Direct Measurement of Fracture Toughness for Life Extension

Authors: Stephen Byrne[1], Christopher Hoffmann[1], Stan Rosinski[2], and John Kneeland[3]
Stan Rosinski, Electric Power Research Institute, Charlotte, NC, U.S.A.
John Kneeland, Consumers Energy, Covert, MI, U.S.A.

ABSTRACT

The Electric Power Research Institute Materials Reliability Project (MRP) is pursuing the resolution of selected existing and emerging pressurized water reactor materials performance, safety, reliability, operational and regulatory issues. A focus of the MRP Reactor Pressure Vessel Integrity Issue Task Group is to resolve technical issues associated with application of fracture toughness properties for reactor vessel integrity assessments. The direct measurement of fracture toughness utilizes the Master Curve approach for testing in the brittle-to-ductile transition region. It has been accepted as an alternate method for determining a materials reference temperature in the ASME Code (Code Case N-629). However, several issues have been identified that will require resolution prior to successful application of this technology for reactor pressure vessel life attainment and life extension. An objective of the EPRI MRP is to develop a strategy using direct measurement of fracture toughness that is consistent with the current approach based on Charpy V-notch measurements.

A comparison is provided using both the direct measurement approach and the Charpy based approach for results from two reactor pressure vessel welds. The single edge beam [SE(B)] specimens were tested in three-point bending in accordance with ASTM E1921-97, "Standard Test Method for Determination of Reference Temperature, T_o, for Ferritic Steel in the Transition range". Testing was performed on specimens obtained from two welds that had been irradiated in a reactor vessel surveillance capsule and on specimens in the unirradiated condition.

An assessment was performed of the fracture toughness transition temperature shifts (i.e., K_{IC} shifts) in comparison to the Charpy transition temperature shifts using the data generated in an earlier evaluation of the same weld materials. (The Charpy V-notch data were from specimens irradiated in the same surveillance capsule as the specimens used to determine the K_{IC} shifts.) The irradiated reference temperature can be computed using three different approaches: 1) computed directly from the irradiated value of T_o in accordance with ASME Code Case N-629; 2) computed using the initial (unirradiated) value of T_o in accordance with ASME Code Case N-629 plus the irradiation induced transition temperature shift measured using the Charpy impact specimen measurements; and 3) computed using the initial (unirradiated) value of T_o in accordance with ASME Code Case N-629 plus the irradiation induced transition temperature shift predicted using empirical correlations based on the copper and nickel content of the welds and neutron fluence for the surveillance capsule. The first approach was used to illustrate the potential benefits of the direct measurement approach.

The results of this evaluation were then used to assess the various strategies intended for maintaining adequate margins for continued vessel operation. The strategies considered were for application of the fracture toughness measurements that preserved the conservatisms inherent in the Charpy based approach but credited the increased accuracy of the direct measurement approach. The benefits realized from application of the strategies based on this approach were assessed in terms of maintaining vessel integrity throughout an extended lifetime. Successful demonstration and regulatory acceptance of the direct measurement methodology will allow owners of operating nuclear power plants to use lower material reference temperatures of the reactor pressure vessel in the evaluation of pressurized thermal shock and in establishing heat-up and cool-down limits for normal operation. This will result in greater plant operating flexibility and will provide a viable strategy for demonstrating adequacy of the reactor pressure vessel for life extension while retaining appropriate margins of safety.

INTRODUCTION AND OBJECTIVE

The Electric Power Research Institute Materials Reliability Project (MRP) is pursuing the resolution of selected existing and emerging pressurized water reactor materials performance, safety, reliability, operational and regulatory issues. A focus of the MRP Reactor Pressure Vessel Integrity Issue Task Group is to resolve technical issues associated with application of fracture toughness properties for reactor vessel integrity assessment [1]. The direct measurement of fracture toughness utilizes the Master Curve approach for testing in the brittle-to-ductile transition region. It has been accepted as an alternate method for determining a materials reference temperature in the ASME Code (Code Case N-629). However, several issues have been identified that will require resolution prior to successful application of this technology for reactor pressure vessel life attainment and life extension. A goal of the EPRI MRP is to develop a strategy using direct measurement of fracture toughness that is consistent with the current approach based on Charpy impact measurements.

Given the recent interest in extending the operating lifetime for an additional twenty years it is necessary to monitor vessel embrittlement very closely, including the license renewal period. In the newer vessels in which radiation resistant materials were used, monitoring entails performing a set of standard tests over a longer period of time. In the older vessels in which more radiation sensitive materials were used, monitoring often necessitates use of a more precise testing approach. This is called the direct measurement approach.

This work entailed the testing and evaluation of reactor vessel welds using both the direct measurement approach and the Charpy based approach. An assessment was performed of the fracture toughness transition temperature shifts (i.e., K_{IC} shifts) in comparison to the current approach based on Charpy transition temperature shifts. The results of this evaluation were then used to assess the various strategies intended for maintaining adequate margins for vessel operation. Strategies were considered for application of the fracture toughness measurements that preserved the conservatisms inherent in the Charpy based approach but credited the increased accuracy of the direct measurement approach. The following describes the approach being taken to demonstrate vessel integrity during the license renewal period, and to illustrate how this approach can be accomplished.

DESCRIPTION OF THE TESTING PERFORMED

This work entailed the testing and evaluation of two unirradiated and irradiated reactor pressure vessel welds. The welds were obtained from pressure vessels fabricated by Combustion Engineering using the submerged arc process with Linde 1092 flux. The data were evaluated using the direct measurement approach and the Charpy based approach. The single edge beam [SE(B)] specimens were tested in three-point bending in accordance with ASTM E1921-97 [2]. Testing was performed on two welds that had been irradiated in a reactor vessel surveillance capsule. In addition, testing was performed on SE(B) specimens obtained from the same welds in the unirradiated condition.

Test Method

ASTM has developed a standard test method for determination of a reference temperature, designated T_o, for characterizing the fracture toughness properties of ferritic materials in the transition region [2]. The test method requires a minimum number of valid test results on compact tension or three point bend specimens for each material to be evaluated. Testing is performed at or near the temperature where the material exhibits a fracture toughness of approximately 100 MPa√m (91 ksi√in). The method and data analysis are based on a standard one inch thick compact tension (1TCT) specimen. The tests in this investigation were performed using Charpy-sized (10 x 10 mm cross section) three point bend specimens.

A key feature of the test method is that the test results can be used to construct a complete curve of fracture toughness as a function of temperature. The toughness curve generated by this method is referred to as the "Master Curve" [1,3]. The Master Curve is based on a Weibull statistical analysis of the fracture toughness test data. It provides a statistically based median fracture toughness curve and tolerance bounds. A method is also included to quantify the uncertainty in the value of T_o determined from the test data, ΔT_o, which can be used to define a lower bound for the median or tolerance bound curves.

Test Results

For each of the materials (identified as Heats A and B), fracture toughness transition reference temperature values, T_o, were calculated in accordance with the analysis procedure of ASTM E 1921 [2]. Valid K_{Jc} values for each data set were used to calculate the T_o values. [Note: In the case of Heat A, unirradiated data were obtained using a combination of specimens. One set of specimens was machined from virgin material and tested. A second set of specimens was from broken specimens that were reconstituted, and the tests were conducted at the same temperature as for the first set of specimens.]

The results of these analyses are summarized in Table 1. The T_o values were used to construct the master fracture toughness curves for each material in Figures 1 and 2, using the following equations from [2]:

$$K_{Jc(med.)} = 30 + 70 \exp[0.019(T - T_o)] \quad (\mathrm{MPa}\sqrt{\mathrm{m}})$$

$$K_{Jc}(0.05) = 25.4 + 37.8 \exp[0.019(T - T_o)] \quad (\mathrm{MPa}\sqrt{\mathrm{m}})$$

The T_o results were used to develop median and 5% tolerance bound curves for each material. In addition, the lower bound to the 5% tolerance bound on the Master Curve for each material was determined by including the uncertainty in T_o defined as:

$$\Delta T_o = \sigma (Z_{85})$$

where: $\sigma = \beta / \sqrt{N}$,

$\beta = 18$, and

Z_{85} = the standard two-tail normal deviate for 85% confidence.

The lower bound to the 5% tolerance bound to the Master Curve is then defined by the relationship:

$$K_{Jc(0.05)} = 25.4 + 37.8 \exp[0.019(T - T_o + \Delta T_o)] \quad (\mathrm{MPa}\sqrt{\mathrm{m}})$$

The results of the Charpy V-notch tests for the two weld heats are shown in Table 1 together with the index temperature. For each heat, the Charpy index temperature, T_{30}, is given for the unirradiated and irradiated data. T_{30} is the temperature corresponding to 41 J (30 ft-lb) on the impact energy transition curve. This is the index temperature used for evaluating the irradiation induced shift, ΔT_{30}. The corresponding fracture toughness transition reference temperature values, T_o, are shown for the two weld heats in Table 1. For each heat, the index temperature given for the unirradiated and irradiated data along with the irradiation induced shift, ΔT_0.

ASSESSMENT OF THE TEST RESULTS

The direct measurement approach is intended to replace the current practice of using Charpy impact energy shift to establish an adjusted reference temperature (ART), and then to use the ASME K_{IR} curve, indexed to the ART value, to provide the irradiated fracture toughness value for use in P-T curves and PTS analysis. The direct approach is expected to significantly improve both PTS margins and P-T curve operating windows by removing redundancies inherent in the current indirect approach (Charpy shift used to determine ART that is then used to enter the K_{IR} curve).

Table 1 can be used to compare the two approaches. The test results described above were presented in terms of an index temperature and a shift in index temperature for both the Charpy V-notch data and for the fracture toughness (F/T) data. Heat A is seen to have a lower initial (unirradiated) index temperature than Heat B for the Charpy data and for the F/T data. The same relationship is seen for the irradiated Charpy data, but the corresponding irradiated T_o values are nearly the same for both heats. The Charpy shift, ΔT_{30}, is the same for the two heats but the F/T shift, ΔT_0, is not. In contrast, the Charpy shift equals the F/T shift for Heat B but not for Heat A. The expectation would be that the irradiation induced shift would be the same for the same material; however, this difference between Charpy and F/T shift (in this case, 22 °C vs. less than 1 °C) is consistent with the findings by others [4].

Included in Table 1 are values of Adjusted Reference Temperature (ART) following [5] and $RT(T_o)$ following the ASME Code Case N-629. The ART value is used as a reference temperature to index the ASME Code fracture toughness curve to establish the heat-up and cool-down curves for normal operation and as a screening value, RT_{PTS}, for vessel embrittlement assessments. In Table 1, the ART values were computed using the measured shift, ΔT_{30} coupled with the so-called "generic initial RT_{NDT}" for Linde 1092 flux welds and associated margin from [5]. For example, for Heat A, the ART equals the sum of ΔT_{30} plus generic initial RT_{NDT} plus margin which is 138.9 + (-48.9) + 36.4 = 126.4°C. (A generic value of initial RT_{NDT} was used rather than a measured value such as would be obtained following the ASME Code [6]. Use of the generic value tends to inflate the ART value but is often necessary in practice because measured values are not available for many vessel welds.) The $RT(T_o)$ value is used in the same manner and is computed using the sum of the irradiated T_o plus 19.4°C (35°F) in accordance with Code Case N-629. Based on a comparison of the ART and the $RT(T_o)$ values, it is an obvious benefit to use the $RT(T_o)$ value.

ASSESSMENT OF THE DIRECT MEASUREMENT APPROACH

In the case of the Heat A and B data, the direct measurement approach produces a 71.4 to 72.0°C reduction of the reference temperature relative to the current practice based on using Charpy shift measurements. This reduction is a result of two factors. One is the use of a test that measures fracture toughness directly rather than using a bounding approach based on a presumed relation between Charpy impact test results and crack initiation toughness. The other is the fact that the reference temperature is computed directly from the measurement rather than using several different inputs to compute the reference temperature adjustment. In Table 1, ART is based on the measured shift for the specific material, but this shift is added to an initial reference temperature plus a margin to account for uncertainties in the material properties and the irradiation environment.

It is important to point out that this illustration of the application of $RT(T_o)$ does not include a margin term to account for the uncertainties considered in the Charpy based approach. If the 36.4°C (65.5°F) margin used for the ART calculation is used as a conservative upper limit for the direct measurement approach and added to $RT(T_o)$, the $RT(T_o)$ is still 35.0 to 35.6°C lower than the reference temperature obtained using the Charpy based approach. (Note that one of the objectives of performing these tests and others is to resolve technical issues associated with the margin to be applied to $RT(T_o)$ for reactor pressure vessel integrity assessment [1].) In terms of extending vessel operating lifetime, the 35°C benefit could translate to many more years of operation and enhance operating flexibility (e.g., faster heat-up and cool-down) during normal operation.

SUMMARY

A potential benefit of the fracture toughness properties generated using ASTM E1921 [2] is to redefine the fracture toughness properties of reactor pressure vessel materials. The current ASME Code approach to fracture toughness properties was originally adopted in 1972 and is still the same in the current ASME Code [6]. An assessment was performed of the fracture toughness transition temperature shifts (i.e., K_{IC} shifts) in comparison to the Charpy transition temperature shifts using the data generated in an earlier evaluation of the same weld materials. The assessment considered the irradiated reference temperature computed directly from the irradiated value of T_0 in accordance with ASME Code Case N-629 in comparison to the Charpy based approach. The direct measurement approach yielded a 71.4 to 72.0°C reduction of the reference temperature. If a conservative margin were added to account for uncertainty in the material properties and the irradiation environment, the direct measurement approach still yields a 35°C reduction of the reference temperature. One of the goals of performing fracture toughness tests such as the ones addressed here is to provide a rational basis for assigning suitable uncertainties while preserving as much of the benefits of the direct measurement approach as possible. This approach offers significant promise for use in various strategies intended for maintaining adequate margins for vessel operation through the current operating period and throughout an extended lifetime while retaining appropriate margins of safety.

REFERENCES

1) "Validation of Master Curve Fracture Toughness Methodology for RPV Integrity Assessment," EPRI Technical Report, PWRMRP-26, December 2000.

2) ASTM E 1921-97, "Test Method for the Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range," ASTM, American Society for Testing and Materials, West Conshohocken, PA, 1997.

3) K. Wallin, "The Scatter in K_{IC} Results," *Engineering Fracture Mechanics*, 19(6), pp. 1085-1093, 1984.

4) T.M. Rosseel, "Heavy-Section Steel Technology Irradiation Program, Semi-Annual Progress Report for October 1996 – March 1997", NUREG/CR-5913, US Nuclear Regulatory Commission, 1997.

5) 10 CFR 50.61, "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events," Code of Federal Regulations, December 19, 1995.

6) ASME Boiler and Pressure Vessel Code Subsection NB, Subarticle NB-2300, Winter 1972 Addenda to the 1971 Edition, American Society for Mechanical Engineers, New York, NY.

Table 1
Comparison of Charpy V-Notch
and Master Curve Test Results

Material	Heat A	Heat B
T_{30} Unirradiated, °C (°F)	-63.3(-82)	-40.6(-41)
T_{30} Irradiated, °C (°F)	75.6(168)	100(212)
ΔT_{30}, °C (°F)	138.9(250)	140.6(253)
Adjusted Ref. Temp., °C (°F)	126.4(259.5)	128.1(262.5)
T_0 Unirradiated, °C (°F)	-123.0(-189.4)	-91.5(-132.6)
T_0 Irradiated, °C (°F)	35.0(95.1)	37.3(99.2)
ΔT_0, °C (°F)	158.0(284.5)	128.8(231.8)
$RT(T_0)$, °C (°F)	54.4(130.1)	56.7(134.2)

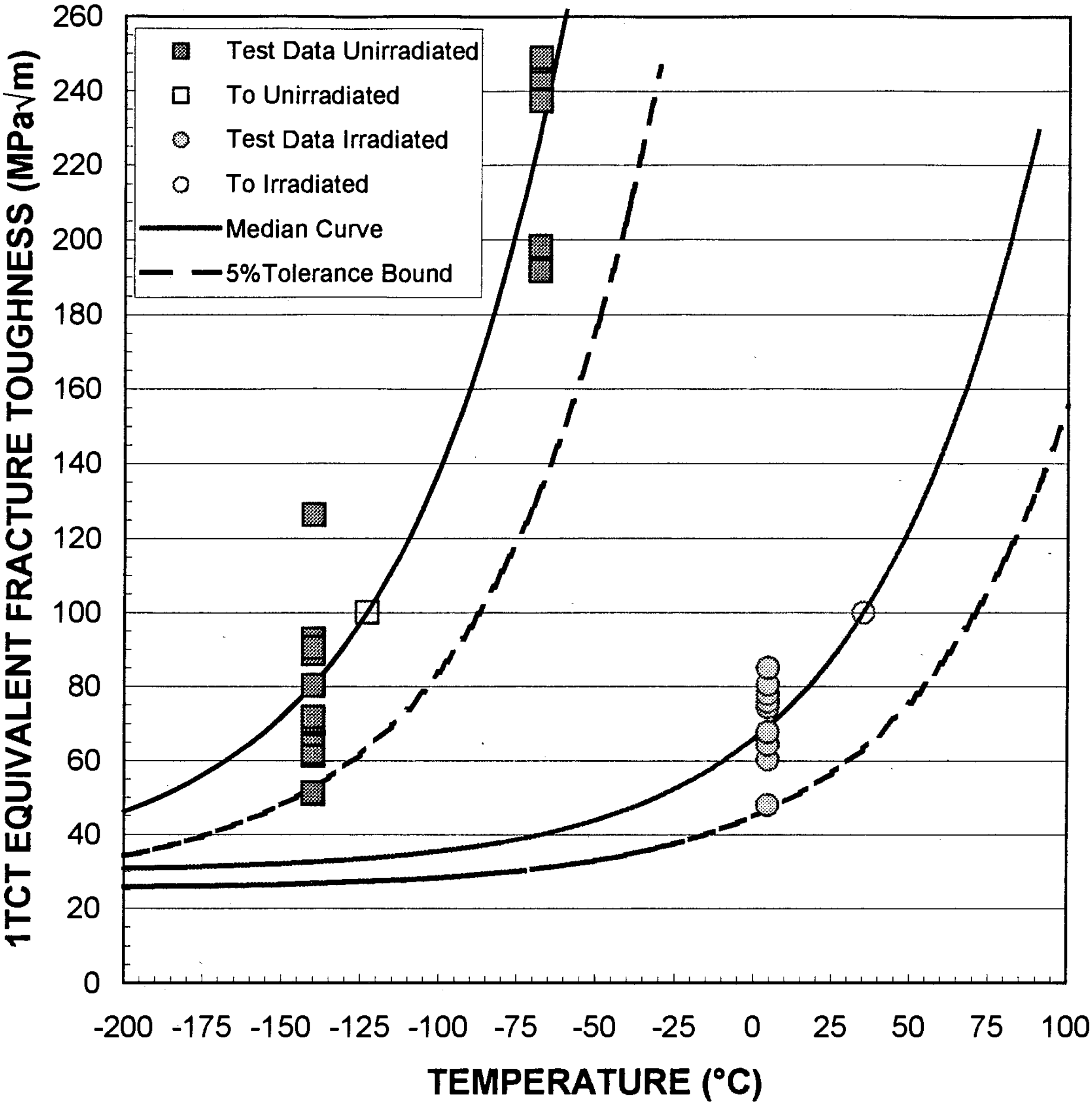

Figure 1 Heat A Fracture Toughness Results

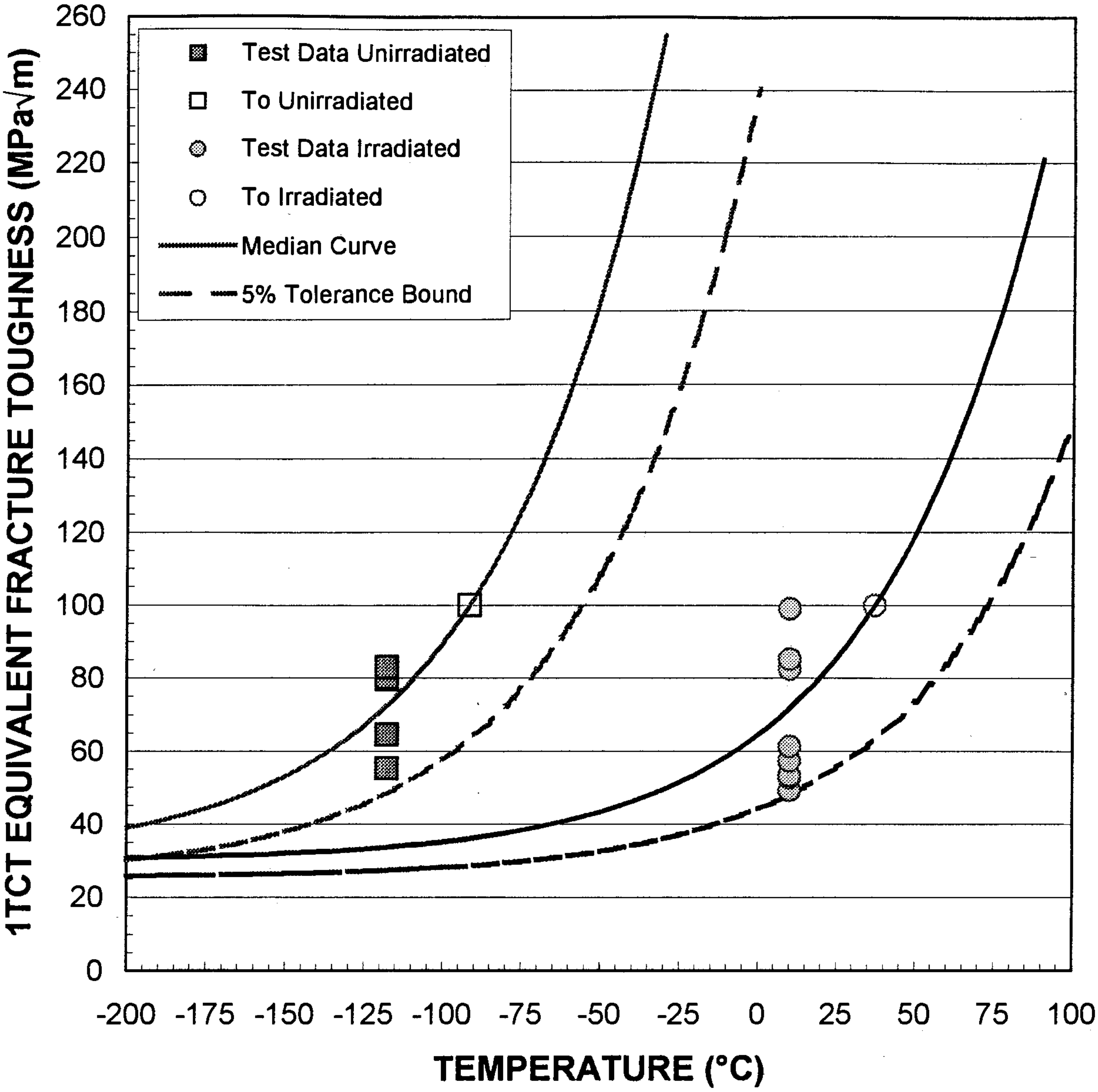

Figure 2 Heat B Fracture Toughness Results