CONF-840647--22

DEVELOPMENT OF THE PRESENT REFERENCE FRACTURE TOUGHNESS CURVES IN THE ASME NUCLEAR CODE*

S. Yukawa
General Electric Company
Schenectady, New York

and

J. G. Merkle*
Oak Ridge National Laboratory
Oak Ridge, TN

CONF-840647--22

DE84 014281

INTRODUCTION

Since the early 1970's, the Sections of the ASME Boiler and Pressure Vessel Code concerned with nuclear power plant components have included fracture mechanics procedures to analyze the effects of postulated or detected flaws. These procedures are contained in Appendix G of Section III and in Appendix A of Section XI of the Code. Specifically, Appendix G procedures are concerned with designing for protection against nonductile failures while Appendix A procedures are for evaluating the disposition of flaws detected during in-service inspection.

An important element of the procedures is the inclusion of recommended material fracture toughness values. This paper describes the origin and development of these recommended fracture toughness values. Since these values appear in the Code in a graphical format, the values are often referred to as "reference toughness curves". In the context of Code terminology, "reference toughness" means the allowable values of fracture toughness for the materials of concern that can be used in conjunction with the analytical procedures of Appendices G and A. The paper discusses the basis and rationale underlying the original formulation of these reference toughness curves and the modifications incorporated into them in the course of their adoption into the Code.

CHRONOLOGY OF DEVELOPMENT

The reference toughness curve in Appendix G of Section III was the first to be developed. It resulted from the efforts of a Pressure Vessel Research Committee (PVRC) Task Group [1] organized in 1971 for the purpose of formulating a fracture mechanics based analysis methodology for assuring the structural integrity of pressure boundary components of light-water cooled nuclear systems. Special emphasis was given to the reactor pressure vessel in developing the analysis procedures and material fracture toughness properties.

The PVRC Task Group completed its work in the latter part of 1971 and transmitted its recommendations on analysis procedures and material properties to Section III of the ASME Code shortly thereafter. The recommendations were adopted by Section III with a few changes as Appendix G which was first published in the Summer 1972 Addenda to the Code. Among the few changes was a slightly modified version of the reference toughness curve initially formulated by the PVRC Task Group.

---

*Research sponsored by the General Electric Company and by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreements 40-551-75 and 40-552-75 with the U.S. Department of Energy under Contract W-7405-eng-26 with the Union Carbide Corporation.

DISCLAIMER

The reference toughness curves in Appendix A of Section XI were formulated about a year after the Section III, Appendix G activity was completed. Appendix A was prepared during 1972-1973 by the Working Group on Flaw Evaluation of Section XI. The proposed analytical procedures and the material properties were adopted by Section XI in June, 1973 and Appendix A was first published in the 1974 edition of the Code.

REFERENCE CURVE DATA BASE

The available fracture toughness data on reactor pressure vessel steels in 1971 consisted of those generated by the Heavy Section Steel Technology (HSST) Program plus a few other results. They showed that the plane strain fracture toughness (K_{Ic}, K_{Id}) of the low alloy, medium strength steels used in pressure vessel construction exhibited a strong dependence on temperature and on the loading rate imposed on the test specimen. Furthermore, results showed that the toughness obtained under rapid loading conditions (K_{Id}) was generally lower than the value for a quasi-static loading rate (K_{Ic}). In addition, test results for the so-called crack arrest toughness (K_{Ia}) were also available. This is the statically calculated value of K_I which prevails at the arrest of a rapidly propagating crack; in this respect, K_{Ia} would be utilized in exactly the same manner as K_{Ic} except to analyze crack arrest.

The PVRC Task Group adopted the view that the largest safety margin would be obtained if the allowable or reference value of fracture toughness were based on the K_{Ia} values. This implies that Section III, Appendix G methodology is based on the premise that even if crack extension were initiated, it would be almost immediately arrested; i.e., the so-called "pop-in" and arrest behavior. Additionally, it was observed that the K_{Id} values at fairly high loading rates for these steels were approximately similar to K_{Ia} values and so K_{Id} and K_{Ia} data were combined. On this point, it should be clearly recognized that the use of K_{Id} values were not based on a premise that the component will be subjected to rapid, dynamic loading rates. Rather, K_{Id} was utilized to complement the available K_{Ia} data [2].

TEMPERATURE INDEXING OF FRACTURE TOUGHNESS

The PVRC Task Group recognized that it is not practical to require the determination of K_{Id} or K_{Ia} values on each piece of material in each component in an engineering design procedure. A convenient way of determining fracture toughness based on the results of simple tests is necessary and several possibilities for doing this were examined. The general approach eventually adopted was to derive a curve for the reference values of fracture toughness, denoted as K_{IR}, as a function of temperature adjusted to an indexing temperature obtained from a relatively simple test. The nil-ductility temperature (NDT) of the steel as determined by the drop-weight test (ASTM E208) was selected as the indexing temperature. The K_{IR} curve was derived from the K_{Id} and K_{Ia} data available at the time for reactor pressure vessel steels utilizing a plot of these data versus temperature minus the NDT of each material used in the toughness testing. The K_{IR} curve was then determined as a lower bounding envelope curve of the data and also fitted to a theoretically expected value of K_{Id} at the NDT temperature. Figure 1 shows the data available and the K_{IR} curve developed by the Task Group by this procedure. Further details of the development of the K_{IR} curve can be found in Reference 1.

There are a number of other indexing temperatures that could have been used, such as the Charpy 30 ft-lbs. (41 J) transition temperature and the Charpy fracture appearance transition temperature (FATT) and the PVRC Task Group examined several of these possibilities. However, for the data available at the time for nuclear component steels, the NDT was judged to be as useful as any of these other possible indexing temperatures.

The PVRC Task Group was also concerned with the possibility that various heats of a material might have the identical drop weight NDT's, but have markedly different toughness versus temperature behavior. To use the derived reference toughness curve for general design purposes, the Task Group considered it necessary to include requirements to assure that each individual piece of material would have a rapid increase in toughness at temperatures above the NDT. It was originally proposed to do this by required a minimum Charpy V-notch (CVN) impact energy of 50 ft-lbs (68 J) at a temperature of NDT +60°F (NDT +33°C). This criterion was subsequently modified by the Task Group to a Charpy test lateral expansion requirement of 40 mils (1mm) lateral expansion at NDT +60°F (NDT +33°C). The basis of the modification was that the lateral expansion criterion would provide a constant level of fracture toughness irrespective of yield strength variations. However, the adequacy of the data supporting this hypothesis was questioned, especially for irradiated steels, by the Code Committee responsible for implementing the PVRC Task Group recommendations into the ASME Code. Consequently, after observing that experimental data did show an approximate correspondence between a CVN value of 50 ft-lbs (68 J) and an lateral expansion value of 35 mils (0.9 mm), the method of determining the indexing temperature for reference toughness purposes was modified for adoption by the ASME Code. A new indexing temperature, denoted as RT_{NDT}, was used where RT_{NDT} is the higher of:

1. The drop-weight NDT, or
2. The temperature 60°F (33°C) below the temperature at which the Charpy V-notch impact test specimen exhibits 50 ft-lbs (68 J) and 0.035 in. (0.9 mm) lateral expansion.

The specific details of the determination of RT_{NDT} are given in Article NB2300 of Section III of the Code. Overall, it can be noted that several considerations were involved in the use of two different test values to establish RT_{NDT} as a temperature index. First, the two separate tests serve as a check to minimize gross errors that might occur in one of the tests. Second, the requirement for certain minimum Charpy values at a temperature 60°F (33°C) above the RT_{NDT} is intended to provide assurance that the material has a rising fracture toughness behavior with temperature.

APPENDIX G K_{IR} CURVE

The reference fracture toughness values derived in the manner described in the preceding paragraphs and as adopted for Appendix G of Section III is shown in Figure 2. As mentioned earlier, the curve of these values is denoted as the K_{IR} curve in Appendix G. By the rules of Section III, the applicability of this curve was and is limited to carbon and alloy steels with a specified yield strength no higher than 50 ksi (345 MPa). In actuality, the K_{IR} curve in Figure 2 is identical to the lower bounding curve in Figure 1, even though the indexing temperatures are different. This happened because the RT_{NDT} values for all the test materials involved were determined by the drop-weight NDT and not by the Charpy requirements at NDT +60°F (NDT +33°C). It should be mentioned that this is not always the situation.

Also by present Section III rules, each piece of base metal and each lot of weld metal in a reactor pressure vessel must be tested to determine the RT_{NDT} to be used in an Appendix G analysis. Additionally, Section III requires that consideration shall be given to possible increases in RT_{NDT} due to irradiation effects over the service life of a nuclear power plant.

APPENDIX A REFERENCE TOUGHNESS CURVES

As earlier noted, the reference toughness curves for Appendix A of Section XI were developed about a year after Appendix G had been incorporated into Section III. Since Appendix A requires both crack initiation and crack arrest analysis, reference toughness values for both conditions were needed.

The Section XI Working Group on Flaw Evaluation used the same approach as in Appendix G by relating fracture toughness to temperature adjusted to RT_{NDT}. In fact, since the K_{IR} curve of Appendix G had been derived implicitly on a crack arrest rationale, the arrest toughness (K_{Ia}) curve of Appendix A was made identical to the K_{IR} curve of Appendix G.

The static initiation (K_{Ic}) reference curve for Appendix A was derived in the same manner as the K_{IR}/K_{Ia} curve except that it is the lower bounding envelope curve to the available K_{Ic} data in the early 1970's for reactor vessel steels. The K_{Ic} curve was derived with the same mathematical form as the K_{IR}/K_{Ka} curve but displaced to higher toughness values at all temperatures. A complete tabulation of the K_{Ic}, K_{Id}, and K_{Ia} data used in the development of reference toughness curves as described in the preceding discussion have been published in an EPRI report [3].

DISCUSSION

More than ten years has elapsed since these reference toughness curves were developed and much additional fracture toughness data have been generated on the grades of steels to which the curves apply. Virtually none of the new data have been consistently lower than these reference curve values and to this extent, the curves have seemingly worked well. However, some questions, difficulties, and deficiencies associated with their use have arisen.

One area of the concern relates to the definition of RT_{NDT} and its adequacy for temperature indexing purposes. One aspect of this involved the Charpy lateral expansion requirement in defining RT_{NDT} which was included on the basis that it provides for a constant level of toughness at various yield strengths. An analysis supporting this aim using empirical relationships is given in Ref. 1. However, there are other empirical relations, one of which is discussed in Ref. 1 which relates toughness to Charpy impact energy only without yield strength as a parameter. A similar result is also implied by the J-integral equations for the notched beam [4] and the compact specimens [5] wherein the toughness to energy (area under load-displacement curve) relation does not involve the yield strength of the material. Actually, it may be noted that the concern over whether the lateral expansion requirement is appropriate or not involves a more fundamental fracture mechanics question of whether energy quantities such as G and J or crack-tip opening displacement (CTOD) which involves the yield and/or flow stress are the most applicable parameters.

Other aspects of the use of RT_{NDT} which have been questioned are that:

1. RT_{NDT} does not adequately adjust for differences among materials. In some instances, fracture toughness data from several heats shows more scatter if corrected for heat-to-heat differences by RT_{NDT} than does the uncorrected data [6].

2. A simple shift of the fracture toughness behavior along the temperature axis does not compensate for differences which are observed between materials in the range of temperature over which the transition from brittle to ductile behavior takes place; specifically, the slope of the toughness-temperature relation is not taken into account.

3. One deficiency of the present reference toughness curves is that they do not show any limiting toughness values for higher temperatures. This deficiency was recognized in the original deviation but lack of data precluded any action. As new data have become available through elastic-plastic fracture testing techniques applicable in the upper shelf regime, differences among materials have become evident. As a result, definition of reference toughness at these temperatures has become important.

Another concern involves the statistical significance or implication of the present reference toughness curves. It is possible to make some restricted statements about the statistical nature of a curve derived by a lower bounding envelope approach. One approach is by calculation of a distribution-free tolerance bound [7] which obviates the need for any assumptions about the form of the distribution of dependent variation (e.g., toughness) at an index value (e.g., temperature). However, this approach has to assume that the underlying population variance is identical at all index values. The tolerance bound is simply the smallest observed value and the statistical calculations give the fraction of all future values which will exceed this bounding value of the dependent variable with some specified confidence level. The exceedance value depends on the quantity of data available and the specified confidence level. For example, with 100 test values, the exceedance will be 97% at a 95% confidence level. For 50 and 27 test values, the corresponding exceedance values are 94 and 89%. Since the reference toughness curves involve somewhere between 50 and 100 test values, it can be stated by this statistical approach that for a 95% confidence level, about 95% of future values should exceed the reference curve values. The experience with new data generated after the development of the curves is generally consistent with this expectation.

These distribution-free limits are appealing because of the ease with which they are obtained, but they tend to be more conservative than those based on distributional forms. One difficulty with this method, if one is interested in drawing a smooth lower bound curve, can arise if unequal numbers of observations are available at each index value. Each lower tolerance bound will have a different confidence level-population fraction combination associated with it. The general effect is to be conservative when many data are available and optimistic when there are few data. This precludes the derivation of a single lower bound curve with the same statistical property over the range of the index.

REVISED REFERENCE TOUGHNESS CURVES

The concerns and limitations noted in the preceding discussion provided the impetus for an effort to revise and improve the reference toughness curves presently in the ASME Nuclear Codes. This effort was initiated several years by a Working Group organized under the joint sponsorship of the Metal Properties Council and the Pressure Vessel Research Committee. The goal of this effort has been to develop a practical method of determining reference toughness values with a defineable statistical basis. Other papers in this Symposium report on the results of this effort.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the assistance received from G. Jouris, a member of the MPC/PVRC Working Group on Reference Toughness, for his analysis of the statistical significance of the present reference toughness curves.

REFERENCES

1. PVRC AD Hoc Group on Toughness Requirements, "PVRC Recommendations on Toughness Requirements for Ferritic Materials", WRC Bulletin No. 175, Welding Research Council, August, 1972.

2. S. Yukawa, "ASME Nuclear Code Applications of Structural Integrity and Flaw Evaluation Methodology", In Structural Integrity Technology, J.P. Gallagher and T.W. Crooker, (eds.) ASME, 1979.

3. T.U. Marston (ed.), "Flaw Evaluation Procedures: ASME Section XI", EPRI NP-719-SR, Electric Power Research Institute, Palo Alto, CA, August, 1978.

4. J.R. Rice, P.C. Paris and J.G. Merkle, "Some Further Results of J-Integral Analysis and Estimates", Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, American Society for Testing and Materials, 1973, pp. 231-245.

5. J.G. Merkle and H.T. Corten, "A J-Integral Analysis for the Compact Specimen, Considering Axial Force as Well as Bending Effects", Trans. ASME, Journal of Pressure Vessel Technology, Vol. 96 (4), November, 1974, pp. 286-292.

6. W. Oldfield, "Development of Fracture Toughness Reference Curves", Trans. ASME, Journal Eng. Mat'ls. and Tech., Vol. 102, 1980, pp. 107-117.

7. A.M. Mood and F.A. Graybill, Introduction to the Theory of Statistics, McGraw-Hill, 1963, Chapter 16.

pam/#731
Disc #13

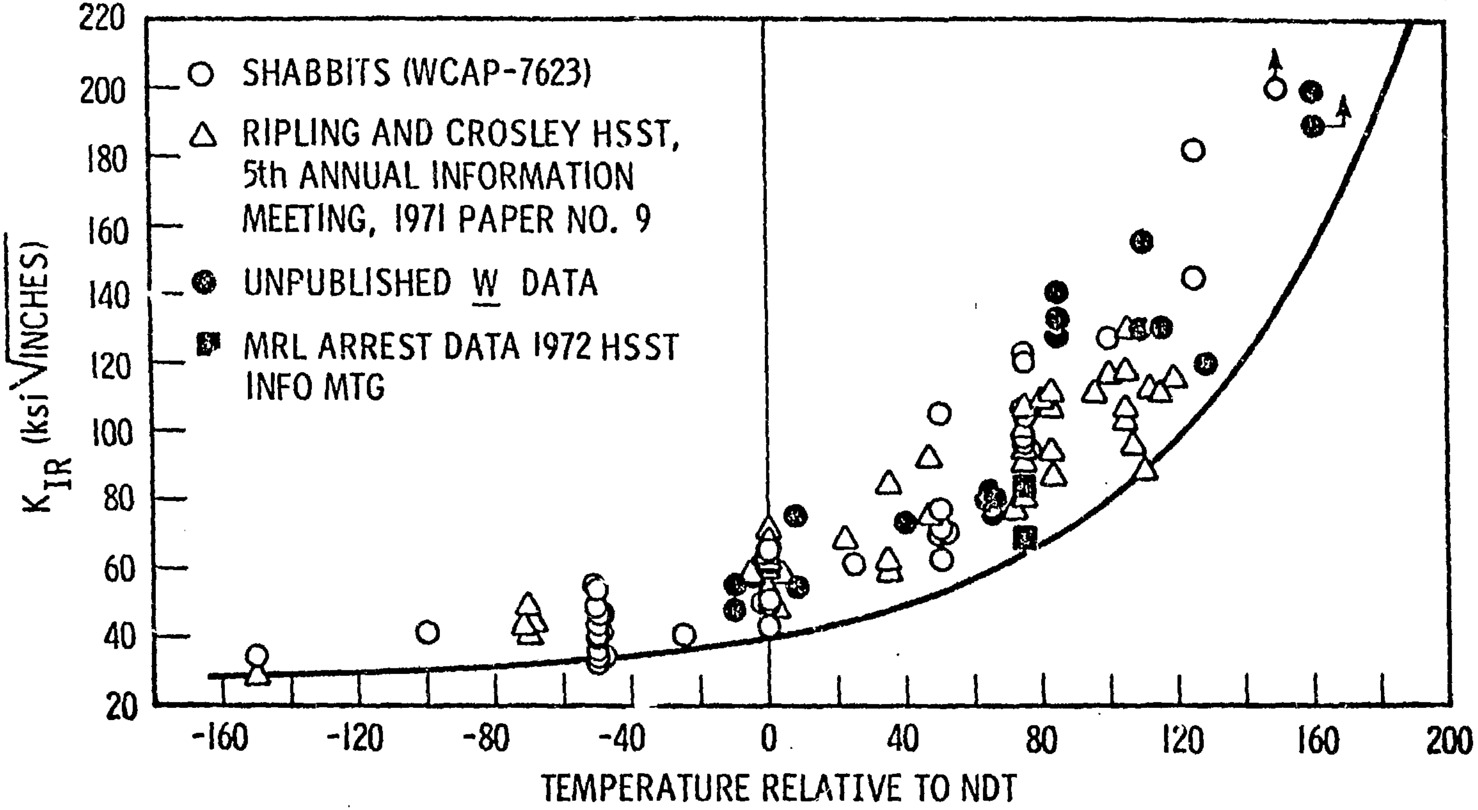

Figure 1 Derivation of Curve of Reference Stress Intensity Factor (K_{IR})

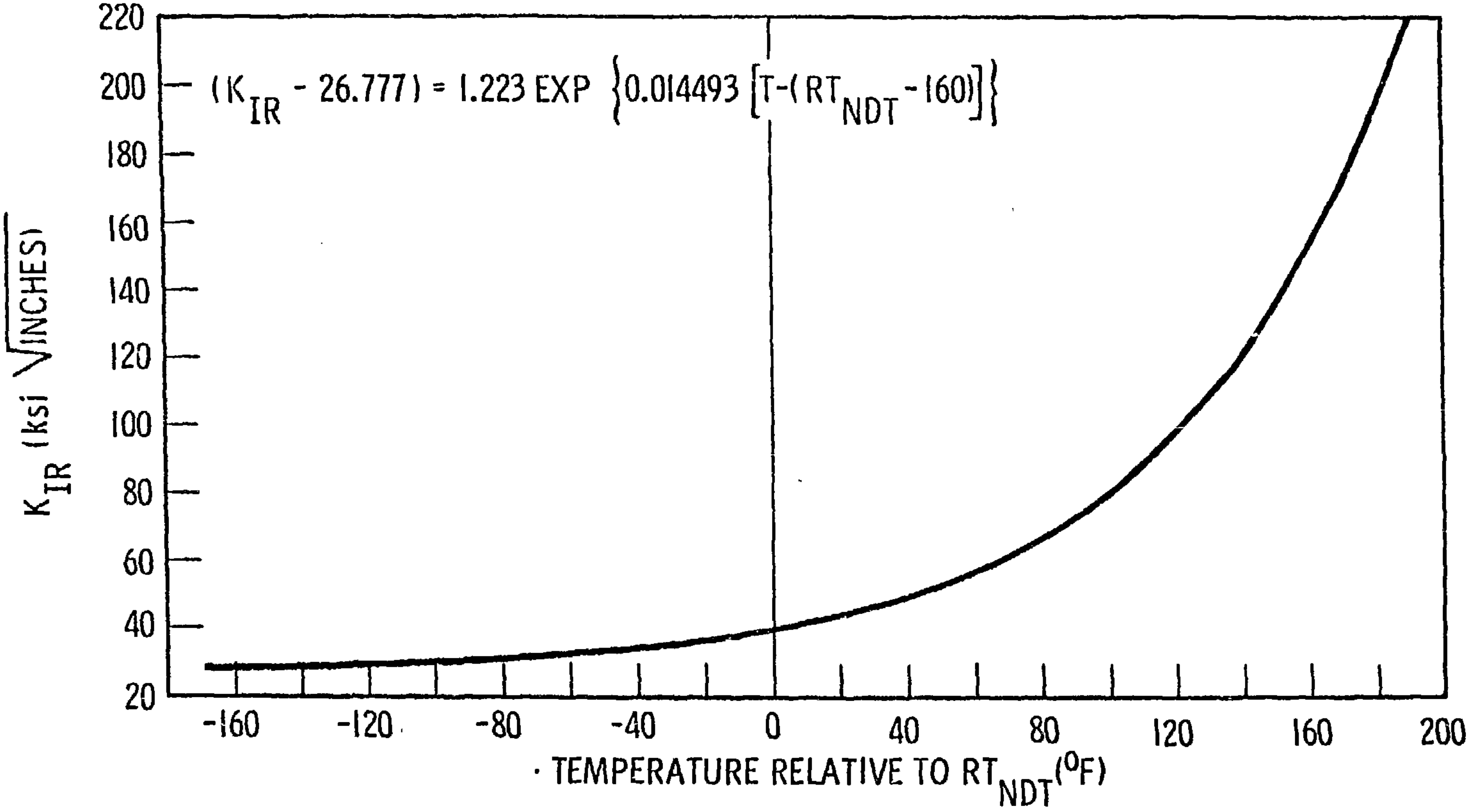

Figure 2 Reference Stress Intensity Factor

ERRA SHEET

Page 3, line 13: Change "required" to "requiring"

Page 3, line 22: Change "an" to "a"

Page 3, line 39: Change "is" to "are"

Page 4, line 30: Delete "the"

Page 5, line 13: Change "deviation" to "derivation"