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Recommendations for the Shallow-Crack Fracture Toughness Testing Task Within the HSST Program

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Recommendations for the Heavy-Section Steel Technology Program's investigation into the influence of crack depth on the fracture toughness of a steel prototypic of those in a reactor pressure vessel are included in this report. The motivation for this investigation lies in the fact that probabilistic fracture mechanics evaluations show that shallow flaws play a dominant role in the likelihood of vessel failure, and shallow-flaw specimens have exhibited an elevated toughness compared with conventional deep-notch fracture toughness specimens. Accordingly, the actual margin of safety of vessels may be greater than that predicted using existing deep-notch fracture-toughness results.

The primary goal of the shallow-crack project is to investigate the influence of crack depth on fracture toughness under conditions prototypic of a reactor vessel. A limited data base of fracture toughness values will be assembled using a beam specimen of prototypic reactor vessel material and with a depth of 100 mm (4 in.). This will permit comparison of fracture-toughness data from deep-cracked and shallow-crack specimens, and this will be done for several test temperatures. Fracture-toughness data will be expressed in terms of the stress-intensity factor and crack-tip-opening displacement.

Results of this investigation are expected to improve the understanding of shallow-flaw behavior in pressure vessels, thereby providing more realistic information for application to the pressurized-thermal shock issues.

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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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RECOMMENDATIONS FOR THE SHALLOW-CRACK FRACTURE TOUGHNESS TESTING TASK WITHIN THE HSST PROGRAM

T. J. Theiss

1. INTRODUCTION

Conventionally, the fracture toughness of a material is determined using specimens in which the crack depth is approximately one-half the depth of the specimen ($a/w = 0.5$). This eliminates the influence of the specimen boundaries on the crack-tip region as much as possible and provides a plane-strain value for the fracture toughness. Recent attention has been given to shallow-crack laboratory specimens in which either the toughness near the surface is actually reduced, such as in certain weldments, or situations in which the structural application is known to possess shallow rather than deep cracks. In these cases, shallow-crack specimens may yield more meaningful results than conventional deep-notch specimens. Recent research[1,2] has shown that the fracture toughness of shallow-crack specimens can be significantly higher than the toughness determined using conventional deep-notch specimens in materials whose stress-strain properties bound the properties of reactor pressure vessel (RPV) steel. Examination of the conditions governing the failure probability of an RPV shows that shallow, rather than deep, flaws are of primary significance.[3-5]

The Heavy Section Steel Technology (HSST) Program under contract to the Nuclear Regulatory Commission (NRC) is currently investigating the material fracture toughness in the presence of shallow cracks (typically referred to as the shallow-crack fracture toughness) under conditions as prototypic as practicable of a pressurized-water reactor (PWR) vessel. This will involve the development of a limited data base of fracture toughness results for both deep- and shallow-crack specimens at various temperatures. The testing is to be performed under conditions as close as possible to those outlined in the applicable American Society of Testing and Materials (ASTM) standards.[6-8] The aim of this document is to provide recommendations on the selection of parameters that are consistent with the above guidelines for the shallow-flaw test program.

Specific topics addressed in this report are the (1) motivation for investigating the fracture toughness of shallow cracks, (2) specimen geometry to be tested and the conditions under which the testing should occur, (3) requirements for the testing facility and data acquisition system, (4) matrix of tests to be performed, and (5) anticipated results and benefits of the program.

2. MOTIVATION

Interest in the fracture toughness of shallow cracks under RPV conditions centers on two main points. First, recent investigations into the influence of crack depth on fracture toughness in non-nuclear applications have shown a significant increase in the toughness of steels containing shallow rather than deep cracks.[1,2] The phenomenon of elevated fracture toughness caused by shallow cracks appears to be because of the relaxation of crack-tip constraint based on the proximity of a free surface. The behavior of shallow cracks in reactor-grade material (A533) has yet to be investigated; however, the stress-strain behavior of A533 is bounded by the steels that the University of Kansas used in shallow-crack research.[1,2] Therefore, it is anticipated that shallow-crack A533 specimens will exhibit elevated fracture toughness when compared with conventional deep-crack specimens.

Probabilistic fracture mechanics evaluations of operating nuclear reactor vessels in the Integrated Pressurized Thermal Shock (IPTS) studies have shown that shallow rather than deep cracks contribute to the calculated probability of vessel failure.[3-5] These results are due in part to the flaw distribution used in a probabilistic fracture mechanics analysis that assumes more shallow than deep flaws in a reactor vessel. Other major factors include the negative, radiation-damage gradient and the positive thermal gradient in the wall of the vessel during a pressurized-thermal-shock (PTS) scenario. A fracture toughness increase resulting from shallow cracks similar to those shown in other applications[1,2] would have a substantial impact on the probabilistic fracture evaluation of the vessels governed by Regulatory Guide 1.154.[9]

2.1 PREVIOUS INVESTIGATIONS

Research of shallow-crack testing has taken place at the University of Kansas and at the Edison Welding Institute (EWI) in the United States as well as at The Welding Institute (TWI) in the United Kingdom. Research at the University of Kansas has involved two very different steels, A36 and A517, both showing an increase in fracture toughness for shallow cracks.[1,2] The EWI is also using A36 steel to investigate the elevation in fracture toughness resulting from shallow-crack depths with work directed toward modifying existing standards on fracture toughness testing to include consideration of shallow flaws.[10-14]

The HSST Program is using the experience gained by both the University of Kansas and EWI in the development of the HSST shallow-crack project. Dr. S. T. Rolfe, who directed the investigations into the fracture toughness of shallow cracks at the University of Kansas, is a consultant to the HSST shallow-flaw testing program. In addition, the NRC is a corporate sponsor of the research at EWI and can benefit from the experience and data of that program.

The shallow-crack fracture toughness investigations at the University of Kansas are summarized to illustrate the basis for interest in shallow-crack testing under RPV conditions.[1,2,15] The specimens used in the shallow-crack work at the University of Kansas were fabricated from A36 and A517 steel, using the single-edge-notch bending (SENB) configuration, and were tested in three-point bending. Both square and rectangular cross sections were tested using specimens of three different thicknesses B (31.8, 25.4, and 12.7 mm). Four depths W (12.7, 25.4, 31.8, and 63.5 mm) were used. The specimen span S was equal to 4W. Figure 1 illustrates the specimens used. The source plates used for the specimens were in the as-rolled condition, and the specimens were cut such that the tests were conducted in the L-T orientation. The source plates exhibited no significant microstructural differences between the surface and centerline positions.

An increase in the fracture toughness of a specimen caused by shallow flaws was found to take place at temperatures in the transition region of the crack-tip-opening-displacement (CTOD) temperature transition curve (Fig. 2). Testing at temperatures within the lower shelf of the toughness curve indicted that for shallow cracks no increase in fracture toughness was present. In other words, elevated fracture toughness caused by shallow cracks takes place at temperatures at which the failure mode is primarily brittle, but is preceded by small amounts of ductile tearing. The plastic zone at the crack tip for the shallow flaws is quite large because of the high stresses required to initiate the shallow flaw. Thus the use of elastic-plastic fracture mechanics is required.

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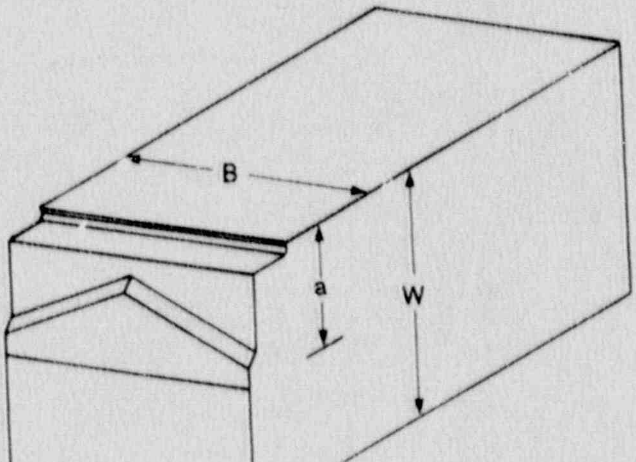

SPECIMEN SIZES (THICKNESS, B X DEPTH, W)

12.7 mm (0.5 in.) X 12.7 mm (0.5 in.)
25.4 mm (1.0 in.) X 25.4 mm (1.0 in.)
31.8 mm (1.25 in.) X 31.8 mm (1.25 in.)
12.7 mm (0.5 in.) X 25.4 mm (1.0 in.)
31.8 mm (1.25 in.) X 63.5 mm (2.5 in.)

Fig. 1. Beam specimens used for shallow-crack research at the University of Kansas.

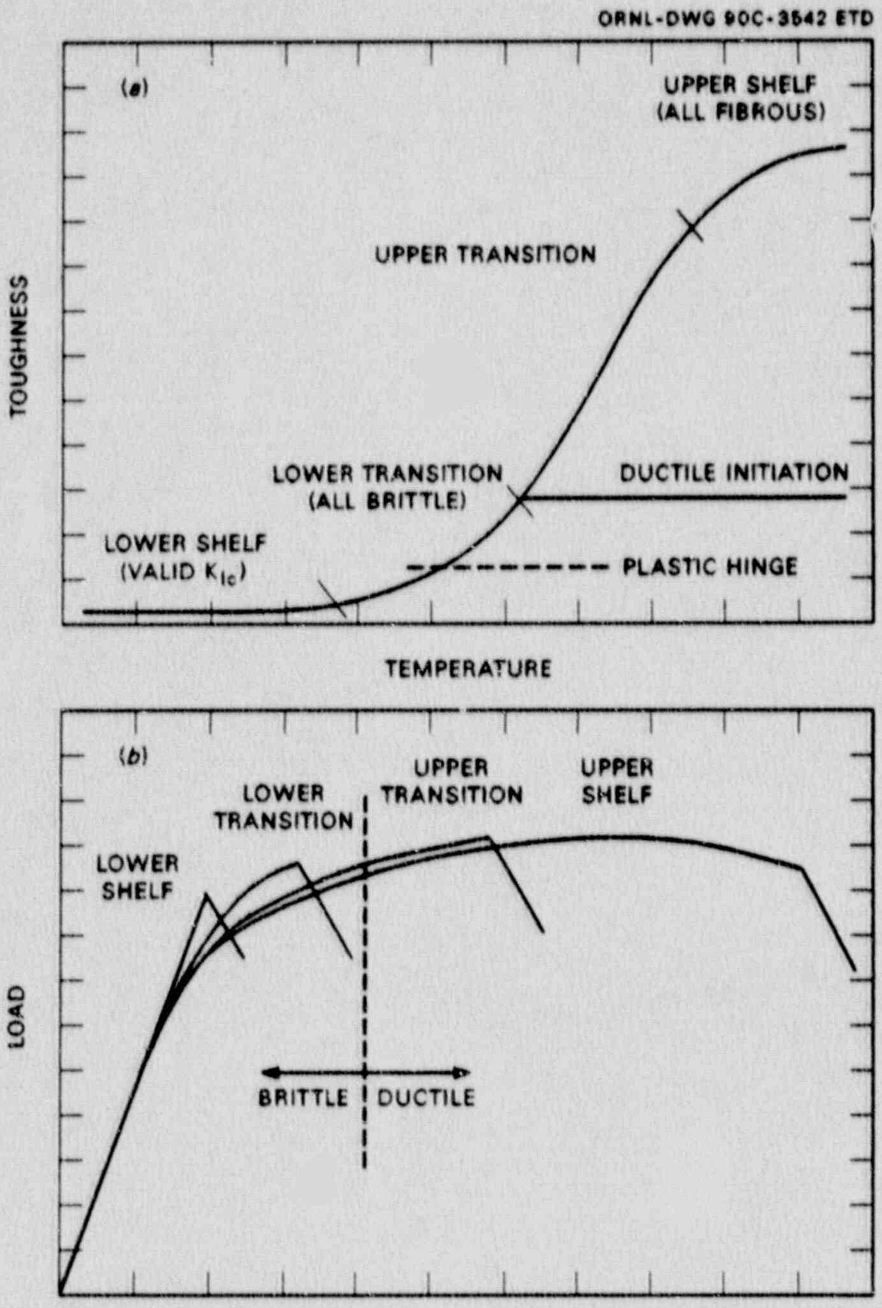

Fig. 2. Schematic transition curves for low-strength steels. (a) Toughness vs temperature transition curve; (b) load vs CMOD.

Finite-element analyses indicated that the cause of the elevated toughness is geometry dependent rather than a material property; that is, the crack-tip constraint of a deep crack is different from the constraint of a shallow crack. The plastic zone around the crack tip was found to be distinctly different for flaws having an a/w ratio of 0.15 (a = 4.8 mm) or less, as opposed to deep flaws. For the shallow flaws, the plastic zone surrounding the crack tip interacted with the specimen surface from which the crack extends well before the formation of a plastic hinge. For deep cracks, the opposite was true: a plastic hinge was formed before the plastic zone interacted with the cracked face of the specimen. Figure 3 shows shallow- and deep-cracked specimens and the developing plastic zones for comparison. The distinction between shallow- and deep-crack behavior depends on the material involved but generally occurs at a/w ratios between 0.15 and 0.20.[16-22] The deepest absolute crack depth, a, that has experimentally shown a shallow-crack fracture toughness increase is 10 mm (0.39 in.).[22]

The results of the shallow-crack research at the University of Kansas show that the fracture toughness increase for shallow cracks compared with conventional deep-cracked fracture specimens is significant in the transition region. Figures 4 and 5 show the elevated toughness of the shallow-crack specimens in terms of CTOD. A36 material is a low-strength, high-strain-hardening material, while A517 is a high-strength, low-strain-hardening material. For A36 material, the critical CTOD for shallow-crack specimens was ~2.5 times the CTOD for deep-crack specimens[1,15] in the transition region. The A517 specimens showed an

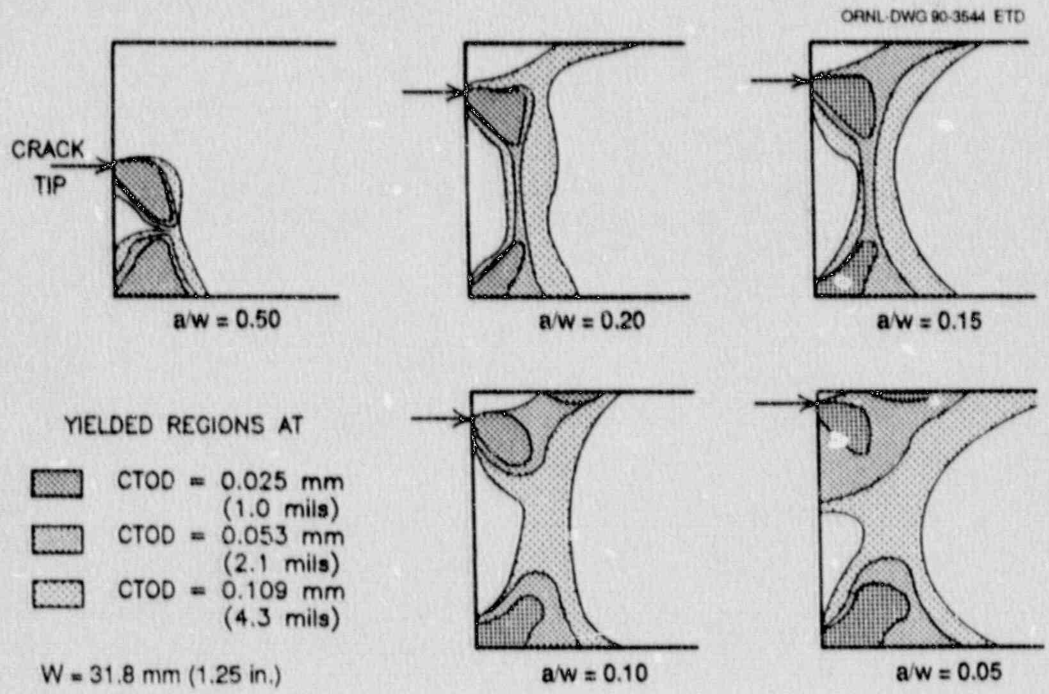

Fig. 3. Von Mises stress distributions for 2-D plane-strain A36 steel specimens.

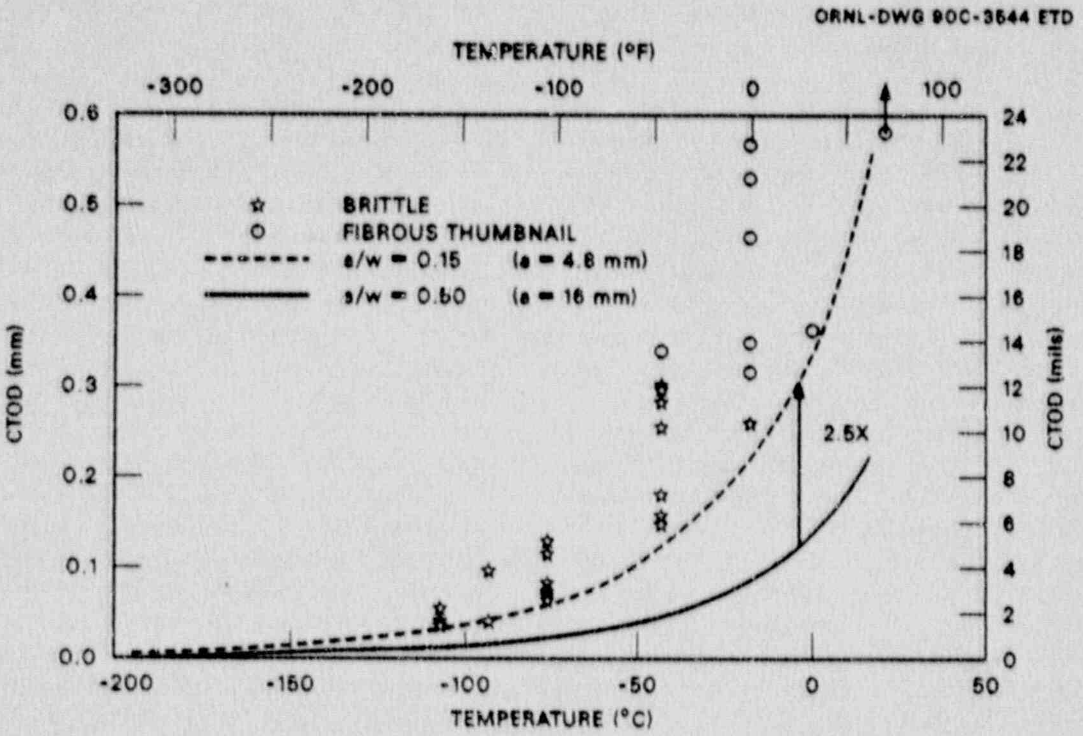

Fig. 4. CTOD vs temperature for A36 specimens with a/w ratios of 0.15 and 0.50.

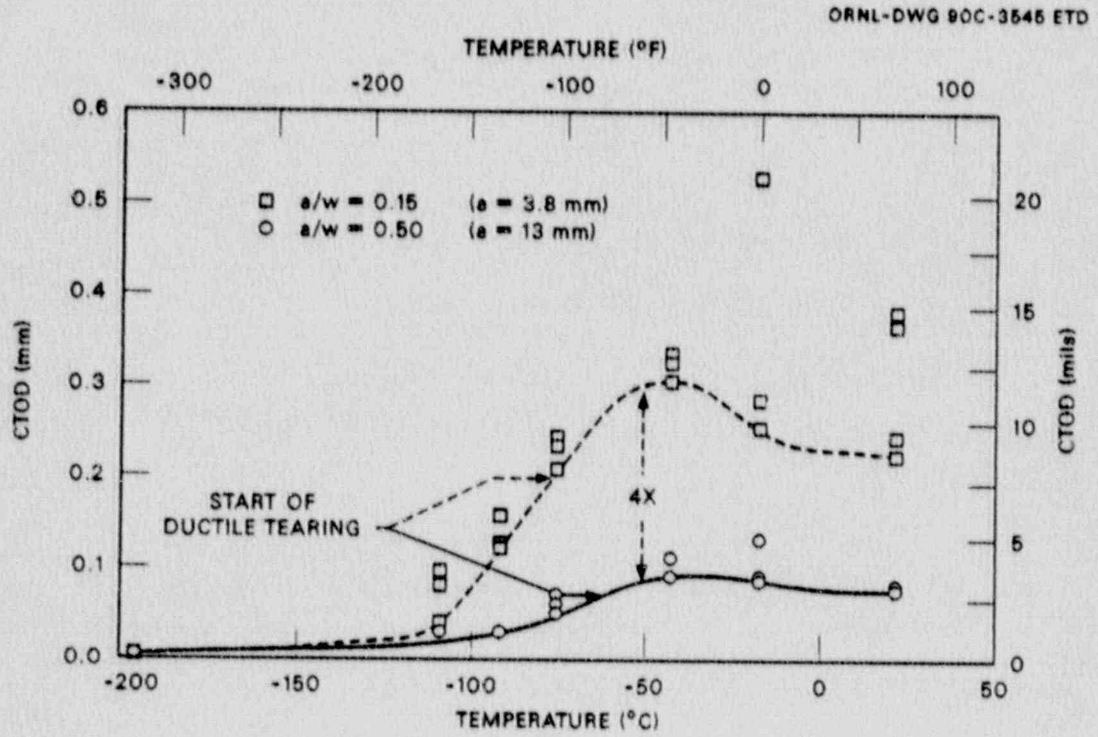

Fig. 5. CTOD vs temperature for A517 specimens with a/w ratios of 0.15 and 0.50.

even more pronounced effect with CTOD for the shallow specimens as high as 4 times that of the deep-cracked specimens.[2] The normalized crack depth, a/w, for the shallow-crack specimens from A36 and A517 material was 0.15. The absolute crack depths, a, for which the shallow-crack effect was observed were 4.8 mm (0.19 in.) for the A36 specimens and 3.8 mm (0.15 in.) for the A517 specimens. The stress-intensity factor K_{Jc} is related to the square root of the CTOD, which means that the A36 shallow-crack specimens exhibited an ~60% increase in K_{Jc}; in the A517 specimens, K_{Jc} for shallow cracks would be twice that of deep cracks. The temperature range in which the shallow-crack elevated toughness took place was roughly within the transition range for each steel. The temperature at which tearing took place was ~20°C (36°F) lower in the shallow-crack specimens than in the deep-crack specimens for both steels.

One of the primary goals of the shallow-crack research at EWI is the inclusion of shallow-crack testing in the various American and British standards on fracture toughness testing.[10-14] The testing program at EWI therefore differs somewhat from that at the University of Kansas. The material being used for the shallow-crack tests at EWI is A36, but several very different specimen configurations are being used, including SENB specimens, single-edge-notch tension (SENT) specimens, and a single-edge-notch arc-bending (SENAB) specimen. The SENAB specimens are oriented in the L-S direction, using multiple geometries (B × B, B × 2B, B × 3B) in which B = 25 mm. Because the research at EWI is in progress, results are preliminary, but they also show an increase in the fracture toughness measured for a specimen when it is tested with a shallow rather than deep crack.

2.2 PROBABILISTIC FRACTURE MECHANICS EVALUATIONS

To understand the significance that elevated fracture toughness of shallow flaws would have with respect to the safety of PWR vessels, recent IPTS studies need to be considered.[3-5] The IPTS studies evaluated the probability of vessel failure (through-the-wall crack) caused by PTS for three operating nuclear facilities. Many probabilistic fracture-mechanics calculations were performed for each vessel by randomly varying parameters such as fracture toughness (K_{Ic}, K_{Ia}, RT_{NDT_0}), material chemistry (percentage of copper and nickel), and radiation damage (fluence, ΔRT_{NDT}) for specified thermal and pressure transients. The probability of failure per event was then defined as the number of failures divided by the total number of calculations. In this way, conditions that have a relatively strong influence on the overall probability of vessel failure are determined and evaluated. Likewise, a small number of pressure and thermal transients showing the greatest likelihood of resulting in vessel failure (i.e., dominant transients) can be identified and examined further.

The region of concern in a reactor vessel with respect to crack initiation and propagation during PTS loading is the beltline region (the area of greatest radiation damage). Within the beltline region, three subregions are considered: axial welds, circumferential welds, and plate segments. In most vessels, welds are more susceptible to radiation damage than plate segments. However, plate segments occupy a much larger area than welds. Thus, axial welds and plate segments both have a strong influence on the likelihood of failure. (The above discussion applies only to vessels fabricated using plates rather than ring forgings because ring-forged vessels have no axial welds. Plate vessels constitute ~70% of the PWR vessels in the United States.)

Flaw depths which were <20% of the wall thickness of the vessel were assumed to be two dimensional (2 D) (i.e., infinitely long). This assumption was made because short, shallow flaws tend to grow on the surface to become long, shallow cracks (in the absence of cladding)[23] and because long, shallow flaws are essentially 2 D.

The majority of flaws that initiated during the various PTS events simulated in the IPTS studies were <13 mm (0.5 in.) deep as illustrated in Figs. 6–8. These results are due in part to the flaw distribution used in a probabilistic fracture mechanics analysis that assumes more shallow than deep flaws in a reactor vessel. Other major factors include the negative radiation damage gradient and the positive thermal gradient during a PTS scenario in the wall of the vessel. Thus, the shallow flaws in these vessels contribute more to the likelihood of vessel failure than do deep flaws. A histogram showing the percentage

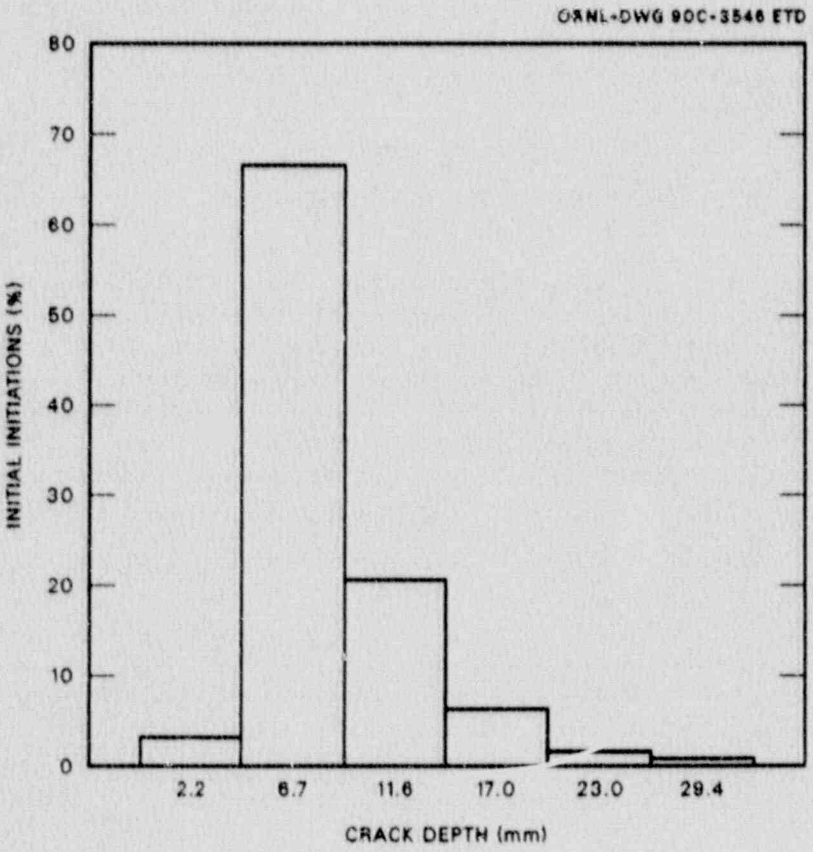

Fig. 6. Histogram of percentage of initial initiations vs crack depth for Calvert Cliffs Unit 1.

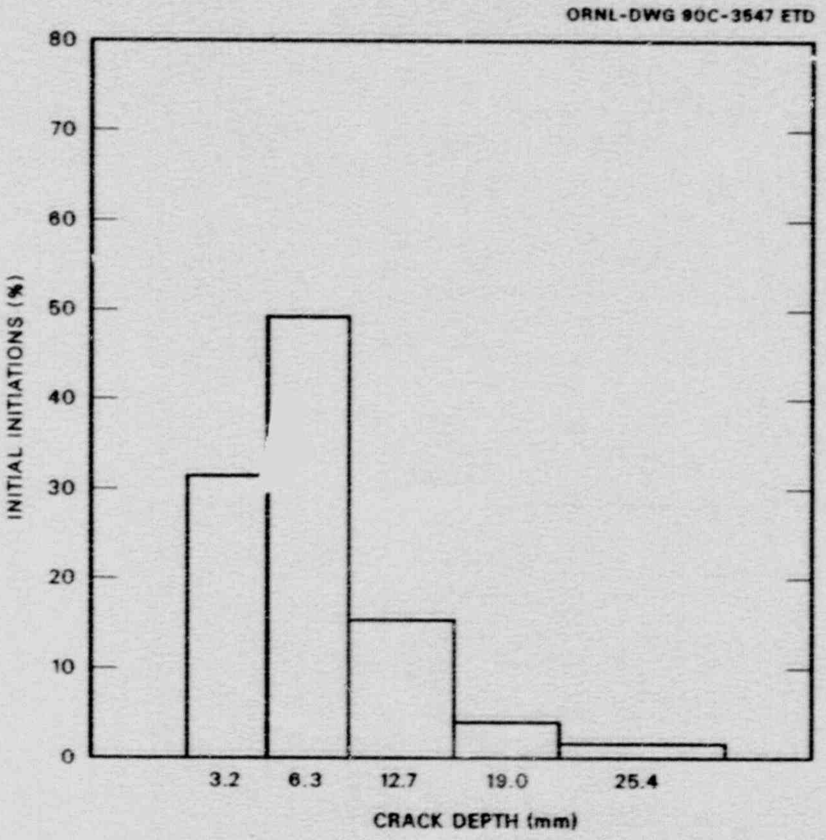

Fig. 7. Histogram of percentage of initial initiations vs crack depth for Oconee-1.

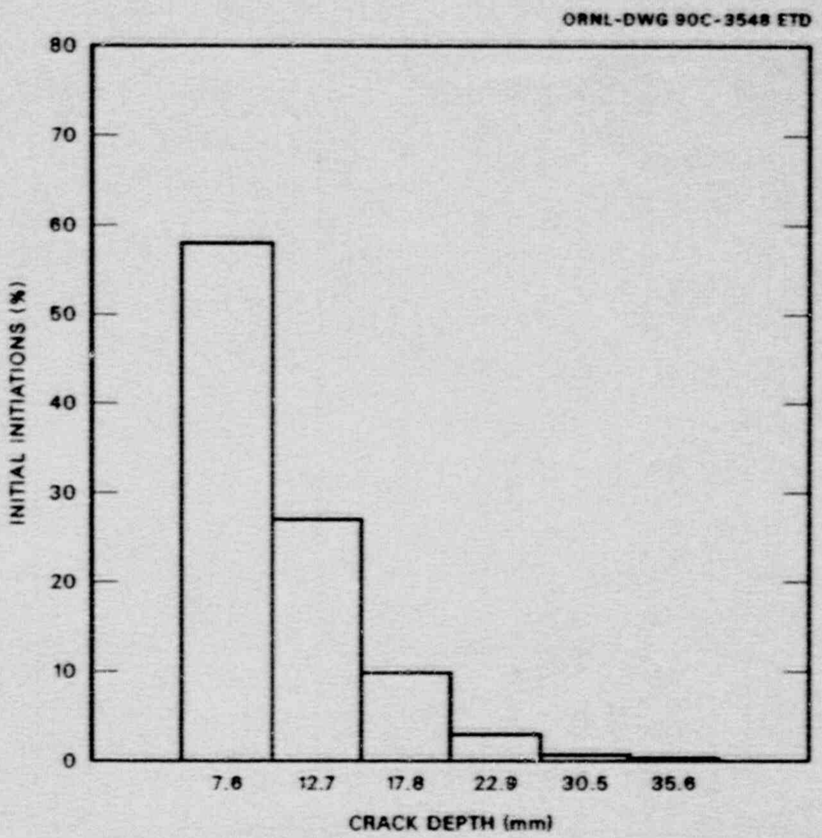

Fig. 8. Histogram of percentage of initial initiations vs crack depth for H. B. Robinson.

of cracks that resulted in initiation for a dominant transient in the Calvert Cliffs IPTS study is shown in Fig. 6. Similar histograms for the Oconee [illegible] and H. B. Robinson studies are shown in Figs. 7 and 8, respectively. While these histograms are not all-inclusive, they clearly indicate that for the dominant transients shown, flaws <13 mm (0.5 in.) deep have a significant impact on the probability of vessel failure.

Examination of the results of the IPTS studies[3-5] shows that ~95% of the initial initiations for all three plants took place within the relative temperature ($T - RT_{NDT}$) range from −50 to 50°C (−58 to 122°F) assuming 32 effective full-power years (EFPYs). This trend is illustrated in Fig. 9.

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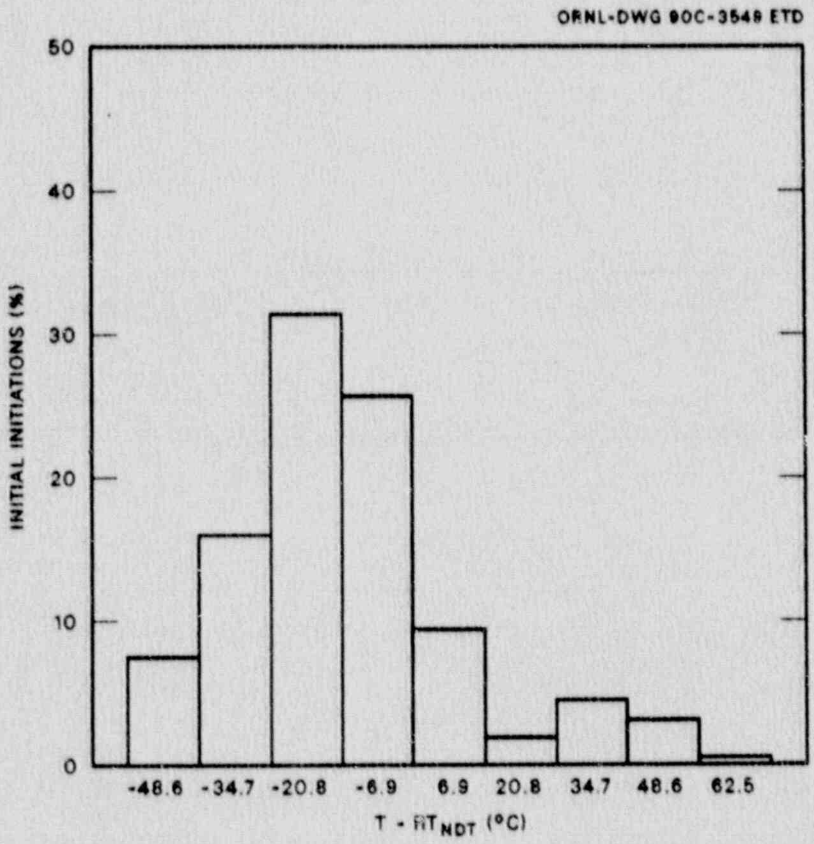


Fig. 9. Histogram of percentage of total initiations vs relative temperature at initiation for Calvert Cliffs Unit 1.

2.3 BENEFITS

To illustrate the potential benefits associated with an elevated toughness of shallow cracks, the conditions of potential flaws in a reactor vessel need to be summarized. The material of construction of the majority of plate-formed PWR vessels in this country is A533 grade B class 1 steel. A set of Charpy curves for unirradiated A533 material taken from HSST Plate 13A in the T-L orientation is shown in Fig. 10. The transition region of this material in the T-L direction is roughly between −100 and 20°C (−150 and 68°F). Cleavage initiation values were recorded at temperatures as high as 24°C.[24] A toughness curve for HSST Plate 13A is shown in Fig. 11. The nil-ductility reference temperature

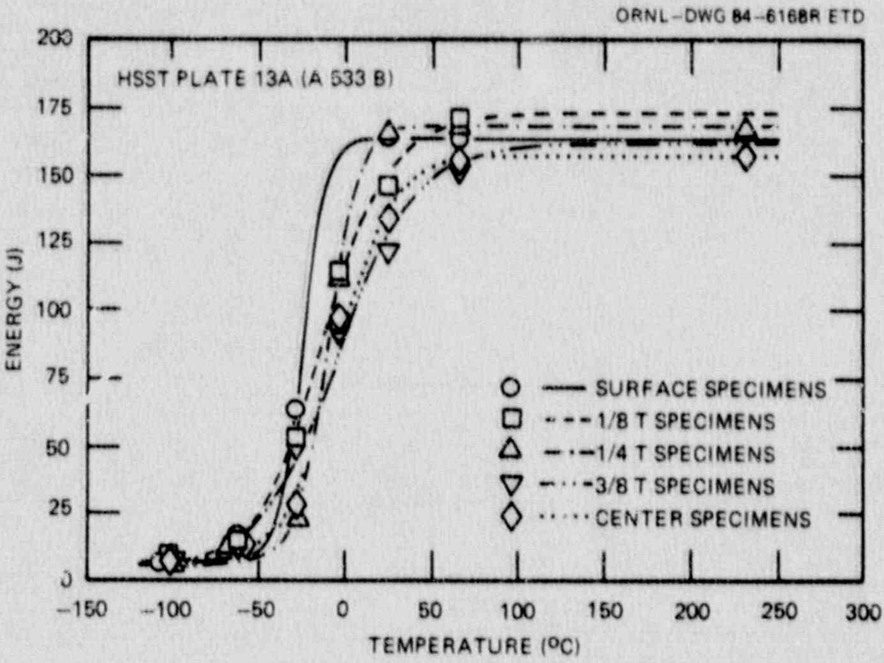


Fig. 10. CVN through-thickness results for LT specimen from HSST Plate 13A.

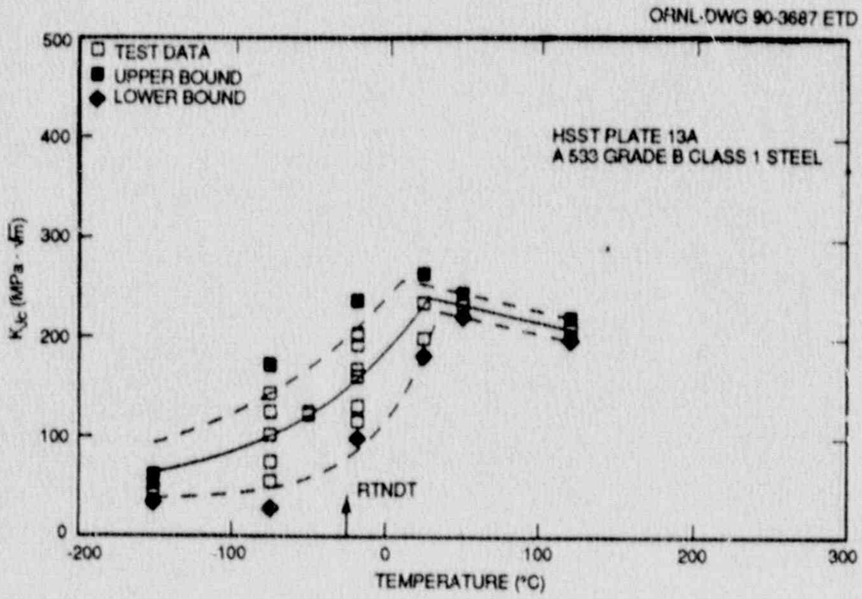
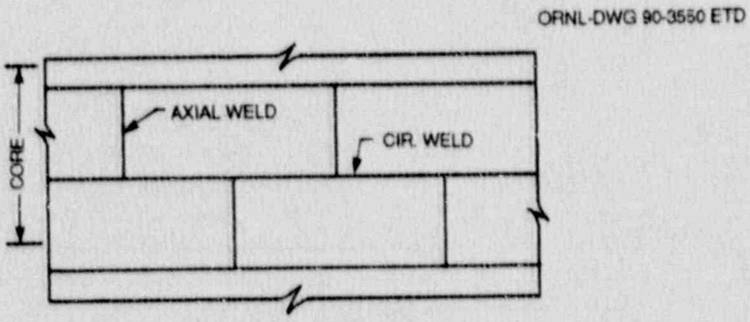


Fig. 11. Fracture toughness for HSST Plate 13A in the T-L orientation.

for this particular plate is −23°F (−10°F).[24] The wall thicknesses in a PWR vessel range typically from 203 to 280 mm (8 to 11 in.) thick.[25] Axially oriented flaws in a vessel are situated in the L-S direction using standard ASTM convention[6] (Fig. 12).

The substantial benefits that could be realized with an elevated toughness caused by shallow flaws in a reactor vessel are obvious when the research at the University of Kansas,[1],[2] the IPTS studies,[3-5] and the conditions in an RPV are considered jointly. Significant increases (between 60 and 100%) in K_{Jc} caused by shallow cracks were found for both A517 and A36 material. A36 steel is a low-strength, high-strain-hardening material, while A517 is a high-strength, low-strain-hardening material. The strength and strain hardening of A533 is between that of A36 and A517 (Fig. 13).[2],[24] Therefore, it is anticipated that a significant increase in the toughness of shallow flaws in A533 takes place.



DEVELOPED VIEW OF BELTLINE REGION OF RPV

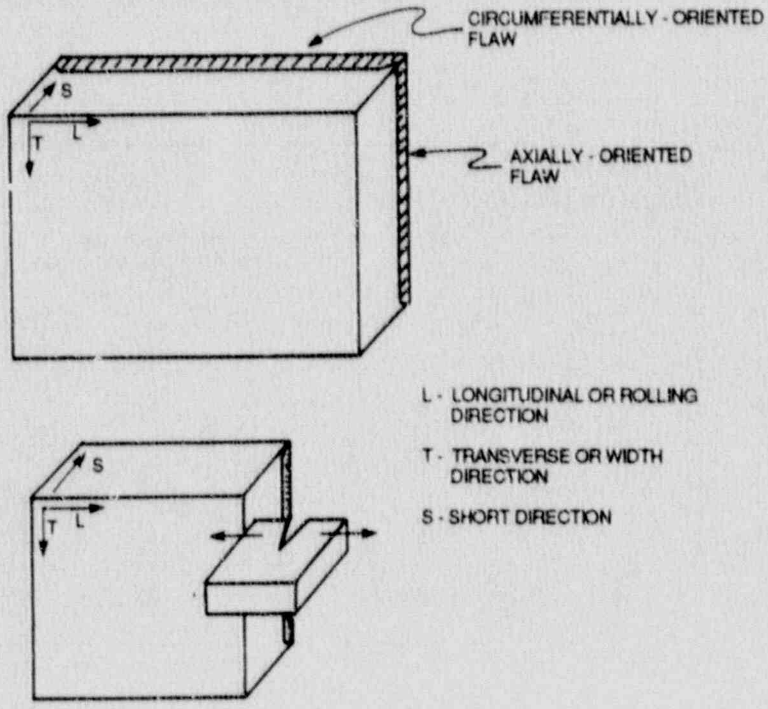


Fig. 12. Testing orientation to represent axial flaws in an RPV.

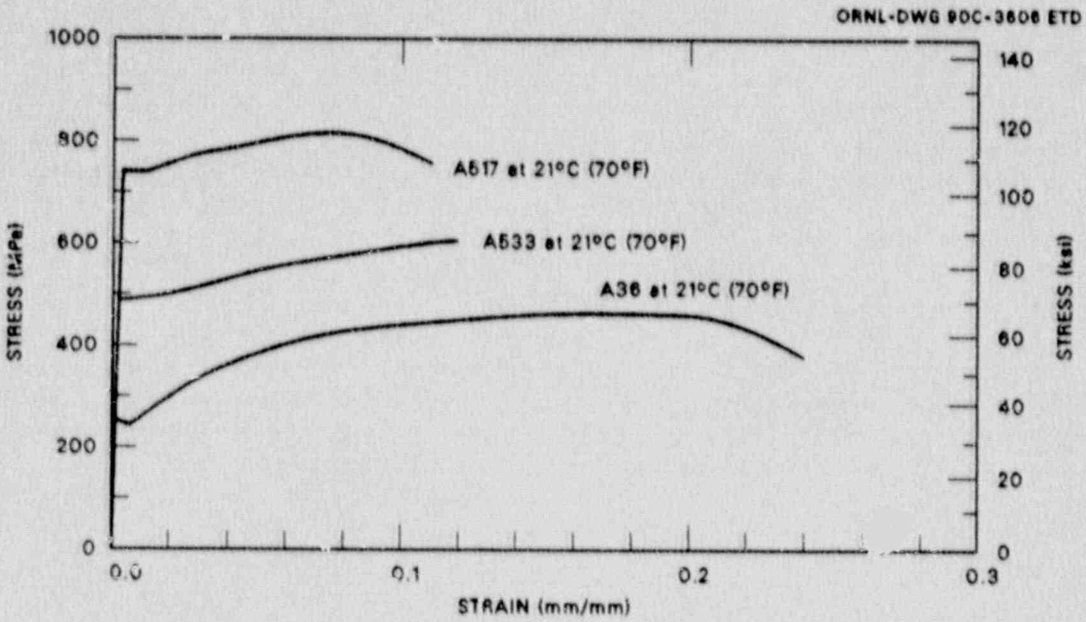


Fig. 13. Comparison of stress-strain curves for A36, A517, and A533 steels.

IPTS studies[3-5] indicate that a substantial portion of all the flaws that are predicted to initiate during the dominant transients for the three plants considered were 13 mm (0.5 in.) deep or less. Specimens with crack depths about 5 mm (0.2 in.) deep have exhibited shallow-crack behavior in A36 and A517 steel.[1,2] The deepest crack with an elevated toughness due to a shallow-crack effect found in the literature is ~10 mm (0.4 in).[22] It is therefore anticipated that a large portion of the flaws of interest in an RPV could exhibit a shallow-flaw effect.

As discussed previously, the temperature range of interest $T - RT_{NDT}$ in an RPV is roughly between −50 and 50°C (−58 and 122°F). Assuming that RT_{NDT} for the T-L and L-S orientations is similar (−23°C), the temperature range applicable to vessels is −73 to 27°C (−100 to 80°F) using unirradiated A533 material. Thus the temperatures of interest in an RPV are largely within the range of temperatures at which an elevated toughness as a result of shallow cracks is anticipated. Furthermore, the toughness vs temperature function assumed in the probabilistic evaluations was found to strongly influence vessel failure. This means that the toughness for a large portion of the cracks that were predicted to initiate could be significantly higher than considered in the IPTS studies. Thus the understanding of the behavior of shallow flaws in a reactor will lead to a better assessment of the risk of vessel failure during a PTS event. It is anticipated that the HSST shallow-crack program will show sufficient conservatism in the present treatment of shallow flaws to allow modification of Regulatory Guide 1.154,[9] which currently dictates the content and format of PTS analysis.

3. SPECIMEN DEFINITION

Because the goal of the HSST shallow-crack program is to investigate the fracture toughness of shallow cracks in flawed reactor vessels, the test specimen for this project must be as prototypic as practicable of RPV conditions. Furthermore, to isolate and quantify the influence of crack depth on the toughness of a specimen, applicable ASTM standards should be followed as closely as possible. The national standards considered in the HSST shallow-crack effort include ASTM E399, Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials;[6] ASTM E813, Standard Test Method for J_{Ic}, A Measure of Fracture Toughness;[7] and ASTM E1290, Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement.[8]

3.1 GEOMETRY

The specimen configuration chosen for testing shallow cracks in the HSST shallow-crack project is the SENB specimen with a straight-through crack (as opposed to surface crack). The bend specimen better simulates the varying stress field in a reactor wall under PTS conditions. In addition, shallow flaws are much better suited to investigate in a bend specimen then in a compact tension specimen; thus, the majority of previous shallow-crack work has utilized SENB specimens.[1,2,10] The straight-through notch simulates the infinitely long, 2-D crack. To maintain consistency with ASTM standards, the beams will be tested in three-point bending.[6-8]

To better simulate the conditions of a shallow flaw in the wall of a reactor vessel, the specimen depth W and thickness B should be large enough to simulate the stress state in a vessel wall. PWR vessel walls are nominally 203 to 280 mm thick (8 to 11 in.). Beams near the size of vessel walls are much too large for multiple specimen testing and are not necessary to meet the program goals. A 100-mm-deep (4-in.) beam has been selected for use in the HSST shallow-crack project (see Fig. 14). This size is large enough to accurately simulate the stress state in a flawed vessel wall but small enough that existing facilities can be used for testing. ASTM standards[6-8] allow beams of either rectangular ($W = 2B$) or square ($W = B$) cross sections to be used (i.e., 50 by 100 mm or 100 by 100 mm). For the HSST shallow-crack program, rectangular beams (50 by 100 mm) will be used for the majority of tests. The rectangular specimen is of sufficient size to give valid K_{Ic} results with a deep crack at lower shelf temperatures. The rectangular beams are easier to handle than the larger square beams. A limited number of square beams will be tested for comparing the two beam sizes.

The beam span S for the rectangular specimen will be equal to 4W, as defined in the ASTM standards;[6-8] however, to adequately test a beam with a square cross section (100 by 100 mm) the span of the beam S between the supports may need to be extended beyond the span of 4W. An extended span of 6W, or 610 mm (24 in.) is currently being considered to produce sufficient bending within the beam to ensure failure within the

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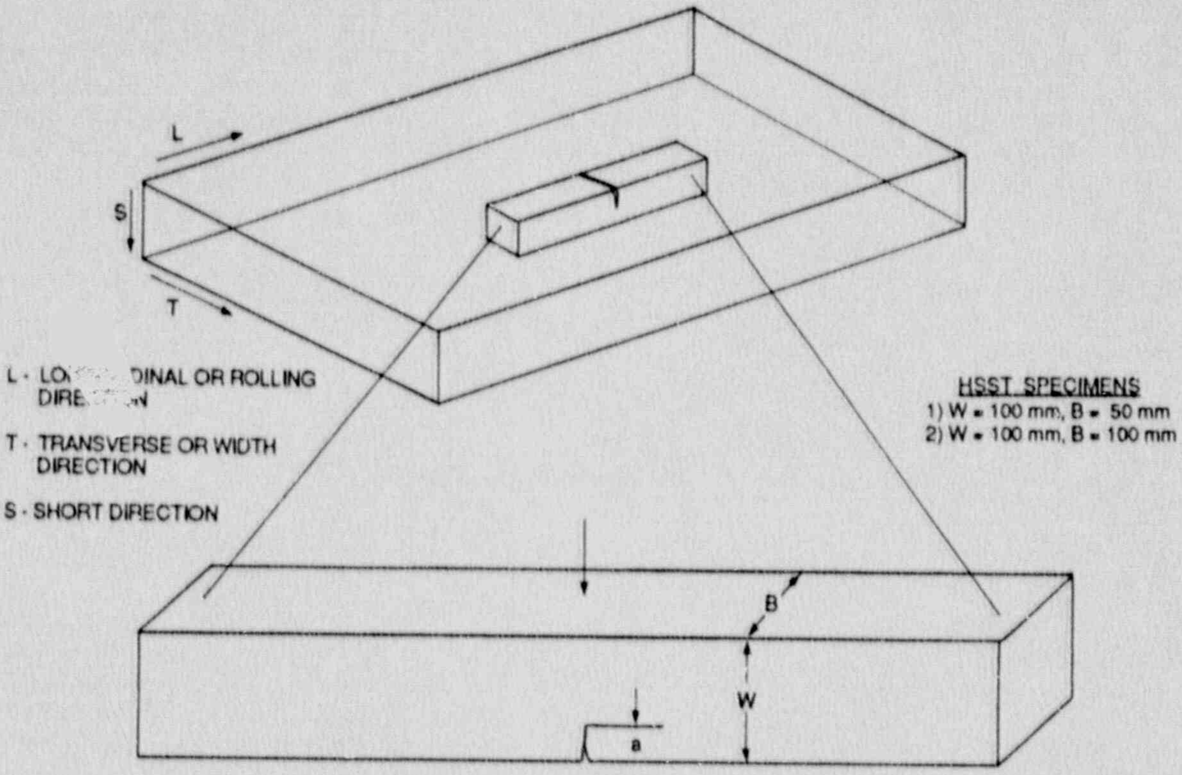


Fig. 14. HSST shallow-crack specimen.

capacity of the testing machine. Final beam design and equations relating the toughness of the specimen to the recorded data can be determined for the extended beam with the same accuracy as those used for the standard span beam from finite-element analysis. This deviation from the standards should not negatively impact the test procedures or outcome of the tests.

3.2 METALLURGY

The flaws of interest in the HSST shallow-crack study are axially oriented cracks in the weld and plate material. Flaws are generally more likely to exist in weld material; however, plate material must also be considered because of the larger area of plate and the increased radiation damage in higher copper plate sections. The shallow-crack fracture toughness elevation appears to be dependent on the geometry of the specimen (i.e., differences in crack-tip constraint)[1],[2] and not on the metallurgy of the cracked material. For those reasons, specimens for the HSST shallow-crack testing are to be cut from the surface of HSST Plate 13B, which is A533 grade B class 1 steel plate material. The specimens are to be cut from the surface of the source plate to maintain consistency with an RPV plate. Previous characterization of HSST Plate

13A reveals that there is very little microstructural difference between the surface and center portions of the plate.[24] Therefore, it is anticipated that any fracture toughness differences quantified in the shallow-crack tests will be due to the depth of the crack and not because of any metallurgical surface effects of the plate material.

To maintain consistency with the conditions of an RPV, specimens for this project will be cut with the cracks oriented in the L-S orientation (Fig. 11). This orientation was chosen over weaker material orientations because of the dominance of axially oriented flaws in reactor vessels in the IPTS studies.[3-5] The HSST shallow-crack program is interested in the initiation toughness of shallow, infinitely long flaws through the thickness of the wall of a reactor vessel. The influence of cladding will not be considered for the HSST shallow-crack project.

Figure 14 is a schematic of the specimen location within the source plate and the HSST shallow-crack specimen geometry.

3.3 SPECIMEN PREPARATION

Multiple specimens will be tested as a part of the HSST shallow-crack project, and all will be fabricated from existing A533 material. The fabrication process includes cutting blank specimens from the center portion of the plate, surface machining the specimens to the requirements of ASTM E399,[6] and inserting the starter notch from which a fatigue crack will be grown. Side grooving of the specimens is not anticipated.

Once the specimens have been fabricated, they will be instrumented so that they can be fatigued until a suitable crack is grown from the starter notch. The fatigue precracking will take place in the same testing machine as the fracture toughness tests. The fatigue crack growth will be detected visually on the surface of the specimen. Fatigue precracking will take place at room temperature and involve ~100,000 cycles for each specimen and is discussed further in Sect. 6.1.

After the appropriate crack depth in a specimen has been reached, the conditions for that particular test will be set. The specimen will be cooled to the appropriate test temperature, and the instrumentation will be checked. Once the test conditions are met, load will be applied to the specimen at a specified rate until the test is concluded. Tests at lower temperatures are expected to result in crack initiation and catastrophic failure of the specimen. Tests at higher temperatures that result in more ductility may require the use of the single-specimen elastic compliance technique (ASTM E1152)[26] for determining the fracture toughness.

4. TEST FACILITY REQUIREMENTS

To successfully complete the HSST shallow-crack project, several requirements have been established for the test facilities. The primary concern of the test facility is adequate load capacity for testing shallow-cracked beams. Due to the large amounts of scatter in the material toughness of the specimens in this project, limit-load calculations were used to predict the load requirements for the various beam specimens considered for use in the project. Limit-load calculations are simple, 2-D analyses based on the development of a fully plastic zone across the net cross-sectional area, ignoring the influence of the crack tip in the beam. Therefore, the limit load of the net section of a beam should provide a conservative estimate of the load requirements of a cracked-beam test. Details of the limit-load calculations along with computations for the 100-mm (4-in.) beams are given in the Appendix. Results of the calculations indicated that for the square 100-mm (4-in.) beam with a span of 610 mm (24 in.), a maximum load no greater than 1 MN (220 kip) would be required. The HSST Program has available for its use on the shallow-crack project either an Instron 2.4-MN (550-kip) testing machine or a 1-MN (220-kip) MTS test machine.

The beam fixture for the shallow-crack tests must also meet special requirements. The guidelines concerning roller size, material hardness, etc., detailed in the ASTM standards, will be followed for the beam fixture.[6–8] In addition, the span of the fixture should be adjustable so that the shallow-crack project can retain a degree of flexibility. The beam fixture should be designed so that the interfaces between the specimen and the required instrumentation and cooling system pose no difficulties.

A cooling system that will cool, record, and control the specimen test temperature is required. An environmental chamber will be constructed surrounding the cracked area of the beam and cooled with nitrogen vapor, or the specimen will be immersed in a liquid bath. The temperature will be controlled and recorded by using thermocouples attached to the specimen and connected with a data acquisition and control system. The temperature accuracy will be within or better than the requirements of ASTM E399.[6]

The shallow-crack tests at lower temperatures will likely culminate in catastrophic failure of the specimen. Therefore, the test facility must provide adequate protection of test personnel and equipment. Restraint devices attached to each end of the specimen will be designed to capture the specimen ends upon failure. In addition, a shield placed around the test area of the testing machine will protect personnel from small objects that might be thrown during a test. The test facility will also be designed to protect the instrumentation and other equipment during a test.

In addition to loading the specimens to the point of crack initiation, the test facility will also be used to fatigue precrack the specimens. Fatigue precracking is the most expedient method of growing an initial notch into a sharpened crack suitable for testing according to ASTM E399.[6] As a result, the test facility must be capable of withstanding large numbers of load cycles (~100,000 cycles/specimen).

5. DATA ACQUISITION REQUIREMENTS

The HSST shallow-flaw project requires that the fracture toughness of the specimens be determined in terms of J-integral and CTOD. Fracture tests in the transition region usually dictate that both elastic and elastic-plastic fracture toughness expressions be utilized. For nuclear applications, toughness is conventionally expressed in terms of K_{Ic} (elastic) and J_c or J_{Ic} (elastic-plastic). Quite often, calculations are performed in terms of J_c, then converted and expressed in terms of K_{Jc} according to the expression $K_{Jc} = \sqrt{J_c E'}$, where E′ is the plane-strain elastic modulus. CTOD, however, can be calculated for both elastic and elastic-plastic cases. Previous shallow-crack work at both the University of Kansas[1,2] and EWI[10-14] has been in terms of CTOD. Previous fracture mechanics cleavage evaluations by the HSST Program have been in terms of K_{Ic} or K_{Jc}. These toughness expressions are used because they can be applied to a flawed structure where CTOD cannot. Toughness measurements in terms of CTOD and the J-integral will provide comparisons with previous shallow-crack work and data that are applicable to flawed reactor pressure vessels.

To calculate the fracture toughness, the following data must be collected and recorded. The load as measured by the load cell is necessary for all toughness measurements.[6-8] Crack-mouth-opening displacement (CMOD) is needed for both K_{Jc} and CTOD measurements[6,8] and is usually recorded using a clip gage located at the mouth of the starter notch. CMOD can also be used to monitor crack growth during the fatigue precracking phase of the specimen tests. The vertical load-line displacement (LLD) is used for J-integral[7] determination and typically measured with a linear variable differential transformer (LVDT) (see Fig. 15). The plastic rotation factor defined as the point of rotation ahead of the crack front for a cracked specimen is used to determine CTOD from CMOD. The rotation factor has been determined both analytically with 3-D finite-element analysis[1,2] and experimentally using a dual clip-gage approach[27-30] or the η-factor approach[15] for shallow-crack beams. It is currently anticipated that the HSST shallow-crack

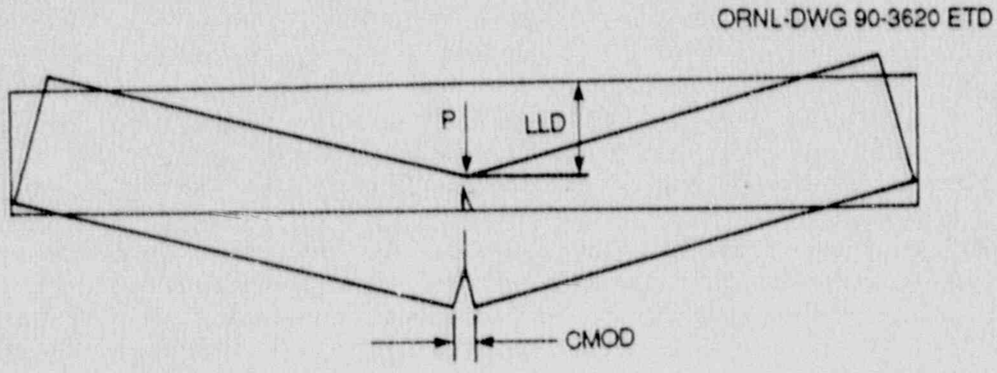


Fig. 15. Measurement requirements during testing.

program will determine the rotation factor analytically by finite-element analysis and experimentally using the η-factor approach.

Care must be taken in placement of the clip gage(s) at the crack mouth to prevent the placement of the clip gage(s) from influencing the recorded data. For shallow cracks the region near the crack tip for location of any instrumentation is very small, requiring that special clip-gage attachment techniques be developed. Section 6.1 contains more information concerning clip-gage attachment.

To adequately size the required instrumentation, elastic-plastic calculations have been performed on both deeply cracked and shallow-crack beams to estimate the beam response as a function of applied load. Details of these calculations are given in the Appendix. The estimates were performed for square and rectangular specimens with normalized crack depths a/w of 0.50 and 0.125. The CMOD at the specimen limit load was found to vary between ~0.9 mm (35 mils) for the shallow-cracked, rectangular case and 2.2 mm (86 mils) for the deep-cracked, square specimen. The LLD at the limit load increases as the crack depth decreases and varies between 5.6 and 1.9 mm (220 and 76 mils) for the shallow, square and deep-crack rectangular specimen, respectively.

Accuracy and sensitivity requirements for the data acquisition system (including instrumentation) are given in the various ASTM standards.[6-8] These requirements will be met or exceeded. The data acquisition system will record and reduce data during the fatigue precracking procedures as well as during the fracture toughness evaluation tests. This data acquisition system can be assembled primarily from existing HSST equipment.

6. PROJECT EVOLUTION

The evolution of the HSST shallow-crack program is described in this chapter. The program is designed to investigate shallow-crack specimens that are as prototypic as practicable to an RPV. To properly apply the experimental results to pressure vessels, the HSST shallow-crack project needs to have an analytical understanding of shallow-flaw behavior in test specimens and actual reactor vessels. The joint analytical and experimental comparisons will provide insight into shallow-crack behavior not available by either an analytical or experimental study alone.

As with most experimental research programs, certain testing techniques must be developed and verified in this project to investigate the influence of shallow cracks in reactor vessels. However, in addition to the development of shallow-crack testing technology under conditions prototypic of an RPV, the HSST Program anticipates producing a data base of shallow-crack fracture toughness values. To meet these objectives, the HSST shallow-crack project is divided into two experimental phases: a development phase and a production phase. During the development phase the experimental techniques necessary for shallow-crack testing will be established and six verification tests conducted. Once the testing capabilities are confirmed, the toughness of shallow cracks under conditions simulating an RPV will be compared with the toughness of deep-cracked specimens as a part of the production phase of the project.

6.1 ANALYTICAL SUPPORT

Currently three separate analytical investigations are planned as a part of the HSST shallow-crack program. These investigations are necessary to plan the experimental test matrix (Sect. 6.3) and apply the experimental data to RPVs. Initially, the crack depths of interest in the program need to be investigated analytically. Specifically, how shallow cracks will scale between different-sized specimens is uncertain at this time. The HSST shallow-crack test specimen will be analyzed with different crack depths to distinguish the cracks depths that exhibit shallow-crack behavior and the toughness elevation that is anticipated at each crack depth. These analyses will also provide pretest information for proper instrumentation, etc.

The second investigation is to determine the influence of specimen thickness on the fracture toughness of the HSST specimens. Both rectangular (50 by 100 mm) and square (100 by 100 mm) specimens will be tested, although the majority of the tests will be conducted with the rectangular specimens. Both specimens need to be analyzed to compare the specimen response with a shallow-cracked reactor vessel. In addition, the specimen analyses at the University of Kansas were used to determine the plastic rotation factor used in the interpretation of the fracture toughness data.[1,2] This same approach is planned for the HSST shallow-crack specimens (Chap. 5).

The third analytical investigation will determine how the data collected in the HSST shallow-crack program should be applied to a reactor vessel. Specifically, the influence of the difference between the reactor wall thickness and the test specimen width on the shallow-crack behavior needs to be investigated. The specimen width of 100 mm (4 in.) was chosen because it is believed that a 100-m beam is large enough to isolate the tip of a relatively deep crack from the edges of the specimen allowing direct comparison of a shallow crack between the test specimen and the wall of an RPV. In other words, if cracks 10 mm (0.4 in.) or less in depth show an elevated toughness in the test specimen, then cracks 10 mm deep or less are expected to show a similar toughness elevation for a reactor vessel wall. However, this is an important consideration and needs investigation and confirmation.

6.2 DEVELOPMENT PHASE

The development phase of the HSST shallow-crack program has the objective of developing the necessary experimental techniques for the testing of shallow-crack A533 specimens and subsequently to verify these testing capabilities with six preliminary or "shakedown" tests. The development phase of the project is to take place concurrently with the analytical studies described previously. Currently, the two identified topics that need investigation before any shallow-crack testing can take place are (1) fatigue precracking of the beam and (2) application of the instrumentation to the specimen. Fatigue precracking is necessary to sharpen the initial notch in a fracture toughness specimen. The ASTM standards (E399,[6] E813,[7] E1290[8]) contain specific requirements concerning the cyclic load levels that can be used to fatigue the notch and the shape of the sharpened flaw. These requirements are necessary to ensure that the fatigue precrack is representative of flaws found in engineering structures and that the specimen produces fracture toughness values comparable with other fracture testing.

Fatigue precracking a shallow crack is more difficult than for a conventional specimen. Obviously, the starter notch from which the crack emanates must be much smaller for a shallow-flaw specimen. The load level must not exceed certain limits during the final stages of fatigue crack growth, increasing the number of load cycles required. Furthermore, because the beams are 50 to 100 mm thick (2 to 4 in.), the ASTM requirements[6-8] concerning the profile of the crack front (i.e., straightness) are more difficult to meet. In fact, the chevroned notch technique which is used to produce a straight fatigue precrack, cannot be used for shallow flaws because the depth of the chevron (~30 mm) is greater than the depth of the shallow crack.

The most promising method of fatigue precracking a straight crack involves the use of electron discharge machining (EDM) for notching the specimen. Using EDM techniques, very small notches (~0.2 mm) of any depth can be inserted. Because the notch root radius is very small, the notch will be cut close to the desired final crack depth, allowing the fatigue precrack to be grown in fewer cycles and resulting in a straight crack front. The development beams will be examined following testing to observe the crack profile and any edge effects prevalent during fatigue precracking.

The second task requiring developmental work before any shallow-crack testing is the attachment of the instrumentation to the specimen. In particular, as mentioned in Chap. 3, the attachment of the clip gage(s) used to measure CMOD is more difficult with a shallow-crack specimen than with a conventional fracture specimen. In any fracture specimen, the application of the instrumentation must not influence the recorded data; therefore, the clip gage is located in a zone near the crack mouth where the gage will not affect the actual opening of the crack. This "dead zone" is a function of the depth of the crack and is very small for shallow cracks.

Numerous ideas are being considered concerning the problem of attaching the instrumentation to the shallow-crack specimen, including (1) small holes drilled very close to the crack mouth in the beam to hold a fixture to which the clip gage(s) are attached, (2) a mounting bracket with the instrumentation attached to it that is welded to the edge of the crack on the specimen, or (3) very small knife edges machined into the mouth of the crack for attaching the clip gage(s).

The development phase of the HSST shallow-crack project will culminate in a series of preliminary tests for the purpose of validating the testing techniques necessary for shallow-crack tests. These tests are not designed to produce any shallow-crack data but rather to evaluate the test facilities and develop procedures to assure that the data produced subsequently in the project will be acceptable shallow-crack data. There are several objectives for the shakedown tests in addition to validating the development activities described previously. The compliance of each different specimen needs to be measured in the testing machine to accurately set the proper load rate specified in the applicable ASTM standards.[6-8] Each component of the testing facility and data acquisition system will be checked for proper operation during the shakedown tests. Test procedures based on the results of the preliminary tests will be written for the production phase of the HSST shallow-crack project.

At present, it is planned to include six specimens as verification tests. These tests are to include at least two deep-cracked specimens and two shallow-crack specimens that will be tested at a temperature to ensure no prior stable crack growth. The remaining tests will be conducted with a different shallow-crack depth and/or a higher temperature to investigate the behavior of a more ductile specimen.

6.3 PRODUCTION PHASE

Once the shakedown tests have been completed, the production phase of the HSST shallow-crack project can begin with the goal of determining under simulated RPV conditions the fracture toughness of shallow-cracked specimens. The matrix of tests to produce the HSST shallow-crack fracture toughness data base involves the test temperatures to be considered, the crack depths tested, and the number of tests to be conducted at each condition. Recommendations made for the shallow-crack test matrix to provide sufficient data for use in the consideration of flaws in reactor pressure vessels are given below.

The temperature range of interest in the HSST shallow-crack investigation is primarily dictated by the application of the data to RPVs. This temperature range has previously been given as roughly between $T - RT_{NDT} = -50$ and 50°C (-58 and 122°F). Assuming an RT_{NDT} in the L-S orientation similar to that in the T-L orientation, the temperature range of interest is roughly -73 to 27°C (-100 to 80°F), which is close to the anticipated lower transition range for A533.

As described above, the specimen tests will take place at temperatures applicable to reactor vessels. The lower limit of the temperature range will be in the lower-shelf region where shallow-cracked specimens and deep-cracked specimen have identical toughness values. At least one set of shallow- and deep-crack specimens should be tested at a lower-shelf temperature to show that there is no increase in the fracture toughness for shallow cracks at the lower shelf. Testing will take place at increasing temperatures until the material becomes too ductile to initiate in cleavage. The temperature interval between tests will be reduced as the temperature increases because of the rapid toughness increase as a function of temperature. The actual temperature values used in the HSST shallow-crack program will be chosen when the L-S material characterization has taken place. It is anticipated that at least four, and probably as many as six, different test temperatures will be selected.

The crack depths to be considered in the test matrix cannot be conclusively determined until the analytical study described in Sect. 6.2 has been completed. However, specimens with a crack depth roughly half the specimen width (a/w ~ 0.5) should be tested first under identical conditions to those planned for the shallow-crack depths so that a direct influence of crack depth on fracture toughness can be measured. The minimum crack depth of interest in the HSST shallow-crack program a = 5 mm (0.2 m) will be tested next. This depth represents a practical lower limit of the crack depths that initiated in the IPTS studies[3-5] and is roughly the same as the absolute crack depth used in the shallow-crack studies at the University of Kansas.[1] An additional depth to be tested will be determined once the crack depths exhibiting shallow effects are determined analytically for the HSST specimen and the application of the HSST shallow crack data to a reactor vessel has been investigated. Currently, testing three crack depths (including the deep-crack case) is anticipated.

Replicate tests need to be performed in any fracture toughness test program because of the data scatter associated with tests of this type. The shallow-flaw tests seem to produce data with even more scatter than conventional toughness specimens. Based on the experience at the University of Kansas and EWI, it is recommended that at least three specimens be tested at each condition.[1,2,10-15] When the data set from the identical tests is analyzed, additional replicate tests at selected conditions can be performed if necessary.

The test matrix just described will be conducted using rectangular (50- by 100-mm) specimens and consists of ~60 tests. However, a limited number of tests will be conducted using square (100- by 100-mm) specimens for comparing the two specimen thicknesses. It is anticipated that the fracture toughness of the specimen will be independent of the beam thickness; however, this assumption will be investigated. The conditions of the square specimen tests will be determined based on the results of the rectangular specimen tests. Current plans are to test approximately ten square specimens.

6.4 MATERIAL CHARACTERIZATION AND AVAILABILITY

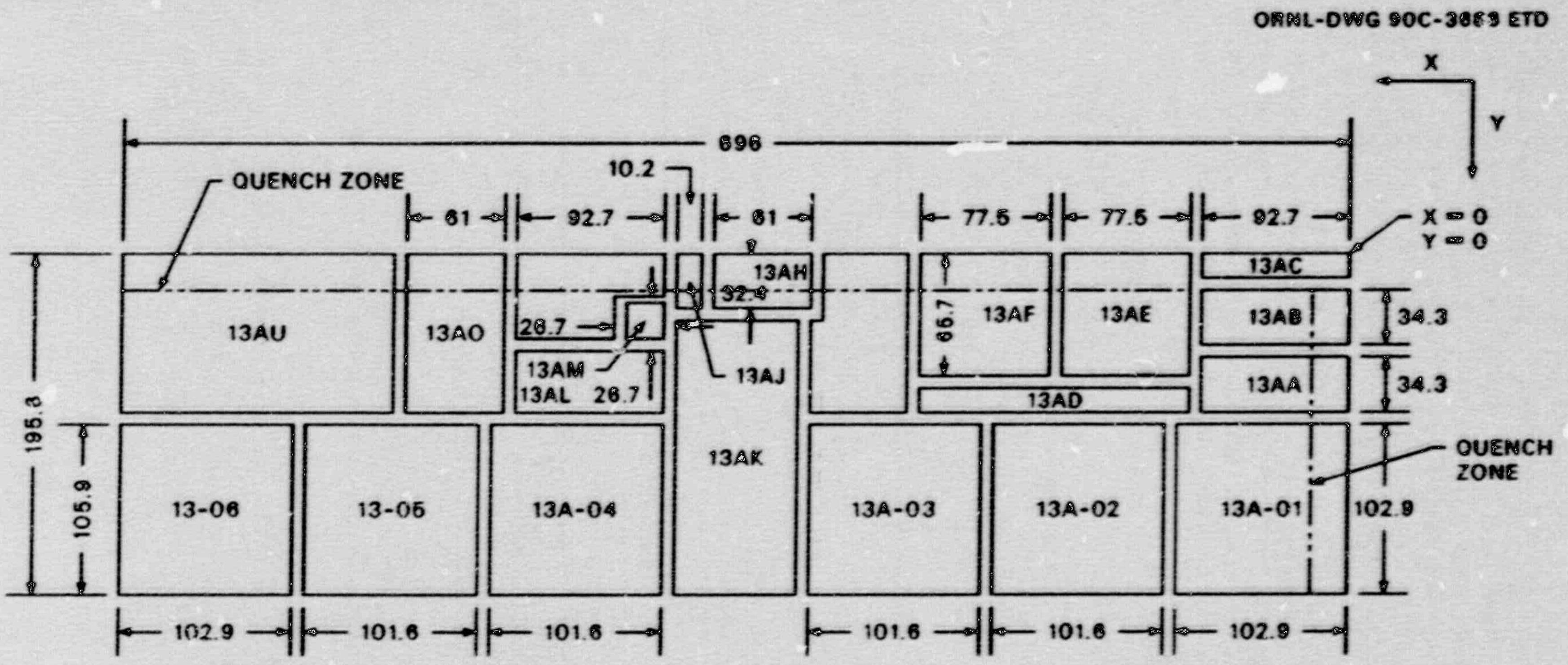
Characterization of the source plate for the HSST shallow crack tests has taken place primarily in the T-L orientation[24] and will need to be performed in the same orientation as axially oriented flaws in a reactor vessel (L-S) before the development of the shallow-crack data base. Material characterization will involve (1) determination of the stress-strain relationship in the L-S orientation, (2) location of the lower transition region by producing a toughness-temperature transition curve in the L-S orientation, and (3) Charpy V-notch (CVN) testing at two different plate thicknesses in the L-S orientation. The characterization will take place using conventional fracture toughness specimens such as compact-tension fracture, tensile, CVN impact, and drop-weight specimens.

The test matrix detailed in the preceding section requires testing at four to six different temperatures and three different crack depths, with three to six specimens tested at each condition. Approximately 60 tests would be conducted using the rectangular specimens with 10 additional square specimen tests. Therefore, an important consideration in this program is the availability of prototypic reactor-grade material.

HSST Plate 13A has been extensively characterized and used as a source plate for several test series including the first six wide-plate tests.[24] A cut-up plan of HSST Plate 13A is shown in Fig. 16. No material from HSST Plate 13A is available for use in the shallow-crack tests; however, HSST Plate 13B is a companion plate to HSST Plate 13A and is available as a source of material for the HSST shallow-crack specimens. HSST plates 13A and 13B are the two halves of HSST Plate 13, which was cut for shipping purposes. The two plates are roughly the same size. HSST Plate 13B has only been used as a source plate for WP-1.7 and -1.8.[31] The remains of WP-1.7 and -1.8 will be used for the shallow-crack tests first, then test material will be cut from the remainder of Plate 13B. Because HSST Plates 13A and 13B are originally from the same plate, the characterizations should be equivalent.

Assuming that the equivalent of 80 rectangular specimens will be needed for the entire production phase of the project, a plate with an area of more than 2 m^2 (22 ft^2) would be required. HSST Plate 13B contains 10 m^2 (109 ft^2) of usable material. Because characterized reactor material is scarce, it may be necessary to conserve material and not use homogeneous beam specimens.

Two alternatives are currently being considered to conserve HSST Plate 13B. The first option is the use of a welded composite beam in which the test coupon taken from HSST Plate 13B is welded to a pair of



TYPICAL CUTTING ALLOWANCE = 2.5

DIMENSIONS IN CENTIMETERS

Fig. 16. Flame cut-up of HSST Plate 13A.

reusable end arms [see Fig. 17(*a*)]. The second alternative is the use of a 914-mm (36-in.) beam, all from HSST Plate 13B, from which three tests could be performed [see Fig. 17(*b*)]. The HSST program has prior experience with using welded composite specimens for large tests.[24]

It is not necessary to use HSST Plate 13B for the preliminary (shakedown) tests; instead, remaining wide-plate material from the WP-CE series of tests[32] has been identified as source material for the preliminary tests. This material is prototypic of that found in a reactor vessel but is not as plentiful nor as well characterized as HSST Plate 13A or 13B. Because only six preliminary tests are to be conducted, homogeneous beams, rather than welded composite beams, will be used in the verification tests of the HSST shallow-crack project.

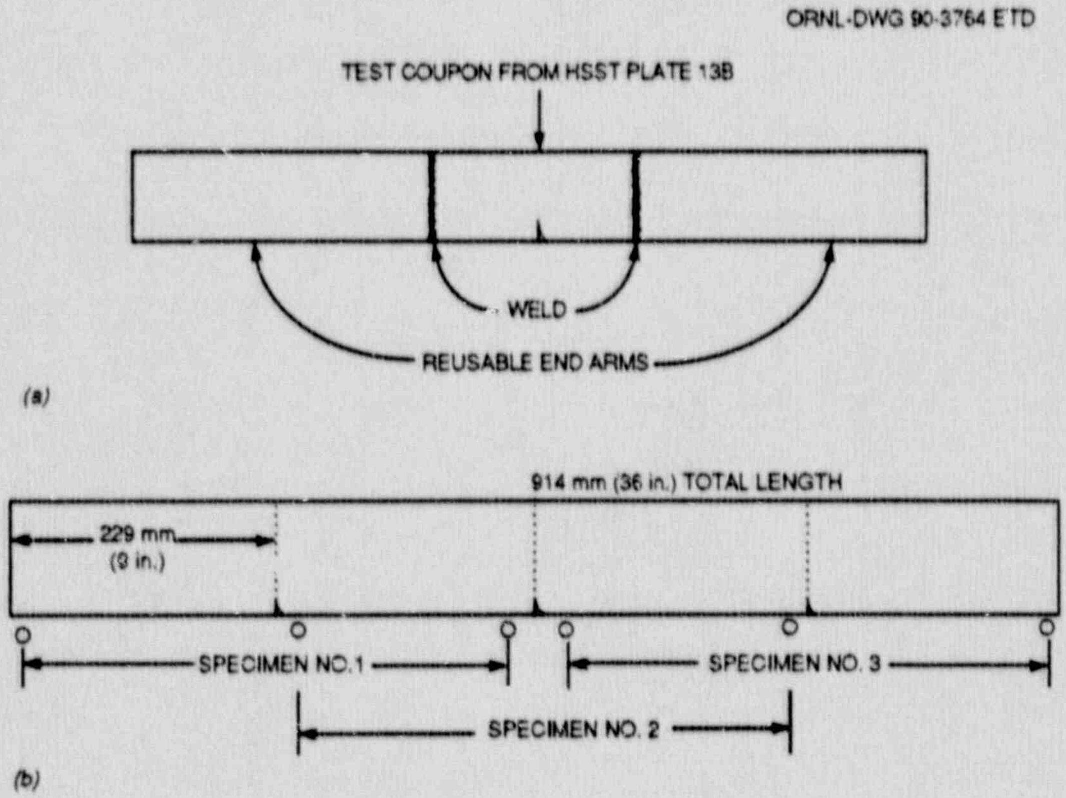


Fig. 17. Alternative methods for conserving A533 material.

7. ANTICIPATED DATA APPLICATION

The primary goal of the HSST shallow-crack project is to investigate fracture toughness values for shallow flaws under conditions prototypic of an RPV. If the investigation progresses as expected, then a limited fracture toughness data base for shallow cracks will be developed. The fracture toughness data base can then be used in either deterministic or probabilistic fracture mechanics evaluations including further probabilistic fracture mechanics evaluations of reactor plants concerning plant-life extension (i.e., the NRC PTS rule)[9] and/or modification of the ASME Sect. XI rules for fracture mechanics evaluation of reactor vessels.[33] Specific licensing issues that will be affected significantly by this study include the PTS, plant-life extension, and reactor vessel support.

The HSST shallow-crack fracture toughness data base and the experience gained in producing it should play a key role in any effort to modify the current standards[6-8] on fracture toughness testing to include shallow cracks. The HSST Program will interface with the appropriate national standards committees on the issue of shallow-flaw testing to gain review of the project by the standards committees and to provide the HSST experience to the committees for their use in modifying the standards to include shallow-flaw testing.

As a part of the production of a data base of shallow-flaw fracture toughness values, this project will produce results that are of interest in other areas of the HSST Program. Task H.6 (Crack Initiation) of the HSST Program is divided into three subtasks: 6.1, Constraint Effects; 6.2, Metallurgical Inhomogeneity; and 6.3, Shallow-Crack Fracture Toughness Testing. Presently, shallow-crack fracture toughness values are believed to depend on the geometry of the crack-tip region and the proximity of a free surface (i.e., varying degrees of crack-tip constraint). The analytical work in support of the development of a shallow-flaw data base will further the understanding of the root cause of the shallow-crack fracture toughness elevation. Because the constraint of a shallow-flaw differs from a deep flaw, the data and analyses from this project can be used to enhance the general understanding of the influence of constraint on initiation toughness.

Task H.6.2 is concerned with the metallurgical inhomogeneity (including anisotropy) of large plates such as those used in reactor vessels. The characterization of HSST Plate 13B in the L-S orientation for the shallow-flaw work will supplement characterizations in other directions of the same plate. Comparisons can then be made that will be used to quantify the anisotropy of a large plate in terms of crack initiation fracture toughness. Quantifying the anisotropy in a large plate will lead to a better understanding of the degree of conservatism built into present requirements for the fracture toughness of reactor vessel plates.

8. SUMMARY

Recommendations for the HSST shallow-crack program have been presented. The motivation for initiating this project is that probabilistic fracture mechanics evaluations[3-5] show that flaws 10 mm deep or less rather than deeper flaws in reactor vessels have more impact on the probability of vessel failure. Furthermore, it is anticipated that shallow cracks in reactor vessel steels will exhibit an increase in toughness similar to that in the structural steels tested previously, in which case the impact on both the deterministic and probabilistic fracture mechanics evaluations of reactor vessels would be substantial.

The primary goal of the HSST shallow-crack project is to investigate the behavior of the fracture toughness for shallow cracks under conditions prototypic of an RPV. To meet this goal a beam specimen is defined with a depth (W) of 100 mm (4 in.) fabricated from A533 material with a crack oriented in the same direction as in an RPV.

The requirements of the test facility and data acquisition system are detailed. A load capacity of 220 kip is required to test the defined specimen. The data to be collected during the tests include load, LLD, and CMOD. These data will allow the fracture toughness to be expressed in terms of K_{Ic}, K_{Jc}, and CTOD.[6-8]

The evolution of the project has been planned and detailed in this report. The development phase of the program will develop and verify the technology necessary for testing shallow-crack beams. A data base of shallow-crack fracture toughness values will be obtained as part of the production phase of the project. The proposed test matrix consists of four to six test temperatures and three crack depths, with three to six specimens to be tested at each condition. Unresolved issues within the program have been identified with suggested solutions.

Results of the HSST shallow-crack program, in addition to the development of a shallow-crack data base, include participation in the efforts to modify current ASTM standards[6-8] to include shallow-crack test specimens, explanation of the underlying cause of the shallow-crack fracture toughness elevation, study of the influence of crack-tip constraint on initiation toughness, and investigation of the orientation differences in the fracture toughness of large plates. All of these results are directed toward the resolution of key licensing issues facing the NRC at this time as well as expanding the basic understanding of crack initiation.

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Appendix

LIMIT-LOAD CALCULATIONS AND SPECIMEN RESPONSE

Details of the limit-load calculations used to determine the load requirements and elastic-plastic calculations to estimate the response of the beam for specimens being considered in the HSST shallow-crack program are included in this Appendix. The calculations were performed using the Handbook on Elastic-Plastic Fracture Analysis.[1]

Simple linear bending theory was used for the limit-load calculations. The plastic limit loads for plane stress and plane strain conditions are respectively given by

$$P_L^{\sigma} = \frac{1.072\ \sigma_y B\ (W - a)^2}{S}$$

and

$$P_L^{\epsilon} = \frac{1.456\ \sigma_y B\ (W - a)^2}{S} ,$$

where

σ_y = yield stress,

B = specimen thickness,

W = specimen width,

a = crack depth,

S = span of specimen.

The square specimen geometry was considered as B = W = 100 mm (4 in.). The span was 610 mm (24 in.), and the yield stress, 471 MPa (68.3 ksi).

Results of these calculations for multiple crack depths are given in Table A.1. Three-dimensional finite-element calculations performed for the EWI shallow-crack program[2] showed that the actual plastic limit load for the cracked specimen analyzed was very well approximated by the plane-stress, uncracked beam limit load. These calculations show that a load capacity of 1 MN (220 kip) should be adequate for testing the HSST shallow-crack specimens.

Calculations were also performed to determine the CMOD and the LLD of the HSST beam specimens as a function of applied load. The three specimens considered were (1) a square beam (100 by 100 mm) with a deep crack (a = 50 mm), (2) a deeply cracked rectangular beam, (3) a shallow-crack square beam, and (4) a shallow-crack rectangular beam. The

Table A.1. Limit loads computed for HSST square specimen (100 by 100 mm) for various crack depths

a/w	Limit load [MN (kip)]	
	P_L^o	P_L^ε
0	0.867 (195)	1.179 (265)
0.063	0.765 (172)	1.036 (223)
0.125	0.667 (150)	0.903 (203)
0.188	0.574 (129)	0.778 (175)
0.500	0.217 (48.8)	0.295 (66.3)

shallowest crack depth that can be considered using the Handbook is $a/w = 0.125$. Calculations are based on use of the Ramberg-Osgood formulation of the stress-strain curve. Input for the calculations included the geometry of the specimens, standard material properties (E, ν, σ_y), and the Ramberg-Osgood coefficients ($\alpha = 3$, $n = 10$, for A533). The CMOD and LLD at the specimen limit load for the plane-strain conditions is summarized in Table A.2. The approximate maximum expected CMOD is 2.2 mm (86 mils) for the deep-crack square specimen, and the maximum expected LLD is 5.6 mm (220 mils) for the shallow-crack square specimen.

Table A.2 CMOD and LLD for four potential HSST configurations at the plane-strain limit load

	CMOD [mm (mils)]	LLD [mm (mils)]
1. Deep crack, square beam	2.2 (86)	3.9 (153)
2. Deep crack, rectangular beam	1.3 (53)	1.9 (76)
3. Shallow crack, square beam	1.5 (59)	5.6 (220)
4. Shallow crack, rectangular beam	0.9 (35)	2.8 (110)

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11. ABSTRACT *(200 words or less)*

Recommendations for the Heavy-Section Steel Technology Program's investigation into the influence of crack depth on the fracture toughness of a steel under conditions prototypic of those in a reactor pressure vessel are included in this report.

The primary goal of the shallow-crack project is to investigate the influence of crack depth on fracture toughness under conditions prototypic of a reactor vessel. A limited data base of fracture-toughness values will be assembled using a beam specimen with a depth of 100 mm (4 in.) using prototypic reactor vessel material.

Results of the investigation are expected to improve the understanding of shallow-flaw behavior in pressure vessels, thereby providing more realistic information for application to the pressurized-thermal-shock issues.

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