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The Behavior of Shallow Flaws in Reactor Pressure Vessels

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ABSTRACT

Both analytical and experimental research studies have shown that the effect of crack length, a, on the elastic-plastic toughness of structural steels is significant. The objective of this report is to recommend those research investigations that are necessary to understand the phenomenon of shallow behavior as it affects fracture toughness so that the results can be used properly in the structural margin assessment of reactor pressure vessels (RPVs) with flaws.

Preliminary test results of A 533 B steel show an elevated crack-tip-opening displacement (CTOD) toughness similar to that observed for structural steels tested at the University of Kansas. Thus, the inherent resistance to fracture initiation of A 533 B steel with shallow flaws appears to be higher than that used in the current American Society of Mechanical Engineers (ASME) design curves based on testing fracture mechanics specimens with deep flaws. If this higher toughness of laboratory specimens with shallow flaws can be transferred to a higher resistance to failure in RPV design or analysis, then the actual margin of safety in nuclear vessels with shallow flaws would be greater than is currently assumed on the basis of deep-flaw test results. This elevation in toughness and greater resistance to fracture would be a very desirable situation, particularly for the pressurized-thermal shock (PTS) analysis in which shallow flaws are assumed to exist.

Before any advantage can be taken of this possible increase in initiation toughness, numerous factors must be analyzed to ensure the transferability of the data. This report reviews those factors and makes recommendations of studies that are needed to assess the transferability of shallow-flaw toughness test results to the structural margin assessment of RPV with shallow flaws.

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FOREWORD

The work reported here was performed at Oak Ridge National Laboratory under the Heavy-Section Steel Technology (HSST) Program, W. E. Pennell, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is M. E. Mayfield.

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STATUS REPORT ON THE BEHAVIOR OF SHALLOW FLAWS IN REACTOR PRESSURE VESSELS

S. T. Rolfe

1. BACKGROUND

Analytical and experimental research at the University of Kansas[1,2] have shown that the effect of crack length, a, on the elastic-plastic fracture toughness of structural steels is significant. Test specimens with shallow flaws have higher toughness levels than test specimens with deep flaws when both specimens are loaded to the same level of crack-opening stress, σ_y, at the crack tip. This higher level of toughness at fracture is caused by a loss of in-plane constraint in specimens with shallow flaws.

Comparison of two-dimensional (2-D) plane strain finite-element results of test specimens with various crack-depth to specimen-width ratios, a/W, showed a fundamental change in the nonlinear stress field at an a/W ratio of ~0.15. Specimens with shorter cracks (a/W = 0.10 and 0.05) showed yielding to the front (tension) surface behind the crack well before the formation of the plastic hinge. Specimens with deeper cracks (a/W ≥ 0.20) developed a plastic hinge before the plastic zone extended from the crack tip back to the front surface.

The analytical results were verified experimentally for an A 36 steel (σ_{ys} = 248 MPa) and an A 517 steel (σ_{ys} = 690 MPa). The yield strengths and strain-hardening exponents of these steels bound that of A 533 B steel (σ_{ys} = 470 MPa), which is used in the construction of reactor pressure vessels (RPVs). The experimental results for the A 36 and A 517 steels tested at the University of Kansas are presented in Fig. 1. Preliminary test results conducted at the Oak Ridge National Laboratory (ORNL)[3] show that similar behavior exists for A 533 B steel (Figs. 2 and 3). The results presented in Figs. 1--3 are in terms of the elastic-plastic fracture mechanics parameter, crack-tip-opening displacement (CTOD). The CTOD parameter was used because the inherent toughness at the temperatures of interest was beyond the limits of plane-strain linear-elastic fracture mechanics K_{Ic}, yet there was no significant stable crack growth, and thus J_{Ic} could not be measured either.

Because current RPV life assessments are strongly dependent on the ability of the vessel material to withstand load in the presence of a flaw (i.e., sufficient fracture toughness), it is important that realistic assessments of the fracture toughness of pressure vessel steels be made. The fracture toughness value used in RPV life assessments to date has been generated using deep-notch specimens. On the basis of the test results presented in Figs. 1–3 and recent finite-

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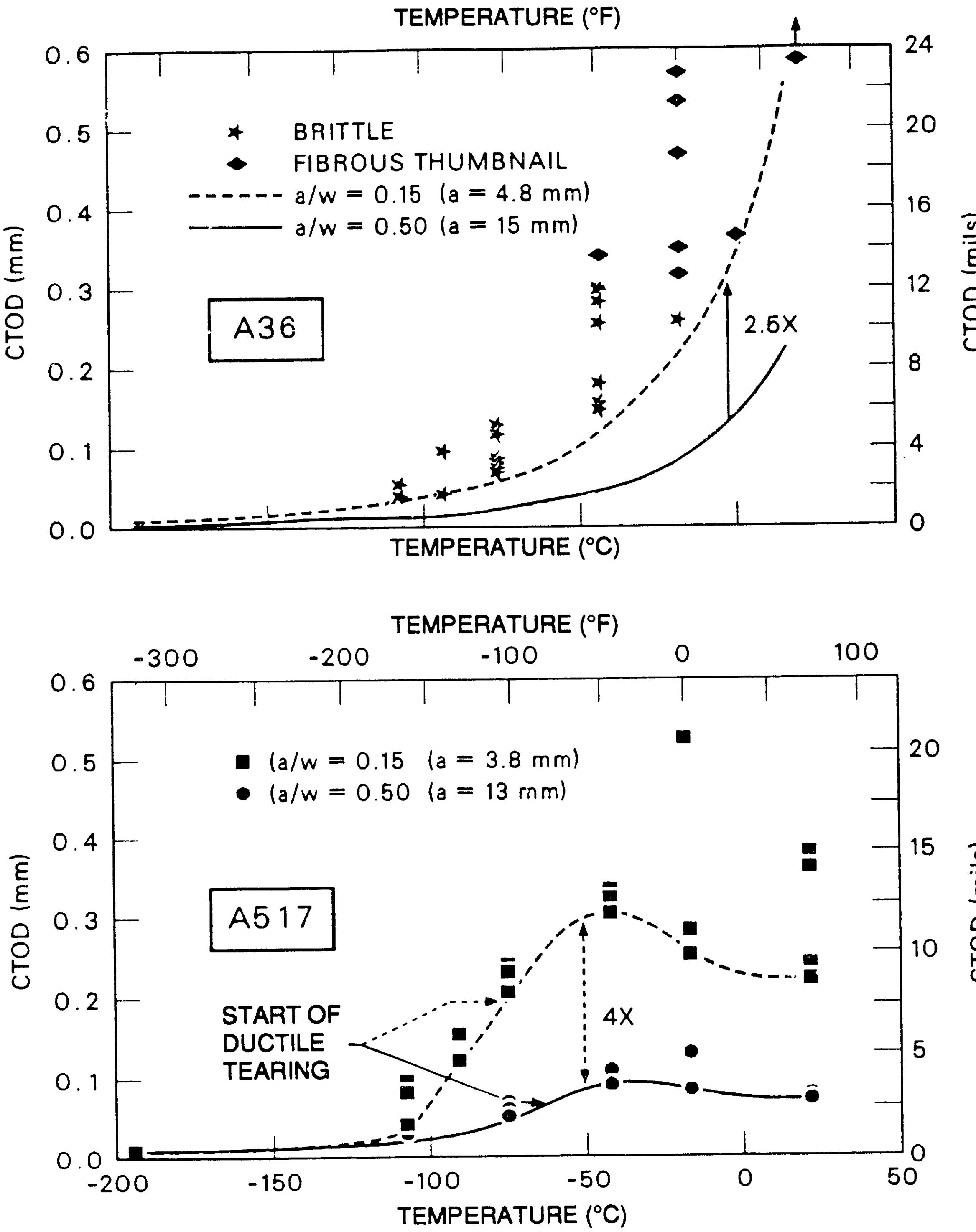

Fig. 1. Effect of a/W ratio on fracture toughness of (*a*) A 36 and (*b*) A 517 steels tested at University of Kansas.

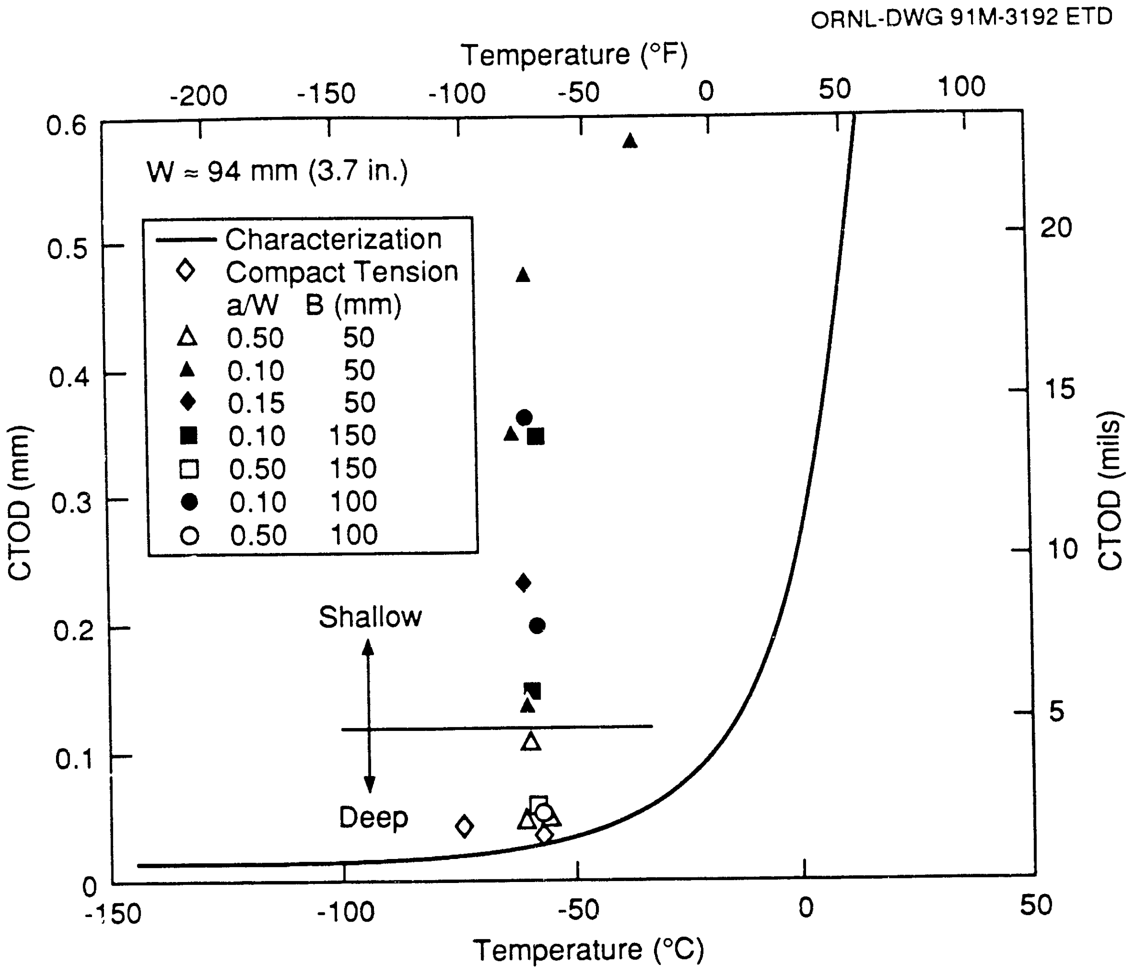

Fig. 2. Effect of crack depth on fracture toughness of A 533 B steel.

element analyses of both deep-notch and shallow-notch specimens,[1,2] it now appears that determining fracture toughness using deep-notch specimens may be an unduly conservative approach for service applications in which shallow flaws are the ones of primary interest. Therefore, the Heavy-Section Steel Technology (HSST) Program under sponsorship of the Nuclear Regulatory Commission (NRC) is investigating the influence of crack depth on the fracture toughness of RPV steel.[4]

The ultimate goal of the investigation is the generation of a limited number of elastic-plastic fracture toughness values appropriate for shallow flaws in an RPV and guidelines concerning the application of these data to reactor vessel life assessments. This study is not intended to be a complete experimental investigation that would result in a new design methodology. Rather, it is a limited experimental and analytical study of the behavior of shallow

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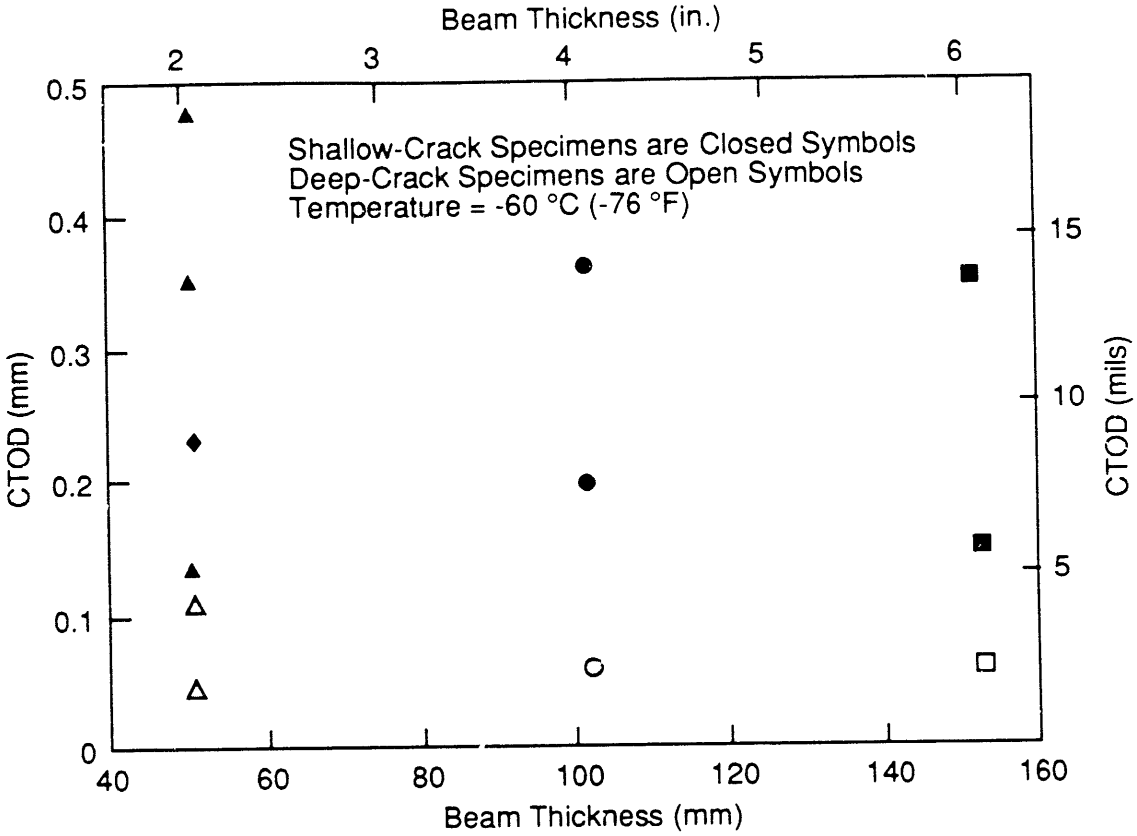

Fig. 3. Effect of specimen thickness on fracture toughness of A 533 B steel.

flaws in reactor pressure vessels. Relatively large beams are being tested (50, 100, and 150 mm thick by 100 mm deep) to simulate the stress state in a flawed RPV as closely as is practical. Crack depths, a, currently being considered range from shallow (10 to 15 mm) to deep (50 mm).

Probabilistic fracture mechanics evaluations of operating nuclear facilities in the Integrated Pressurized-Thermal Shock (IPTS) studies have shown that shallow rather than deep cracks in the RPV contribute predominantly to the calculated probability of vessel failure.[5–7] The dominance of shallow rather than deep flaws in the probabilistic fracture mechanics evaluations in part results from the higher density of shallow flaws assumed or predicted to exist in the vessel wall, the increased radiation damage, and the severity of the thermal shock on the vessel inner surface. IPTS studies[5–7] indicate that ~95% of all the flaws that are predicted to initiate during the dominant transients for the three plants considered were 25 mm (1 in.) deep or less. Thus, the enhancement of the toughness of steels used in vessels with shallow flaws could have a significant impact on the structural margin assessment of RPVs with flaws.

2. EXISTING METHODOLOGY

Existing methodologies to assess the fracture toughness behavior of steels for nuclear RPVs are based in part on Sect. XI of the *American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.*[8] In the *ASME Code* initiation and arrest curves K_{Ic} and K_{Ia} are referenced to the RT_{NDT} temperature as shown in Fig. 4. The K_{Ia} reference toughness curve was developed by plotting all known data (static, dynamic, and arrest values) vs the temperature relative to RT_{NDT} and constructing a lower-level curve not transgressed by any of the data. Data[9] used to develop the K_{Ic} reference curve are presented in Fig. 5.

Subsequent test results for small specimens, some of which were adjusted using Irwin's β_{Ic} correction, as well as several HSST thermal-shock experiments, verify that the ASME Sect. XI reference curve is indeed a lower-bound curve[10] (Fig. 6).

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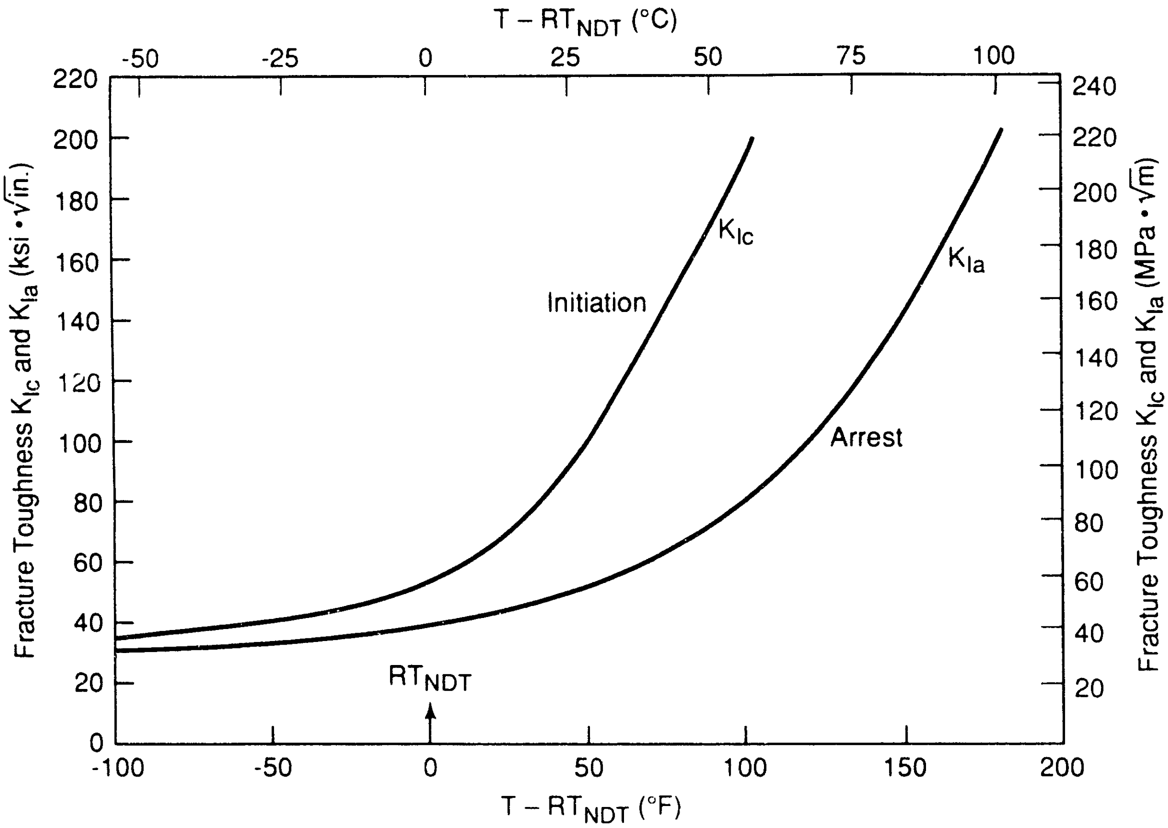

Fig. 4. Lower-bound K_{Ia} and K_{Ic} test data for SA 533 grade B class 1, SA 508 class 2, and SA 508 class 3 steels—ASME Sect. XI.

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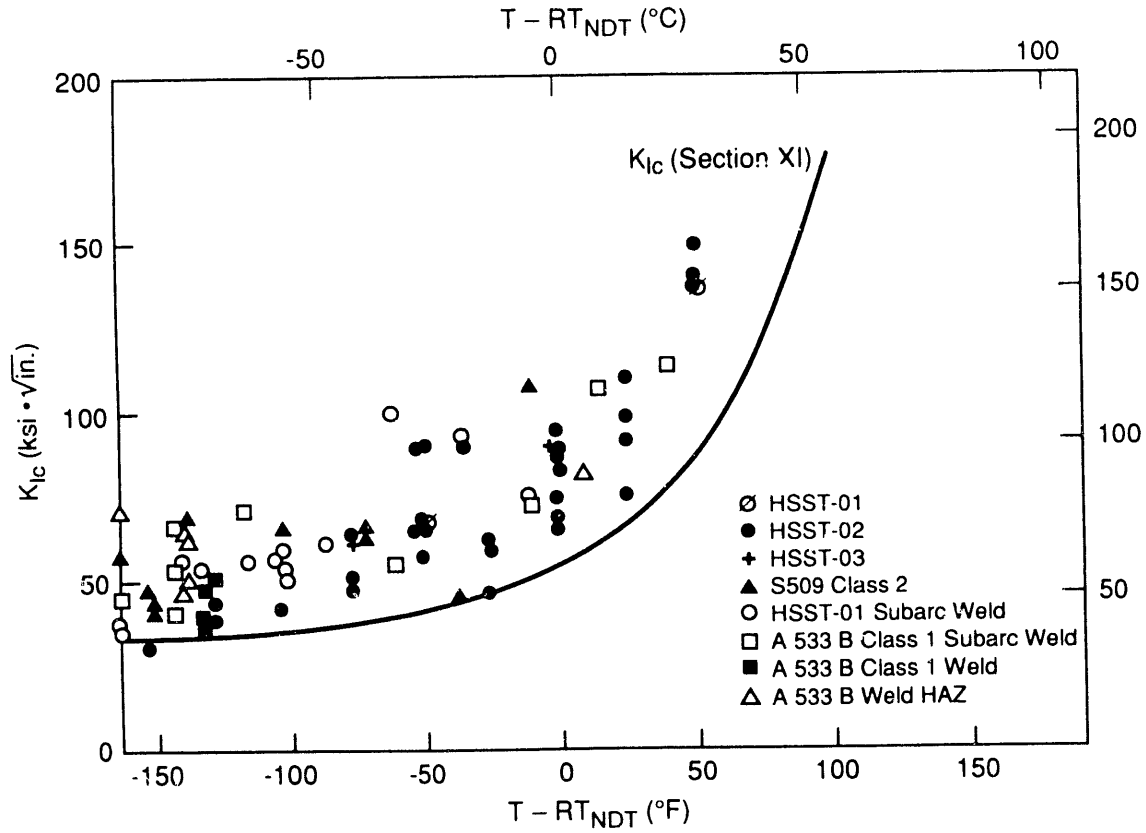

Fig. 5. K_{Ic} reference curve with supporting data. *Source:* T. V. Marston, "Flaw Evaluation Procedures–Background and Applications of ASME Section XI," Appendix A-NP-719-SR, Special Report, August 1978, ASME-Section XI Task Group on Flaw Evaluation.

Use of laboratory test specimens with a/W ratios of 0.5 leads to maximum constraint in most laboratory test specimens and appears to be a conservative approach to analyzing the behavior of pressure vessel steels for nuclear reactors. Concern about PTS loading of vessels with shallow flaws has led to PTS testing of vessels as well as various analyses of the PTS problem with the objective of refining the technology used in analysis of RPV fracture margins under PTS loading.

Among the concerns during PTS loading is the indication that the majority of possible crack initiations would originate at flaws 5 to 15 mm deep (0.2 to 0.6 in.) located on the inside of the wall; the stresses due to thermal shock would be greatest and the resistance to fracture would be lowest because of irradiation damage. Finally, the material would be at its lowest temperature because of the application of cooling water to the inner wall surface. Thus, the toughness would be at a lower level corresponding to the lower service temperature. These 5- to

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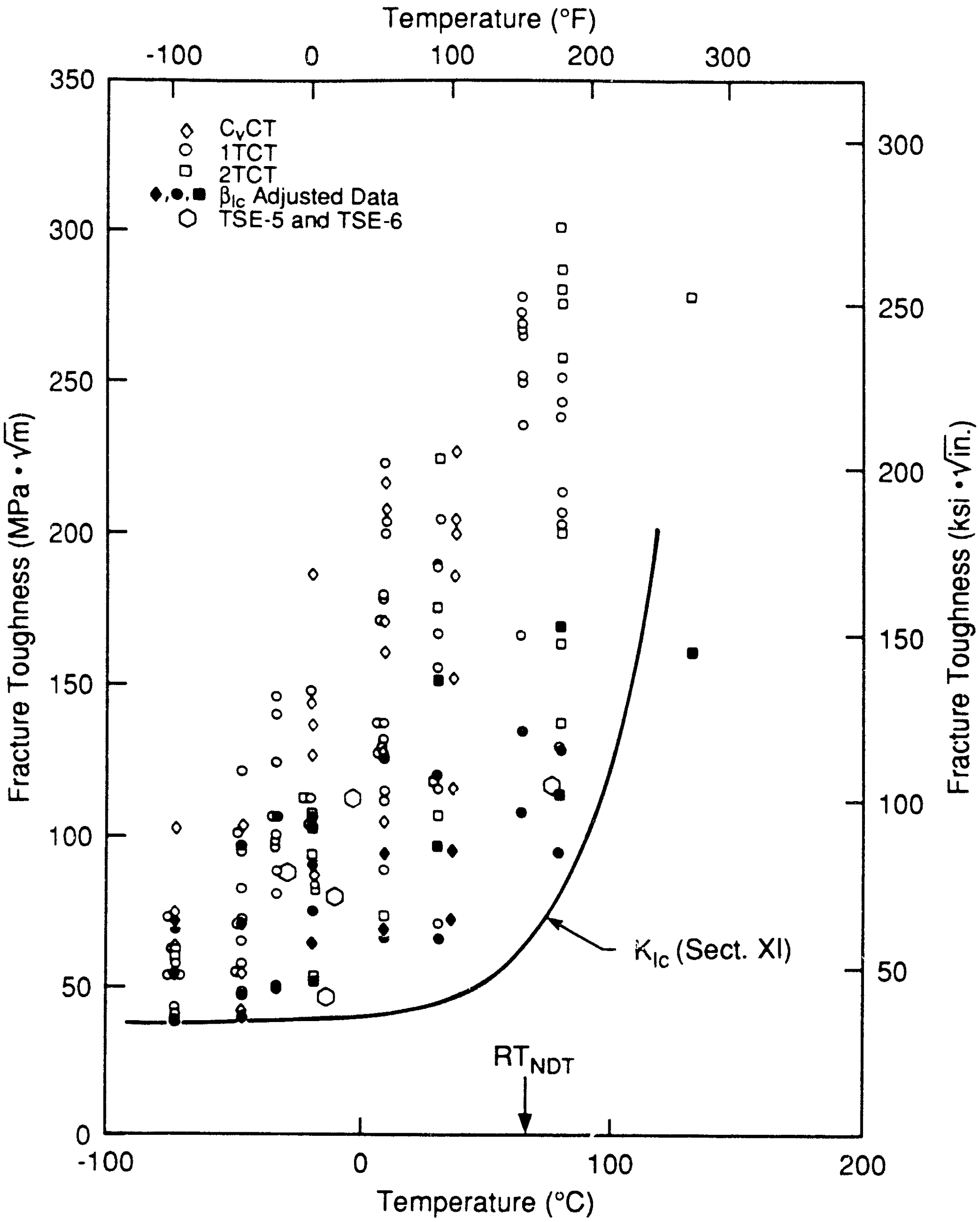

Fig. 6. Comparison of β_{Ic} adjusted small-specimen static initiation toughness values with thick-section test results for TSE-5 and -6 materials. *Source*: J. G. Merkle, Martin Marietta Energy Systems, Inc., Oak Ridge Nat. Lab. "An Examination of the Size Effects and Data Scatter Observed in Small-Specimen Cleavage Fracture Toughness Testing," USNRC Report NUREG/CR-3672 (ORNL/TM-9088), April 1984.

15-mm-deep (0.2- to 0.6-in.) flaws are considered to be shallow and can be better represented by shallow-flaw data; yet the toughness values used to analyze the behavior of actual vessels subjected to PTS loading are based on results of deep-notch fracture toughness specimens.

3. RECOMMENDATIONS

Preliminary test results of A 533 B steel show an elevated CTOD toughness (Figs. 2 and 3) similar to that observed for structural steels tested at the University of Kansas (Fig. 1). Thus, the inherent resistance to fracture initiation of A 533 B steel with shallow flaws appears to be higher than that used in the current ASME design curves based on linear-elastic fracture mechanics K_{Ic}. If this higher toughness can be transferred to a higher resistance to failure in RPV design or analysis, then the actual margin of safety in nuclear vessels with shallow flaws would be greater than is currently assumed on the basis of deep-flaw test results. Obviously, this elevation in toughness and greater resistance to fracture would be a very desirable situation, particularly for the PTS analysis in which shallow flaws are assumed to exist.

Before any advantage can be taken of this observed increase in initiation toughness, numerous factors must be analyzed to ensure the transferability of the data. Accordingly, it is recommended that the following studies be made to assess the transferability of shallow-flaw toughness test results to the structural margin assessment of RPVs with shallow flaws.

1. Obviously, the first step is to conduct shallow-flaw tests of A 533 B steel. If the tests show no significant effect, then continued study of the possible benefits of enhanced toughness levels would be inappropriate. However, preliminary test results (Figs. 2 and 3) clearly indicate an increased toughness associated with shallow-flaw specimens compared with deep-notch specimens. Additional tests of A 533 B specimens with various crack lengths, a, should be conducted at additional temperatures to verify these preliminary results.

The A 533 B steel specimens with shallow flaws tested to date exhibit greater toughness levels than specimens with deep flaws for 50-, 100-, and 150-mm-thick (2-, 4-, and 6-in.) specimens. These large specimens are believed to be fairly representative of actual vessels. Thus, the question of whether crack length, a, or the a/W ratio controls the behavior becomes less important because crack depths of 10 and 15 mm (0.4 and 0.6 in.) are also representative of the shallow-flaw depths believed to be present in actual vessels. The analytical phase of the program (Recommendations 2 and 3) should model full thickness vessels (e.g., 203 mm) and thus help to determine the controlling parameter (a or a/W) for reactor vessel analysis. However, as will be discussed later in this report, crack length, a, is believed to be the primary factor, and the a/W ratio is believed to be a secondary factor.

To date, the test results have exceeded the limits of plane strain American Society for Testing and Materials (ASTM) E-399 behavior, that is, valid K_{Ic} test results. Also, ASTM E-813 criteria for J-integral testing do not apply because in the lower transition region, $\Delta a \cong 0$ and thus J_{Ic} cannot be determined. However, it is possible that a J_c value can be inferred experimentally from the P-Δ curve. Accordingly, use of the ASTM E-1290 CTOD parameter is necessary. However, relations do exist between CTOD, J, and K so that the results can be evaluated in several ways.

2. Concurrently, analytical studies that model the test specimens should be conducted to better understand the reasons for the toughness elevation and to verify the experimental results. Research at the University of Kansas has shown that in the lower transition region, where considerable plastic deformation and crack-tip blunting occurs prior to brittle fracture, the experimental lower-bound fracture toughness results of shallow-crack specimens are two to four times larger than the results of the deep-crack specimens in terms of CTOD at identical temperatures (Fig. 1). At equivalent K_I levels in the elastic-plastic regime, finite-element analyses reveal significant differences in the crack-tip stresses between the deep- and shallow-crack specimens. The deep-crack specimens exhibit significantly higher opening-mode stresses near the crack tip compared to the shallow-crack specimens (Fig. 7). Correspondingly, at

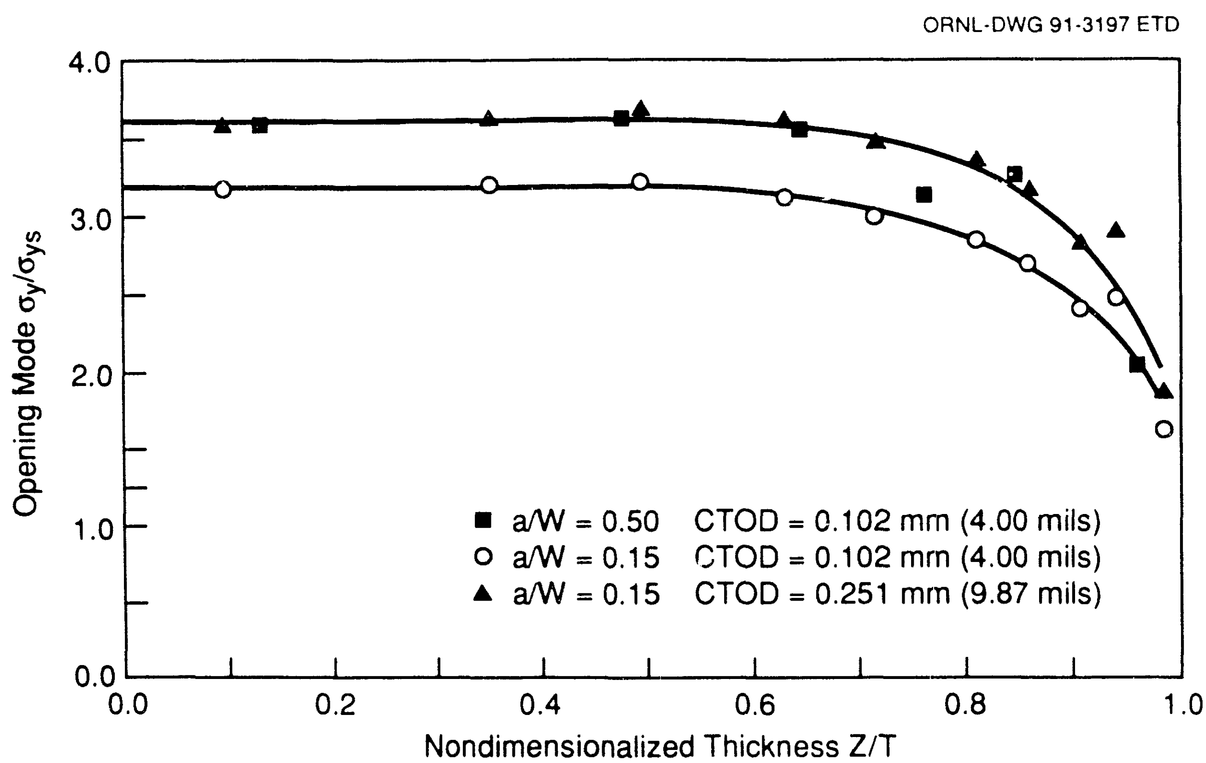

Fig. 7. Crack-opening stress distributions for 31.8- by 31.8-mm A 36 steel specimens. *Source*: W. A. Sorem, R. H. Dodds, Jr., and S. T. Rolfe, The University of Kansas, "An Analytical Comparison of Short-Crack and Deep-Crack CTOD Fracture Specimens of an A 36 Steel," *WRC Bulletin 351*, Welding Research Council, February 1990.

equivalent levels of opening mode stress, the shallow-crack specimens had CTOD (and J-integral) values ~2.5 times that the of deep-crack specimen (CTOD of 0.25 mm compared with 0.10 mm, respectively). The phenomenon of elevated fracture toughness associated with a shallow crack is a consequence of the relaxation of in-plane crack-tip constraint because of the proximity of the front, free surface. It is believed that loss of constraint also will take place at the inside surface of RPVs with shallow cracks. However, as noted in Recommendation 3, finite-element analyses of actual RPVs with shallow flaws should be conducted to verify this assumption.

Analytical studies of A 533 B test specimens under conditions of plane strain (maximum constraint) should serve as a good indicator of the significance of the shallow-flaw test results to be obtained as part of Recommendation 1. The elevated toughness associated with flaws representative of those existing in an RPV (e.g., 10 to 15 mm) appears to exist in multiple specimen sizes (Figs. 2 and 3). The magnitude of the toughness increase also appears fairly consistent in the test data generated to date for specimens with thickness of 50, 100, and 150 mm (2, 4, and 6 in.).

3. Analytical studies that model portions of actual flawed RPV simulating maximum constraint (plane strain) should be made. Hopefully, the laboratory test specimens selected are sufficiently large to provide a close approximation to the constraint levels as obtained analytically under conditions of maximum constraint (plane strain). As discussed in Recommendation 5, current ORNL studies of advanced fracture methodologies should be very useful in verifying that the constraint levels in the laboratory test specimens are representative of the constraint levels in actual vessels. Again, preliminary results of specimens 50, 100, and 150 mm (2, 4, and 6 in.) thick (Figs. 2 and 3) indicate this to be the case in that there is no decrease in the toughness levels of the 100- and 150-mm-thick (4- and 6-in.) specimens compared with the 50-mm-thick (2-in.) specimens. Simulations of actual vessels subjected to PTS loadings should be made. The PTS loading may be representative of the loading experienced by the bend specimens being tested as part of the experimental program, and this point needs further study.

4. A detailed reexamination of the thermal shock experiment and pressurized-thermal shock experiment vessel tests previously conducted should be made to study the influence of crack size on these tests from the perspective of shallow-crack enhancement. These tests were conducted at relatively low test temperatures in which the difference in constraint between shallow and deep flaws would be small. However, because these tests may be ones that most closely approach the service loading of concern, this reanalysis is especially important.

5. Several ORNL investigations of advanced fracture methodologies related to correlation parameters and constraint effects are in progress. These studies were started to obtain an improved understanding of relationships governing the transfer of fracture toughness data from small-scale specimens to large-scale applications and will be valuable in the assessment of safety margins for nuclear vessels with shallow flaws. These investigations consist of several analytical approaches including a maximum principal stress criterion, plastic zone size, and a local stress field approach using K-T or J-Q fracture parameters. Hopefully, these studies will verify the experimental results obtained as part of Recommendation 1 and help to explain theoretically the effect of in-plane constraint on fracture toughness.

6. In the HSST wide-plate tests of A 533 B steel conducted at the National Institute of Standards and Technology (NIST),[11] crack initiation consistently occurred at K_I values ranging from two to four times those predicted by the compact-tension (CT) specimens for the A 533 B specimens. The CT specimens had a/W values of 0.5, whereas the wide-plate specimens had a/W values close to 0.2. Thus, although the wide-plate tests were conducted to study arrest behavior, study of the initiation behavior indicates that an a/W ratio can have a significant effect on the behavior of either large specimens or actual vessels as predicted by small-scale laboratory test results of specimens with a/W = 0.5. It is recommended that the wide-plate results from the tests at NIST be reanalyzed using data from the perspective of shallow-flaw testing.

7. In contrast to the test results mentioned in Recommendation 6, the wide-plate results of a 2 1/4 Cr-1 Mo steel[12] with crack depths such that the a/W ratio was ~0.2 apparently exhibited little effect of crack-depth compared with deep-flaw results. Preliminary assessment indicates that ongoing ORNL studies of advanced fracture methodologies (Recommendation 5) can explain this difference on the basis of a K-T fracture analysis. This difference between the wide-plate test results of A 533 B and 2 1/4 Cr-1 Mo steels should be investigated in detail.

8. The applicability of the Irwin β_c or β_{Ic} correction to elastic-plastic shallow-flaw CTOD test results needs to be studied. The β correction originally was developed to correct for loss of out-of-plane constraint because of inadequate thickness of very high strength materials with relatively low toughness levels. In the present study, the preliminary results of Figs. 2 and 3 suggest that there is not a significant loss of out-of-plane constraint between B = 50 mm (2 in.) and B = 100 or 150 mm (4 or 6 in.) even though the 50- and 100-mm-deep (2- and 4-in.) crack specimens do not meet the validity requirements of E399. However, a distinct difference exists in toughness values for shallow-flaw specimens compared with deep-flaw specimens because of differences in the in-plane constraint.

It may be possible to use the β_{Ic} correction factor in reverse; that is, the β_{Ic} factor can be used to predict the behavior of shallow-flaw specimens starting with the existing deep-flaw K_{Ic} reference curve as a base. Merkle[13] used the β correction to account for the effects of partial transverse restraint on the fracture behavior of vessels with shallow-nozzle corner cracks. This methodology has been used successfully by ORNL[3] to predict the effects of crack length on the fracture of the A 533 B beams to date.

The significance of the β_{Ic} factor as related to in-plane constraint needs to be established inasmuch as its original use was to correct for loss of out-of-plane constraint. However, the results presented in Figs. 2 and 3 show that 50-mm-thick (2-in.) specimens exhibit the same toughness as 150-mm-thick (6-in.) specimens regardless of crack depth. This behavior would not be expected using a β_{Ic} correction, and thus the applicability of the β_{Ic} factor for shallow flaws (if not deep flaws also) should be re-examined.

9. The significance of the correction procedure developed by Dodds and Anderson[14] to account for loss of in-plane constraint in structural applications such as RPVs should be established. The key factor is to establish the conditions of constraint in actual vessels with shallow flaws. Their procedure can be very helpful in analyzing the geometry dependence of fracture toughness values for different a/W ratios. Analytical studies of full-thickness vessels under conditions of plane strain (Recommendation 3) should be helpful in this respect.

4. SUMMARY AND DISCUSSION

The previous investigations need to be conducted to ensure that the increase in fracture toughness observed in laboratory specimens can be explained theoretically so that the enhanced fracture toughness data can be used to predict the behavior of actual RPVs with confidence. This question of transferability of data must be answered before any advantage can be taken in design or analyses of shallow-flaw test results. It is anticipated that the above investigations will verify that the predicted initiation fracture toughness of actual RPVs with shallow cracks is greater than the predicted toughness based on test results of specimens with deep flaws. Even if the increase is small, the improved understanding of the behavior of shallow flaws in vessels subjected to PTS should be well worth the effort. Hopefully, the preliminary experimental results shown in Figs. 2 and 3 will be substantiated, and the transferability will be established on the basis of the analytical studies. If so, that would lead to the conclusion that the reliability of RPVs is greater than is currently predicted on the basis of deep-crack test results.

One way of using the enhanced shallow-flaw toughness results would be to develop a new K_c reference curve for shallow-flaw results. As an *example* only, "shallow-flaw" reference curve for the A 36 steel tested at the University of Kansas is presented in Fig. 8. These data were developed using CTOD specimens although the results also were analyzed in terms of J. Because relationships exist between K, J, and CTOD, it is possible to use K_J or K_{CTOD} results to obtain a new shallow-flaw reference curve. Once again, if the various investigations recommended in this report verify that shallow-flaw toughness results can be used safely to predict the behavior of RPVs, a new reference curve such as the example one shown in Fig. 8 could be developed. A new reference curve would be one way to use the enhanced toughness results; another way would be to modify the crack driving force equations by the addition of such parameters as T or Q (Recommendation 5).

The issue of whether the actual crack depth, a, or the relative crack depth, a/W, is the controlling fracture toughness parameter should be studied as a part of this program. Hopefully, the fact that moderately large specimen sizes are tested will make the issue one of secondary importance.

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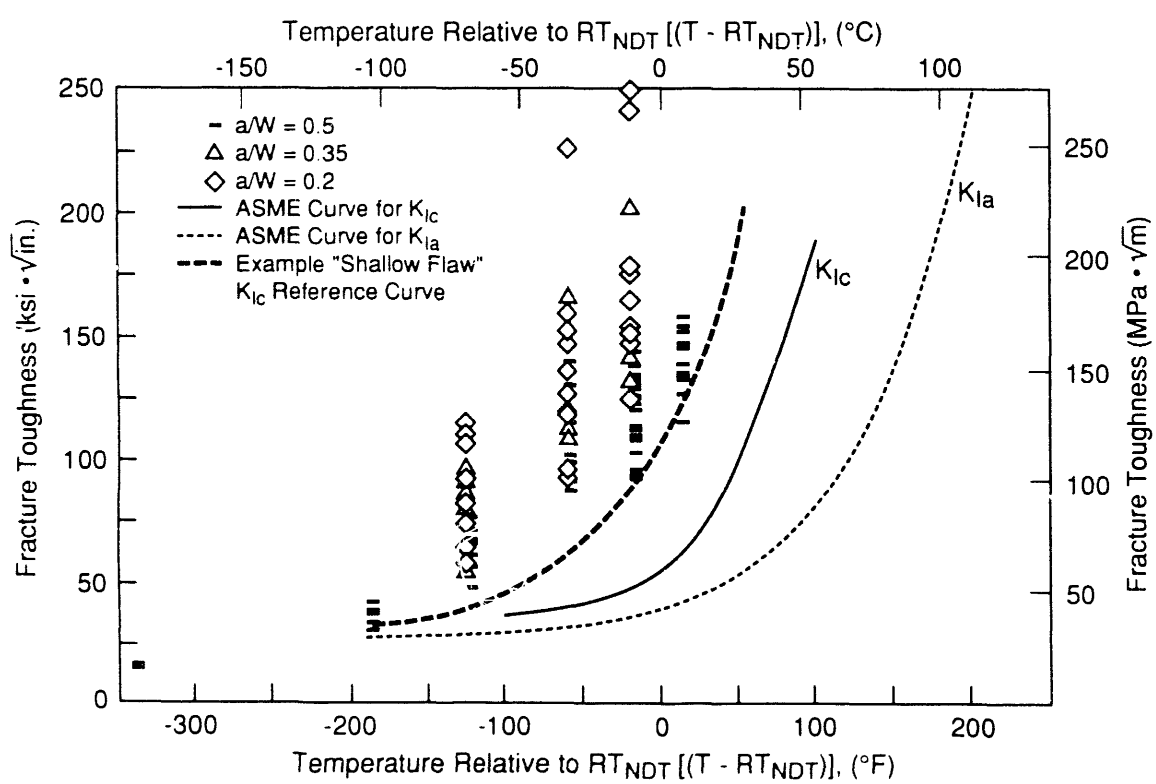

Fig. 8. Comparison of A 36 test results with ASME Sect. XI reference curve as example of "shallow flaw" reference curve.

Preliminary analysis indicates that three primary factors affect shallow-flaw behavior in either laboratory specimens or actual structures:

1. toughness level—whether measured by K, J, or CTOD,
2. strength level—either yield or flow stress, and
3. crack length, a.

These three parameters appear to be the primary ones based on the fact that K, σ, and a, are the primary factors in basic fracture studies of infinite plates. Secondary factors believed to affect shallow-flaw behavior include the inherent size of the specimens and/or structure, again consistent with basic studies of the driving force K_I in finite-width plates. Thus, the a/W ratio would appear to be of less significance than the absolute crack length, a.

In addition to the PTS problem in nuclear RPVs, the preliminary observations in Figs. 1–3 of enhanced shallow-flaw toughness have considerable implications for the application of laboratory test results to failure analyses and specification development in other areas, such as support structures. For failure and fitness-for-purpose analyses, the crack depth selected for laboratory testing should reflect the flaw size and crack-tip constraint present in a given structure. Accurate representation of actual structural conditions should improve the confidence and reliability of using laboratory specimen test results to predict structural behavior; that is, the automatic adoption of lower-bound toughness values obtained using deep-crack specimens may be unduly conservative. Finally, fracture control plans should establish the required toughness levels of materials using the most probable flaw sizes that can occur in actual structures, for example, support structures as well as RPVs. These flaws certainly should be small compared with most structural dimensions and should thus be considered shallow.

In summary, the enhancement in fracture toughness of an A 533 B steel, representative of steel used in RPVs, appears to be real. Additional studies, both experimental and analytical, are desirable to provide a sound engineering basis for transferring this information to the structural margin assessment of RPVs with flaws.

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