Recommendations for Protecting Against Failure by Brittle Fracture

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Category II and III Ferritic Steel Shipping Containers
with Wall Thickness Greater than Four Inches

Prepared by
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Lawrence Livermore National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Recommendations for Protecting Against Failure by Brittle Fracture

Category II and III Ferritic Steel Shipping Containers with Wall Thickness Greater than Four Inches

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ABSTRACT

This report provides criteria for selecting ferritic steels that would prevent brittle fracture in Category II and III shipping containers with wall thickness greater than four inches. These methods are extensions of those previously used for Category II and III containers with wall thickness less than four inches and Category I containers with wall thickness greater than four inches.

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EXECUTIVE SUMMARY

This report extends the fracture toughness criterion for preventing brittle fracture to Category II and III shipping containers with wall thickness greater than four inches but less than twelve inches. It is based upon the fracture arrest concept applied to Category II shipping containers with wall thickness less than four inches. Extension of the fracture arrest concept for thickness greater than four inches requires an extrapolation of the fracture toughness reference curve in a manner similar to that used for Category I shipping containers with wall thickness greater than four inches but less than twelve inches.

As with Category II containers with wall thickness less than four inches, the ability of impact limiters to reduce forces below the dynamic levels used for Category I are exploited. This results in a temperature shift of the dynamic loading fracture toughness reference curve that reflects not only reduction in impact levels but, in addition, the static yield strength of the ferritic steel. Analysis is provided for constructing fracture toughness reference curves for any combination of impact load level (in terms of dynamic strain rate) and yield strength. Curves that may be used to estimate the required nil-ductility transition temperature of the ferritic steel are presented for the specific dynamic strain rate of 0.1 in/in/sec.

In the case of Category III containers with wall thickness greater than four inches, reducing the plane strain relaxation factor in an attempt to reflect the lower safety requirements is not practical and, for this case, plane strain constraint must be presumed. This means that linear elastic fracture mechanics is a viable criterion and may be used as a criterion for the prevention of brittle fracture. Alternatively, provided that the ferritic steel has only minor defects typical of good fabrication practice, the fracture toughness reference curve associated with $\beta = 0.4$ may be used to estimate the required nil-ductility transition temperature of the ferritic steel.

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NOMENCLATURE

A	Temperature relative to the nil ductility transition temperature
AAR	Association of American Railroads
B	Section thickness
β	A dimensionless parameter = $\frac{1}{B} \left(\frac{K_{ID}}{\sigma_{yd}} \right)^2$
CVN, C_v	Charpy V- notch test or the test results
DT	Dynamic tear test
E	Elastic modulus of the ferritic steel
$\dot{\epsilon}$	Strain rate (units in/in/sec)
K_I	Stress intensity factor
K_{IC}	Critical value of K_I for static loading rates. When K_{IC} is exceeded, fracture occurs
K_{ID}	Critical value of K_I for dynamic loading rates
$K_{I(t)}$	Critical value of K_I for intermediate loading rates
LST	Lowest service temperature (lowest metal temperature)
NDTT	Nil Ductility Transition Temperature
σ_{ys}	Yield strength for a static loading rate. This is considered the ASTM minimum yield for a specific steel (units ksi)
σ_{yd}	Yield strength for dynamic loading rate $= \sigma_{ys} + 30$ ksi for steels with $\sigma_{ys} < 60$ ksi $= \sigma_{ys} + 15$ ksi for steels with $\sigma_{ys} > 70$ ksi $= \sigma_{ys} + 20$ ksi for steels with $60 \text{ ksi} < \sigma_{ys} < 70$ ksi
σ_{yD}	Yield strength for the applicable temperature and strain rate
t	Loading time
T	Temperature
T_{Shift}	Shift of the fracture toughness reference curve due to impact loading

Recommendations for Protecting Against Failure by Brittle Fracture

Category II and III Ferritic Steel Shipping Containers with Wall Thickness Greater than Four Inches

1.0 INTRODUCTION

1.1 Objective

The object of this report is to provide criteria for selecting ferritic steels that would prevent brittle fracture in Category II and III shipping containers with wall thickness greater than four inches but less than twelve inches.

1.2 Background

1.2.1 Thickness up to Four Inches

Criteria for selecting ferritic steels that would prevent brittle fracture in Category I, II and III shipping containers with wall thickness up to four inches were recommended in NUREG/CR-1815 in 1981 (Ref. 1) and are reflected in U.S. NRC Regulatory Guide 7.11 (Ref. 2). For Category I containers with wall thickness up to a maximum of four inches, ferritic steels were required to be tough enough to stop a growing crack initiated at a defect. In the case of Category II containers with wall thickness up to four inches, ferritic steels were required to be tough enough to prevent fracture initiation under dynamic load conditions. The chosen approach uses a less conservative version of the fracture arrest criterion to assure that fracture initiation would not occur. Additional rules were provided for Category II that would reduce the toughness requirement where impact limiters were shown to be effective in reducing the dynamic loads. Toughness requirements are established by exploiting the temperature shifts of fracture toughness reference curves which reflect both the reduction of impact strain rate levels and the room temperature quasi-static yield strength of candidate ferritic steels.

For Category III containers with wall thickness up to four inches, fracture toughness had to be sufficient to prevent initiation of the fracture at unavoidable minor defects typical of good fabrication processes. This condition is fulfilled for Category III by exercising good engineering practice and showing that toughness levels as expressed by NDTT, DT and C_v are above specified minima.

1.2.2 Thickness Greater Than Four Inches

The criterion for preventing brittle fracture in ferritic steel shipping containers was extended to thicknesses greater than four inches in NUREG/CR-3826 in 1984 (Ref. 3) and subsequently published as U.S. NRC Regulatory Guide 7.12 (Ref. 4). These documents only considered Category I shipping containers. The recommendations were based upon an extension of the fracture arrest approach described in NUREG/CR-1815 for wall thickness up to four inches. The extension beyond four inches could only be accomplished by a judicious extrapolation of the Pellini fracture toughness reference curve beyond the NDTT plus 100°F limit. This extrapolation was accomplished by extending the Pellini curve using an inverse function asymptotic to NDTT plus 140°F. This is based on the rationale that as the temperature increases beyond the NDTT, the fracture mode changes from primarily cleavage to increasing levels of fibrous or ductile fracture. At the temperature associated with upper-shelf behavior, cleavage is entirely suppressed and brittle fracture cannot occur. That is, a crack can no longer advance catastrophically as a result of crack extension. This behavior is assumed to occur at the limiting temperature assigned to the asymptote of the extrapolated curve.

2.0 RECOMMENDATIONS

2.1 Category II

The criterion for selecting ferritic steels to prevent brittle fracture in Category II containers with wall thickness greater than four inches is similar to that for Category I containers with wall thickness greater than four inches. It will be necessary to extrapolate the Pellini fracture toughness reference curve to accommodate thickness greater than four inches. This extrapolation is done for each of the shifted curves that correspond to the yield strength range of the steel. Equations are developed to describe the shifted fracture toughness curves based upon the temperature shift formulas developed by Barsom and Rolfe (Ref. 5), and assuming an exponential function up to the limit of the Pellini curve. Inverse functions describing the variation of K_{ID}/σ_{yd} with T-NDTT beyond the limit of the Pellini curve are generated such that their coordinates and slope will be identical to the exponential function where the extrapolation begins. The method for determining the required NDTT for the ferritic steel will be the same as described in Figure 7 on page 19 of NUREG/CR-1815.

The recommended criterion for Category II ferritic steels greater than four inches thick is that the NDTT of the material used must be less than the maximum temperature determined from Figure 1. The NDTT temperature of the steel may be determined either by measuring it in accordance with ASTM E-208 or by subtracting 50°F from the midpoint of the 5/8-inch DT energy transition curve measured according to ASTM E-604.

The details of the analysis for generating the K_{ID}/σ_{yd} curves for the reduced loading rates are presented in Appendix A. To determine the required NDTT from Figure 1, start with the design thickness and proceed vertically to the $\beta = 0.6$ curve, from there horizontally to the $K_{I(t)}/\sigma_{yd}$ curve corresponding to the appropriate yield strength, and from that point vertically to the A scale on the horizontal axis. The value of the maximum allowable NDTT is then equal to the lowest service temperature minus the value obtained for A (i.e., $NDTT = LST - A$). The

example shown in Figure 2 relates a value of $A = 36^\circ\text{F}$ to a plate thickness of 6 inches for a yield strength of 60 ksi. While the reduced loading rate impact curves in Figure 1 apply to both a strain rate of 0.1 in/in/sec and yield strengths between 30 and 100 ksi in 10 ksi increments, similar curves may be drawn for any combination of strain rate and yield strength (within the limits of applicability of the basic formulas) by applying the equations explained in Appendix A.

Figures 3 and 4 illustrate the effect of changing the strain rates to 0.5 and 1.0 in/in/sec, respectively, which shows that the maximum allowable NDTT requirements increase with increased strain rate.

2.2 Category III

According to NUREG/CR-1815, the level of safety required for Category III is less than that of Category II insofar as fracture toughness need only be sufficient to prevent initiation at minor defects typical of good engineering practice. High on the list of qualifying procedures for thicknesses up to four inches is the recommendation to use normalized steels made to "fine grain practice" and recognize that the NDTT of the steel need only be less than 10°F. For thickness greater than four inches, a reduced level of safety for Category III relative to Categories I and II would suggest using a still lower value of β , say 0.4, compared to 0.6 for Category II and 1.0 for Category I. However, a value of 0.4 implies a condition of plane strain constraint for through and edge cracks resulting in a condition where linear elastic fracture mechanics (LEFM) is a valid methodology. Fracture arrest is not possible under these circumstances and catastrophic fracture could only be avoided by preventing fracture initiation. Thus, Category III could invoke a fracture initiation criterion. The level of toughness, however, need only be high enough to obviate initiation for pre-existing flaw sizes normally expected to remain in a finished product after the appropriate level of inspection is performed. This level of toughness can be calculated based upon (1) flaw sizes allowed by whatever specification controls the inspection procedure and (2) a conservative level of stress.

A yield-strength level of stress is recommended since it cannot be exceeded without invalidating the LEFM approach. The use of LEFM to assure prevention of brittle fracture requires, in addition to the assumption of yield strength, a convincing demonstration that the flaw sizes assumed are the maximum that can be present and that the fracture toughness in terms of critical stress intensity are derived from a well-developed data base.

An alternative to the use of LEFM analysis is to use a design chart similar to the one recommended for Category II but having a value of $\beta = 0.4$. This design chart is also shown in Figure 1. In this case, it would be permissible to use the curve corresponding to the yield strength of the material being contemplated. An example of the use of the design chart for Category III is shown in Figure 5 where a value of $A = 16^\circ\text{F}$ is associated with a thickness of 8 inches and a yield strength of 40 ksi. The applicant has the choice of selecting materials from the requirement defined by Figure 1 or opting for an LEFM approach.

2.3 Strain Rate Considerations

The validity of the shifted fracture toughness reference curves reflects the circumstances under which the tests leading to the temperature shift equations were performed. For the dynamic tests, strain rate was calculated for a point on the elastic-plastic boundary at the crack tip in accordance with the following equation (Refs. 8 and 9):

$$\dot{\epsilon} = \frac{2\sigma_{yD}}{tE}$$

where σ_{yD} = yield strength for the applicable temperature and strain rate

t = loading time

E = elastic modulus of the ferritic steel

In practice, the strain rate resulting from impact loads in the containment must be determined to demonstrate that it is not greater than that for which the fracture toughness reference curves were drawn. The curves provided in this report are applicable for a strain rate not exceeding 0.1 in/in/sec. If the impact strain rate as defined in the above equation is greater than 0.1, then a set of curves applicable to the higher strain rate must be used. Rules for generating such curves are provided in Appendix A.

The yield strengths for dynamic loading conditions may be approximated as follows:

$$\sigma_{yD} = \sigma_{ys} + 30 \text{ ksi for steel with } \sigma_{ys} < 60 \text{ ksi}$$

$$\sigma_{yD} = \sigma_{ys} + 20 \text{ ksi for steel with } 60 \text{ ksi} < \sigma_{ys} < 70 \text{ ksi}$$

$$\sigma_{yD} = \sigma_{ys} + 15 \text{ ksi for steel with } \sigma_{ys} > 70 \text{ ksi}$$

Alternatively, values for σ_{yD} for ferritic steels under any combination of temperatures and strain rate conditions may be evaluated using the methods proposed by Bennett and Sinclair (Ref. 10).

The loading time is the time required for the velocity of the containment under accident conditions to reduce to zero after impact. This may be approximated by dividing the velocity at impact by the deceleration afforded by the impact limiter.

Figure 1. Design chart for Category II and III fracture critical components and $\dot{\epsilon} = 0.1$ in/in/sec

Figure 2. Illustrative Example for Category II fracture critical components with $\dot{\epsilon} = 0.1 \text{ in/in/sec}$

2.0 Recommendations

Figure 3. Design chart for Category II fracture critical components and $\dot{\epsilon} = 0.5 \text{ in/in/sec}$

Figure 4. Design chart for Category II fracture critical components and $\dot{\epsilon} = 1.0 \text{ in/in/sec}$

Figure 5. Illustrative example for Category III fracture critical components with $\dot{\epsilon} = 0.1 \text{ in/in/sec}$

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APPENDIX A: TECHNICAL BASIS

APPENDIX A: TECHNICAL BASIS

A fracture toughness reference curve for a ferritic steel under dynamic loading (approximately 10 in/in/sec.) can be drawn by shifting the experimental curve developed for quasi-static conditions (K_{IC}) in accordance with the following equation suggested by Barsom and Rolfe :

$$T_{\text{shift}} = 215 - 1.5 \sigma_{ys} \quad (1A)$$

Where σ_{ys} is the room temperature static yield strength in ksi and the temperature is in degrees F. Equation (1A) is valid for a yield strength range between 36 and 140 ksi, with the shifts virtually zero for yield strengths greater than 140 ksi.

For intermediate strain rates from 0.001 to 10 in/in/sec, and for steels having yield strengths of less than 140 ksi, Barsom and Rolfe further suggest the equation:

$$T_{\text{shift}} = (150 - \sigma_{ys})(\dot{\epsilon})^{0.17} \quad (2A)$$

where the strain rate, $\dot{\epsilon}$, pertains to the rate at the crack tip.

The temperature shifts described by equations (1A) and (2A) are illustrated in Figure 1A.

Unlike the shift from K_{IC} to K_{ID} contemplated by Barsom and Rolfe, NUREG/CR-1815 describes a shift from K_{ID} to reference curves reflecting lower strain rates. This follows the practice of the Association of American Railroads (AAR) reported in their "Manual of Engineering Procedures for Fracture Safe Design" (Ref. 6). This document recommends a design reference temperature shift from dynamic (K_{ID}) to intermediate ($K_{I(t)}$) loading of -70°F for steels having a yield strength range of 36 to 70 ksi and a corresponding temperature shift of -30°F for steels having a yield strength range of 80 to 120 ksi. NUREG/CR-1815 uses these same two temperature shifts but for different yield strength ranges; a temperature shift of -70°F for steels having yield strengths less than 60 ksi and a temperature shift of -30°F for steels having yield strengths between 60 and 100 ksi. This difference between the AAR Manual and

NUREG/CR-1815, neither of which provides supporting evidence for these recommendations, made it necessary to invoke the Barsom and Rolfe equations (1A) and (2A) for determining the appropriate temperature shifts.

Following the procedure in both the AAR Manual and NUREG-CR/1815 in describing temperature shifts from the K_{ID} reference curve, such a temperature shift may be expressed by the difference between equations (1A) and (2A) or

$$T_{\text{shift}} = -[(215 - 1.5\sigma_{ys}) - (150 - \sigma_{ys})(\dot{\epsilon})^{0.17}] \quad (3A)$$

Assuming, as was done in NUREG/CR-1815, that impact limiters reduce the loading rate on the order of 0.1 in/in/sec, equation (3A) becomes

$$T_{\text{shift}} = -(113.6 - 0.82\sigma_{ys}) \quad (4A)$$

measured from the K_{ID} fracture toughness reference curve as shown in Figure 1A.

For a room temperature yield strength of 60 ksi, the temperature shift according to equation (4A) would be 64°F. For 100 ksi, the corresponding temperature shift would be -32°F. The fracture toughness reference curves corresponding to these yield strength levels, and for a strain rate of 0.1 in/in/sec, are shown in Figure 2A. Note that these numbers closely correspond to the temperature shifts of -70°F and -30°F used for the Category II curves shown in Figure 7 of NUREG/CR-1815 and which are based on AAR guidelines.

In developing Category II rules for thicknesses greater than four inches, it is necessary to extrapolate these curves to accommodate these larger thicknesses. Following the procedure used for Category I, an extrapolation based on an inverse function asymptotic to $T_{\text{NDTT}} = 140^\circ\text{F}$ is used. Up to $T_{\text{NDTT}} = 100^\circ\text{F}$ —the limit of the Pellini curve—the reference fracture toughness curve is assumed to be an exponential function. What is required for each of the shifted curves is an extrapolation using an inverse function such that the coordinates and slope of

the two curves are identical at the reference temperature where the extrapolation begins.

We start with the equation for the exponential function used for Category I (Ref. 7) and duplicated for reference in Figure 3A.

$$\frac{K_{ID}}{\sigma_{yd}} = 0.39 + 0.2 \text{EXP}[0.02(T - \text{NDTT})] \quad (T - \text{NDTT} \leq 100^\circ \text{F})$$

For Category I the exponential curve was extrapolated using the inverse function

$$\frac{K_{ID}}{\sigma_{yd}} = 0.39 + \frac{60}{140 - (T - \text{NDTT})}$$

The two curves were drawn such that they have the same fracture toughness at $T - \text{NDTT} = 100^\circ \text{F}$ and approximately the same slope at this point. We use the same procedure to generate the extrapolated fracture toughness curve that undergoes a temperature shift.

Substituting A for $T - \text{NDTT}$, and generalizing the fracture toughness reference curve for any temperature shift, we have

$$\frac{K_{ID}}{\sigma_{yd}} = 0.39 + 0.2 \text{EXP}[0.02(A - T_{\text{Shift}})] \quad (5A)$$

where T_{Shift} is defined by equation (3A), generally, and equation (4A) specifically for $\dot{\epsilon} = 0.1 \text{ sec}^{-1}$

The derivative of equation (5A) is

$$\frac{d}{dA} \left(\frac{K_{ID}}{\sigma_{yd}} \right)_{\text{EXP}} = 0.04 \text{EXP}[0.02(A - T_{\text{Shift}})] \quad (6A)$$

For the inverse function, the following expression is assumed

$$\left(\frac{K_{ID}}{\sigma_{yd}} \right)_{\text{INV}} = a + \frac{b}{140 - A} \quad (7A)$$

Where a and b are arbitrary constants. The derivative of equation (7A) is

$$\frac{d}{dA} \left(\frac{K_{ID}}{\sigma_{yd}} \right)_{\text{INV}} = \frac{b}{(140 - A)^2} \quad (8A)$$

Equating expressions (6A) and (8A) for $A = 100 + T_{\text{Shift}}$

$$0.04 \text{EXP}[0.02(100 + T_{\text{Shift}} - T_{\text{Shift}})] = \frac{b}{(140 - 100 - T_{\text{Shift}})^2} \quad (9A)$$

from which

$$b = 0.03 (40 - T_{\text{Shift}})^2 \quad (10A)$$

Also, for all cases where $A = 100 + T_{\text{Shift}}$, equation (6A) yields a constant of

$$\left(\frac{K_{ID}}{\sigma_{yd}} \right)_{100 + T_{\text{Shift}}} = 1.87 \quad (11A)$$

which can be used to evaluate the constant, a , in equation (7A) once b is determined from equation (10A). Thus,

$$a = 1.87 - \frac{b}{40 - T_{\text{Shift}}} \quad (12A)$$

The complete fracture toughness reference curves for each temperature shift may now be plotted using equation (5A) for $A \leq 100^\circ \text{F}$ and equation (7A) for $A > 100^\circ \text{F}$.

Illustrative Example

Suppose we wish to define a shifted fracture reference curve for a strain rate of 0.1 and a yield strength of 50 ksi.

We determine the temperature shift first from equation (4A)

$$T_{\text{Shift}} = -(113.6 - 0.82 \times 50) = -73^\circ \text{F}$$

This value is used in equation (5A) to immediately establish the exponential portion of the shifted curve

$$\frac{K_{ID}}{\sigma_{yd}} = 0.39 + 0.2 \text{EXP}[0.02(A + 73)]$$

For the inverse function, we first determine the constant b from equation (10A)

$$b = 0.03(40 + 73)^2 = 383$$

From equation (7A),

$$\frac{K_{ID}}{\sigma_{yd}} = 1.87$$

at the junction of the two portions of the curve,
so that

$$a = 1.87 - \frac{383}{40 - (-73)} = -1.52$$

For the inverse portion of the fracture toughness
curve (7A) yields

$$\frac{K_{ID}}{\sigma_{yd}} = -1.5 + \frac{383}{140 - A}$$

Where $A = 100 + T_{Shift}$

Using this method, curves were developed for $\dot{\epsilon}$
= 0.1 for a range of static loading yield
strengths, as shown in Figure 1.

Figure 1A Barsom and Rolfe temperature shifts as a function of yield strength and strain rate

Figure 2A Temperature shifts from dynamic fracture toughness reference curves for $\dot{\epsilon} = 10^{-1} \text{ in/in/sec}$ and for two levels of yield strength

Figure 3A Extrapolated fracture toughness reference curve for Category I shipping containers greater than 4-inches thick

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT (200 words or less)

This report provides criteria for selecting ferritic steels that would prevent brittle fracture in Category II and III shipping containers with wall thickness greater than four inches. These methods are extensions of those previously used for Category II and III containers with wall thickness less than four inches and Category I containers with wall thickness greater than four inches.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

brittle fracture, containers, ferritic steels

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