONIC EXAMINATION THEREOF) to detect flaws is now routinely used to ductile cast irons.

3.6.2 Acceptance Standard of Defect
The WB-2574.1(or NB-2574.1) stipulates Acceptance Standards as follows. Requirements for Quality Level 4 of SA-609 shall apply for thickness greater than 4 in. (102 mm), which is the case for Ductile Cast Iron for Transport Packaging. In addition, areas giving the Amplitude Reference Line with any dimension longer than the following numbers are unacceptable.

UT Quality Level	Longest Dimension of Area
1	1.5 in. (38 mm)
4	3.0 in. (76 mm)

Quality Level 1 shall apply for the volume of castings within 1 in. (25 mm) of the surface regardless of the overall thickness.

3.6.3 Demonstration of UT to DCI
The applicability and reliability of the ultrasonic examination to the ductile cast iron has been demonstrated and investigated as shown in the following tables and figure from the literature [7][8]. It was statistically concluded (with 99% probability) that the detectable size of defects by UT in the ductile cast iron is 0.6 inch [17mm] or less.

3.6 Experience and Fabrication of Ductile Cast Iron Casks for Transport/storage Containments

There are accumulative experiences of DCI casks in service in the world as follows.
In 1983, the first loading world-wide was made with CASTOR ® Ic-DIORIT in Switzerland.
In 1985, the first loading in USA was made with CASTOR ® V/21 at INEEL and the cask and the spent fuel were examined in 1999. The result was reported in NUREG Report CR-6745 as follows:
"There is no evidence of degradation of the CASTOR ® V/21 cask systems important to safety from the time of initial loading of the cask in 1985 up to the time of testing in 1999."
By 2003, more than 700 casks for spent fuel and high level radioactive wastes were deployed at 22 sites in the world. At Surry power station in USA, 25 CASTOR ® V/21 and 1 CASTOR ® X/33 have been loaded and stored.


Fig. 3.6.1 DCI casks in service at Surry, USA

3.7 Drop tests of Ductile Cast Iron Casks without Impact Limiters

There are more reports that support this proposed rule. Table 3.7.1 summarizes main feature of drop tests of DCI casks without impact limiters performed in USA, Germany and Japan. The role of the impact limiters is to reduce applied stress to the casks subjected to drop tests, thereby to reduce the stress intensity factor. Without impact limiters, the stress intensity factor may exceed the fracture toughness of the material of the cask depending on the drop height or other test conditions.
The results show no brittle fracture through the wall occurred by drop tests of DCI casks without impact limiters even from the height of 18 m, whereas the regulations require drop test with impact limiters from the height of 9 m. The cracks were extended when the applied stress intensity factor exceeded the fracture toughness of the material,

which demonstrated the applicability of fracture mechanics. It is noted that the cracks were arrested in the casks under the drop test conditions.

Table 3.7.1 Main feature of drop tests of DCI casks without impact limiters

item	SANDIA Report [9]	BAM Report [10]	CRIEPI Report [11]
DCI cask weight (tons)	5.4	21.8	99.3, 92.1 and 91.8
DCI cask length x diameter (mm)	1364 x 1059	3475 x 1155	5235 x 2150, 5270 x 2500 and 5377 x 2040
DCI cask wall thickness (mm)	213	260	355, 310 and 310
Artificial flaw depth (mm)	19-76	120	None
Artificial flaw length (mm)	Six times the depth	704	None
Drop test height (m)	9 and 18	2.3, 3.5 and 14	1.5, 5.0, 7.5 and 17.0
Drop test target	Steel saddle on unyielding target	Rails on unyielding target	Reinforced concrete
Test Temperature (ºC)	-29	Ambient temperature	Ambient temperature
$K_{IC,R}$ of DCI (MPa-m$^{1/2}$)	74.8 at -29 ºC	92-119 at ambient temp.	126-147 at 20 ºC
K_I by the drop test (MPa-m$^{1/2}$)	50.6-83.6	41-118	Not applicable
Observation of brittle fracture	No crack extension through the wall. Crack extension of 0.28 mm was observed after the 18 m drop test.	No brittle fracture. Small fissures were observed between the crack tip and the first nodular graphite after the 14 m drop test.	No crack initiation. No brittle fracture.

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