Reference Fracture Toughness for Irradiated Reactor 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 (CVN) energy curve; i.e., the shift in the 30 ft-lb (41 J) energy level. Estimates of the 30 ft-lb (41 J) transition temperature shifts (including margins for uncertainty) are often utilized based upon Nuclear Regulatory Commission Regulatory Guide 1.99, Revision 2, which includes the effects of material chemistry and fluence exposure. The estimated or measured Charpy shift is then applied to a lower bound reference (K_{IR}) curve 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 reference toughness method developed by W. Oldfield for estimating statistically-based 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. The other margins included by the Regulatory/ASME Code approach (including those in the original unirradiated K_{IR}/K_{Ic} curves) appear to compensate for any nonconservatism in using the CVN shift approach.

KEYWORDS

Reference Toughness, Fracture Toughness, Radiation Embrittlement, Charpy Energy, Transition Temperature Shifts.

INTRODUCTION

As a result of the fission reaction process occurring during the normal operation of a nuclear power plant, the reactor pressure vessel (which is typically made from ferritic pressure vessel steel) is exposed to neutron irradiation. As a result of this irradiation exposure, the constituent parts of the pressure vessel experience 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 CVN 30 ft-lb (41 J) energy level (T_{30}) with the expected shift in fracture toughness for the irradiated material. For the unirradiated material, the reference toughness temperature, RT_{NDT} (ASME Code III, 1983), is generally obtained by measuring the nil-ductility transition temperature and conducting a series of CVN tests. Analytical/correlative methods have been developed to estimate the shift in RT_{NDT}.

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 (ASME Code XI, 1983).

A reference toughness bounding method has also been proposed (Oldfield et al., 1980) in which a data base of CVN data are 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. 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.

BACKGROUND

Regulatory Guide 1.99, Revision 2

Two measures of radiation damage that can be obtained from CVN 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 (ΔRT_{NDT}) corresponds to the change in the 30 ft-lb (41 J) energy level and is termed ΔT_{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 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, ΔRT_{NDT}, from the unirradiated condition to the irradiated state. The shift in RT_{NDT} is dependent on the chemical composition of the steel, the processing history of the material, 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):

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

where the Initial RT_{NDT} is the reference temperature for the unirradiated material. ΔRT_{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, and FF is a fluence function which has been determined to be appropriate for surveillance data irradiations:

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

where f is the irradiation fluence in units of 10^{19} n/cm^2 for 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: 56°F (31°C) for welds and 34°F (19°C) 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 ΔRT_{NDT} shift.

Once the values of the Initial RT_{NDT}, ΔRT_{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):

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

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

where K_{IR} represents dynamic fracture toughness (ASME Code III, 1983) and K_{IC} represents static fracture toughness (ASME Code XI, 1983). 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 CVN 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 large data base of nuclear pressure vessel materials was compiled for the unirradiated condition. Additional data were also collected from research groups in the U.S., Japan, and France in order to verify the methodology (Oldfield et. al., 1978). Additionally, irradiated toughness data were collected to check the application to irradiated materials; the methodology failed in this last test. Additional work was conducted by W. Oldfield to resolve irradiated toughness bounding predictions (Server et. al., 1988). The work presented herein 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:

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

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.

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 (Oldfield et. al., 1984) from relationships to define a new hyperbolic tangent function for estimated lower bound toughness (K) versus temperature (T):

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

except for the fixed lower bound, L, which is a constant. The function of K varying with T can then be plotted with a fixed lower shelf value of L. Values of the tolerance parameters were developed for different loading rates and different probabilities that a certain percentage of future fracture toughness measurements would fall below a certain lower bound.

Available Data For Comparison

In order to compare the RG 1.99, Rev. 2 approach with the reference toughness curve methodology, the available data had to be first identified. As part of the irradiated study for the reference toughness method, a partial data base was created. Recent other 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 additional data in each of the two sets which were not common.

CALCULATIONS AND RESULTS

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 the different materials and heats identified in Table 1.

For the Regulatory Guide procedure, values of the Initial RT_{NDT} were obtained. 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 ΔRT_{NDT} was calculated based on the copper/nickel chemistry factor, CF, and the fluence factor 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.

The actual fracture toughness data points that were plotted were obtained from the data base sources indicated in Table 1. Much of the toughness data were determined using small specimens (typically 1-T and 1/2-T compacts); therefore,

Table 1. Materials evaluated

Material	Heat Code	Testing Laboratory	Fluence (x 10^{19} n/cm^2)	Fracture Toughness
SA508-2	BCB	NRL/B&W	2.8	Static, Dynamic
SA533B-1	CAB	NRL/CE	1.2,1.7,2.1	Static, Dynamic
	CBB	NRL/CE	4.4	Static, Dynamic
	GP	BCL/W	1.4	Static, Arrest
	BP	BCL/W	1.4	Static, Arrest
	03	MEA	1.3,2.7,5.2	Static
SA302B	ENB	NRL/ETI/FCC	2.7	Static, Dynamic
SAW/ LINDE 80	E19	NRL/W	0.1,0.7,2.5	Static, Dynamic
	E23	NRL/W	0.7	Static, Dynamic
	BW	BCL/W	1.4	Static, Arrest
SAW/ LINDE 0091	E24	NRL/W	0.7	Static, Dynamic
	GW	BCL/W	1.4	Static, Arrest
SAW/ LINDE 124	E4	NRL	2.4	Static, Dynamic
SAW/ LINDE 1092	V84	NRL	1.2	Static

American Society for Testing and Materials (ASTM) validity criteria were exceeded in many cases. Note that the reference toughness methodology should provide a reasonable bound for the data points, whereas the shifted K_{IR}/K_{Ic} curve method should in general only bound the cleavage initiation toughness results.

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):

$$FF = f^{1/2} \, . \qquad (8)$$

This fluence factor may be more appropriate for accelerated test reactor irradiations than the expression derived from surveillance program results indicated by Eq. 3.

DISCUSSION

The CVN ΔT_{30} results from this and other (Hiser, 1985) studies are in very close agreement as shown in Figure 1. This

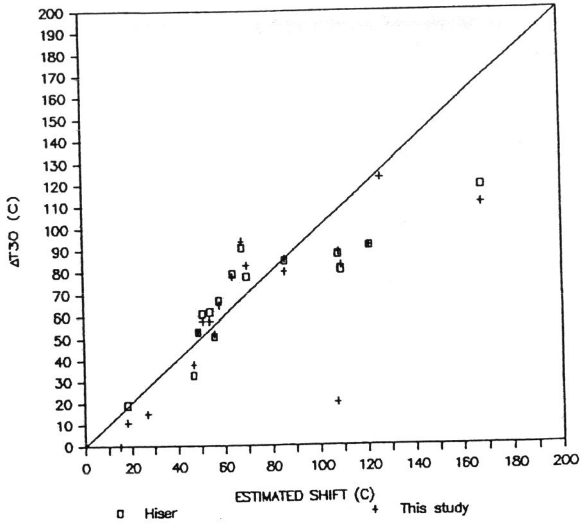

Fig. 1. CVN shifts compared to mean RG 1.99, Rev. 2 predictions.

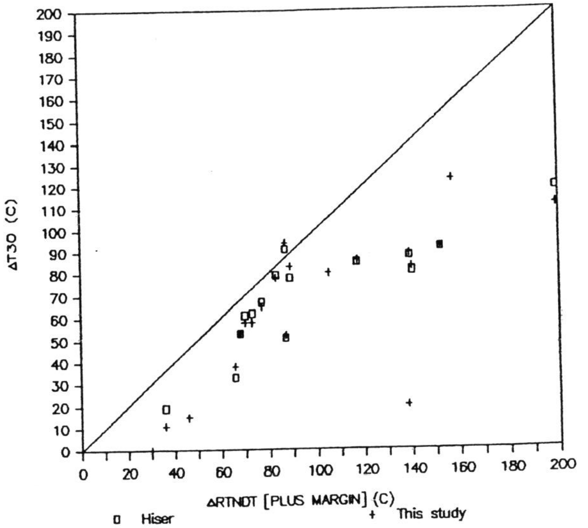

Fig. 2. CVN shifts compared with RG 1.99, Rev. 2 predictions.

good agreement was expected since the approach used here and that used by Hiser were essentially identical: hyperbolic tangent curve fits to both unirradiated and irradiated CVN data were determined, and the temperatures corresponding to the 30 ft-lb (41 J) level were calculated. Figure 1 illustrates the comparison of the ΔT_{30} results with predictions of the shift (without margin) using RG 1.99, Rev. 2; the comparison shows essentially mean behavior with a slight skew to overprediction at higher shift levels.

The comparison of the CVN ΔT_{30} and predicted ΔRT_{NDT} (plus margin) as shown in Figure 2 indicate that the RG 1.99, Rev. 2 method bounds the measured CVN shifts when the margin term is taken into account. The only exception is for the case of a high fluence. In this case, the fluence function of Eq. 8 better estimates the effect of fluence for this accelerated test reactor irradiation. Note that in many cases the Regulatory Guide method significantly overpredicts the CVN measured shifts.

CONCLUSIONS AND RECOMMENDATIONS

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. Except for one case (SA-508-2 forging steel, heat BCB), 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). This one case deserves further investigation, but an adjusted shift in the K_{Ic} curve to account for test reactor flux conditions appears to solve the discrepancy. 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 appear to give a better indication of toughness behavior. 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. 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. Comparisons with some of the other data, which could be made available from NRC sources, would be valuable. Also, values of the adjusted constants for irradiated behavior are needed for other than static fracture toughness and 95%-95% tolerance bounds.

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