Reactor Pressure Vessel Structural Integrity Research In the U.S. Nuclear
Regulatory Commission HSST and HSSI Programs*

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Reactor Pressure Vessel Structural Integrity Research In the U.S. Nuclear Regulatory Commission HSST and HSSI Programs

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Development continues on the technology used to assess the safety of irradiation-embrittled nuclear reactor pressure vessels containing flaws. Fracture mechanics tests on reactor pressure vessel steel have shown that (a) local brittle zones do not significantly degrade the material fracture toughness, (b) constraint relaxation at the crack tip of shallow surface flaws results in increased fracture toughness, and (c) biaxial loading reduces but does not eliminate the shallow-flaw fracture toughness elevation. Experimental irradiation investigations have shown that (a) the irradiation-induced shift in Charpy V-notch versus temperature behavior may not be adequate to conservatively assess fracture toughness shifts due to embrittlement and (b) the wide global variations of initial chemistry and fracture properties of a nominally uniform material within a pressure vessel may confound accurate integrity assessments that require baseline properties.

INTRODUCTION

1. Regulatory requirements limit the permissible accumulation of irradiation damage in the material of a reactor pressure vessel. Irradiation damage limits are set such that required fracture prevention margins are maintained throughout the nuclear plant licensed operating period. Regulatory requirements are based on fracture mechanics technology and utilize materials aging data drawn from mandatory reactor vessel irradiation damage surveillance programs.

2. In recent years it has become evident that a number of nuclear plants will exceed the regulatory limits on irradiation damage to the reactor vessel material before the end of their current operating license period (ref. 1). One result from this development is that a number of nuclear industry organizations have gained experience in the application of fracture margin assessment technology. This experience has resulted in the identification of a number of issues with the technology in its present form. Data from irradiation testing programs, operating plant surveillance programs, and large-scale fracture technology validation tests have identified additional issues. The Nuclear Regulatory Commission (NRC)-funded Heavy Section Steel

Technology (HSST) and Heavy Section Steel Irradiation (HSSI) Programs at Oak Ridge National Laboratory (ORNL) are performing the research required to resolve these issues and further develop and refine the fracture margin assessment technology.

3. This paper presents a brief overview of the current status of fracture prevention regulatory requirements and the associated fracture margin assessment technology. Issues identified with the technology are reviewed, and some of the research programs implemented to resolve those issues are described.

REGULATORY REQUIREMENTS AND RESEARCH NEEDS

4. Irradiation embrittlement and low vessel temperatures both act to reduce the cleavage fracture toughness of reactor vessel material. Regulatory requirements for fracture prevention, therefore, focus on operating and potential accident conditions that generate both low temperatures and high stresses in the reactor vessel material. For some vessels, however, an additional concern exists at higher operating temperatures. These vessels contain materials with a reduced resistance to failure by ductile tearing. Additional requirements are placed on vessels in this latter category to assure that adequate ductile tearing fracture prevention margins are maintained.

5. A summary of the regulatory process for assuring retention of adequate fracture prevention margins in reactor pressure vessels is presented in

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Fig. 1. A mandatory reactor vessel surveillance program (refs 2,3) provides data on the progressive effect of irradiation embrittlement on the vessel material fracture toughness. Changes in fracture toughness are measured using small Charpy specimens rather than large fracture toughness test specimens and are expressed in terms of (a) lateral translation (ΔRT_{NDT}) of the Charpy energy curve at the 41-J (30 ft-lb) energy level and (b) decrease in the upper shelf fracture energy (ΔUSE) of the material. Regulatory requirements for preservation of required fracture prevention margins are expressed in terms of an adjusted reference nil-ductility transition temperature (RT_{NDT}) (refs 4–6) and a minimum acceptable level of upper shelf energy (USE) (ref. 4).

6. Surveillance program data are used to periodically adjust the upper bound to the reactor pressure-temperature (P-T) operating envelope (refs 5, 7), as shown in the left-hand branch in Fig. 1. Adjustment is required to maintain margins against fracture of 2 on pressure loading and 1 on simultaneously applied thermal loading. Fracture prevention margins are calculated assuming an inner surface flaw, having a depth corresponding to 25% of the wall thickness. The fracture margin assessment analysis must be performed using lower-bound (K_{IR}) dynamic fracture toughness properties (ref. 5). Adjustment of the P-T curve in response to irradiation embrittlement of the reactor vessel material has the effect of restricting the permissible reactor P-T operating envelope, as illustrated in Fig. 2. It is evident from Fig. 2 that a high irradiation-induced RT_{NDT} can restrict the P-T operating envelope to the point where reactor heatup and cooldown become very difficult

Fig. 1. Regulatory requirements limit permissible irradiation embrittlement of reactor vessel materials such that adequate fracture prevention margins are maintained under both operating and potential accident loading conditions.

Fig. 2. Adjustment of reactor P-T curve in response to irradiation embrittlement of vessel material severely restricts permitted reactor operating envelope.

operations. This is particularly true for reactors with a fixed setpoint low-temperature overpressure protection (LTOP) system. This difficulty has sparked interest in refinement of the technology used to define the P-T curve and the associated LTOP setpoint. Specific research topics relating to this issue include (a) the effect of local brittle zones and pop-ins on the material fracture toughness and (b) improved correlations for predicting the irradiation-induced shift in the material RT_{NDT} .

7. The center branch of Fig. 1 summarizes the regulatory requirements for demonstration of acceptably low failure probability when the reactor vessel is exposed to pressurized thermal shock (PTS) loading. A probabilistic PTS analysis is required when irradiation damage has caused the adjusted RT_{NDT} for the vessel material to reach screening limits. These limits have been set at 132.2°C (270°F) for plates, forgings, and axial weld material and 148.9°C (300°F) for circumferential weld material (ref. 6). Acceptable methodology for performing a plant-specific probabilistic PTS analysis is defined in NRC *Regulatory Guide 1.154* (ref. 8).

8. Principal features of the fracture mechanics elements of the PTS analysis procedure are illustrated in Fig. 3. Thermal stresses are highest adjacent to the inner surface of the vessel where the effects of irradiation embrittlement and transient temperatures combine to produce the maximum reduction in the material fracture toughness. The net result from this combination of conditions is that the majority of crack initiations are predicted to originate from shallow flaws located in the inner surface of the vessel. The dominant influence of shallow surface flaws

Fig. 3. Intersection of applied K_I curve (stress and flaw geometry dependent) with material fracture toughness curves (temperature, fluence, and material dependent) defines crack initiation and arrest behavior at point in time during a PTS transient.

generates a need for quantitative assessments of (a) the effect of reduced crack-tip constraint on the material fracture toughness associated with shallow flaws, (b) the effect of prototypical biaxial stress states on the material shallow-flaw fracture toughness, and (c) the effect of stainless steel cladding on the initiation of cracks from shallow surface flaws.

9. The requirement for the reactor vessel material to maintain a minimum USE not less than the 68-J (50-ft-lb) regulatory limit is reflected in the right-hand branch of Fig. 1. The regulatory requirement (ref. 4) states that this condition must be maintained "unless it is demonstrated in a manner approved by the Director, Office of Nuclear Power Regulation, that lower values of upper shelf energy will provide margins of safety against fracture equivalent to those required by Appendix G of the ASME Code." Acceptable procedures for demonstrating the retention of adequate margins against fracture for low-upper-shelf (LUS) material have recently been published in American Society of Mechanical Engineers (ASME) Code Case N-512 (ref. 9) and Draft Regulatory Guide DG-1023 (ref. 10). These procedures evaluate the stability of a reference flaw in LUS material using an irradiation-adjusted material J-R curve. A need exists therefore for a J-R curve data base for LUS materials.

FRACTURE MECHANICS RESEARCH

10. Local brittle zones and pop-ins. McCabe et al. have evaluated the K_{Ic} scatter band and lower-bound toughness for pressure vessel material both with and without pop-ins (ref. 11). Results from their evaluation are reproduced in Fig. 4. They show that in general the pop-in results lay within the K_{Ic} scatter band for specimens that failed without pop-ins. At most, the inclusion of the pop-in data marginally lowers the lower bound of the K_{Ic} data. The interim conclusion from this research on irradiated material is that it appears that a case can be made for the use of a fracture toughness curve higher than the K_{IR} curve for defining reactor LTOP setpoints. The selected curve, however, may not be as high as the K_{Ic} curve. Additional data for irradiated material must be included in the data base before this interim conclusion can be validated.

11. Crack-tip constraint effects for shallow flaws. Fracture occurs when the opening-mode tensile stresses at the tip of a crack in a brittle material exceed a critical value over a finite length (ref. 12). Local yielding of the material at the crack tip limits the buildup of opening-mode stresses and thereby directly influences fracture toughness. Tensile hydrostatic stresses contribute directly to the crack-tip opening-mode tensile stresses but do not influence yielding. Crack-tip constraint is the term used to describe conditions that influence the hydrostatic component of the crack-tip stress field. Low constraint reduces the hydrostatic stress contribution to the opening-mode stress and thereby increases fracture toughness. Shallow flaws in a reactor pressure vessel have reduced crack-tip constraint because of the proximity of the inner surface of the vessel. Shallow-flaw fracture toughness would therefore

Fig. 4. Test data for irradiated high-copper weld (73W) indicate that lower-bound fracture toughness curve reflecting pop-in test data differs very little from one derived from K_{Ic} data.

be expected to be higher than the toughness derived from tests on deep-flaw specimens.

12. Fracture toughness tests have been performed on single-edge-notch-bending (SENB) test specimens using both deep ($a/W = 0.5$) and shallow ($a/W = 0.1$) flaws (ref. 13). Beam specimens used in these tests are shown in Fig. 5. The beams were fabricated from A533B material and were nominally 100 mm (4 in.) deep. Use of beams with this depth permitted testing of shallow flaws with depths in the range identified as the critical depth range for PTS analysis. Use of prototypical flaw depths reduced the uncertainties associated with extrapolation of shallow-flaw fracture toughness data for application to full-scale structures.

13. Shallow-flaw and deep-flaw fracture toughness data generated in these tests are plotted in Fig. 6. The data are seen to be grouped into two separate families corresponding to the shallow and deep flaws, respectively. Lower-bound curves fitted to the data show a 35°C (63°F) shift in

Fig. 5. 100-mm-deep beams were used in shallow-flaw test program to permit full-scale testing of surface flaws having depths in the range that PTS analysis has shown to be the controlling range for crack initiation.

Fig. 6. Data from shallow-flaw fracture toughness testing program show that shallow-flaw effect produces substantial increase in toughness at temperatures in transition region of fracture toughness curve.

RT_{NDT} between the two data sets. It is appropriate to note that most of the shallow-flaw fracture toughness data plotted in Fig. 6 are for a flaw depth of 10 mm (0.4 in.). Shallow-flaw fracture toughness would be expected to be flaw-depth-dependent, with larger shifts in the RT_{NDT} anticipated as the flaw depth decreases. Note that the shallow-flaw effect on fracture toughness is significant in the lower transition range of the fracture toughness curve, which is the area of the curve important to PTS analysis, but is not significant on the lower-shelf portion of the curve.

14. Dual parameter fracture toughness corrections and correlations have been proposed to provide a quantitative assessment of the effect of reduction of crack-tip constraint on fracture toughness. Principal features of the J-A_{cr} fracture toughness correction proposed by Dodds, Anderson, and Kirk (ref. 14) and the J-Q dual parameter fracture toughness correlation proposed by O'Dowd and Shih (refs 15,16) are illustrated in Fig. 7. In the J-Q fracture toughness correlation, Q defines the departure of the stress-state-dependent

A_{cr} is the area over which stresses exceed the reference stress ratio (σ_R/σ_0) for crack initiation

Q is a parameter characterizing the hydrostatic stresses and therefore the maximum principal stresses ahead of the crack

Fig. 7. Dual-parameter corrections and correlations have been proposed as means for adjusting fracture toughness data for effects of crack-tip constraint.

opening-mode stress distribution on the crack plane from the opening-mode stress distribution derived by Hutchinson (ref. 17) and Rice and Rosengren (ref. 18) (HRR) for a highly constrained crack tip. Q is therefore expressed as follows:

$$Q = \frac{\sigma_{yy} - (\sigma_{yy})_{HRR}}{\sigma_0} \quad (1)$$

where σ_{yy} is the crack-tip opening-mode stress distribution for a specific constraint condition, $(\sigma_{yy})_{HRR}$ is the corresponding stress distribution for the HRR constraint condition, and σ_0 is the material yield stress. In physical terms, Q is the difference between the hydrostatic stress associated with the reference HRR crack-tip stress distribution and the crack-tip hydrostatic stress associated with a specific constraint condition.

15. The data set of reference 13 covers two constraint configurations. These are deep flaws with a crack depth (a) to beam depth (W) ratio (a/W) of 0.5 and shallow flaws with an a/W ratio of 0.1. Professor R. Dodds of the University of Illinois has performed a J-Q analysis of these test specimens under an HSST Program subcontract. J-Q trajectories for both the shallow- and deep-flaw beams are shown in Fig. 8 together with a J-Q loading trajectory from one of the HSST Program wide-plate tests (ref. 19). Fracture toughness data from each of the test series are shown in Fig. 8 superimposed on the appropriate J-Q loading trajectory. Upper and lower bounds to the resulting J-Q scatter band are represented in Fig. 8 by straight lines. The dual parameter (J-Q) fracture toughness scatter band shows that both fracture toughness and data scatter increase as crack-tip

Fig. 8. J-Q failure locus scatter band shows increased toughness and increased scatter as crack-tip constraint decreases (Q becomes more negative).

constraint is reduced. Both of these trends can have a significant influence on the outcome of a probabilistic analysis of reactor vessel failure rates under PTS loading.

16. Biaxial fracture toughness testing of shallow flaws. Biaxial stress fields are produced in a reactor pressure vessel wall by both pressure loading and through-wall temperature gradients. A typical biaxial stress field is shown in Fig. 9, together with a constant-depth, shallow-surface flaw. One of the principal stresses is seen to be aligned parallel to the crack front. There is no counterpart of this far-field, out-of-plane stress in the shallow-flaw fracture toughness tests described previously. The far-field, out-of-plane stress has the potential to increase stress triaxiality (constraint) at the crack tip and thereby reduce some of the fracture toughness elevation associated with shallow flaws. The HSST biaxial test program was instituted to investigate this effect (ref. 20).

17. A cruciform test specimen was developed to investigate the effects of biaxial loading on the shallow-flaw fracture toughness of pressure vessel steels. Conceptual features of the specimen are illustrated in Fig. 10. The specimen design is capable of reproducing a linear approximation of the nonlinear biaxial stress distribution shown in Fig. 9. The cruciform design, coupled with a statically determinate load reaction system, permits the specimen to be loaded in either uniaxial (four-point bending) or biaxial (eight-point bending) configurations. Tests of nominally identical specimens can thus be performed with the level of stress biaxiality as the only test variable.

18. Test values for K_{Jc} are shown in Fig. 11 superimposed on data from the shallow-flaw and deep-flaw SENB tests. The cruciform beam data

Fig. 9. PTS loading produces biaxial stresses in reactor vessel wall with one of the principal stresses aligned parallel with tip of constant-depth shallow surface flaw.

Fig. 10. Conceptual features of cruciform shallow-flaw biaxial fracture toughness test specimen.

Fig. 11. Biaxial loading resulted in shallow-flaw fracture toughness values below lower-bound values obtained under uniaxial loading.

plotted in Fig. 11 correspond with the point on the crack front at which posttest examination showed the crack to have initiated. The cruciform specimen tested under uniaxial loading produced a fracture toughness close to the lower bound of the fracture toughness scatter band from the shallow-flaw SENB tests. Biaxial loading of the cruciform specimen produced two results below the lower bound of results from the shallow-flaw SENB data

set. The two data points from biaxial loading tests on the cruciform specimen are seen to be closely matched.

19. Test data generated to date are consistent with expectations for the biaxial tests. Biaxial loading appears to reduce K_{Ic} below the values associated with shallow flaws, but not down to the lower-bound values associated with highly constrained deep flaws. There are also indications that biaxial loading may reduce the scatter of shallow-flaw fracture toughness data. The biaxial testing program is, however, in its infancy, and the data currently available from the program are not sufficient to support an assessment of biaxial loading effects on shallow-flaw fracture toughness at this time.

IRRADIATION EFFECTS RESEARCH

20. K_{Ic} curve shifts in high-copper welds. To account for the effects of neutron irradiation on toughness, the initiation and arrest fracture toughness curves as described in Sect. XI of the *ASME Boiler and Pressure Vessel Code* are shifted upward in temperature without change in shape by an amount equal to the shift (plus a margin term) of the Charpy V-notch (CVN) impact energy curve at the 41-J (30-ft-lb) level. Such a procedure implies that the shifts in the fracture toughness curves are the same as those of the CVN 41-J energy level and that irradiation does not change the shapes of the fracture toughness curves.

21. The objectives of the HSSI Fifth and Sixth Irradiation Series are to determine the K_{Ic} and K_{Ia} curve shifts and shapes for two irradiated high-copper, 0.23 and 0.31 wt %, submerged-arc welds (72W and 73W, respectively). Irradiations were performed at 288°C (550°F) to average fluences of about 1.5×10^{19} neutrons/cm² ($E > 1$ MeV). Tests included tensile, CVN impact, drop-weight, and fracture toughness. Compact specimens up to 203 and 101 mm (8 and 4 in.) in thickness were tested in the unirradiated and irradiated conditions, respectively. The detailed results of testing have been presented previously (ref. 21). For the CVN results, the 41-J (30-ft-lb) transition temperature shifts were 72 and 82°C (130 and 148°F), while the 68-J (50-ft-lb) shifts were 82 and 105°C (148 and 189°F) for welds 72W and 73W, respectively.

22. For those fracture specimens that met the American Society for Testing and Materials (ASTM) E 399 criteria for a valid K_{Ic} , the K_{Ic} value is used in the analysis. For those specimens

that exhibited curvature in the load-displacement record, indicative of plastic deformation and, perhaps, stable ductile tearing, the K_{IC} value was used. To include both linear-elastic and elastic-plastic fracture mechanics calculations, data have been designated K_{cI} for cleavage fracture toughness. As was illustrated in Fig. 4, an unexpectedly large number of cleavage pop-ins occurred in the irradiated data set. Of 156 unirradiated compact specimens, only two exhibited pop-ins, as compared to 36 pop-ins for the 110 irradiated specimens. To be conservative, only the initial pop-in is used herein to determine cleavage fracture toughness for those specimens exhibiting pop-ins.

23. Linearized two- and three-parameter nonlinear regression analyses similar in form to the K_{IC} curve in Sect. XI of the *ASME Code* gave fracture toughness temperature shifts, measured at the $100\text{-MPa}\sqrt{\text{m}}$ ($91\text{-ksi}\sqrt{\text{in.}}$) level, of about 83 and 99°C (149 and 178°F) for 72W and 73W, respectively. The analyses show some decreases in slopes for the irradiated data for both welds. These decreases, however, are only about 4.1 and 6.9% for 72W and 73W, respectively, with large enough standard errors to imply a low statistical significance of the slope changes. For the combined data sets, with temperature normalized to RT_{NDT} , the differences are about 10, 15, and 17°C (18, 27, and 31°F) between the unirradiated and irradiated mean fracture toughness curves at K_{cI} values of 50, 100, and 200 $\text{MPa}\sqrt{\text{m}}$ (46, 91, and 182 $\text{ksi}\sqrt{\text{in.}}$), reflecting the average change in curve shape.

24. Figure 12 shows a plot of the irradiated fracture toughness data and various curves for 73W. The ASME K_{IC} curve is shown for both the unirradiated and the irradiated conditions after shifting the curve upward. The dashed curves labeled 1 through 3 represent different methods for shifting the K_{IC} curve. The curve labeled 4 represents the ASME K_{Ia} curve shifted upward in temperature equal to the Charpy 41-J (30-ft-lb) shift (ΔTT_{41}). The curve labeled 5 is the five-percentile curve produced using the method of Wallin (ref. 22). For 72W, the data are bounded by the ΔTT_{41} + margin curve and the ΔK_{cI} curve, but neither of these curves quite bound all the data for 73W. The margin is 15.6°C (28°F) as defined in *Regulatory Guide 1.99* (Rev. 2) assuming credible surveillance data. The K_{Ia} curve is shown to allow for comparison of that curve with the shifted K_{IC} curves, especially regarding curve shape, in view of the observation

Fig. 12. Fracture toughness, K_{cI} , versus test temperature for irradiated HSSI weld 73W. The ASME K_{IC} curve for the unirradiated data is shown, as is the same curve after shifting it upward in temperature equal to the Charpy 41-J shift. The curves labeled 1, 2, and 3 represent the ASME curve shifted by the indicated criterion, where margin is 15.6°C. The K_{Ia} curve represents the ASME K_{Ia} curve shifted by the Charpy 41-J shift. The $K_{0.05}$ curve is the five-percentile curve for all the HSSI 72W and 73W combined data using the Wallin procedure.

that the irradiated K_{cI} curves for these two welds appear to have exhibited some shape change after irradiation. Figure 13 shows a plot of all the irradiated fracture toughness data for 72W and 73W plotted versus temperature normalized to the RT_{NDT} . As shown in the figure, a total of eight data points fall below the ASME K_{IC} curve. To

Fig. 13. Fracture toughness, K_{cI} , versus normalized temperature, $T - RT_{NDT}$, for irradiated welds 72W and 73W. The dashed curve is the ASME curve shifted upward in temperature to just bound the irradiated data.

bound all data, the dashed K_{Ic} curve must be shifted upward in temperature 18°C (32°F).

25. Observations from the HSSI Fifth and Sixth Irradiation Series included the irradiation-induced temperature shift. Statistical analyses and curve fitting showed that the temperature shifts at a fracture toughness of $100\text{ MPa}\sqrt{\text{m}}$ ($91\text{ ksi}\sqrt{\text{in.}}$) were greater than those at a Charpy energy of 41 J (30 ft-lb) but were in good agreement with the Charpy 68 J (50 ft-lb) transition shifts. The 68 J temperature shifts were greater than the 41 J shifts, reflecting the change in the slope of the CVN curves following irradiation.

26. Results from the HSSI Sixth Irradiation Series on crack-arrest toughness indicate no irradiation-induced curve shape changes in the K_{Ia} curve. Similar shifts were measured at the 41 J (30 ft-lb) level for CVN specimens and the $100\text{ MPa}\sqrt{\text{m}}$ ($91\text{ ksi}\sqrt{\text{in.}}$) level for K_{Ia} (ref. 23). Figure 14 shows a comparison of the fracture toughness and crack-arrest toughness for the

combined irradiated data for 72W and 73W normalized to the RT_{NDT} . The mean irradiated K_{Ic} curve has been shifted much closer to the irradiated K_{Ia} curve than is the case for the unirradiated conditions. The fact that the average separation in initiation and arrest toughness at any given temperature is reduced in the irradiated condition may help explain the enhanced propensity for pop-in events following irradiation.

27. Irradiation embrittlement in a commercial LUS weld. The HSSI Program includes examination of the fracture resistance of LUS welds. This class of submerged-arc welds was produced using Linde 80 welding flux because it produced a very fine dispersion of inclusions within the weld and a resultant low number of reportable defects observed by radiography. Unfortunately, this fine dispersion of inclusions provided such a large number of microvoid initiation sites that the macroscopic resistance of these welds to ductile crack extension by the microvoid growth and coalescence process was significantly reduced. This fine inclusion dispersion, in combination with the common early practice of using copper-coated welding wire, has resulted in a significant number of pressure vessels in which major fabrication welds have both relatively low resistance to ductile fracture in the unirradiated condition and a high sensitivity to further degradation from neutron exposure.

28. The principal current activity within the HSSI Program to examine LUS welds is the Tenth Irradiation Series in which the effects of irradiation on the fracture toughness of commercially fabricated LUS submerged-arc welds from the reactor pressure vessel of the canceled Midland Unit 1 nuclear plant are being investigated. The welds from the Midland plant carry the Babcock and Wilcox Company designation WF-70, a specific combination of weld wire and welding flux that exists in several commercial pressurized-water reactors. The initial part of this study involved the determination of variations in chemical composition, RT_{NDT} , tensile properties, and fracture toughness throughout the welds (ref. 24). Four 1.17 m -long (46 in.) sections of beltline weld and two similar sections of nozzle course weld have been examined. Nil-ductility transition temperatures ranged from -40 to -60°C (-40 to -76°F). Because the Charpy impact energy did not achieve 68 J (50 ft-lb) at $NDT + 33^\circ\text{C}$ (59°F), the RT_{NDT} values are all controlled by the Charpy behavior. The RT_{NDT} values vary from -20 to 37°C (-4 to $+99^\circ\text{F}$) with position in the vessel

Fig 14. Comparison of mean fracture toughness and crack-arrest toughness versus normalized temperature for welds 72 and 73W in (a) unirradiated and (b) irradiated conditions.

(Fig. 15) while the upper-shelf energies varied from 77 to 108 J (57 to 80 ft-lb). Analysis of the combined data revealed a mean 41-J (30 ft-lb) temperature of -8°C (18°F) with a mean USE of 88 J (65 ft-lb). Even though both welds carry the WF-70 designation, their bulk copper contents range widely, from 0.21 to 0.34 and 0.37 to 0.46 wt % in the beltline and nozzle course weld, respectively.

29. Tensile and fracture toughness properties were determined on nozzle and beltline weld metals at six temperatures ranging from -100 to 288°C (-148 to 550°F). The yield strength of the nozzle weld metal was significantly higher than that of the beltline weld, on the order of 100 MPa (14.5 ksi). All the fracture toughness tests to characterize the unirradiated material, using compact specimens ranging up to 101 mm (4 in.) in thickness, have been completed. Data to characterize ductile-to-brittle transition temperature were evaluated using a test standard currently under development by the American Society for Testing and Materials (ASTM). This involves the determination of the position of a median fracture toughness transition curve (master curve), using only the data from six 12.5-mm-thick (0.5-in.) (1/2T) compact specimens, to compare with data from large specimens. The "reference temperature" for the master curve was found to be -60°C (-76°F) for the beltline weld and -43°C (-45°F) for the nozzle weld. This appears to agree well with the fact that the mean fracture toughness versus temperature behavior for the beltline weld is higher than for the nozzle weld (Fig. 16).

Fig 15. Distribution of RT_{NDT} values for different sections of Midland LUS beltline (BL) and nozzle (NZ) course welds as function of through-thickness position.

Fig 16. Mean values of unirradiated transition-temperature-range fracture toughness of Midland LUS beltline and nozzle course welds as function of test temperature and specimen size.

30. The irradiation of the Midland weld is in progress. The exposure of the first of the two large irradiation capsules, containing tensile, CVN, and fracture toughness specimens, to the primary target fluence of 1×10^{19} neutrons/cm² (>1 MeV) has been completed, and the second one has begun. Small fracture toughness and CVN specimens are also being exposed in low- and high-fluence scoping capsules to 5×10^{18} and 5×10^{19} neutrons/cm² to examine fluence effects over this range.

INTERIM CONCLUSIONS

31. Fracture toughness tests on irradiated material containing local brittle zones gave toughness values that suggest that the current procedure for defining a reactor vessel P-T curve is conservative. Shallow-flaw fracture toughness tests have shown that both fracture toughness and data scatter increase as crack-tip constraint is reduced. These effects could have a significant positive impact on predictions of reactor vessel failure rates under PTS transient loading. Biaxial loading reduces but does not eliminate the shallow-flaw effect. There are wide ranges in initial fracture properties observed in some vessel materials, and the current methods using CVN-based indices may not be adequately conservative to account for irradiation-induced shifts in fracture toughness.

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