Methods for Estimating Fracture Toughness and Bounds for Irradiated Pressure Vessel Steels

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ABSTRACT

Transition temperature shift effects due to neutron radiation embrittlement for ferritic nuclear pressure vessel steels are currently evaluated using changes in the Charpy V-notch energy curve at the 30 ft-lb (41 J) energy level. Transition temperature shifts (including margins for uncertainty) are often utilized based upon Nuclear Regulatory Commission Regulatory Guide 1.99, Revision 2. The estimated (or measured) Charpy shift is then applied to a lower bound reference (K_{IR}) curve to establish plant operating pressure-temperature limits by moving the curve the same shift amount but leaving the shape of the curve unaltered. Similarly, the flaw evaluation procedures in nonmandatory Appendix A of Section XI of the ASME Boiler and Pressure Vessel Code utilize the shifts in the equivalent of the K_{IR} curve (termed the K_{IA} curve for crack arrest) and a lower bound static crack initiation toughness (K_{IC}) curve. This approach has been reviewed and tested as well as a statistically-based reference toughness method for estimating tolerance bounds. Comparisons of actual, but limited, fracture toughness data and the predicted bounding curves indicate that the shifted K_{IR}/K_{IC} curves are conservative in all cases. The reference toughness approach for 95%-95% tolerance bounds is not as conservative as the Regulatory and ASME Code method and may provide a more realistic bounding method.

INTRODUCTION

As a result of the fission reaction process occurring during the normal operation of a nuclear power plant, a portion of the reactor pressure vessel (which is typically made of ferritic steel) is exposed to neutron irradiation. As a result of this exposure, the beltline region of the pressure vessel (i.e., the constituent plates, forgings, and welds) experiences a degradation of material properties: yield and ultimate tensile strengths increase, upper shelf toughness decreases, and the brittle-to-ductile transition temperature increases. The degree to which these effects are manifested depends upon the chemical composition and processing history of the materials and the temperature and neutron fluence levels to which the pressure vessel is exposed.

In terms of predicting the potential for failure of the reactor pressure vessel due to a pressurized thermal shock transient, the increase or shift in the transition temperature is the major parameter. Current procedures involve equating the shift in the temperature corresponding to the Charpy V-notch 41 J (30 ft-lb) energy level (T_{30}) with the expected shift in fracture toughness for the irradiated material.

For the unirradiated material, the ASME Boiler and Pressure Vessel Code reference toughness temperature, RT_{NDT}, is generally obtained by measuring the

nil-ductility transition temperature and conducting a series of Charpy V-notch (CVN) tests. Due to the limited amount of space available in commercial reactor pressure vessel surveillance programs it is impossible to obtain a large enough sample of materials on which to perform the same tests to derive the irradiated value of RT_{NDT}. Therefore, analytical/correlative methods have been developed to estimate the shift in RT_{NDT} due to irradiation.

Nuclear Regulatory Commission (NRC) Regulatory Guide 1.99, Revision 2, provides a generally conservative method of estimating the shift in RT_{NDT} that includes the effects of fluence and material chemistry. This transition temperature shift is then applied to a shift in the lower bound reference toughness (K_{IR}) curve or the lower bound static toughness (K_{IC}) curve, moving the curve the same shift amount but leaving the shape of the curve unaltered. The shifted K_{IR} (or equivalently K_{IA}, crack arrest toughness) curve is then used to establish pressure-temperature operating limits for the reactor pressure vessel or for assessing a flaw in the vessel wall found during inservice inspection.

A reference toughness bounding method has also been proposed (Oldfield, 1980, and Oldfield and Server, 1984) in which a data base of CVN data is used to establish a statistically-based lower bound reference curve fitted to the form of a hyperbolic tangent function. This methodology has been developed in the hopes of either augmenting or replacing the shifted K_{IR}/K_{IC} curve approach.

A comparison between the lower bounds predicted by these methods and actual measured irradiated toughness data has not been fully made, although some attempts have been made to compare mean fracture toughness shifts with shifts in CVN data. It was the purpose of this study to produce comparisons of the existing irradiated fracture toughness data and the lower bounds determined by the Regulatory Guide, measured CVN shifts, and reference toughness methods.

Regulatory Guide 1.99, Revision 2

Two measures of radiation damage that can be obtained from Charpy V-notch impact tests are the shift in the transition temperature and the decrease in the value of the upper shelf energy. The reference transition temperature shift (RT_{NDT}) corresponds to the change in the 41 J (30 ft-lb) energy level and is termed T_{30}. In performing this particular study, only the shift in transition temperature is considered, although some upper shelf fracture toughness data are used for comparison.

The Nuclear Regulatory Commission (NRC) guidelines in Regulatory Guide 1.99, Revision 2 (RG 1.99, Rev. 2) are a set of procedures that have been established to estimate the adjustment of the reference transition temperature, RT_{NDT}, from the unirradiated condition to the irradiated state. The shift in RT_{NDT} is dependent on the chemical composition of the steel (in particular, the presence of copper and nickel), the processing history of the material (i.e., whether it is base material or weld metal), and the temperature and fluence to which the metal is exposed.

The basic procedure for using RG 1.99, Rev. 2 involves the calculation of the final Adjusted Reference Temperature (ART):

$$\text{ART} = \text{Initial } RT_{NDT} + \ RT_{NDT} + \text{Margin} \qquad (1)$$

where the Initial RT_{NDT} is the reference temperature for the unirradiated material. RT_{NDT} is the mean value of the adjusted reference temperature due to radiation damage and is calculated from:

$$\Delta RT_{NDT} = [CF]\ [FF] \qquad (2)$$

CF is a chemistry factor which is primarily dependent on the copper and nickel

content of the pressure vessel material (the Regulatory Guide provides tables for CF for both weld and base metal), and FF is a fluence function which has been determined to be appropriate for surveillance data irradiations:

$$FF = f^{[0.28 - 0.1 \log(f)]} \quad (3)$$

where f is the irradiation fluence in units of 10^{19} n/cm^2 for neutron energies greater than 1 MeV.

The margin term is a quantity that is added to obtain conservative upper bound values of the adjusted reference temperature and is determined from statistical considerations. For the cases described here where the Initial RT_{NDT} is known for each heat, the margin is twice the estimated standard deviation of the surveillance data base used to derive RG 1.99, Rev. 2: 31°C (56°F) for welds and 19°C (34°F) for base metal, except when the estimated shift amount is quite small. In this latter case, the twice standard deviation amount need not exceed the mean RT_{NDT} shift.

ASME Code K_{IR} and K_{IC} Curves

Once the values of the Initial RT_{NDT}, RT_{NDT}, and the margin have been determined, they can be input to the following functions which relate fracture toughness to temperature (units are degrees Fahrenheit for temperature and ksi-in$^{1/2}$ for toughness):

$$K_{IR} = 26.78 + 1.233 \exp(0.0145 [T - (ART) + 160]) \quad (4)$$

$$K_{IC} = 33.20 + 2.806 \exp(0.0200 [T - (ART) + 100]) \quad (5)$$

where K_{IR} represents dynamic fracture toughness and K_{IC} represents static fracture toughness. T is any temperature of interest. These adjusted toughness curves are intended to represent lower bound fracture toughness due to a transition temperature shift of a fixed shape curve.

Reference Toughness Methodology

A statistically-based method for predicting lower bounding fracture toughness values of pressure vessel steels by using a referencing procedure applied to measured Charpy V-notch energy has been developed over the last several years (Marston et al., 1984). The procedures were intended to be applicable to both unirradiated and irradiated materials and to provide a link between CVN data collected in surveillance programs and valid fracture toughness results.

In developing the procedures, a substantial data base of nuclear pressure vessel materials was compiled for the unirradiated condition (Server and Oldfield, 1978). Additional data were also collected from research groups in the U.S., Japan, and France in order to verify the methodology (Oldfield and Oldfield, 1983). Additionally, irradiated toughness data were collected to check the application to irradiated materials; the methodology failed in this last test. Additional work was conducted to resolve irradiated toughness bounding predictions (Server and Caldwell, 1988). The work presented in this report is a check on the revised reference toughness methodology for irradiated materials.

The reference toughness procedure requires that both measured fracture toughness and temperature values be referenced by CVN data. This referencing is done by first fitting the CVN test data as a function of temperature (T) to a hyperbolic tangent relationship of the form:

$$Y = A + B \tanh[(T - T_o)/C] \quad (6)$$

where Y is normalized CVN (i.e., $[E \times CVN]^{1/2}$); A, B, T_o, and C are regression curve parameters; and, E is the elastic modulus.

Two reference values, k (reference toughness) and t (reference temperature), were then developed relating measured fracture toughness data from the same piece of material to the normalized CVN coefficients A, B, T_o and C. The values of k and t then provide a true measure of the bias between the CVN and fracture toughness data, and these values could be evaluated for all materials depending on the rate of stress intensification loading (i.e., static, dynamic, high strain rate dynamic, or crack arrest).

Global tolerance bounds were then developed for each loading condition. These bounds were found to be well approximated by the hyperbolic tangent equation. The tanh expression was fitted to these curves although the lower shelf was independently fixed at a separate lower bound (L) since it exhibited non-Gaussian response. To enable a specific bounding K (static, dynamic, high strain rate, or crack arrest fracture toughness) versus T (temperature) curve to be plotted, the values of a, b, t_o and c can be calculated from relationships to define a new hyperbolic tangent function for estimated lower bound toughness (K) versus temperature (T):

$$K = a + b \tanh[(T - t_o)/c] \qquad (7)$$

except for the fixed lower bound, L, which is a constant (Oldfield et al., 1984).

COMPARISONS AND RESULTS

In order to compare the RG 1.99, Rev. 2 approach with the reference toughness methodology (and with actual fracture toughness data), the available data had to be assembled. Recent work (Hiser, 1985) has used some of the same data to make comparisons of mean fracture toughness shift behavior with that of actual and estimated CVN shifts. The two sets of data included much of the same accelerated irradiation results, but there were some additional data in each of the two sets which were not common.

Comparisons were made of the available measured fracture toughness data and the lower bounds developed by both the Regulatory Guide (RG 1.99, Rev. 2) and the reference toughness methods for seven different pressure vessel materials (SA508-2, SA533B-1, and SA302B base metal and Linde 80, Linde 0091, Linde 124, and Linde 1092 submerged arc weld metal).

For the Regulatory Guide procedure, values of the Initial RT_{NDT} were obtained from the specified sources. The Initial RT_{NDT} for the SA-302B steel was chosen as the nil ductility transition temperature (NDTT) since it is not possible to measure RT_{NDT} due to the initial upper shelf energy being only slightly greater than 50 ft-lb (68 J). The value of RT_{NDT} was calculated based on the copper/-nickel chemistry factor, CF, and the fluence factor (FF) determined using Eq. 3. The margin was selected depending upon whether the material was base metal or weld material as described earlier. These values were then combined to determine ART as indicated in Eq. 2, and the resultant lower bound curves for dynamic (K_{IR}) and static (K_{IC}) loading were determined and plotted. For the reference toughness calculations, an iterative computer code was used to best fit the hyperbolic tangent curve of the form given in Eq. 6 to the available CVN data.

Much of the actual cleavage-initiation toughness data were determined using small specimens (typically 1-T and 1/2-T compacts); therefore, American Society for Testing and Materials (ASTM) validity criteria were exceeded in many cases.

The curves were also evaluated to compare mean toughness shift behavior as well

as bounding shift behavior with measured ΔT_{30} results. Another calculational measure of mean shift was also determined using the RG 1.99, Rev. 2 chemistry factor, but a different fluence factor (FF):

$$FF = f^{1/2} \tag{8}$$

This fluence factor is more appropriate for accelerated test reactor irradiations than the expression derived from surveillance (commercial reactor) program results indicated by Eq. 3.

The CVN ΔT_{30} results from both this study and other studies (Hiser, 1985) are in very close agreement.

The comparison of the CVN ΔT_{30} and predicted ΔRT_{NDT} (plus margin) bounds the measured CVN shifts when the margin term is into account. The only exception is for the case of high fluence, in which the fluence function of Eq. 8 better estimates the effect of fluence for this accelerated test reactor irradiation.

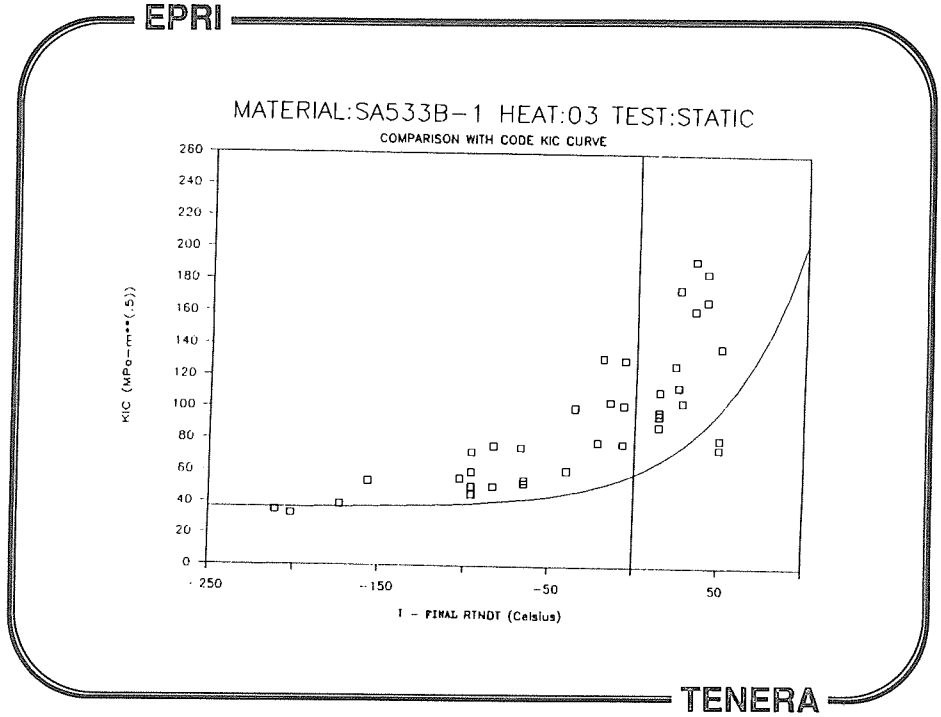

Figure 1
Cleavage-initiation irradiated static toughness
compared to Code K_{IC} curve for HS57 Plate 03
(no margin term used in shift and power reactor FF)

The reference toughness methodology applied to irradiated pressure vessel steels has been demonstrated to be appropriate for the limited data base of available test reactor results. The reference toughness approach also has been compared with the RG 1.99, Rev. 2 method for adjusting the K_{IR}/K_{IC} curves. In all cases when using an appropriate fluence function, the RG 1.99, Rev. 2 method for shifting the K_{IR}/K_{IC} curves is conservative for estimating the bounding shifts in fracture toughness (both static, dynamic, and arrest). In terms of mean toughness shift behavior, the shifts predicted by CVN tests are not a

true indicator of the actual mean fracture toughness shift, but the extra margin included in the RG 1.99, Rev. 2 method (plus the margin built into the original unirradiated K_{IR}/K_{IC} curves) appears to compensate for any CVN shift nonconservatism. The results shown in Figure 1 for a heat of SA533B-1 steel (HSST Plate 03) show the comparison between irradiated static fracture toughness measurements and the shifted K_{IC} curve. Note that two of the higher temperature data values fall outside the curve, but this curve has not included the appropriate fluence function (Eq. 8) nor the RG 1.99, Rev. 2 margin term. If these are included the curve would effectively shift a minimum of an additional 100°F (56°C), which would easily encompass these data values.

The reference toughness approach using 95%-95% tolerance bounds is not quite as conservative as the RG 1.99, Rev. 2 method, but the developed bounds give a better indication of toughness behavior. More data are needed to better make these comparisons; in particular, data from irradiations with lower lead factors (i.e., from actual power reactors) would be most beneficial.

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