Reference Fracture Toughness Procedures Applied to Pressure Vessel Materials

edited by
THOMAS R. MAGER

MPC-24

Reference Fracture Toughness Procedures Applied to Pressure Vessel Materials

presented at

THE WINTER ANNUAL MEETING OF
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
NEW ORLEANS, LOUISIANA
DECEMBER 9-14, 1984

sponsored by

THE METAL PROPERTIES COUNCIL, INC.
THE PRESSURE VESSELS AND PIPING DIVISION, ASME

edited by

THOMAS R. MAGER
WESTINGHOUSE ELECTRIC CORPORATION

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

Library of Congress Catalog Card Number 84-72648

FOREWORD

In October 1972, the NRC (AEC at that time) made it known that additional research was needed to demonstrate the toughness requirements for ferritic materials in nuclear power plant components as published in Appendix G to Section III. In response to the AEC, a Task Group was formed under the joint sponsorship of the Pressure Vessel Research Committee (PVRC) and the Metal Properties Council (MPC) with the objective of defining a program to demonstrate that the toughness requirements for ferritic materials in nuclear power plant components, as specified in the Summer 1972 Addenda for Section III were conservative. The Task Group was identified as the "MPC/PVRC Joint Task Group on Fracture Toughness Properties for Nuclear Components."

At the request of the NRC, the joint MPC/PVRC Task Group did not disband with the issuance of its initial recommendations. The joint MPC/PVRC Task Group directed its attention to other areas of research pertinent to nuclear safety; namely, crack arrest analysis, elastic-plastic analysis, and dynamic fracture toughness testing. Working groups were formed for each of the three subject areas. The accomplishments of the Task Group were published in Reference 1.

In October 1977, an additional working group was organized; the MPC/PVRC Working Group on Reference Toughness. Its primary goal was to collect the available fracture toughness data throughout the world, and to assess them relative to the reference toughness curves of the A.S.M.E. Code. In doing this, it became evident that an improved referencing technique could be developed and the work of the committee was continued to develop the new technique and then validate it relative to all available data. The papers contained in this volume represent the culmination of the group's efforts.

In June 1978, the Metal Properties Council, Inc. (MPC) initiated an extensive world-wide data soliciation effort to generate the large data base required to assess the new prediction methods. The information solicited included: material description, chemistry, heat treatment, tensile, drop weight, Charpy V-notch and fracture toughness test results. This package was sent to a large number of investigators worldwide, including Canada, Germany, France, England, Holland, Japan, and Switzerland, in addition to U.S. industrial concerns. The response from some countries was excellent; as of July 1, 1981 the MPC data, including the original EPRI data base, included 750 heats of data. It should be noted that some material entries include only chemistry and Charpy data while others (over 200 heats) include all required information. Other data were also used in addition to the above. This included results from the HSST program which had been used in the generation of the current K_{IR}, K_{Ic} and K_{Ia} reference curves. All these data are included in the data base printed separately as Reference 2.

The Working Group on Reference Toughness built on the earlier work of Wullaert, Server and Oldfield [3] in interpreting the data obtained in a rather large fracture toughness testing program, sponsored by EPRI and begun in 1974. Some of the key results obtained in that study were:

1. The hyperbolic tangent (tanh) curve fit models the temperature response of both Charpy V-notch and fracture toughness data.

2. The variance of Charpy V-notch data was not generally constant over the entire temperature range, and the variance in the transition temperature regime is similar for both longitudinal and transverse orientation tests (absolute transition temperature behavior is also not statistically different between orientations).

3. Real differences between laboratories were seen for drop weight NDTT tests. Ignoring differences between laboratories, the 95% confidence limit was $\pm$ 11.6°F.

4. No significant differences between laboratories were seen in the fracture toughness results. The results from the several fracture toughness tests were obviously not equivalent, and there is significant bias in the transition temperature range. Differences in loading rate, elastic-plastic initiation definition, and specimen size appear to account for these distinct biases.

5. The heat-affected-zone results are more scattered than the parent base or weld metals.

6. The precracked Charpy tanh curve fit tends to describe the mean of larger specimen high strain rate toughness results in the lower shelf and lower transition temperature region.

7. The lower bound K_{IR} curve was transgressed infrequently by test data at the lower sheld position. A definite need to have upper shelf initiation toughness was identified.

In developing an improved reference toughness predictive procedure the philosophy and technical basis of the present code reference toughness curves were carefully reviewed so that the new procedure could retain the benefits of these curves and improvements could be added where possible. This background information is provided in the first paper.

Since the EPRI testing program was completed, work has continued to develop and improve the predictive procedure. The mathematical development of the procedure is presented in the second paper and the technical details of its derivation are contained in the Appendix to that paper.

Application of the method to reactor pressure vessel steels, which formed the largest part of the data base, is covered in the third paper. This paper also includes treatment of application to cases where little or no Charpy data are available. The methodology was also applied to a sizeable data base of irradiated reactor vessel steels, and the results are presented in the fourth paper. The last paper deals with the application of the method to higher yield strength steels and to lower strength steels such as piping and support materials.

The philosophy adopted by the committee was that fracture toughness and crack arrest toughness for any given material should be predictable based on information readily available for that material. This is consistent with the earlier reference toughness work which led to the K_{Ic} and K_{Ia} lower bound curves. For pressure vessel steels, which were the major materials of interest for this work, only Charpy and drop weight test information are available. Early in the study it was found that the Charpy test was the most useful of these two and work proceded to develop Charpy-toughness correlations for a range of loading rates and for crack arrest.

The methodology, having been established based on 50 heats of carefully checked data, was then verified by predicting the toughness curves for over 200 heats of pressure vessel steels, and comparing the predictions with actual toughness data. The predictions were also compared with the predicted toughness using the present Code method. The new method was found to provide very accurate predictions in all cases, while the present code method was either accurate or conservative in all cases. In some cases, the code method was extremely conservative.

In addition to verifying the new method, its application to all the steels in the data base revealed that it is equally applicable to higher yield strength pressure vessel steels. This provides the technical basis for raising the Code specified limitation on the minimum yield strength of 50 ksi (345 MPa) to 65 (449 MPa).

The extensive data base was used in another way to provide methods for predicting the full fracture toughness curve when only limited material property information is available. Techniques were provided for limited Charpy data, or no Charpy data at all. In the latter case a prediction was provided as a function of the material chemistry and date of fabrication for SA533B Cl steel. Also generic unreferenced toughness predictions were provided for SA533B Cl and SA508 C2 as well as the two most common types of submerged arc weldments. These toughness predictions should prove very useful for assessing the integrity of older reactor vessel steels, where limited data or no data are available.

The newly developed methodology offers the opportunity for considerable improvement in the methods for dealing with irratiation effects. The three parameters involved provide the capability for fully characterizing all the changes which occur in Charpy and fracture toughness curves with irradiation, which are transition temperature shift, transition slope, and upper shelf level. The presently used methods only account for the shift in transition temperature.

Fracture toughness predictions have been provided for three different levels of global tolerance bounds, 90% - 90%, 95% - 95% and 99% - 99%. A tolerance bound (X% - Y%) in this context in a curve above which X percent of future data will fall with Y% confidence. Thus the level of the bound can be chosen based on the intended application of the reference curve. The statistical basis of the new reference toughness curves also makes them useful for probabilistic reliability assessments, an area which is receiving increasing emphasis in structural integrity analysis.

This volume presents the accomplishments of the MPC/PVRC Working Group on Reference Toughness and the contributions of all the members of this group are gratefully acknowledged. They are listed here:

W. H. Bamford - Chairman	W. G. Howe	J. G. Merkle
R. Cipolla	R. E. Johnson	W. Oldfield
J. F. Ely	G. Jouris	J. Panesar
A. S. Heller	T. U. Marston	R. N. Randall
S. Ranganth	W. A. Server	S. Yukawa

Also, the support of the Metals Properties Council, Pressure Vessel Research Committee, and the financial support of the Electric Power Research Institute were very helpful.

Thomas R. Mager, Chairman
MPC/PVRC Joint Task Group
on Fracture Toughness for
Nuclear Components

REFERENCES

1. Mager, T. R., "PVRC/MPC Task Group on Fracture Toughness for Nuclear Components: Final Report," MPC, WRC, October 1977.

2. Server, W., Oldfield, W., and Wullaert, R., "Experimental and Statistical Requirements for Developing a Wall-defined K_{IR} Curve," EPRI-NP-372, May 1977.

3. Oldfield, W. and Oldfield, F., "Pressure Vessel Steel Database: International Data Solicitations - Data and Analysis" Electric Power Research Institute Report, August 1983.

CONTENTS

Development of the Present Reference Fracture Toughness Curves in the ASME Nuclear Code
S. Yukawa and J. C. Merkle 1

Fracture Toughness Prediction for Pressure Vessel Steels: The Development of a Statistically Based Method
W. Oldfield and W. L. Server 9

Reference Toughness Curves for Reactor Pressure Vessel Steels
T. U. Marston, W. Oldfield, and W. L. Server 27

Reference Toughness Curves for Moderately High Yield Strength Pressure Vessel Steels and Lower Strength Pressure Vessel, Piping, and Structural Steels
W. Bamford, R. Cipolla, J. Panesar, and J. Ely 73

Application of Fracture Toughness Prediction Procedures to Irradiated Reactor Vessel Steels and Welds
W. Oldfield, T. U. Marston, and W. L. Server 89

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

S. Yukawa
General Electric Company
Schenectady, New York

J. G. Merkle
Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

This paper describes the background, chronology and formulation of the guideline or reference fracture toughness values presently contained in the nuclear sections of the ASME Boiler and Pressure Vessel Code. Also, the considerations leading to recent efforts on developing an improved procedure for obtaining reference toughness values are discussed.

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.

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.

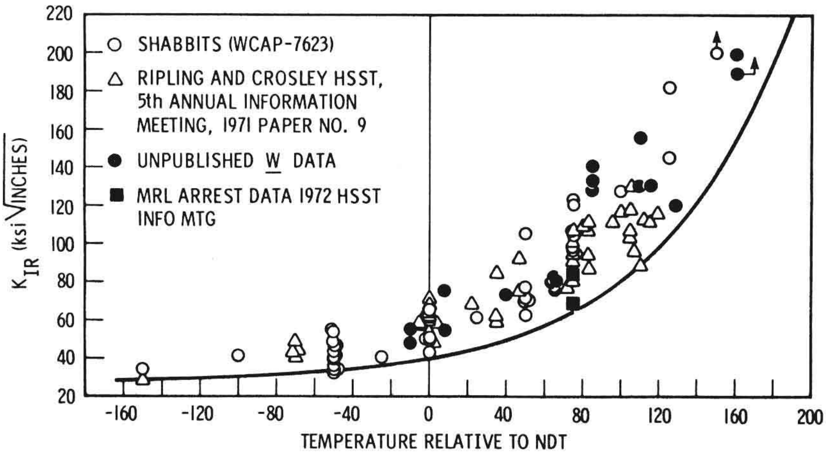

Fig. 1: Formulation of reference stress intensity factor (K_{IR}) curve and supporting data (from Ref. 1)

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 requiring 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 a 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 are 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 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 noted that this is not always the situation.

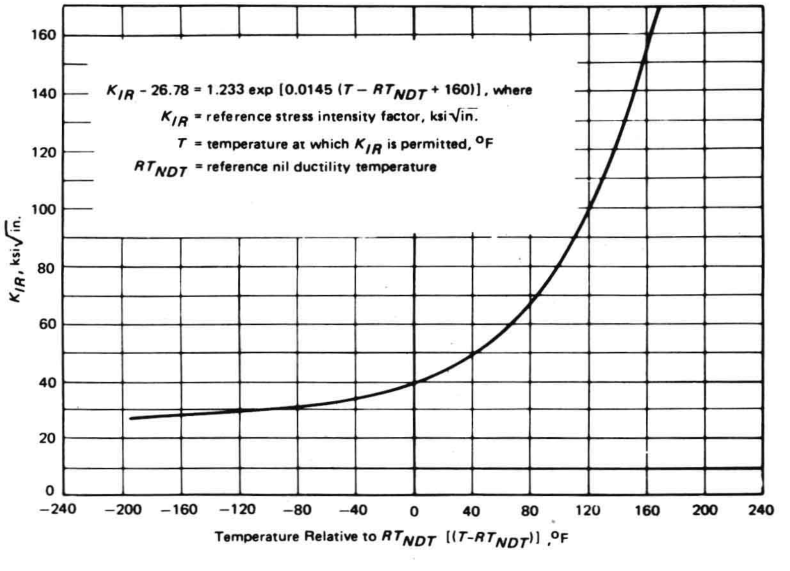

Fig. 2: Section III Appendix G
reference stress intensity factor curve.

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 formulated 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 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 relate 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 values such as G and J or a quantity such as 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 show 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 derivation 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 acknowledges 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.

Research sponsored in part by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulator 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.

FRACTURE TOUGHNESS PREDICTION FOR PRESSURE VESSEL STEELS: THE DEVELOPMENT OF A STATISTICALLY BASED METHOD

W. Oldfield
Materials Research & Computer Simulation, Inc.
Santa Barbara, California

W. L. Server
Materials Engineering Branch
EG&G
Idaho Falls, Idaho

ABSTRACT

A referencing procedure has been developed to permit statistical bounds to be predicted to fracture toughness from Charpy V-notch test data. The concepts underlying the procedure have been presented by the description of an earlier and simpler method using the precracked instrumented Charpy test. They were then extended to apply to the standard Charpy test method. The development of the referencing equations has been shown. A table of coefficients has been presented to permit the prediction of statistical bounds to fracture toughness of a sample of steel on the basis of a set of Charpy V-notch tests taken over a suitable range of temperature.

INTRODUCTION

A reference curve in this context is the curve of a mathematical function chosen to relate fracture toughness (or a bound to it) to temperature, using one or more adjustable parameters. These adjustable parameters are determined by a reference test procedure. For example, the K_{IR} curve is defined as:

$$K_{IR} = 26.77 + 1.233 \exp[0.014493\ (T_{ref} + 160)]\ \text{ksi}.\sqrt{\text{in}} \quad (1)$$

$$= 29.43 + 1.344 \exp[0.2611\ (T_{ref} + 106.7)]\ \text{MPa}.\sqrt{\text{m}} \quad (2)$$

where $T_{ref} = T - RT_{NDT}$ is the referencing temperature[1], T is the temperature in appropriate units (deg. C or F), and the K_{IR} curve is the lower bounding envelope to a set of fracture toughness measurements. The vertical axis (Y-coordinate) of the curve (equations 1 and 2) is fracture toughness, while the horizontal axis (X-coordinate) is the quantity $(T - RT_{NDT})$, T_{ref}. Since the original reference curves were installed in the Code, a considerable body of data has been obtained from many samples of the plates, forgings, and weldments used in pressure vessel construction. Some of these new data (contained in the PVS database)[2] are shown compared to the K_{IR} relationship in Figure 1. (Note that the units for Figure