Lonnie E. Schubert,¹ Arvind S. Kumar,² Stan T. Rosinski,³ and Margaret L. Hamilton⁴

Effect of Neutron Irradiation on the Impact Properties of A533B Steel

ABSTRACT: A new methodology is proposed to correlate the upper shelf energy (USE) of full size and subsize Charpy specimens of a nuclear reactor pressure vessel plate material, ASTM type A 533 Grade B (A533B) having a low USE (USE < 100 J). The methodology appears to be more satisfactory than those methodologies proposed earlier. The USE was normalized by a normalization factor involving the dimensions of the Charpy specimen, the elastic stress concentration factor, and the plastic constraint at the notch root. The normalized values of the USE were found to be invariant with specimen size. In addition, it was also found that the ratio of the USE of unirradiated to that of irradiated materials was approximately the same for full, half, and third size specimens. The ductile-to-brittle transition temperature (DBTT) increased due to irradiation at 150°C to a nominal fluence of 1.0×10^{19} n/cm² (E > 1 MeV) by 78°, 83°, and 70°C for full, half, and third size specimens, respectively. These shifts in DBTT appeared to be independent of specimen size and notch geometry.

KEY WORDS: Ferritic Steel, A533B, upper shelf energy, size effect, Charpy, embrittlement, correlation.

¹ Graduate Student, Nuclear Engineering, University of Missouri, Rolla, MO 65401

² Professor and Chairman, Nuclear Engineering, University of Missouri, Rolla, MO 65401

³ Senior Member of Technical Staff, Sandia National Laboratories, Albuquerque, NM 87185

⁴ Senior Scientist, Pacific Northwest Laboratory, Richland, WA, 99352

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Introduction

The continued operation of nuclear power plants will depend, in part, on a thorough characterization of reactor pressure vessel (RPV) material properties during the original license period and through extended operation. This can be accomplished through existing, or enhanced, materials surveillance programs. To characterize radiation-induced property changes in RPV materials, specifically ductile-to-brittle transition temperature (DBTT) and upper shelf energy (USE) as determined by the Charpy V-notch test, surveillance programs ideally contain archive samples of what are considered to be the limiting materials (materials most susceptible to irradiation embrittlement) for the RPV. For continued operation of existing commercial plants the continuation, or expansion, of surveillance programs will require large amounts of archive RPV materials which may not be readily available for older RPVs. The available supply of RPV archive materials can be greatly extended through the utilization of subsize specimens.

The use of subsize specimens can also allow direct measurement of material properties through the testing of small amounts of material removed from in-service components. For example, RPV thermal annealing has been shown to be an economic option in a utility's embrittlement management strategy [1]. If a licensee chooses to anneal its RPV, the verification of material property recovery may be required. This can be accomplished through subsize specimen testing of material removed from the RPV.

These examples are only a small number of the potential applications for subsize specimens in the characterization of material properties. The benefits associated with the use of subsize specimens cannot be realized, however, without demonstration of a proper correlation between the test results for subsize and full-size specimens. A correlation is necessary due to the change in specimen behavior when subsize specimens are used. The effect of using subsize specimens is an apparent decrease in both the USE and DBTT. USE is reduced primarily because of a decrease in the specimen cross-section. The DBTT is reduced as a result of a reduction in the constraint for plastic deformation and fracture.

Past attempts to develop appropriate correlation methodologies for USE [2-11] were based on normalizing the value of the USE by an appropriate normalization factor. The resulting value, USE_n , is independent of the specimen size and allows a direct comparison between subsize testing results and anticipated full-size specimen behavior.

The form of the normalization factor is an important element in the development of a correlation methodology that is applicable for materials in both the ductile and brittle regimes. Several previous efforts have identified the fracture volume under the notch root as the normalization factor. The fracture volume was defined in these studies as $(Bb)^{3/2}$ [2,3], and Bb^2 [4,5] where B is the sample width and b is the ligament thickness below the notch. These studies indicated that the use of fracture volume to correlate the USE of full size and subsize specimens proved suitable for a number of highly ductile materials ($USE > 150$ J) [6,7,8].

The use of fracture volume alone as the normalization factor did not work well for correlating the USE of full size and subsize specimens of relatively brittle materials ($USE < 100$ J) [6]. As described in Reference 6, a new correlation factor was developed that was more suitable for relatively brittle materials compared with volume normalization. The

correlation factor was equal to the ratio of the fracture volume and the product of the stress concentration factor at the notch root (K_t) and the span of the specimen (L). This normalization factor considered the effects of the notch root radius and L , which were not included in the previous correlation methodologies. However, the effect of the notch angle and plastic constraint (Q) were not included in this normalization.

In later publications Rosinski et al. [9] and Kumar et al. [10,11] developed correlation methodologies that required partitioning the USE into two components, that is, the energy required for macro-crack initiation (ΔUSE) and crack propagation (USE_p). USE_p was assumed to be equal to the upper shelf energy of fatigue-precracked specimens in which the precrack depth was half the total width of the specimen. ΔUSE was equal to the difference between the upper shelf energy of notched-only specimens (USE) and USE_p and was normalized by the fracture volume.

Having determined ΔUSE of full size specimens based on subsize data, one needs to determine USE_p in order to obtain the USE . It was experimentally determined that the ratio of USE and USE_p were approximately equal for full and subsize specimens.

Kumar et al. [11] later improved the above methodology further by normalizing the ΔUSE by the ratio of the fracture volume, and the product of the specimen span and the plastic stress concentration factor. The ratio of USE and USE_p was still required to be invariant with specimen size. In this methodology, the effect of the notch angle was not included in the normalization factor.

Kayano et al. [12] considered the effects of the notch angle and plastic constraint in their methodology, which worked well for correlating the USE of full size and subsize specimens fabricated from a number of ferritic steels. Their normalization factor was equal to the ratio of the fracture volume and a modified stress concentration factor, K_t'' , equal to the product of K_t and the ratio ($Q_{\text{subsize}}/Q_{\text{full size}}$). For the full size specimens K_t'' is equal to K_t .

The present study continues the application of the previously developed methodology [6] to include the effects of plastic constraint and the notch angles on the upper shelf energy. Both unirradiated and irradiated (1.0×10^{19} n/cm², $E > 1$ MeV) A533B plate material was tested. When the effect of the notch angle is included, as in the present study, the normalization provides better correlation between full size and subsize upper shelf energies. The normalization factor used in this study is given below:

$$\text{Normalization factor (NF)} = \frac{Bb^2}{K_t' L} \quad (1)$$

where B = specimen thickness

b = specimen thickness under notch (ligament)

K_t' = modified stress concentration factor = $K_t \times Q$

L = specimen span

The effect of specimen size on the DBTT has also been studied extensively. The correlation methodologies developed can be grouped into two basic categories. In the first category of methodologies, the difference between the DBTT of full size and subsize specimens is a constant independent of the material [8,13]. However, the width of the scatter band in these studies varied from 25° to 65°C for half size, 50°C for third size, and 65°C for 3 x 4 mm specimens.

In the second category of DBTT correlation methodologies, the effects of stress concentration factor and/or specimen dimensions are considered. Kurishita et al. [14] concluded that the DBTT of full and subsize specimens were equal provided the elastic stress concentration factor, K_t , for full and subsize specimens was equal ($K_t = 4.8$). Kayano et al. [12] claimed that the DBTTs of full and subsize specimens were equal if the DBTTs were determined

from a graph of USE and temperature, T , normalized by $Bb^2/K_t''L$ and $\sqrt{K_t''}$, respectively.

Louden et al. [6] showed that for a number of steels the shift in the normalized values of DBTT due to thermo-mechanical treatments was equal for full and subsize specimens. DBTT was normalized by the maximum elastic normal stress at the notch root.

Experimental Procedure

All specimens used in this study were machined from A533B plate material obtained from the Electric Power Research Institute, Charlotte, NC. The chemical composition of this material is 0.22 C, 1.35 Mn, 0.012 S, 0.010 P, 0.18 Si, 0.53 Mo, 0.62 Ni, and 0.14 Cu. The microstructural analysis is described in an earlier publication [9].

Dimensions for both full and subsize specimens are given in Figure 1. The spans for full, half, and third size specimens are 46 mm, 20 mm, and 20 mm, respectively. The full size specimen dimensions are in accordance with ASTM standard E23. The dimensions used in this study for half and third size specimens are similar to those used in other investigations.

All the specimens were tested in the same instrumented drop tower utilizing an anvil with two test locations for the two specimen lengths and a moveable striker. Note that the half size and third size specimens have the same length. Data from each test were recorded on a digital oscilloscope and transferred to an IBM PC AT for storage and analysis.

Two load cells (4,500 kg for full-size and 1,600 kg for subsize) were used to increase the sensitivity over the lower load ranges that were relevant to the subsize specimens. Both load cells were calibrated statically to ensure that their response was linear over the desired range.

The impact velocity of the crosshead was calibrated for each specimen size by attaching a flag of known dimensions to the crosshead; it was positioned so that the flag passed an infrared sensor just prior to impact, causing a change in voltage. The duration of this change was measured on the oscilloscope and the velocity calculated. Velocity was determined as the average of at least 5 calibration runs.

SPECIMEN CONFIGURATION - All Dimensions in mm

Figure 1. Specimen configurations of full, half, and third size specimens.

Temperature control for all specimens was accomplished in a conditioning chamber where high temperatures were attained with a heated stream of argon and low temperatures were achieved by using cold nitrogen gas. Temperature control was achieved by adjusting the rate of gas flow into the conditioning chamber. Independent temperature calibrations were performed for each specimen size; 4 thermocouples were attached at various locations along the length of the specimen to quantify the variability in temperature. Each specimen was kept at the test temperature for a sufficient amount of time prior to testing to ensure temperature stabilization.

The specimens were placed by pneumatically driven pistons that moved a specimen from its initial position, into the conditioning chamber, and out of the chamber onto a positioning arm. A stepping motor was used to rotate the arm, dropping the specimen into the appropriate position on the anvil for testing. The elapsed time between the exit of the sample from the conditioning chamber and the impact was 1 - 2 seconds, well within the maximum 5-second delay permitted by ASTM standard E23.

Results and Discussion

Neutron irradiation of the A533B steel at ~150°C to a nominal fluence of 1.0×10^{19} n/cm² ($E > 1$ MeV) caused a moderate reduction in the upper shelf energy and a substantial increase in the DBTT. Test results and the application of the developed correlation methodologies are discussed below.

The Charpy impact test results of full, half, and third size specimens (unirradiated and irradiated) are presented in Figures 2, 3, and 4, respectively. The data were curve fit using a hyperbolic tangent function of the form

$$E = a + b * \tanh[c(T - d)] \quad (2)$$

where E = absorbed energy, J
 a, b, c = constants
 d = constant = DBTT
 $a + b$ = USE
 T = temperature, °C

Upper Shelf Energy (USE)

The USE values obtained through tanh curve fitting of the data generated from testing unirradiated and irradiated full, half, and third size Charpy samples are given in Table 1. The irradiation was performed at 150°C to a target fluence of 1.0×10^{19} n/cm² ($E > 1$ MeV). It is interesting to note that the ratio of full size unirradiated USE and irradiated USE is within 5% of the half size and third size ratios. A similar conclusion was reached in two other irradiation experiments that were conducted by the authors [15,16]. For the reference correlation material studied (HSST Plate 02 Heat D with a USE of 152 J), the ratios of unirradiated and irradiated USE for full and third size specimens were 1.14 and 1.10, respectively [15]. For HSST

Figure 2. Charpy impact energy of unirradiated and irradiated full size specimens (1×10^{19} n/cm², $E > 1$ MeV).

Figure 3. Charpy impact energy of unirradiated and irradiated half size specimens (1×10^{19} n/cm², $E > 1$ MeV).

Figure 4. Charpy impact energy of unirradiated and irradiated third size specimens (1×10^{19} n/cm², $E > 1$ MeV).

weld 72W, the ratios for full, half, and third size specimens were 1.22, 1.40, and 1.36, respectively.

Table 1 - Unirradiated and Irradiated USE Values For A533B Material

Size	Unirradiated USE (J)	Irradiated USE (J)	Ratio
Full	63.4	51.8	1.22
Half	13.3	11.3	1.18
Third	4.7	4.0	1.18

This trend suggests that if the ratio of the unirradiated and irradiated USEs for subsize specimens is known, the full size USE of an irradiated specimen can be predicted within approximately 10% of the experimental value. However, this prediction requires that the unirradiated USE for full size specimens be known. For example, if third size specimen test data were used from the present study (Table 1) to predict the value of full size USE in the irradiated state, the predicted value would be 53.7 J (= 63.4 J/1.18, where 63.4 J equals the full size USE in the unirradiated condition and 1.18 equals the ratio of unirradiated and irradiated USE for third size specimens). The predicted value of 53.7 J compares well with the measured value of 51.8 J for the irradiated full size specimens. This trend should be further investigated for different materials under varying irradiation conditions.

Table 2 shows the measured and normalized USE values of full, half, and third size specimens, under both unirradiated and irradiated conditions. The USE is normalized by the normalization factor in Equation 1. The values of the parameters used in Equation 1 are given in Table 3. K_t' is the product of K_t , the elastic stress concentration factor at the notch root, and the plastic constraint

$$Q = 1 + \frac{\pi}{2} - \frac{\theta}{2} \quad (3)$$

where θ is the notch angle in radians [17]. Based on the notch angles given in Table 3, the values of plastic constraint, Q , for full, half, and third size specimens are 2.18, 2.83, and 2.83 respectively. Therefore, the values of K_t' for full, half, and third size specimens are 10.49, 17.23, and 14.23, respectively. Normalization of the experimental USE values by the normalization factor in Equation 1 yields the values of USE_n : 4768, 5100, and 5053 J/cm² for full, half, and third size specimens, respectively. The half size USE_n is only 7% higher and the third size USE_n is only 6% higher than the full size USE_n .

Table 2 - Measured and Normalized USE Values for Unirradiated and Irradiated A533B Material

Size	Unirradiated USE (J)	Unirradiated USE _n (J)	Irradiated USE (J)	Irradiated USE _n (J)
Full	63.4	4768	51.8	3896
Half	13.3	5100 (+7%)	11.3	4340 (+11%)
Third	4.7	5053 (+6%)	4.0	4300 (+10%)

Table 3 - Specimen Parameters

Size	Span, L (cm)	Thickness, B (cm)	Ligament Size, b (cm)	K _t	θ (radians)	Notch Root Radius, ρ (cm)
Full	4.6	1.0	0.80	4.81	0.785	0.025
Half	2.0	0.5	0.424	6.09	0.524	0.008
Third	2.0	0.33	0.282	5.03	0.524	0.008

In order to predict the USE of full size specimens in the unirradiated state based on subsize specimen data (e.g. third size specimen data), one would assume that the full size USE_n is equal to the third size USE_n, 5053 J/cm². A USE_n value of 5053 J/cm² predicts a USE for full size specimens of 67.0 J:

$$\begin{aligned}
 \frac{USE_{\text{full size}}}{\left(\frac{Bb^2}{K_t' L} \right)_{\text{full size}}} &= \frac{USE_{\text{third size}}}{\left(\frac{Bb^2}{K_t' L} \right)_{\text{third size}}} = 5053 \text{ J/cm}^2 \\
 USE_{\text{full size}} &= 5053 \text{ J/cm}^2 \times \left(\frac{Bb^2}{K_t' L} \right)_{\text{full size}} \\
 &= 5053 \text{ J/cm}^2 \times \frac{1 \text{ cm} \times (0.8)^2 \text{ cm}^2}{10.49 \times 4.6 \text{ cm}} \\
 &= 67.0 \text{ J}
 \end{aligned}$$

This compares well with the experimentally measured value of 63.4 J given the normal scatter in the experimental Charpy data. If a similar calculation was performed with the half size data,

the predicted value of full size specimens would be 67.6 J, showing a reasonably good prediction (within 7%).

For the irradiated material the predicted values of the full size USE based on half and third size specimen data are 46.5 and 46.9 J, respectively. These values are within ~10% of the measured full size USE of 51.8 J in the irradiated condition. Given the normal scatter in the measured values of Charpy impact energies, the predicted values are quite satisfactory.

Table 4 compares the normalized USE values obtained for full, half, and third size Charpy samples through the correlation methodology used in this study and the application of earlier correlation methodologies to the data generated in this study for unirradiated A533B plate material with an upper shelf energy < 100 J. The maximum deviation in the normalized values of subsize specimens compared with full size specimens is approximately 7% for the correlation used in this study. Larger deviation from full size results was observed for the remaining correlation methodologies.

Table 4 - Comparison of Normalized USE Values for Unirradiated A533B Material (Methodologies Applicable for USE < 100 J)

Size	This Study $NF = Bb^2/K_t L$ (J/cm ²)	Louden et al. [6] $NF = Bb^2/K_t L$ (J/cm ²)	Kayano et al. [12] $NF = Bb^2/K_t''$ (J/cm ³)	Lucas et al. [4,5] $NF = Bb^2$ (J/cm ³)
Full	4768	2192	476	99
Half	5100 (+7%)	1802 (-18%)	901 (+89%)	148 (+49%)
Third	5053 (+6%)	1785 (-19%)	893 (+88%)	178 (+79%)

The correlation methodology of Loudon et al. does not work as well for this material. The predicted full size values based on subsize data are lower by 18 - 19% of the measured value in the unirradiated condition. This was expected since the correlation methodology of Loudon et al. does not include the effects of plastic constraint.

Use of the correlation methodology of Kayano et al. on the data generated in this study demonstrates a significant deviation from the experimentally obtained full size Charpy USE. This correlation does not include the effect of specimen span, L, in the normalization factor. Therefore, the varying specimen length utilized in this study cannot be accommodated by the Kayano correlation.

The volume normalization utilized by Lucas et al. also demonstrated a significant deviation from the experimentally obtained full size Charpy USE. This was expected since this correlation was previously shown to not work well for materials with a USE value < 100 J [6,14].

Table 5 compares the normalized USE values obtained for full, half, and third size Charpy samples through the correlation methodology used in this study and the earlier studies discussed above for irradiated A533B plate material with an upper shelf energy < 100 J. The maximum deviation in the normalized values of subsize specimens compared with full size specimens is approximately 11% for the correlation used in this study. Again, a larger deviation from full size results was observed for the remaining correlation methodologies.

Table 5 - Comparison of Normalized USE Values for Irradiated A533B Material (Methodologies Applicable for USE < 100 J)

Size	This Study $NF = Bb^2/K_t L$ (J/cm ²)	Louden et al. [6] $NF = Bb^2/K_t L$ (J/cm ²)	Kayano et al. [12] $NF = Bb^2/K_t''$ (J/cm ³)	Lucas et al. [4,5] $NF = Bb^2$ (J/cm ³)
Full	3896	1791	389	81
Half	4340 (+11%)	1531 (-14%)	994 (+155%)	126 (+55%)
Third	4300 (+10%)	1520 (-15%)	986 (+153%)	151 (+87%)

The use of half and third size Charpy samples and the Loudon correlation methodology predicts full size USE values that are approximately 15% lower than the measured full size value. The use of the Kayano correlation predicts full size USE values that are over 150% higher than the measured full size value. Use of the volume normalization correlation of Lucas et al. predicts full size USE values that are 55 - 87% higher than the measured full size value. These correlations demonstrate larger deviations from full size results than the methodology presented in this study for the same reasons identified above.

It is to be noted that the A533B plate material used in this study exhibited a very low unirradiated USE, which is atypical of A533B Class 1 steels. The unusually low USE was a result of a very large grain structure in this material (grain size ASTM 0.5). As a consequence, only the correlation methodologies developed for low USE material (i.e., < 100 J) were compared with the methodology developed in this study. Previous correlation methodologies developed for higher USE material (i.e., > 150 J) were not applicable to the results obtained in this effort. However, preliminary results obtained through the application of the methodology developed in this study to other higher USE RPV materials (> 150 J) suggest a more reasonable correlation for these materials than use of the volume normalization alone.

Ductile-Brittle Transition Temperature

DBTT values of both unirradiated and irradiated specimens are given in Table 6. The irradiation was performed at 150°C to a target fluence of 1.0×10^{19} n/cm² (E > 1 MeV). The shifts in DBTT for full, half, and third size specimens were 78°, 83°, and 70°C, respectively. Considering the normal scatter in Charpy data, it appears that the shifts were independent of specimen size and geometry. Further investigation into a suitable correlation for DBTT is under way.

Table 6 - DBTT Values of Unirradiated and Irradiated A533B Material

Size	Unirradiated, °C	Irradiated, °C	Shift, °C
Full	88	166	78
Half	120	203	83
Third	100	170	70

Conclusion

A new methodology has been developed to correlate the upper shelf energy of full size and subsize specimens and was successfully demonstrated on a low USE material. The methodology incorporated the effects of all of the specimen dimensions, including the effects of the notch root radius and the notch angle. This energy can be normalized with the normalization factor equal to $(Bb^2/K_t'L)$. K_t' is the modified stress concentration factor at the notch root and is the product of the elastic stress concentration factor and the plastic constraint. B, b, and L are the width, ligament size, and the span of the specimen. The predicted values of full size specimen USE in the unirradiated condition, based on half size and third size data exceeded the measured values by 7% and 6%, respectively. For the irradiated material, the predicted values were 11% and 10% higher based on the half and third size specimens, respectively. It was also observed that the ratio of the upper shelf energies of unirradiated and irradiated materials was approximately equal for full, half, and third size specimens. The shifts in DBTT due to irradiation were found to be practically independent of specimen size or notch geometry.

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