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Draft Fracture Mechanics Code Case for American Society of Mechanical Engineers NUPACK Rules

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1. Introduction

The containment boundaries of most spent-fuel casks certified for use in the United States by the Nuclear Regulatory Commission are constructed with stainless steel, a material that is ductile in an engineering sense at all temperatures and for which, therefore, fracture mechanics principles are not relevant for the containment application. Ferritic materials may fail in a nonductile manner at sufficiently low temperatures, so fracture mechanics principles may be applied to preclude nonductile fracture.

Because of the need to transport and store spent nuclear fuel safely in all types of climatic conditions, these vessels have regulatory lowest service temperatures that range down to -40°C (-40°F) for transport application. Such low service temperatures represent a severe challenge in terms of fracture toughness to many ferritic materials. Linear-elastic and elastic-plastic fracture mechanics principles provide a methodology for evaluating ferritic materials under such conditions.

Circa 1985, the American Society of Mechanical Engineers (ASME) Section III, Division 3 Subgroup on Containment Systems for Spent Fuel and High-Level Waste Transport Packagings (NUPACK) developed three alternatives for evaluating the potential for nonductile fracture in transport cask containment boundaries. All three were included in some form in WB-2331.2 “Acceptance Standards for Ferritic Steel Material for Containment Vessels” of the NUPACK rules. These are the paragraphs in NUPACK that provide for acceptance of containment boundary material on the basis of “fracture toughness” properties (variously defined).

One of the three alternatives represents an extremely conservative approach that is essentially identical to that embodied in U.S. Nuclear Regulatory Commission Regulatory Guides [1, 2]. These Guides address the potential for nonductile fracture of transport cask containment boundaries constructed of ferritic steel with wall thickness either less than or equal to [1], or greater than [2], four inches. A common basis for ensuring adequate “fracture toughness” of a material is that of a thickness-dependent difference between the nil-ductility transition temperature of the material (T_{NDT}) and the LST defined for the containment boundary. Such a basis is used in the NRC Regulatory Guides and NUPACK Table WB-2331.2.1 (Table 1). Other approaches (e.g., fracture mechanics methodology) require a greater degree of material testing or design analysis, but with a concomitant decrease in conservatism.

The second of the three alternatives is based on the measured fracture toughness of the material, at an appropriate loading rate, at the lowest service temperature (LST). Table WB-2331.2-2 in NUPACK (Table 2) provides these alternative requirements.

The third alternative in WB-2331.2(b)(2)(a) states “Rules for fracture toughness requirements based on fracture mechanics methodology are *in preparation*.” [italics added]

A Section III Division 3 Nuclear Code Case was submitted to Subgroup on Containment Systems for Spent Fuel and High-level Waste Transport Packagings (NUPACK) that contains the alternative rules for the unresolved “fracture mechanics methodology” called for in WB-2331.2(b)(2)(a). This paper provides a discussion of the Code Case. An overview of existing fracture mechanics methodologies within existing ASME Code is provided.

The fracture mechanics methodology alternative has a long history of application in the ASME Code Section III, Division 1 and Section XI. The approach has been found to be acceptable by regulatory authorities for many safety-related applications, including demonstration of fitness for continued service of embrittled reactor pressure vessels. This same approach has also been included as one of the three options for the revised International Atomic Energy Agency (IAEA) Safety Series documents that provide requirements for radioactive material (RAM) transport packagings [3].

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The fracture mechanics approach has three important variables: 1) design, or applied, stress, 2) the flaw size in the structure, and 3) *fracture toughness*, a material property, just as is yield strength, determined by means of test specifications (e.g., ASTM [4]). Fracture mechanics methodology deterministically quantifies the critical combination of these three variables [5].

Table 1. Required LST-RT_{NDT} Values for Ferritic Steel Material for Containment Vessel Material (ASME NUPACK Table WB-2331.2-1).

Nominal Wall thickness		A = LST - RT_{NDT}	
in.	mm	°F	°C
5/8	16	25	14
1	25	45	25
2	51	75	42
3	76	90	50
4	102	103	57
8	203	115	64
12	305	120	67

Table 2. Required Fracture Toughness Values for Ferritic Steel Material for Containment Vessels Having a Specified Yield Strength of 50 ksi (345000 kPa) or Less at 100°F (38°C) (ASME NUPACK Table WB-2331.2-2).

Nominal Wall thickness		Rapid-load Fracture Toughness	
in.	mm	ksi√in.	kPa√mm
5/8	16	50	55000
1	25	64	70000
2	51	94	103000
3	76	113	124000
4	102	130	143000

2. Draft ASME Code Case Based Upon Fracture Mechanics Principles

A rational reference flaw / material [fracture toughness] acceptance approach consists of the following three elements:

- A *reference flaw* is selected with a sufficient degree of conservatism to preclude the need to perform crack growth calculations for load cycling or environmental considerations. The reference flaw depth in the Code Case would be identical to that prescribed in Appendix K-2300 of Section XI for Level C and D loadings -- 10% of the wall thickness.
- The *applied stresses* may be assumed to be primary membrane stresses at some fraction of yield strength levels for conservatism or, as in the Code Case, the calculated stresses may be used for the purpose of computing the applied (fracture mechanics) stress intensity following the approach in Appendix K-5210.
- The allowable material *fracture toughness* would be based on actual fracture toughness data obtained using ASTM test specifications to measure the material fracture toughness. Alternatively, a lower bound Appendix G "K_{IR}" curve or lower-shelf fracture toughness values may be used.

A draft Code Case inquiry, "Use of Fracture Mechanics for the Design of Confinement or Containment Components for Nuclear Material Casks"[1], was submitted to ASME NUPACK in November 2000 and a ballot was taken for acceptance of the Code Case of the NUPACK members May 2001. The ballot passed, but substantial negative votes and comments placed the Code Case on hold until resolved. (In addition, the Code Case has been inactive due to major rewrite of the entire NUPACK rules, which has occupied the focus of the membership.)

This Code Case initiates an attempt to rectify the open issue of ASME Section III, Division 3 WB-2331.2(b)(2)(a): "*Rules for fracture toughness requirements based on fracture mechanics methodology are in preparation*." The Code Case provides requirements for applying fracture mechanics principles for the prevention of nonductile failure and directs the reader to fracture mechanics-based procedures within Appendices G and R of Section III, Division 1 and Appendix A and, in particular, Appendix K in Section XI, Division 1.

The Reply to the Code Case Inquiry is based upon existing procedures within ASME Code. The Code Case requires determination of 1) a reference flaw, 2) the applied stress intensity based upon loads applied to the containment boundary, and 3) the fracture toughness, K_{Ic}, (or reference material stress intensity factor, K_{IR}) of the containment boundary material.

DRAFT **Case N-XXXX**

Use of Fracture Mechanics for the Design of Confinement or Containment Components for Nuclear Material Casks

Section III, Division 3

Inquiry: What requirements and pertinent sections of the ASME Code may be used for evaluation against nonductile fracture of confinement or containment components for nuclear material casks?

Reply: It is the opinion of the Committee that existing requirements and guidance for acceptability for protection against nonductile fracture are contained in 1) Article NB-3211(d)(1) and Article NC-3124 [Section III, Division 1], which refer to Nonmandatory Appendix G, 2) Article NC-2331 [Section III, Division 1], which refers to Nonmandatory Appendix R, and 3) Nonmandatory Appendices A and K of Section XI, Division 1.

It is also the opinion of the Committee that protection against nonductile fracture for Levels C and D loadings can be met through the alternative requirements listed below:

(a) The reference material stress intensity factors, K_{IR}, are given in FIG. G-2210-1. Alternative fracture toughness values may be determined through testing as defined in ASTM E 1820-96, *Standard Test Method for Measurement of Fracture Toughness*, or other ASTM methods noted in ASTM E 1820-96. This ASTM test method covers the determination of the fracture toughness parameters, *K*, *J*, and CTOD of metallic materials.

(b) The reference flaw used to evaluate acceptability against nonductile fracture shall be sized according to Section XI, Division 1, Nonmandatory Appendix K, Articles K-2300 and K-2400, except that the flaw shall be assumed to lie in a plane normal to the direction of the maximum applied stress.

(c) The stress intensity factor, K_I, and the applied J-integral, J_I, shall be calculated in accordance with Section XI, Division 1, Nonmandatory Appendix K, Article K-5210, except that the calculation of K_I shall also include stresses due to mechanical loads such as impact.

(d) The applied J-Integral, J_I, shall meet the requirements of Section XI, Division 1, Nonmandatory Appendix K, Article K-5220(a) for both Levels C and D service loadings.

As an alternative to (d), an applied stress intensity factor, K_{IR}, related to Level C and Level D loading rates, shall be compared to $K_{Ic}(t)$ of the material determined at an equivalent, rapid loading rate in accordance with Annex A13 of ASTM E 1820-96. For this case, a multiplier of 1.4 shall be applied to the stress intensity factor, K_{IR}.

[1] *Confinement systems*, as defined in 10CFR72.3, are "those systems, including ventilation that act as barriers between areas containing radioactive substances and the environment".
Containment systems, as defined in 10CFR71.4, are those "components of the packaging intended to retain the radioactive material during transport".

3. Appendix K, Section XI, Division 1

Most of the ASME Code approaches for ensuring adequate fracture toughness of a material (hence, integrity of a structure), while conservative, are somewhat empirical in that they rely on a *correlative* measure of the material fracture toughness, e.g., T_{NDT}. In addition, the approaches specify conservative factors of safety on applied stresses and require assumption of large flaw sizes. A more *fundamental* fracture mechanics methodology is provided within existing ASME Code, however - Appendix K, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels", Section XI, Division 1 [6]. Appendix K is the most current and straightforward discussion of the application of true (elastic-plastic) *fracture mechanics* principles within the ASME Code. The fracture mechanics methodology within Appendix K is *non-empirical and non-correlative*; it does not rely on non-fracture toughness measurements of the material fracture toughness (such as T_{NDT}).

The procedures of Appendix K provide for determination of:

1) flaws in the structure,

2) loading conditions (applied stresses), and

3) material properties (i.e., fracture toughness, determined via "accepted test procedures" [i.e., ASTM elastic-plastic fracture toughness specifications]).

Flaws are postulated to exist in the structure at specified locations. Although flaw size is postulated (1/10 the thickness for Level C and D loadings), actual flaw sizes may be used if "justified". Applied loads, stresses, and stress intensities (J_{Iap}) are calculated (elastic-plastic J-integral analyses). The fracture toughness of the material is measured ($J_{Imaterial}$) and "shall be a conservative representation of the toughness of … the material". The applied elastic-plastic (J-integral) parameter is calculated and compared with the elastic-plastic fracture resistance of the material. To determine acceptability: J_{Iap} is compared to $J_{Imaterial}$.

(Appendix K also allows for application of the Failure Assessment Diagram procedure to assess flaw stability [5] – this method is not included in the fracture mechanics Code Case.)

This fundamental application of fracture mechanics is the basis of the Code Case for cask containment presented herein.

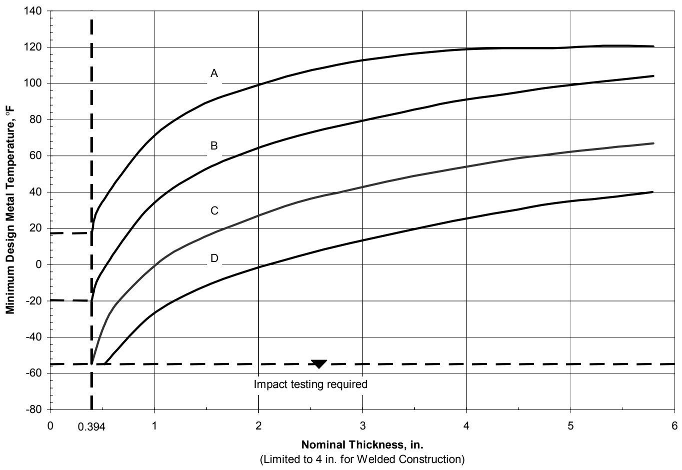
4. Other ASME Fracture Mechanics Methodologies

4.1. Section VIII, Division 1 and Appendix R, Section III, Division 1

Ferritic materials used in the fabrication of nuclear components are required to be ductile and resistant to nonductile fracture over the entire range of expected service temperatures. A commonly used approach for ensuring such resistance is based on two principles. First, ferritic materials are characterized by a transition from nonductile behavior at relatively low temperatures (i.e., the lower-shelf temperature) to ductile behavior at relatively high temperatures (i.e., the upper-shelf temperature). (Austenitic stainless steels exhibit ductile behavior at all temperatures.) Second, experience has shown that inexpensive material tests (e.g., Charpy V-notch or drop weight tests) can be used to empirically establish the available temperature margin between the LST expected during vessel operation and a reference temperature that guarantees ductile behavior during service.

Two sections of the ASME Code are based upon this approach. The first example is from the ASME Code Section VIII Division 1 [7]. Figure UCS-66 (see Figure 1) shows impact test exemption curves for ferritic steels. The minimum design metal temperature, in ^{o}F, is plotted against the nominal vessel wall thickness, in inches, for four classes of ferritic steels, denoted by curves designated A, B, C, and D, with Class D material being the ferritic material with superior low temperature fracture toughness behavior. Impact testing is required for any ferritic steel with a minimum design metal temperature less than –55^{o}F, and for ferritic steels of the designated class below the curves. For example, a vessel fabricated from a ferritic steel in Class A, with a nominal wall thickness of three inches, would require impact testing for a minimum design metal temperature of 110^{o}F, or less. The wall thickness dependency of the impact testing requirements extends down to 0.394 inches for Classes A, B, and C, and down to about 0.5 inches for Class D ferritic material. The upper limit of the curves is five inches (four inches for welded construction).

Fig. 1. Impact Test Exemption Curves, ASME Code Section VIII, Division 1, Figure UCS-66.



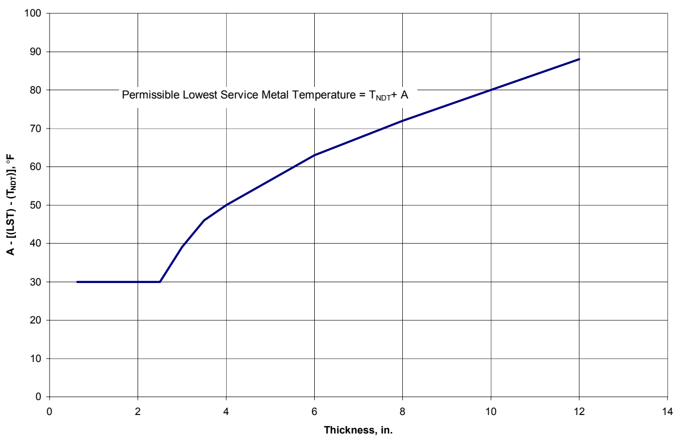


Fig. 2. Permissible Lowest Service Metal Temperature for Class 2, Class 3, Containment and Support Structure Ferritic Steels, ASME Code Section III, Division 1, Figure R-1200-1.

The second example is taken from the ASME Code Section III Division 1 [8]. Figure R-1200-1 (see Figure 2) from the non-mandatory Appendix R provides the permissible lowest service metal temperature as a function of nominal wall thickness. Appendix R applies to Class 2 (Subsection NC) and Class 3 (Subsection ND) ferritic steel nuclear vessels, as well as ferritic steel containment structures (Subsection NE) and ferritic steel component supports (Subsection NF). Unlike Section VIII Division 1, Appendix R does not directly specify the minimum temperature; instead, that minimum temperature is referenced to a characteristic property of the ferritic material – the nil ductility transition (NDT) temperature, termed T_{NDT}. The thickness dependency of the Appendix R reference curve extends from a wall thickness of 2½ inches to a wall thickness of 12 inches.

4.2. Appendix G, Section III and Appendix A, Section XI

Linear-elastic fracture mechanics provides the basis for procedures used by designers of Class 1 nuclear reactor pressure vessels and components in the ASME Code Section III, Appendix G [8], and in the ASME Code Section XI, Appendix A [6]. The Appendix G approach can be described as a reference flaw procedure, since the flaw size against which the component must be evaluated is prescribed. In this case, the reference flaw is required to have a depth equal to 25% of the wall thickness, for vessels with a wall thickness less than 12 inches, with the depth limited to 3 inches for a wall thickness greater than 12 inches. The location of the flaw is assumed to be in the worst location in the component, relative to calculated stresses, and in the worst orientation, relative to the highest principal stress, for Mode 1 crack initiation. The calculated (applied) stress intensity, with a factor of safety of two applied to the membrane stress, is compared to an allowable material fracture toughness, given by the lower bound to static, dynamic and crack arrest data--K_{IR} fracture toughness curve.[2]

The Appendix G reference flaw procedure is very conservative for a number of reasons. The flaw depth is extremely large in order to accommodate both for uncertainty in preservice fabrication flaw detection and sizing, and for service-induced flaw growth mechanisms that are not accounted for in conventional design practice. The factor of safety of two on the applied primary stress intensity accounts for uncertainty in the calculation of stresses. Finally, the K_{IR} fracture toughness curve, as referenced to the specific measured material T_{NDT} (called RT_{NDT}) accounts for the variability in fracture toughness and adds considerable conservatism because of its bounding character.

A variation on this reference flaw approach is contained in Appendix A of Section XI of the ASME Code [6]. Here the flaw depth requirement is reduced substantially, to the actual size determined by inservice inspection, and the actual location of the flaw is used in the evaluation, irrespective of the location of highest stress. However, the flaw growth due to cyclic and time-dependent crack growth mechanisms must be considered in the evaluation. The limiting fracture toughness is still K_{IR}.

The conservatism embedded in the Appendix G approach stems from three sources:

- The assumption of a ¼-thickness flaw (virtually no credit is taken for preservice or inservice inspection);
- The assumption that the primary stresses are at yield strength levels (no credit is taken for the control of stress through design); and
- The requirement that the material fracture toughness satisfy the lower bound of static, dynamic, and crack arrest data (the "K_{IR}" curve).

The Appendix G reference flaw approach, with the three sources of conservatism, provides a level of safety even greater than the criteria contained in Regulatory Guide 7.12. Both the regulatory guide and the Appendix G reference flaw approach are much more conservative than the Appendix R reference curve.

The Appendix G approach with full conservatism in reference flaw depth, applied stress level, and material fracture toughness can be compared to the Appendix R thickness-dependent temperature difference between the RT_{NDT} of the material, as measured by drop weight testing, and the LST. By relaxing the Appendix G reference flaw depth from 25% to 10% of the wall thickness, while maintaining the conservatism on the applied stress level and the material fracture toughness, comes very close to matching the Appendix R requirements. Also, relaxing the conservatism on the applied stress level, while maintaining the conservatism on the reference flaw depth and the material fracture toughness also comes very close to matching the Appendix R requirements.

However, the most convincing argument for the conservatism of Appendix G and the realism of Appendix R is provided when the Appendix G conservatism on the material fracture toughness is relaxed, while maintaining the conservatism on the reference flaw depth and the applied stress level. When the average material fracture toughness is used (as opposed to the lower bound K_{IR} curve), a design curve even less conservative than the Appendix R requirements is generated. When a 95% - 95% bound is used, the design curve almost precisely matches the Appendix R requirements.

5. Conclusion

A Code Case for application of fracture mechanics principles to spent-fuel cask containment has been submitted to ASME NUPACK based upon existing ASME fracture toughness methodologies. This Code Case provides for non-correlative methodology to assess nonductile failure of ferritic materials for containment applications. The Code Case is largely based upon methodology in Appendix K, Section XI, Division 1 of the ASME rules. Interactions with pertinent ASME groups and committees are necessary to more fully develop a fracture mechanics methodology suitable for spent-fuel cask containment application with technical consensus of the ASME membership. Other

[2] A Code Case inquiry "Use of Ductile Cast Irons ASTM A 874 / 874M-98 or JIS G 5504-1992 for Containment Vessel Transport Packagings" has been submitted to ASME which uses a fracture toughness methodology for qualifying the ductile iron based largely on the Appendix G, Section III ASME rules [9].

approaches to the implementation of fracture mechanics methodologies for containment applications may be more appropriate [see Ref. 9]. Development of true fracture mechanics methodologies for evaluating the suitability of a material for containment application would permit a wider selection of materials for that application.

6. References

[1] U.S. Nuclear Regulatory Commission Regulatory Guide 7.11, "Fracture Toughness Criteria for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of Four Inches (0.1m)", U. S. Nuclear Regulatory Commission, Washington, June 1991.

[2] U.S. Nuclear Regulatory Commission Regulatory Guide 7.12, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels With A Wall Thickness Greater Than 4 Inches (0.1 m) But Not Exceeding 12 Inches (0.3 m)", U. S. Nuclear Regulatory Commission, Washington, June 1991.

[3] International Atomic Energy Agency, "Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material – Safety Guide", Safety Standard Series No. TS-G-1.1 (ST2), IAEA, Vienna, 2002.

[4] American Society for Testing & Materials "Standard Test Method for Measurement of Fracture Toughness, E-1820-96", ASTM International.

[5] T. L. Anderson, *Fracture Mechanics – Fundamentals and Applications*, CRC Press, Boca Raton, 1991.

[6] ASME Boiler and Pressure Vessel Code, "Rules for Inservice Inspection of Nuclear Power Plant Components", Section XI, Division 1, American Society of Mechanical Engineers, New York, 1995.

[7] ASME Boiler and Pressure Vessel Code, "Rules for Construction of Unfired Pressure Vessels", Section VIII, Division 1, American Society of Mechanical Engineers, New York, 1998.

[8] ASME Boiler and Pressure Vessel Code, "Rules of Construction of Nuclear Power Plant Components", Section III, Division 1, American Society of Mechanical Engineers, New York, 1998.

[9] T. Saegusa, T. Arai, M. Hirose, T. Kobayashi, Y. Tezuka, N. Urabe, R. Hüggenberg, "Draft ASME Code Case on Ductile Cast Iron for Transport Packaging", The 14th International Symposium on the Packaging and Transportation of Radioactive Materials, Berlin, 2004.