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A SUMMARY OF THE LOW UPPER SHELF TOUGHNESS SAFETY MARGIN ISSUE*

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ABSTRACT

The low upper shelf toughness issue has a long history, beginning with the choice of materials for the submerged arc welding process, but also potentially involving the use of A302-B plate. Criteria for vessels containing low upper shelf materials have usually been expressed in terms of the Charpy upper shelf impact energy. Although these criteria have had several different bases, the range of limiting values for wall thicknesses approaching 229 mm (9 in) has remained between 54 to 68J (40 to 50 ft. lbs). Allowable values for vessels with thinner walls and/or only circumferential low upper shelf welds might conceivably be less.

A decision on criteria to be incorporated into the ASME Code is now being made. Choices to be made concern the method for estimating the decrease in upper shelf impact energy, flaw geometry for circumferential welds, statistical significance of toughness values, the choice between J_D and J_M, reference pressure, safety factors and the inclusion of tearing stability calculations by means of R curve extrapolation. NRC research programs have contributed significantly to the resolution of the low upper shelf issue. These programs embrace all aspects of the issue, including material characterization, large scale testing, analysis and criteria development.

INTRODUCTION

The problem of low upper shelf welds in some U.S. PWR vessels fabricated by Babcock & Wilcox between 1965 and 1973 exists because of the choice of materials used in the submerged arc welding process. The subject welds initially had rather low Charpy upper shelf impact energies because of the flux used, which was Linde 80. This particular flux was chosen because it resulted in the non-metallic inclusions being very small and finely dispersed, thus producing good radiographs and minimizing required weld repairs. Unfortunately, it was not generally recognized at the time that the local strain required to debond an inclusion and begin void growth decreases as the particle size decreases (Refs. 1 and 2), so that the fineness of the inclusions also led to a relatively low initial Charpy upper shelf impact energy. However, since the 1965 version of Section III of the ASME Code had no Charpy upper shelf impact energy requirements for reactor vessel materials, the relatively low initial Charpy upper shelf energy values were not considered a problem. The vulnerability of the same welds to neutron irradiation damage is due largely to their relatively high copper content, this being the result of using copper coated weld wire. The purposes of using copper coated weld wire were to prevent rusting of the weld wire and to improve its electrical conductivity. The copper content of the welds involved is not only relatively high but it is also quite variable, because the hot dip coating process that was used produced a variable film thickness. At the time the vessels involved were being fabricated, the prevailing understanding of fracture prevention in the pressure vessel industry was based on the NRL Fracture Analysis Diagram (Ref. 3) shown in Fig. 1.

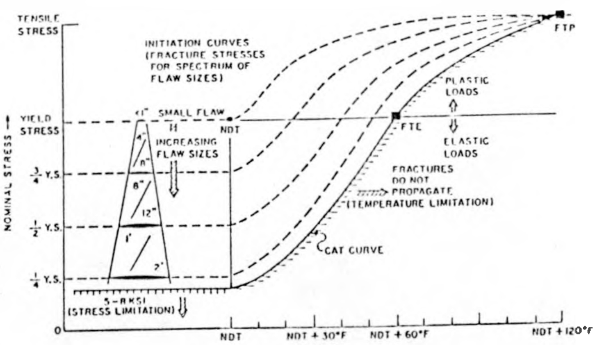

Fig. 1. Fracture analysis diagram (FAD).

Accordingly, it was believed that in the upper shelf temperature range of the Charpy impact energy curve, only plastic collapse failures could occur, even in the presence of flaws. Nevertheless, there was some evidence of unexpected ductile fractures, both in service and in test. The service failures (Ref. 4) were a series of forged steel retaining rings for some aluminum extrusion devices. It was found that, by re-heat treating the surviving retaining rings so that their Charpy upper shelf energies at maximum service temperature were between 68 and 81 J (50 and 60 ft lb), additional failures could be prevented (Ref. 4). The unexpected failure of an experimental high strength steel pressure vessel by ductile fracture (Ref. 5) focused attention on the possibility of low upper shelf failures, and the NRL began to modify its Fracture Analysis Diagram accordingly (Ref. 6) as shown in Fig. 2. Consequently, the AEC began considering safety requirements for the upper shelf temperature range as well as for the transition temperature range. Draft documents containing proposed criteria were written in 1967 and in 1969. The latter document (Ref. 7) contained a requirement for annealing for any vessel having material with a Charpy upper shelf impact energy during service less than 68J (50 ft lb).

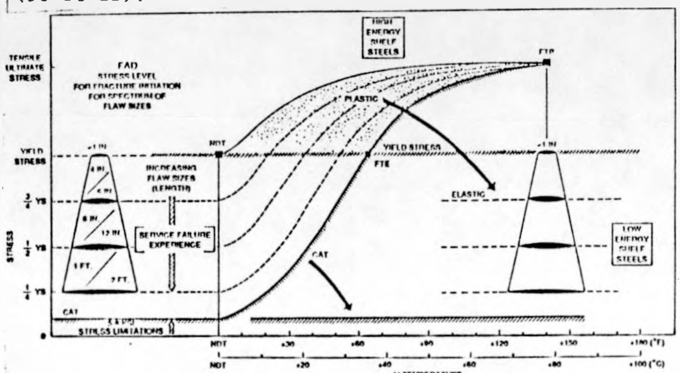

Fig. 2. Fracture analysis diagram, modified to show the effects of low upper shelf toughness.

A draft AEC technical background document (Ref. 8), gave the bases for the 68J (50 ft lb) criterion as the *NRL ratio analysis diagram* (Ref. 9), a Charpy upper shelf energy versus toughness correlation developed by Rolfe and Novak (Ref. 10), and a fracture mechanics leak-before-break calculation for a 254-mm (10 in) thick vessel wall. Requirements added to 10CFR50 by publication in the Federal Register (Ref. 11) on July 3, 1971 stated the 68J (50 ft lb) requirement for thicknesses equaling or exceeding 127 mm (5 in) plus initial Charpy upper shelf requirements for the same thickness of between 88 and 102J (65 and 75 ft lb), depending on the expected irradiation induced temperature shift of the Charpy curve.

In August 1972, the PVRC issued WRC-175 which contained recommended fracture control procedures for nuclear pressure vessels (Ref. 12). WRC-175 contained the K_{IR} curve, indexed to the RT_{NDT}, which was based on the Drop Weight NDT and the higher temperatures at which CVN ≥ 68J (50 ft lbs) and MLE ≥ 0.89 mm (35 mils). In January, 1972, the ASME-BPVC approved the original version of Appendix G of Section III, patterned closely after a draft of WRC-175. Appendix G was originally published in the Summer 1972 Addenda to Section III.

In July 1973, Appendix G to 10CFR50 was revised (Ref. 13) to be as consistent as possible with the ASME Code. The quantity ΔRT_{NDT} was defined as the irradiation induced temperature shift of the 68J (50 ft lb) point on the Charpy curve. Consequently, ΔRT_{NDT} would become undefinable for CVN < 68J (50 ft lbs). The general state of metallurgical knowledge, admittedly incomplete, concerning the low upper shelf problem was described by Steele (Ref. 14) in 1975, including a note of caution concerning the seriousness of the problem (see Ref. 14, pp. 164-169).

In November 1975, the objective of the Second HSST Irradiation Series was changed, focusing on the upper shelf toughness of high copper weld metals (Ref. 15). Seven Linde 80 submerged arc welds were furnished by Babcock and Wilcox and by Westinghouse, providing material for both the Second and the Third HSST Irradiation Series (Ref. 15). Several organizations were involved in the work, and much technical development was required to obtain the toughness data. Tearing resistance curves for six of the seven HSST high copper low shelf Linde 80 welds were obtained (Ref. 16) by 1980. (The complete results for the Second and Third HSST Irradiation Series were published (Ref. 17) in 1984.).

In November 1980, a proposed rule change was published (Ref. 18) by the NRC, whereby ΔRT_{NDT} was based on the 41J (30 ft lb) energy level, and the minimum Charpy upper shelf impact energy level during service, without special evaluation, of 68J (50 ft lb) was stated explicitly. Also during 1980, an NRC task group, specifically focused on the low upper shelf weld issue, held a series of meetings to consider proper analytical methods. The J-T diagram was considered an acceptable method, and a report was issued (Ref. 19). However, parametric calculations needed as a basis for developing safety margin criteria were not performed, and the development of criteria was later transferred by request to the ASME Section XI Working Group on Flaw Evaluation.

In August 1982, the HSST Program tested Vessel V-8A, which contained an 88-mm (3.46 in) deep external surface crack in a low upper shelf weld having an upper shelf Charpy impact energy of 57J (42 ft lb) (Ref. 20). The tearing instability pressure was slightly above 138 MPa (20 ksi), more than double the code design pressure of 67 MPa (9.7 ksi). With the V-8A test results in hand, the NRC finalized the 68J (50 ft lb) minimum upper shelf rule (Ref. 21) in May 1983.

The status as of 1986 of U.S. PWR vessels with respect to the low upper shelf weld problem (Ref. 22) is summarized in, which includes vessel fabricator, cylinder wall thickness, and the identity of vessels with only circumferential low upper shelf welds. It can be seen that all five vessels that presently do not satisfy the 68J (50 ft lb) criterion are Westinghouse designed plants with *B&W* fabricated vessels, for which the upper shelf drop was estimated by the conservative procedure of Reg. Guide 1.99 (Ref. 23). In addition, four of the five vessels have only circumferential low upper shelf welds. The reason that all five vessels presently containing weld metal with estimated upper shelf CVN values less than 68J (50 ft lbs) are in Westinghouse designed plants is that Westinghouse plant vessels have less water shielding between the core and the vessel than do the vessels in B&W designed plants.

SURVEILLANCE PROGRAMS

Fracture mechanics as we now know it did not exist when the original surveillance programs were designed. The technical basis of the original surveillance program designs was the NRL Fracture Analysis Diagram shown in Fig. 1, and the original programs were designed without adequate knowledge of the effects of copper, phosphorous and nickel (Ref. 24). In 1966, surveillance programs were only required to have tensile and Charpy specimens from one heat of base metal, one weld and one heat affected zone, all representative of the vessel (Ref. 25). Thus, specimens of each individual weld were not required. Reference correlation monitor specimens of an A302-B plate manufactured by U.S. Steel (Ref. 26) were required. This plate turned out to have an initial Charpy upper shelf impact energy of 65J (48 ft lbs) (Ref. 27), as shown in Fig. 3.

Table 1. Calculated Charpy USEs for PWR reactor vessels with Linde 80 weld metal[a]

PWR plant	Nuclear Steam Supply System	End of license	Wall thickness [mm (in)]	Charpy USE at end of license [J (ft-lb)]	RPV Mfg.	Charpy USE on Jan. 1, 1986 [J (ft-lb)]	ΔCVN method
Point Beach-2	W	2013	165 (6 1/2)	C 46 (34)	B&W/CE	53 (39)	RG 1.99
Point Beach-1	W	2010	165 (6 1/2)	52 (38)	B&W	58 (43)	RG 1.99
Turkey Point-3	W	2007	197 (7 3/4)	C 54 (40)	B&W	60 (44)	RG 1.99
Turkey Point-4	W	2007	197 (7 3/4)	C 54 (40)	B&W	60 (44)	RG 1.99
Ginna	W	2006	165 (6 1/2)	C 57 (42)	B&W	64 (47)	RG 1.99
Arkansas One-1	B&W	2008	219 (8 5/8)	60 (44)	B&W	>68 (50)	B&W
Rancho Seco	B&W	2008	219 (8 5/8)	60 (44)	B&W	>68 (50)	B&W
Crystal River-3	B&W	2008	219 (8 5/8)	60 (44)	B&W	>68 (50)	B&W
TMI-1	B&W	2008	219 (8 5/8)	60 (44)	B&W	>68 (50)	B&W
Oconee-1	B&W	2013	219 (8 5/8)	60 (44)	B&W	>68 (50)	B&W
Oconee-3	B&W	2014	219 (8 5/8)	C 60 (44)	B&W	>68 (50)	B&W
Surry-2	W	2008	200 (7 7/8)	62 (46)	B&W/RDM	69 (51)	RG 1.99
Zion-1	W	2008	219 (8 5/8)	64 (47)	B&W	>68 (50)	CECO
Zion-2	W	2008	219 (8 5/8)	66 (49)	B&W	>68 (50)	CECO
Oconee-2	B&W	2013		C 66 (49)	B&W	>68 (50)	B&W
Surry-1	W	2008	200 (7 7/8)	72 (53)	B&W/RDM	77 (57)	RG 1.99
Davis Besse	B&W	2011		C 76 (56)	B&W	>68 (50)	B&W
Yankee Rowe	W	1997	200 (7 7/8)	Low copper welds			
Bryon-1	W	2024		Low copper welds			

[a]W = Westinghouse
C = Circumferential low-shelf welds only
CE = Combustion Engineering
RDM = Rotterdam Drydock
CECO = Commonwealth Edison Company

The nuclear system vendors, the utilities and the NRC are often faced with incomplete data from individual plants. Consequently, there is a need to treat the whole body of surveillance data collectively, both for statistical purposes and to compensate for missing plant specific data. In the case of potentially low shelf welds, since material from only one weld was required to be included in the early surveillance programs, some potentially low upper shelf welds were not represented by original surveillance specimens. Consequently, when potentially service limiting material was required to be included in the surveillance programs, Babcock and Wilcox fabricated new welds from the same materials (weld wire and flux) and with the same welding procedures used for the actual vessel welds (Ref. 22). Surveillance specimens, including tensile, Charpy and round 1/2 T Compact specimens, were made from the duplicate welds. A B&W Owners' Group was formed, and the specimens were placed in vessels as space and scheduling permitted, some specimens being placed in surrogate vessels (Ref. 22). Not all of the utilities that would eventually need the data initially joined the B&W Owners' Group, believing that they could solve their problems by other means. Consequently, B&W kept their owners' group data proprietary, hoping to increase their membership in order to reduce their costs per member- utility. Quoting from Ref. 24, "The users' group approach has produced some very delicate situations with respect to the dissemination of information resulting from the work funded by the member utilities of the group." For example, it was recently stated, at a meeting of the ASME Section XI Working Group on Flaw Evaluation, that there is a direct correspondence between the seven welds in the Second and Third HSST Irradiation Series and specific welds in actual commercial PWR vessels (Ref. 22). Thus, the HSST data are even more valuable than previously realized, because they are not only generally applicable to Linde 80 high copper welds, but they are also individually related to particular plants in service. However, before full advantage can be taken of this fact, the correspondence between HSST welds and plant specific welds will have to be developed from non-proprietary data.

The original B&W surveillance capsules included only tensile and Charpy specimens. 1/2 T CT specimens were added later (Ref. 28). In 1980, Westinghouse capsules included tensile, Charpy and 1X WOL or 1/2 T CT specimens (Ref. 29). Reference 29 contains a detailed discussion of the surveillance data from the first two capsules withdrawn from Ginna, which began operation in 1970. The Charpy upper shelf impact energy of the surveillance specimens from one weld had reached 68J (50 ft lbs) after four years of operation. The lead factor between the surveillance specimens and the 1/4 t location in the vessel wall was approximately four, implying that the vessel would fall below the 68J (50 ft lb) criterion in 1986. Reference 26 includes specific discussions of the surveillance data from Point Beach Units 1 and 2, Turkey Point Units 3 and 4 and Ginna, i.e. all the units listed in Table 1 that presently do not satisfy the 68J (50 ft lb) criterion.

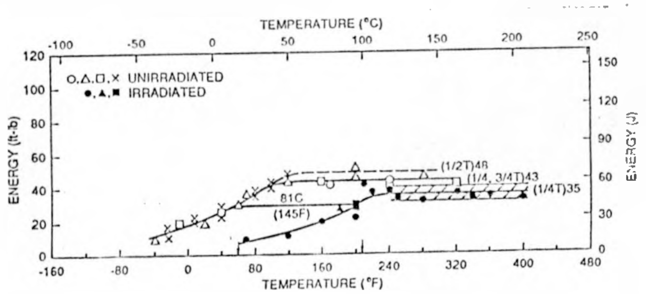

Fig. 3. Charpy V-notch impact energy of A302-B plate, Code N, before and after irradiation to an estimated fluence of 3 x 10^{19} n/cm^2, E> 1 MeV.

Because of the recent cancellation of Consumers Power Midland plant late in construction, some important Linde 80 weld material has become available for irradiation effects studies (Ref. 30). The vessel of this particular plant contained two circumferential welds which consisted wholly or partly of WF-70 weld metal. Welds with this designation, which represents a particular combination of weld wire and flux, are the controlling welds in several operating nuclear vessels. However, until the Midland plant cancellation, no archival WF-70 weld metal was available. A cooperative effort between Commonwealth Edison, the B&W and Westinghouse owners' groups and ORNL (representing the NRC) is underway. Material has been removed from the vessel and is being distributed. Detailed chemistry as well as mechanical and toughness characterization tests will be performed. Unirradiated and irradiated toughness tests will be performed in the transition range as well as the upper shelf range. In the upper shelf range, particular attention will be paid to specimen size effects on the measured R-curves. These data will provide a valuable supplement to scarce surveillance data and therefore, be quite useful in the evaluation of plants in service (Ref. 22).

TECHNICAL BASIS DEVELOPMENT

In 1977, calculations were made by the NRC staff (Ref. 22), based on the Rolfe-Novak correlation (Ref. 10) and otherwise according to Section III, Appendix G of the ASME Code, leading to the conclusion that PWR vessels with 229-mm (9 in) thick walls would have adequate safety margins on the upper shelf as long as CVN $\geq$ 61J (45 ft lbs). The NRC used these results as justification for assuming that time was available for dealing with the problem (Ref. 22). Concurrently, Paris et al (Ref. 31) were working intensively under NRC sponsorship to consolidate the principles and application methods for elastic plastic tearing instability analysis. It was recognized that material tearing resistance would probably need to be considered in order to deal with the increases in K_I due to pressure acting in an inside surface crack, thermal loading and crack tip plastic zone effects which were not fully considered in the original NRC calculations.

As mentioned previously, the NRC's A-11 task group focused mainly on analysis methods, did not perform parametric calculations and did not recommend criteria. The latter two functions were transferred by request to the ASME Code. One development undertaken by the task group that has had particular significance, because of the possibility of vessels having only Charpy and tensile specimens in their surveillance capsules, was the formulation of a preliminary correlation between Charpy impact energy and tensile properties and the parameters of a power law tearing resistance curve. This correlation, (Refs. 19 and 32) when applied to three of the previously tested HSST intermediate test vessels, led to calculations agreeing well with the experimental data (Ref. 20).

HSST Vessel V-8A, containing a flawed low upper shelf weld (Ref. 20), was tested in August 1982, and the ASME Section XI Working Group on Flaw Evaluation (WGFE) began its official consideration of the low upper shelf weld criteria issue in September 1982. Example tearing instability calculations were done by Merkle and Johnson (Ref. 33) using LEFM with a plastic zone size correction. In the absence of pressure in the crack and thermal loading, a safety factor of 2.0 with respect to code design pressure was found possible for Charpy impact energies between 54 and 68J (40 and 50 ft lbs). The WGFE decided to prepare a technical basis document on the low upper shelf issue. Considerable time was spent comparing alternative analytical approaches. By October 1985, a draft had been prepared including an example problem demonstrating that, for the resistance curve assumed for Linde 80 weld, a tearing instability pressure of about 34 MPa (5000 psi) could be expected for a 1/4 t depth inside surface crack in a 216-mm (8.5 in) thick PWR vessel. This example considered the effects of pressure acting on the faces of an inside surface crack, the effects of the crack tip plastic zone and the effects of nominal plastic strain in the vessel cylinder near general yielding. Thermal loading was not considered. This example problem implied that a factor of safety of 2.0 on the upper shelf could be achieved for realistic conditions, thus fostering a general sense of optimism about the problem. The October 1985 draft also contained proposed safety margin criteria, the development of which was aided by W. E. Cooper's written discussions (Ref. 34) on the subject. The recommended criteria were of two types: a criterion to limit stable crack growth to small amounts, called an initiation criterion, and a criterion to prevent tearing instability based on Appendix G of Section III. For Levels A and B loading conditions, both types of criteria used the Appendix G quarter thickness depth flaw. The criteria for Levels C and D used a flaw depth of 25.4 mm (1.0 in). The proposed criteria and the associated safety factors have since evolved with succeeding drafts as R-curve data and correlations have been examined and trial calculations performed.

Shortly after the A-11 task group finished their meetings, a paper was presented by Ernst (Ref. 35) in which it was pointed out that some existing J-Integral tearing resistance curves exhibit size effects and/or develop negative slopes. Ernst proposed a remedy for these problems in terms of a modified J Integral parameter, J_M. The parameter J_M quickly gained popularity because it not only seemed to eliminate the size effects and negative slopes observed previously with deformation theory J_D, but also produced higher R-curves, thus implying higher calculated safety margins.

Recognizing the potential need for a correlation between Charpy properties and R-curve parameters, and the apparent benefits of using J_M, Materials Engineering Associates (MEA) developed a new correlation (Ref. 22) based on J_M to replace the preliminary one developed by ORNL. In the new correlation, base metal and weld metal were treated separately, because it was observed that the A302-B Code V50 plate material had lower R-curves for CVN values near 68J (50 ft lb) than did weld metal. The resulting correlation was, for a time, part of the WGFE draft technical basis document. This step was justified largely on the basis of a successful analysis of Vessel V-8A by B&W (Ref. 36), based on J_M and the approximate procedure called the Deformation Plasticity Failure Assessment Diagram (DPFAD) (Refs. 37 and 38).

In the process of preparing the test report for Vessel V-8A, ORNL performed post-test analyses (Ref. 20). One pair of analyses produced a comparison between the graphical tearing instability solutions for V-8A based on J_D and J_M, using applied J values calculated by elastic-plastic finite element analysis (EPFEA) and an accurate piecewise linear representation of the stress-strain curve. The instability pressure based on J_D was about seven percent conservative, but the solution based on J_M was nonconservative, because no instability pressure was predicted. It was evident that the applied J values estimated by EPFEA and by the DPFAD procedure must differ, and assuming the former to be more accurate, the applicability of J_M became uncertain.

In addition to the analytical discrepancies described above, it was shown, both by the Vessel V-8A results and by the calculations done for the WGFE, that the values of Δa at tearing instability, even for low upper shelf materials, are likely to be beyond the measuring capacities of small surveillance specimens. Consequently there was a need to both resolve the questions of whether J_D or J_M displays the least size effects and which better represents the behavior of flaws in real vessels, and to develop reliable J-Δa extrapolation procedures. All of these results are needed if the conditions at tearing instability, and therefore the margins of safety inherent in nuclear pressure vessels, are to be determined. Consequently, in August 1987, the NRC organized a J_D/J_M Working Group, led by the David Taylor Research Center, to explore and coordinate the resolution of these issues. Significant results were soon obtained. Landes and Herrera (Ref. 39) showed that the apparent size effects that were partly the motivation for the development of J_M were spurious, being the result of errors in crack length caused by errors in unloading compliance measurements. All that was really needed to eliminate the apparent size effects was to correct the near final crack lengths (Refs. 39).

The J_D/J_M working group examined R-curves from many sets of data, mostly from plate but also some for weld metal. The problems of size effects and extrapolation were found to be somewhat connected. Hackett and Joyce (Ref. 40) found that J-controlled behavior apparently exists only where there is a linear relation between the normalized plastic load point displacement, Δ_{pl}/W, and the normalized crack length increase, $\Delta a/W$, where W is the specimen width, and that discarding data beyond this range reduces size effects and facilitates extrapolation. J-controlled data were found to be obtainable for $\Delta a/b_o \lesssim 0.3$ where b_o is the initial ligament width. In general, the size effects in J_D and J_M, where observed, tend to be of opposite type, and in general, power law curve extrapolations of small specimen data are accurate or conservative for J_D and accurate to nonconservative for J_M (Ref. 40).

Some of the data examined by the J_D/J_M Working Group were from transversely oriented specimens of A302-B plate. These specimens developed delaminations caused by flat nonmetallic inclusions oriented perpendicular to the crack front (Ref. 41). In addition, the A302-B J-R curves exhibited size effects unlike those from the other plate and weld materials. Consequently, while these data may be applicable to the development of safety criteria for vessels containing A302-B plate, which do exist (Ref. 42), they are not applicable to the development of criteria for irradiated Linde 80 welds.

The discrimination between J_D and J_M requires resolving which parameter works better for the analysis of vessels. The best opportunity to compare analysis with experiment, for low upper shelf conditions and simple internal pressure loading, is to analyze HSST Vessel V-8A. Because there appear to be differences in calculated values of $J_{applied}$ depending on the method used, ORNL undertook additional elastic-plastic finite element analyses of V-8A and other HSST intermediate test vessels. Mesh convergence studies showed that as long as the flaw is assumed to remain semielliptical, J_D leads to a better estimate of the tearing instability pressure than J_M. However, the calculated values of Δa at instability are larger than the approximately 6 mm measured in the test (Ref. 43). Consequently, as shown in Fig. 4, progressive changes in shape of the crack by lateral tunneling, as estimated from the V-8A fracture surfaces (Ref. 20), were modelled analytically. The results of this analysis are that the graphical tearing instability solution based on J_D underestimates the measured instability pressure, while the solution based on J_M is quite close, both with respect to the instability pressure and the crack growth at instability. From these results, it is apparent that three dimensional flaw geometry changes and stress redistribution alter the picture. Provisionally, if these effects are considered, J_M seems applicable, but neglecting these effects it seems best to use J_D (Ref. 43).

Several other HSST Program pressure vessel tests have included extensive stable ductile crack growth prior to failure, but only one other test involved a flaw in low upper shelf material and careful measurements of progressive crack extension occurring by both ductile tearing and cleavage. In Pressurized Thermal Shock Experiment No. 2 (PTSE-2), conducted in late 1986, a long shallow external surface crack in a low upper shelf 2 1/4 Cr-1 Mo steel insert underwent a succession of ductile and cleavage fracture events (Ref. 44). The succession of events consisted of ductile tearing prior to cleavage including an interval of warm prestressing, a cleavage crack advance, ductile tearing after arrest and prior to reinitiation, a second cleavage crack advance, crack arrest and finally ductile tearing instability. The initial stable tearing is of special interest because of its relation to the accuracy of calculated safety margins against cleavage initiation. By using the measured crack depth, the value of K_{Ic} calculated for the first cleavage initiation in PTSE-2 agrees well with characterization data. However, the crack depth at first cleavage initiation would have been considerably underestimated if the amount of prior stable crack growth had been estimated incrementally, assuming that the slope of the J-R curve depends on the instantaneous values of J and crack tip temperature. This would have led to an overestimate of the thermal shock that the vessel could tolerate without cleavage initiation. Thus, J-R curve and analysis techniques need to be improved to eliminate this deficiency in the technology.

Past discussions of proposed criteria by the ASME Section XI Working Group on Flaw Evaluation (WGFE) and the NRC's J_D/J_M Working Group can now be viewed in perspective. In April 1987, it was proposed that the CVN-R curve correlation to be used in the ASME Code should be based on lower bound properties but unchanged safety factors. In August 1987, the results of trial calculations based on this approach indicated that some vessels evaluated by using the proposed lower bound correlation and unchanged safety factors would still have slightly inadequate margins of safety

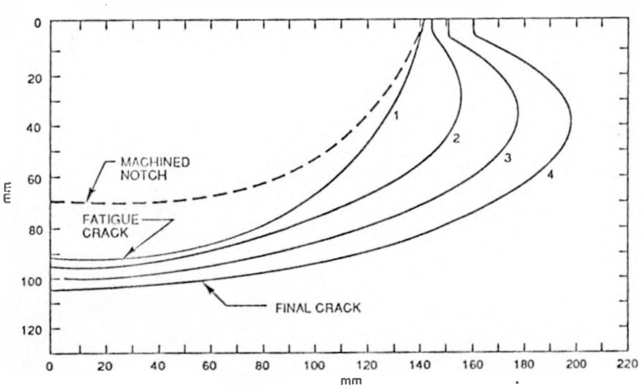

Fig. 4. Estimated crack shape changes during loading for the external surface flaw in HSST Intermediate Test Vessel V-8A.

even if the upper shelf Charpy impact energy of the controlling material were 68J (50 ft lbs). This result no doubt influenced some utilities and vendors to question the validity of correlations, as well as created a contrast in conclusions with the WGFE example problem discussed previously. The explanation turned out to be that the R-curve used in the original

WGFE example problem was for a Linde 80 weld that had a Charpy upper shelf impact energy greater than 68J (50 ft lbs). This situation provided some additional impetus for utilities to join a vendor owners group, in order to lessen their dependence on correlations (Ref. 22).

The Nuclear Regulatory Commission (NRC) has been pursuing parallel paths, dealing with the utilities and owner's groups on an individual basis, developing and updating its regulatory guides and provisions of 10CFR50, and participating in the development of ASTM and ASME consensus standards. An important part of these activities has been the development of NRC Regulatory Guide 1.99, which describes conservative procedures, acceptable to the NRC, for estimating transition temperature shifts and upper shelf energy decreases due to neutron irradiation. In the latest revision to Regulatory Guide 1.99, Rev. 2, only power reactor surveillance data were used as a basis for the ΔRT_{NDT} correlations given, because no satisfactory conversion could be found between test reactor data and power reactor surveillance data (Ref. 45). However, no change was made in the procedure for estimating the upper shelf energy decrease, due to lack of time (Ref. 45). Nevertheless, the NRC prefers that utilities use at least some power reactor surveillance data in their plant specific analyses. In fact, the NRC has rejected specific plant low upper shelf analyses, partly because surveillance data were not used and also partly because Level C and D loadings were not considered (Ref. 22).

In some cases, the NRC has made regulatory decisions with respect to individual plants and owners' groups, particularly in the absence of fully developed ASME code provisions. This creates a question of relevancy with respect to code provisions under development. The utilities and vendors appear to have two options, one being separate agreements between individual utilities or owners' groups and the NRC, and the other being ASME code development, contingent upon NRC acceptance. Judging by the amount of effort expended by the NRC staff to help develop ASME and ASTM standards, it is clear that, despite exceptions, the NRC strongly prefers to regulate on the basis of consensus rather than unilaterally developed standards (Ref. 46).

One problem facing the utilities, that depends for its solution on the resolution of the J_D/J_M issue, is the development of the proper testing procedure for small fracture mechanics surveillance specimens. These are mainly 1/2T CT and 1X WOL specimens, but this group could also include precracked Charpy specimens. The 1X WOL specimens have less arm height relative to their ligament dimension than a CT specimen and so are prone to arm yielding in bending, the effect of which is to artificially elevate J. Specimen modifications are being considered, but the criteria for judging the end result in the upper shelf temperature range, still lacking, must come initially from the results obtained by the NRC J_D/J_M Working Group and then from ASTM Subcommittee E24.08.

FORMULATION OF CRITERIA

In 1989, the ASME Section XI Working Group on Flaw Evaluation (WGFE) was considering a preliminary draft of a non-mandatory Appendix specifying low upper shelf criteria and acceptable analysis methods (Ref. 22). For Level A and B conditions, the postulated flaw was the Section III, Appendix G, 1/4t flaw. Stable crack growth was not to exceed 1 mm (0.04 in.), and the safety factors against tearing instability were to be at least 2.0 for pressure and 1.0 for thermal loading. For Level C and D conditions, all flaws of the same shape as the 1/4t flaw up to a depth of 25.4 mm (1.0 in) were to be considered, and all such flaws were required to either not extend, based on safety factors of 1.0 for all loads, or, if they extend, were required to stop within a depth of 0.75t. If repressurization is limited, warm prestressing could be considered. The reasons for considering a range of initial flaw sizes smaller than 1/4t for Level C and D conditions are that such flaws are more likely to exist, and they are also more likely to initiate under the steep stress gradients caused by thermal shock loading. Warm prestressing describes the fact that crack extension will not occur unless the near crack tip plastic strains exceed their maximum previous values. Two concerns were raised about these proposed criteria. One pertained to the proposed safety factors of unity on both pressure and thermal loading for Level C and D conditions, and the other pertained to the need for extrapolating R-curves in order to calculate the instability loads required for calculating safety margins.

The argument in support of the nominal safety factors of unity for Level C and D conditions was that the largest flaw that might be missed actually has a depth of 12.7 mm (0.5 in), and therefore, there is an implicit safety factor of 2.0 on flaw size, or $\sqrt{2}$ on load, for LEFM conditions. There were objections to this proposal. In fact, according to the estimates of flaw occurrence and detectability frequencies given in the first Marshall report(Refs. 47 and 48), on the average about 10 flaws with depths equaling or exceeding 12.7 mm (0.5 in) occur in every 20 vessels, and one of these is likely to escape detection. Consequently, the proposed assumption appeared to lack an adequate statistical basis. On the other hand, some other considerations were recognized that may mitigate the problem. Among these are the precedent set by Appendix A of Section XI for using a less conservative value of fracture toughness for Level C and D conditions than for Level A and B conditions. Also, the pressure relief valves and head seal greatly reduce the probability of pressures exceeding certain limits. Past practice has been to consider pressure relief valves as a means of reducing the probability of overloads to the vessel, but not as a substitute for the strength that should be inherent in the vessel itself. Nevertheless, it does seem proper to consider the existence of pressure relief valves and the head seal when choosing factors of safety. In addition, it also seems proper to recognize the existence of load categories beyond Levels C and D for such low probability non-design basis events as pressurized thermal shock. The original WGFE draft attempted to include criteria for such cases, but they have since been deleted, at NRC's request, in order to avoid conflicts between simplified code criteria and the results of detailed individual plant analyses. Finally, the mandatory inspection required by 10CFR50 for vessels not satisfying the 68J (50 ft lb) criterion may provide a basis for reducing the reference flaw size, provided of course, that all parties involved can agree on the reliability of the inspection data (Ref. 49).

In an effort to avoid errors in calculated safety margins due to R-curve extrapolations, a criterion was proposed based solely on the calculated and material values of J and dJ/da at a value of Δa within the measuring capacity of small specimens (Ref. 22). The proposal was that, assuming a 1/4t flaw, the calculated values of J and dJ/da for a pressure of 1.25 times design pressure (the shop and pre-service hydrotest pressure) and a cooldown rate of 56°C/Hr (100°F/hr) should not exceed the material values at Δa= 2.5 mm (0.10 in). In response, it was pointed out that there is a risk in this approach, namely in not estimating the margin of safety against tearing instability because that is the mode of failure to be prevented, and indirect methods may not be reliable. In particular, a J-R curve that suddenly becomes nearly horizontal might satisfy a small crack growth criterion at 25 percent above design pressure, but then cause tearing instability at only a slightly higher pressure. Following discussions, a material evaluation diagram, an example of which is shown in

Fig. 5. was constructed by ORNL in terms of the required slope of the R-curve at $\Delta a = 2.5$ mm (0.1 in.) to ensure a safety factor of 2.0 on pressure against tearing instability. versus the same ratio of $J_{material}/J_{applied}$ at $\Delta a = 2.5$ mm (0.1 in.) suggested previously (Ref. 22). The analysis is based on LEFM with a plastic zone size correction. which is shown in the WGFE draft report (Ref. 50) to be accurate at least up to a pressure of twice the operating pressure. Safety margin analyses by nearly the same procedure were made by Novetech for EPRI (Ref. 51). and the results of the ORNL and Novetech analyses are in good agreement. Considering pressure loading only for the tearing instability calculations. a factor of safety of 2.0 based on operating pressure and mean toughness appears to exist for upper shelf energies greater than 57J (42 ft lbs). The Novetech

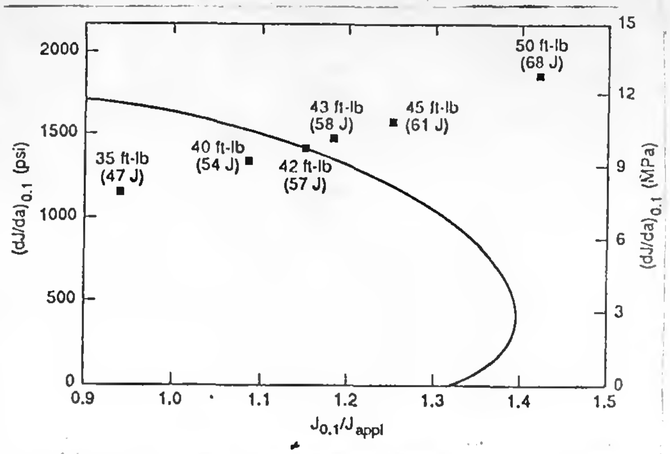

Fig. 5. Material evaluation diagram for application to low upper shelf toughness materials.

calculations. which included the effects of thermal loading at instability. indicated that the required valve of CVN is 61J (45 ft. lbs).

The calculations just discussed showed that the required upper shelf energy is sensitive to several factors. which must therefore be carefully considered. These factors include vessel wall thickness. pressure in the crack. thermal stress. plastic zone size effects. the assumption of plane strain versus plane stress (plane strain is more accurate). flaw orientation. the reference pressure for the safety factor calculation. and the statistical significance of the toughness values (mean or lower bound). Since the calculated instability pressures are going to be above the safety valve settings and therefore of low probability. it seems reasonable to consider reducing the required safety factors on pressure as the probability of exceeding the required toughness value increases.

As mentioned previously and shown in Table 1. some vessels may have only circumferential low upper shelf welds. For those vessels. an axially oriented quarter-thickness deep surface crack in the beltline region is highly improbable. A more reasonable set of flaw configurations for this case would be an axially oriented through crack across the low upper shelf weld with a total length equal to the maximum width of the weld (and therefore with the crack fronts in base metal) and a circumferentially oriented internal quarter-thickness part-through surface crack in the low upper shelf weld. This suggestion was originally made by a utility to the ASME. with no qualifications concerning fracture mode. and the NRC objected (Ref. 22). The idea seems sound for the upper shelf temperature range. but less so for lower temperatures. This is because the postulated flaw configuration is not likely to be produced by stable tearing originating in the weld. provided the base metal has good upper shelf toughness. but could more easily be produced by unstable cleavage. This proposal was reconsidered by the ASME WGFE for the upper shelf temperature range only. Such consideration implicitly couples the redefined reference flaw geometries to the results of the mandatory reinspection of a low upper shelf vessel in order to guard against prior pop-ins as well as fabrication defects.

Considering the merits and limitations of the initial proposals. guidelines were formulated for the development of firm criteria. It was recognized that criteria are needed both to limit the amount of ductile crack extension and to prevent tearing instability. It was also recognized that J-R curves exhibit scatter and size effects only partially understood. making extrapolations for instability calculations subject to error. Therefore. it was decided to formulate criteria in terms of conservative measures of toughness for Levels A. B. and C. and to replace the instability calculations necessary to determine full safety margins with calculations demonstrating flaw stability for specified load margins. The latter calculations will require less J-R curve extrapolation. Compensating adjustments were made to the specified load margins. based on the expected ratio of lower bound toughness to mean toughness. so that results in terms of safety would remain roughly the same as those obtained by using the previous criteria based on mean toughness.

In developing the criteria for Levels C and D. it was deemed desirable to specify different safety criteria for the two load categories. because of the differences in the associated event probabilities and structural performance requirements. It was also deemed undesirable for the code to deal explicitly with pressurized thermal shock loadings. or to specify system analysis procedures or definitions. because this might interfere with the regulatory process for individual plants. Since the criteria being developed apply only to upper shelf conditions. meeting these criteria cannot be a substitute for meeting the pressurized thermal shock criteria described in USNRC Reg. Guide 1.154.

For Levels A and B. the reference flaw is the Appendix G flaw. oriented along the weld of concern or having whatever orientation in low upper shelf base metal is most conservative. A conservative measure of toughness is also employed. A reference pressure called the accumulated pressure (Ref. 52). P_{acc}. is used for safety verification. The accumulated pressure is the highest pressure that can occur in the system. as estimated by a calculation that includes the effects of pressure relief valve settings and fluid discharge rates through those valves. The accumulated pressure is limited to 10 percent above component design pressure. so for a vessel design pressure of 17 MPa (2500 psi) the accumulated pressure cannot exceed 19 MPa (2750 psi). The limited crack growth criterion requires that at a pressure of 1.15 P_{acc} and specified thermal loading. stable crack growth must not exceed 2.5 mm (0.10 in). The stability criterion requires that at a pressure of 1.25 P_{acc} and the same thermal load. ductile flaw growth must remain stable.

For Levels C and D. the reference flaw depth range is from zero to one-tenth of the base metal wall thickness. plus the clad thickness. but not to exceed 25.4 mm (1.0 in). Flaw shapes and orientations are the same as for Levels A and B. The reference toughness for Level C is conservative. while for Level D it is the mean toughness. Loads are as determined by plant specific analyses for the specified load categories. with no additional safety factors. For Level C. stable crack growth must not exceed 2.5 mm (0.10 in) and the flaw must remain stable. For Level

D. the flaw must either remain completely stable or it must not extend beyond a/t of 0.75 and the remaining ligament must be safe against tensile instability.

CONCLUSIONS

The low upper shelf toughness issue has a long history, beginning with the choice of materials for the submerged arc welding process, but also potentially involving the use of A302-B plate. Historically, proposed criteria for safe operation of vessels containing low upper shelf materials have been expressed in terms of the Charpy V notch upper shelf impact energy. Although these criteria have had several different technical bases, the range of limiting values for vessels with wall thicknesses approaching nine inches has remained between 54 to 68J (40 to 50 ft lbs). Allowable values for vessels with thinner walls and/or only circumferential low upper shelf welds might conceivably be less.

Progress in resolving the low upper shelf weld issue may appear to have been slow, but that is mainly because progress has been controlled by the rate of technical developments in elastic-plastic fracture mechanics and tearing instability analysis. Recognizing that the analysis of vessels can, in many cases, be performed with satisfactory accuracy by LEFM with a plastic zone size adjustment allows attention to be focused on validating representations of material behavior through the analysis of test data. These data are mainly the resistance curve data examined by the NRC J_D/J_M Working Group, data from the NRC Degraded Piping Program and the test results from HSST Program Intermediate Test Vessels V-8A and PTSE-2.

A decision on criteria to be incorporated into Section XI of the ASME Code is now being made. The most important choices concern flaw geometry for circumferential welds, statistical significance of toughness values, the choice between J_D and J_M, reference pressure, safety factors, and the inclusion of tearing stability calculations by means of R curve extrapolation. The method for estimating the decrease in upper shelf impact energy is also important. At present, the ASME draft code provisions do not include such a method, so the only methods available are Reg. Guide 1.99 and proprietary methods.

The restriction of some of the information concerning the low upper shelf issue as proprietary has tended to obscure the definition of the problem and therefore to delay its solution. Early efforts to reduce the scope of proprietary information on the subject would have been beneficial, especially to the development of regulatory guides, ASTM standards and the ASME code.

NRC cooperative research programs have contributed significantly to the resolution of the low upper shelf issue. NRC contractors participated in the writing of WRC-175 and both NRC and its contractors have participated, from the beginning, in the work of the ASME Section XI Working Group on Flaw Evaluation. The NRC A-11 task group determined that J-R curve tearing instability analysis methods are applicable to nuclear pressure vessels. NRC personnel and contractors participate actively in the development of elastic-plastic fracture mechanics testing methods by ASTM Subcommittee E24.08. The NRC J_D/J_M Working Group and the HSST Program led the effort to determine the J-R curve parameter (J_D or J_M) most applicable to low upper shelf vessel materials. The HSST Program has produced the J-R curves for irradiated low upper shelf Linde 80 weld metal that are being used for example vessel calculations and criteria development. The forthcoming cooperative testing of Midland weld material will provide a valuable supplement to scarce surveillance and test reactor data for this material. The HSST Program large vessel tests, especially V-8A and PTSE-2, have demonstrated the performance of vessels containing flawed low upper shelf materials, and provide a focal point for the validation and improvement of safety analysis methods. NRC and contractor personnel continue to work closely together on the evaluation and development of safety margin criteria, suitable for insertion into the ASME code and acceptable to the NRC, for vessels containing low upper shelf welds.

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