Technical Note
on
Critical Crack Size Evaluations for Circumferential Cracks in Dissimilar Metal Welds

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1. Introduction

In February 2007, industry proposed performing advanced finite element fracture mechanics analyses to address NRC staff concerns that rupture could occur without prior evidence of leakage for cracks in pressurizer weld nozzles. In March 2007, the Electric Power Research Institute provided results of a draft calculation to the Expert Review Panel for Advanced Finite Element Analysis (FEA) Crack Growth Calculations. In a conference call with the industry Expert Panel on March 20, 2007, the NRC and its contractor expressed several items of concern with the Phase 1 analysis. These concerns were sent to Alex Marion on April 4, 2007 in a letter from Michele Evans. In an effort to provide industry with additional information to evaluate the basis for these concerns, the NRC staff has prepared this technical basis document to address Item #4 from the aforementioned letter, i.e., determination of critical crack size.

The determination of critical circumferential crack sizes has been extensively investigated in experimental and analytical efforts since the 1970's for nuclear piping. Much of that work was summarized in Reference 1 (this reference contains over 200 references for work in this field). The evaluation of cracks in nuclear piping for in-service flaw evaluation procedures is incorporated in ASME Section XI Articles IWB-3600 as well as Appendix C and H, Refs. 2 and 3. This flaw evaluation procedure incorporated safety factors on stress that vary for service level. There are criteria for circumferential cracks in stainless steel piping and their welds, ferritic piping and their welds, but not yet for high nickel alloy welds like Alloy 82/182. The Code development for the nickel alloy welds is in progress, with Emc^2 developing proposed criteria. A tentative criterion was presented at the December 2006 Working Group on Pipe Flaw Evaluation Meeting, and since then additional work done as part of the Emc^2 Wolf Creek scoping analyses (Ref. 4) has been incorporated to justify that criterion.

For the determination of critical circumferential crack size, there is a wealth of past experimental and analytical programs conducted by the NRC, the U.S. nuclear industry, and the international nuclear industry. Some of the larger or more relevant efforts are listed below:

- EPRI NP-192, NP-2347 [Original development of net-section collapse (limit-load) solution for circumferential cracked pipe, and a large number of stainless pipe tests.], Refs. 5 and 6.

- EPRI NP-1931, NP-3607, NP-5596 [Original development GE/EPRI J-estimation scheme development], Refs. 7, 8, and 9.
- EPRI NP-4690-SR; NP-6045 [Technical basis document used for developing of simplified EPFM solutions for circumferential crack in stainless steel pipe and pipe welds – Z-factor in IWB-3640 and Appendix C; ferritic pipe EPFM developments for ASME Code application (IWB-3650, Appendix C and earlier Appendix H)], Refs. 2 and 3.
- NRC NUREG/CR-3142 Vol. 1-2; NUREG/CR-4082 Vol. 1-8 [Degraded Piping Program – Phase I and II with ten additional topical NUREG reports – significant full-scale circumferentially cracked pipe test data at LWR temperatures with bending and/or pressure, material property development at LWR temperatures, and initial development of several J-estimation scheme analyses.], Refs. 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21.
- NRC NUREG/CR-4599 – seven semiannual reports [Short Cracks in Piping and Piping Welds program with ten additional topical NUREG reports, Refs. 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, and 32. Additional pipe fracture experiments with through-wall cracks typical of LBB cracks and in-service cracks, material property development, and additional EPFM analyses refinement. Includes one topical report (Ref. 25) on a cold-leg pipe bend test with a circumferential through-wall crack in the fusion line of an Alloy 182 weld at LWR temperatures (NUREG/CR-6297)].
- NRC NUREG/CR-6233 Vol. 1-4 with two topical reports, Refs. 33, 34, and 35; NUREG/CR-6452 and 9 topical reports, Refs. 36, 37, 38, 39, 40, 41, 42, 43, 44, and 45; [IPIRG -1 and -2 programs, conducted pipe system tests with circumferential cracks at LWR conditions, separate effect tests on inertial loading, cyclic loading, and combined inertial and displacement-controlled loading.]
- NRC NUREG/CR-4538 Vol. 1, Ref. 46; NUREG/CR-3740, Ref. 47 [This report contains the results of one of several DTRC programs. This report documents circumferential through-wall and complex-cracked pipe tests in the center of TIG welds, a second report on A106 B pipe tests, and various other reports on J-R curve testing of piping materials (Ref. 48.)]
- NRC NUREG/CR-4894, Ref. 49. [MEA program on nuclear piping material property testing and the development of a database for piping material strength and toughness. This database was later updated in the IPIRG program (Ref. 33), and recently it was converted to a web-based database in the NRC LB-LOCA program (Ref. 50). This database contains over 800 stress-strain curves and 800 J-R curves for statistical analyses. It will be updated in the ongoing NRC MERIT program[1]
- NRC NUREG/CR-6837 Vol. 1-2 [Battelle Integrity of Nuclear Piping program, Ref. 51. This program included pipe system tests to evaluate the effects of secondary stress on fracture, along with several other technical topics.]
- NRC - various joint programs at Batelle/Emc[2] on; (a) Technical Basis for LBB Regulatory Guide (NUREG/CR-6765) Ref. 52, which included J-R curve testing on Alloy 182 welds (Ref. 53), (b) LOCA redefinition program (NUREG-1829 for TBS elicitation efforts, Ref. 54) and separate developments on a new probabilistic piping fracture mechanics code (PRO-LOCA, Ref. 50).

[1] The MERIT program is an on-going international research program conducted at Battelle-Columbus and Emc[2].

- NRC – various programs at Emc^2 on; (a) Alloy 600 Cracking (CRDM analyses and PWSCC analyses for Calvert Cliffs and Wolf Creek, Ref. 55), (b) Seismic LOCA analysis (evaluation of probability of pipe fracture using plant specific seismic hazard curves – staff report on NRC Web page December 2005, Ref. 56), and Barrier Integrity program (NUREG/CR-6861 with Argonne on leak-rate analyses, Ref. 57).

In addition to these reports, there are several hundred other references given in Reference 1 (that was written in 1995) on this topic. This technical basis document is meant as a reference to document the relevant experimental and analytical results for accurately predicting the critical size of both surface and through-wall cracks. It is not meant as a comprehensive review of all of the technical issues pertaining to the criticality of these cracks, but more as a reference document that the reader can use as a guide to finding more technical detail if desired. Hence there is an incredible amount of information that can only be very briefly summarized in this document. The rest of this document will summarize the following; (a) the important historical background relative to the concerns for critical crack size evaluation, (b) summary of current limit-load analyses, (c) definition of flow stress in limit-load analyses, (d) EPFM analyses and when they are needed, (e) importance of secondary stresses, (f) recommendations for DMW critical crack evaluations, (g) summary and conclusions, and (h) list of references.

2. Historical Background

Reference 1 ("State-of-the-Art Report on Piping Fracture Mechanics") perhaps gives the best historical background on piping fracture mechanics developments for the nuclear industry, including international efforts. Even with over 200 references in that report (back in 1995), only a brief summary of many different pipe fracture analysis topics were summarized. The reader of this document may wish to look at that report for additional information.

2.1. Development of NSC Equations

The original Net-Section Collapse solution was developed by Dr. David Broek in EPRI NP-192, Ref. 5. This analysis is frequently called a limit-load solution, although there are many limit-load solutions for circumferentially cracked pipes. This analysis involves a very simple concept that can be used to determine the maximum load-carrying capacity (moment or combined bending and axial force) for materials that are so tough that a further increase in toughness will not increase the maximum load-carrying capacity.

In this analysis, the material is assumed to reach fully plastic conditions above and below the neutral axis of the cracked section, see Figure 1. In reality these materials strain-harden with different plastic stresses and strains as a function of the distance from the neutral axis (and the stress/strain concentration at the crack tip), but a simplifying assumption that the material reaches a unique "flow stress" value is made. The flow stress is an

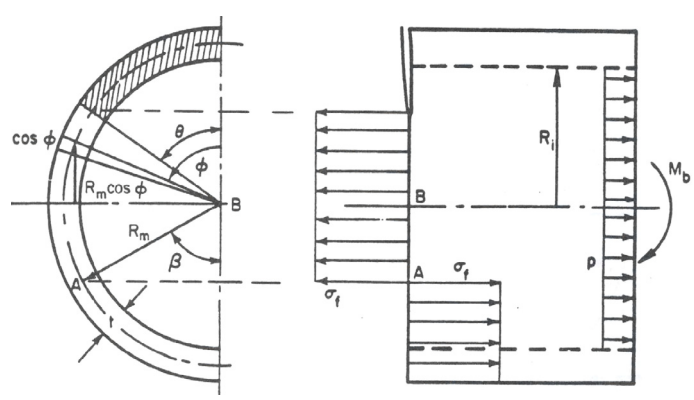
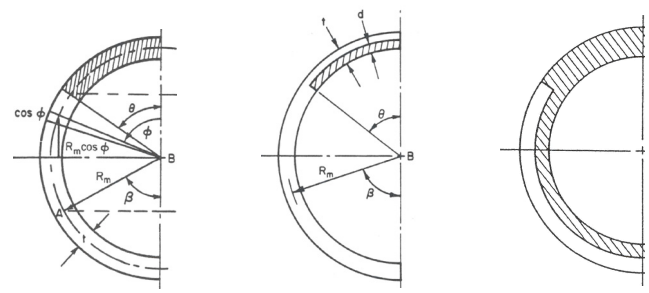


Figure 1

empirical value between the yield and ultimate strengths. The most frequently used definition of flow stress is the average of the yield and ultimate strengths, but many other definitions have been proposed, i.e., 2.4 S_m or 3 S_m in the ASME Section XI flaw evaluation code (Refs. 2 and 3), some factor times the average of actual yield and ultimate strengths or Code strength values (Ref. 58), yield strength plus 10 ksi (Ref. 59), etc. The key in any limit-load analysis is to validate the flow stress from experiments, but only using tests where the material is tough enough to reach the maximum load-carrying capacity without significant crack growth.

The original Net-Section-Collapse solutions were developed using a thin-wall shell assumption. This equation was the basis of the ASME Section XI limit-load solutions; although the original equation was in terms of moments and forces, the ASME code source equations are in terms of stress, Refs. 2 and 3. The thin-walled Net-Section-Collapse equations have been developed for idealized circumferential through-wall cracked, constant depth internal or external surface cracked, as well as arbitrary shaped surface cracked, and complex-cracked (a 360-degree surface crack of constant depth that has a finite length surface crack in the same plane) pipe, see Figure 2. In EPRI NP-2347 a set of experiments was conducted with constant depth internal surface cracks and variable depth surface cracks. It was found that if the variable depth surface crack area was taken and divided by the maximum depth, the equivalent length could be used in the constant depth surface crack Net-Section-Collapse analysis to reasonably predict the maximum load-carrying capacity (Ref. 6– see Volume 2).



Idealized TWC **Constant depth Surface crack** **Idealized Complex crack**

Figure 2

A thick-walled solution for an idealized circumferential through-wall crack was published in the EPRI Ductile Fracture Handbook (Ref. 60), and in NUREG/CR-4872 (Ref. 21) in the development of a thick-walled pipe J-estimation scheme. Since the stresses in the cracked section are equal to the flow stress in tension or compression, the key aspect in using either a thin-walled or thick-walled Net-Section analysis is the definition of the fully-plastic neutral axis. For the idealized through-wall-crack case, a comparison was made of the maximum moments predicted by the thin-wall and thick-wall solutions as a function of the through-wall-crack length for pipe with an R_i/t of 2 (Wolf Creek relief nozzle). The graph in Figure 3 shows that there is essentially no difference in the two through-wall-crack solutions until the crack length is greater than 50-percent of the circumference.

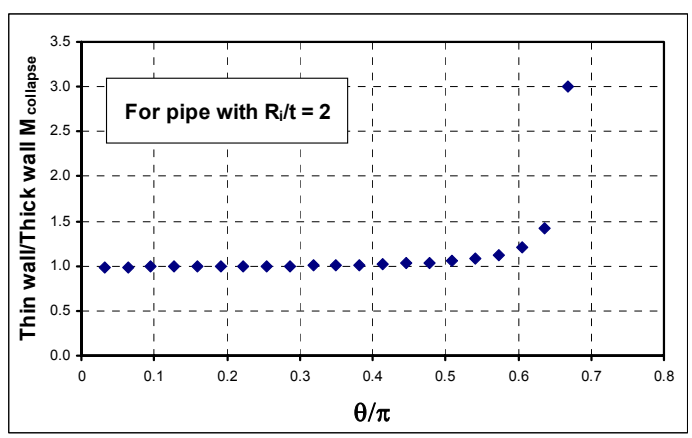


Figure 3

2.2. Other Consideration in Limit-Load Analyses

There are some additional aspects for a limit-load analysis that also need to be discussed prior to examining comparisons with experimental data.

2.2.1. Limitation on the Net-Section-Collapse Analysis for Deep Cracks

The ASME Code limits the maximum depth of a surface crack to a/t < 0.75. In the Wolf Creek analyses being conducted, the surface crack depths can exceed the ASME maximum depth limit. One of the reasons that this limit was placed into the ASME code comes from experimental results that showed that the Net-Section-Collapse (NSC) analysis will over predict the experimental failure loads for deep surface cracks. Kurihara (Ref. 61) from JAERI developed test data with a/t values up to 0.9, and proposed an empirical correction to the thin-wall Net-Section-Collapse solution. Figure 4 shows the proposed Kurihara NSC modification / original NSC predicted failure loads for different circumferential crack lengths (θ/π) and curves for different surface cracks depths (a/t). His empirical fit that worked well for the data he generated, shows his predicted failure stresses for the very deep cracks is significantly lower than that predicted by the original thin-wall Net-Section Collapse solutions. For example, if the surface crack was 80-percent of the thickness and 40 percent of the circumference, then the Kurihara modification would predict the failure stress to be 50 percent of the original Net-Section-Collapse predicted failure load. *Hence, extreme care should be taken when using the Net-Section-Collapse solutions for deep cracks.*

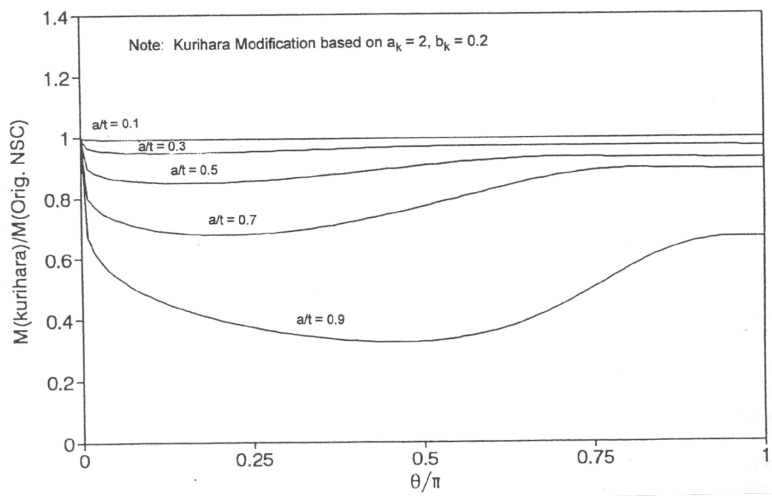


Figure 4

2.2.2. Crack Shape Effects on Critical Crack Size Analyses

The three basic types of circumferential cracks are; (1) idealized through-wall crack (TWC), (2) surface crack (constant depth or variable depth, and ID or OD surface breaking), and (3) a combination of a surface and through-wall crack called a complex crack. Very large stress-corrosion cracks can develop into complex cracks as occurred in a Duane Arnold safe end, see Figure 5.

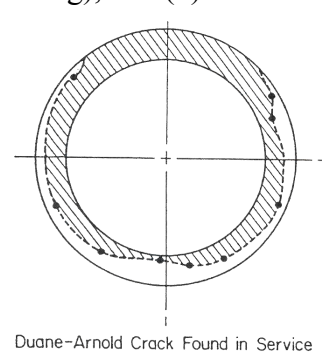


Figure 5

Experimental pipe tests show the following trends:

- A circumferential surface crack will fail closer to limit load than other crack shapes for a given material toughness developed from a standard C(T) test in the same pipe diameter. This effect is due to the low constraint condition ahead of the surface crack, which increases the apparent material toughness as compared to the toughness from a standard C(T) fracture

toughness specimen. The pipe experimental data suggests that due to the higher apparent toughness of a surface crack, limit-load conditions will dominate, except for very low toughness pipe. (Ref. 62 and see later discussion on DPZP). There is a subbranch of fracture mechanics that deals with constraint theory, which is consistent with these observations.

- A circumferential idealized through-wall-cracked pipe has an apparent toughness that is less than a surface-cracked pipe due to the difference in constraint. Experimental and analytical results have shown that the constraint conditions of a through-wall crack are similar to those in the C(T) specimen.
- The complex-crack geometry is the most sensitive to fracture toughness. Experimental results (Refs. 5 and 16, and 46) have shown that the apparent toughness in the complex crack case will be significantly lower than that in an idealized through-wall-cracked pipe. The plastic zone from an idealized through-wall crack extends circumferentially and axially from the crack tip. With a complex crack, the plastic zone is constrained in the ligament of the surface-cracked region (due to the difference in thickness at the location) and hence can not extend axially as in the idealized through-wall crack. This can significantly reduce the apparent toughness as shown in Figure 6. The Y-axis is the ratio of the J-R curve calculated in a pipe tests for a complex crack (J_{cc}) divided by the J-R curve for a pipe test with an idealized through-wall crack (J_{TWC}). The X-axis is the depth of the surface crack in the complex crack ligament. Since the Wolf Creek relief nozzle can involve the development of such a crack, a reduction in the laboratory test J-R curve should be made using Figure 6. Consequently, failure stresses may be below that calculated with limit load for such a complex-cracked pipe (depends on pipe diameter and material toughness) and would require an EPFM analysis. The LBB.ENG2 analysis in NRCPIPE (a J-estimation scheme for elastic-plastic fracture analysis of circumferential through-wall-cracked pipe, see later discussion for more detail) has an option for a complex crack analysis, where the thickness of the pipe is reduced in the surface-cracked ligament. The material J-R curve then needs to be reduced for the constraint effects, as per the trends in Figure 6. Additionally, pipe test results (Ref. 11 see Volume 5) have shown that it takes very little compliance for a complex-crack pipe to fail in a DEGB manner with pure secondary stresses.

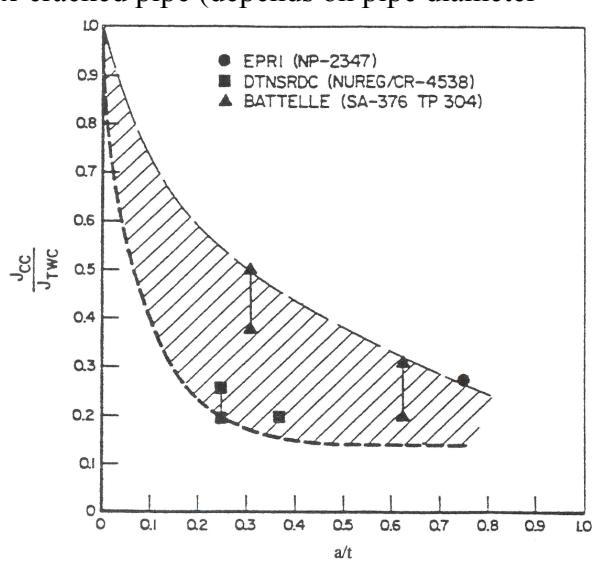


Figure 6

2.2.3. Screening Criterion for Limit-Load Conditions

There are at least two ways to determine if a cracked pipe will fail in a limit-load manner, or if the toughness is low enough for elastic-plastic fracture mechanics (EPFM) conditions to control.

The first way to determine if a limit-load analysis is applicable is to use the failure assessment diagram (FAD) approach. This approach was initially developed by the staff at CEGB (Ref. 63) in the UK, and was also adopted in the ASME Section XI Code Case N-494 and in the newest version of Appendix H. An alternative (but essentially comparable) approach is to use a reliable EPFM analysis (J-estimation scheme or FEA analysis) and determine how the load increases with increasing toughness for the crack in that pipe size. As the toughness increases, a proper analysis should show that the load saturates to the limit-load for that case. These types of analyses are somewhat cumbersome, and perhaps most importantly, they do not account for the constraint conditions effects on the material toughness. An alternative and quick way to determine limit-load applicability is to use an empirically based analysis from hundreds of pipe tests that is called the Dimensionless Plastic Zone Parameter (DPZP) screening criterion (Ref. 62). This analysis is based on the size of the plastic zone at the crack tip relative to the pipe size. Initially it was based on the through-wall-crack-tip plastic-zone size relative to the distance from the crack tip to the fully plastic neutral axis, see Figure 7.

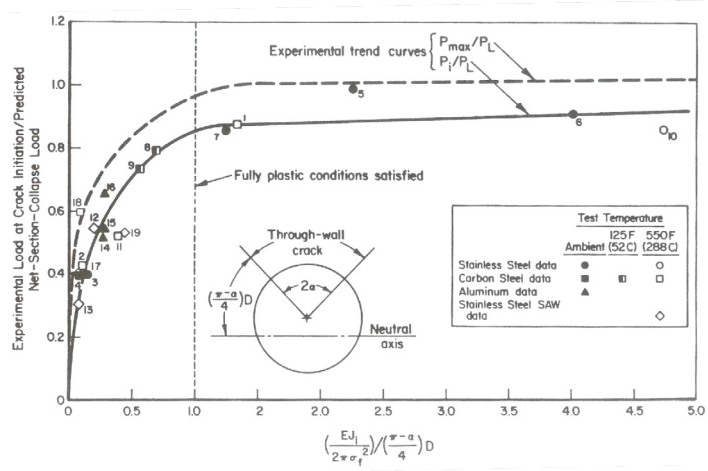


Figure 7

Separate solutions were developed for surface cracks. For simplicity, it was found that if the crack-tip plastic zone was greater than the pipe radius, the pipe would become fully plastic and limit-load conditions would exist. Figure 8 shows this empirical trend, where the plastic zone is calculated from a standard C(T) specimen. Results for pipe tests with idealized through-wall cracks show that if the dimensionless plastic zone parameter (DPZP) was equal or greater than 1.0 then limit load was applicable. For circumferential surface-cracked pipe, the DPZP parameter only had to reach a value of ~0.25 for limit-load conditions to control. Hence, the high apparent toughness of a surface crack in a pipe will allow it to fail at limit load.

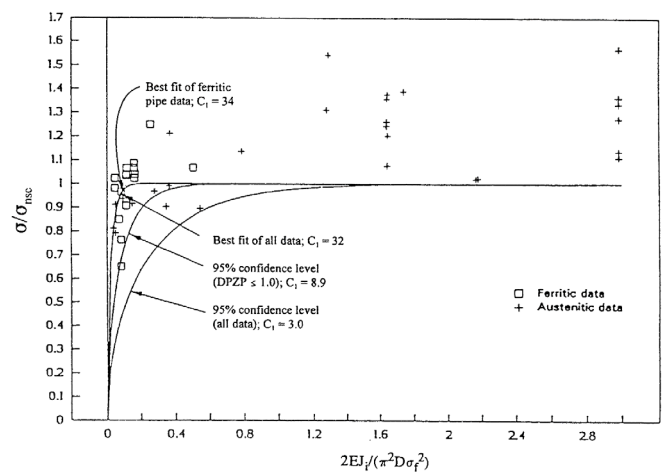


Figure 8

Complex-cracked pipes are much more difficult to analyze, but using the empirical toughness relationship seen in Figure 6, the apparent toughness for a complex cracked pipe is about four times lower than an idealized through-wall-cracked pipe. Hence, for pipes with the same C(T) J-R curve, an idealized through-wall-crack would fail at limit load, while a complex crack would fail at a lower load controlled by EPFM.

EPFM analyses also show that not all wrought stainless steel pipes will fail at limit-load conditions. Wrought stainless steel pipes that have higher sulphur content have a significantly lower toughness (Ref. 52), and if the pipe diameter is big enough, there are conditions where the pipe will fail below limit load. This occurred in some pipe tests (Ref. 11 see Volume 2).

2.2.4. Thin-Shell versus Thick-Shell Limit-Load Confusion Factors

It should be noted in this report that there can be several confusing factor when doing thin-shell, thick-shell, and ASME Code Net-Section-Collapse analyses.

The first confusion factor is the definition of stresses. It can be less confusing to use the equations in terms of forces and moment than the equations with stresses. This is because there is a mixture of thin and thick-shell stress equations in the Code, as well as conservatisms for stress components, i.e., the pressure-induced axial stresses equation in the Code uses the OD of the pipe for conservatism. Extreme care is needed when comparing the different results in terms of stress. On the otherhand, the original thin-shell Net-Section-Collapse equations only consider axial stresses due to pressure loading, but could be modified for axial force.

A second aspect that can be confusing is in defining the crack length. Most of these Net-Section-Collapse equations are generally expressed in this report in dimensionless crack lengths, i.e., a/t or θ/π. If one is talking about absolute crack lengths, the location of the crack length on the ID or mean radius needs to be carefully considered.

2.2.5. Crack-Face Pressure in Limit-Load Analyses

None of the Net-Section-Collapse analyses (the original thin-shell, thick-shell, or Code source equations) consider the crack-face pressure. In the past NRC pipe fracture programs, the tests that had combined pressure and bending were either through-wall-cracked pipe tests with an internal patch (no pressure applied to the crack faces), or internal surface-cracked pipe tests (full internal pressure on the crack faces). However, generally the axial stress from the pressure was less than 10% of the bending stress in those pipe tests, so that the additional bending stress for the pressure loading on the crack face would probably be small and lost in the scatter of the test results. The strictly correct way to handle the crack-face pressure for a limit-load analysis would be to consider the crack-face pressure as applying an induced-bending stress, i.e., induced moment is equal to the pressure times the area of the crack face times the distance from the centroid of the crack area to the fully-plastic neutral axis. There was insufficient time to conduct such analyses for this report.

2.2.6. Estimating Critical Surface-Crack Size from Through-Wall-Crack Calculations

A separate aspect in the use of the Net-Section-Collapse analysis in the recent industry report (Ref. 64) was that the thick-walled through-wall-crack Net-Section-Collapse solution was used to determine the failure stress for a circumferential surface crack. To do this, they took the area of a surface crack, and converted it to an equivalent idealized through-wall crack. This procedure was probably used since there was no thick-walled surface-crack solution in the EPRI Ductile Fracture Handbook (Ref. 65). Since we have not seen anyone make such an analysis before, we made a comparison of maximum predicted moment of an equivalent through-wall crack/surface crack as a function of the dimensionless surface-crack length. To do this, surface

cracks of various a/t values (0.1, 0.3, 0.5, and 0.7) and various lengths were used to calculate the maximum load-carrying capacity using the thin-walled Net-Section Collapse analyses. This was done with pipes having R_i/t of 2 (Wolf Creek relief line) and 4 (Wolf Creek surge line), which illustrated that the effect of R_i/t in this range was minimal. It was also assumed that the upset load would be primarily bending, so that there could be crack closure below the fully plastic neutral axis. The area of the surface crack was then used to calculate an equivalent idealized through-wall-crack length, and that length was used to determine the maximum moment-carrying capacity. In this sensitivity study, it was assumed that there was no internal pressure, but similar results with internal pressure could be generated. Figure 9 shows the results. The Y-axis is the ratio of the maximum load for the equivalent through-wall-crack length divided by the surface-crack maximum load, and the X-axis is the normalized circumferential surface-crack length. This figure shows that if the surface-crack length is less than about 30-percent of the circumference ($\theta/\pi < 0.3$), then the assumption of using the surface-crack area as an equivalent area for an idealized through-wall crack is reasonable. However, for long deep cracks, as in the projections of the critical crack sizes for the Wolf Creek relief line, the equivalent through-wall-crack approach is significantly conservative on the prediction of maximum load, i.e., for a/t of 0.7 and θ/π = 80-percent of the circumference, the equivalent area through-wall-crack approach gives a maximum load capacity of only 40-percent of the maximum load from a surface-crack analysis.

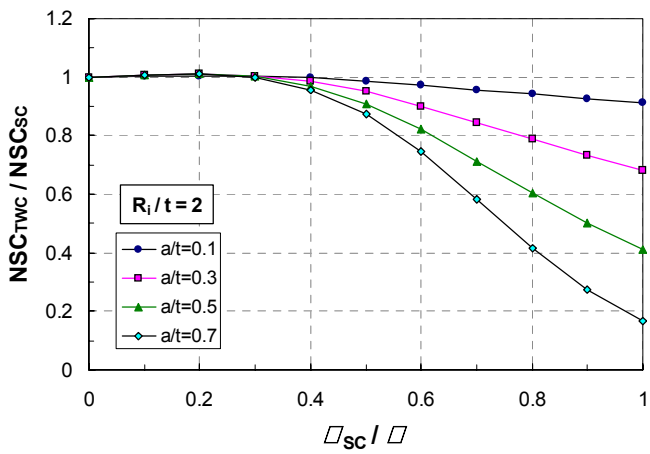


Figure 9

2.3. Experimental Validation of Limit-Load Analyses

The experimental database was used to first validate the accuracy of the thin versus thick-shelled through-wall-cracked solutions. Secondly, the sensitivity of the predictions to pipe R/t ratio was examined. This comparison was done for cracks in base metals first, where analysis results for cracks in welds are given later. The experimental data in the CIRCUMCK database from the IPIRG program was used. This database contains over 700 circumferentially cracked full-scale pipe tests from international programs with different crack geometries, different loading conditions, and different materials (Ref. 36). The pipe tests were first separated by crack type, and then the DPZP screening criterion was used to determine which pipe experiments should have enough toughness so that limit-load analyses would be applicable. The flow stress

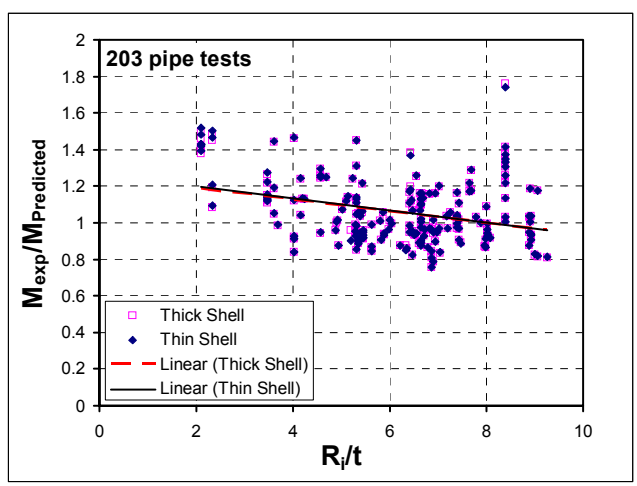


Figure 10

was defined as the average of the actual yield and ultimate strengths for the pipes tested. The results of comparing 203 idealized circumferential through-wall-cracked pipe tests where limit-load should be applicable (DPZP > 0.95) is given in Figure 10 for both the thick-shell and thick-shell analyses. This include stainless and ferritic base metal tests (as long as limit-load was applicable), but no weld tests. As was illustrated in Figure 3, the thick and thin-shell analyses for through-wall cracks gave similar results except for extremely long crack lengths. The pipe test with the greatest crack length in this database was 62 percent of the circumference, and the average crack length was 26 percent of the circumference. There were a number of crack tests with crack lengths around 50% of the circumference, but only one test with the 62% crack length. Consequently there is essentially no statistical difference between the thin and thick shell analyses, see Figure 10. In addition, there is a gradual trend that shows as the pipe R/t decreases, the Net-Section-Collapse solutions (thin-shell and thick-shell) become more conservative. The average experimental/predicted value was 1.03 with a coefficient of variance of 14.5%. *Given that both analyses have the same accuracy, the simpler thin-shell analysis is preferred.*

There was a similar analysis for surface-cracked pipe tests in Reference 24 for comparison of the experimental/predicted Net-Section-Collapse thin-shell solution. These results (in Figure 11) showed a similar trend to that for through-wall-cracked pipe in Figure 10. *Hence all analyses show that there is some inherent margin in the Net-Section-Collapse analyses for low R/t pipe with either idealized through-wall cracks or surface cracks.*

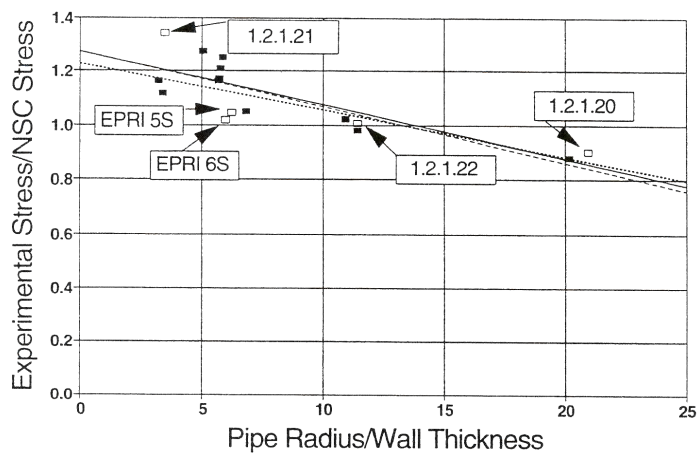


Figure 11

2.4. Definition of Flow Stress for Limit-Load Analysis of Cracks in Girth Welds

Analysis of cracks in girth welds has been a concern for over 25 years in nuclear piping, going back to IGSCC cracking in BWR piping. A significant amount of work was done about 20 to 30 years ago in the development of the flaw evaluation standards in Section XI of the ASME Code (Refs. 2, 3, and 11). That work showed that to analyze a crack in a girth weld, the base-metal stress-strain curve should be used with the weld metal J-R curve. These analyses and experiments were for base metals with the same strength on either side of the weld.

To illustrate this point, all the through-wall-cracked pipe weld tests in the CIRCUMCK database were evaluated. Again, the DPZP screening criterion was used to select pipe tests where limit-load should be applicable. The results using the base-metal flow stress gave an average experimental/predicted value of 1.02 with a coefficient of variance of 13 percent, see Figure 12. This is virtually identical to the base-metal data set. The trend with R/t is different with the weld tests, but the regression coefficient is very low.

A similar comparison was made using the weld metal flow stress for these same set of tests. The results showed an average shift of 18 percent in the predicted failure stresses as compared to the base metal flow stress. In this case, the experimental/predicted value was 0.84. These failure predictions were greater than the experimental results, so using the weld metal flow stress in the limit-load analysis gives non-conservative result.

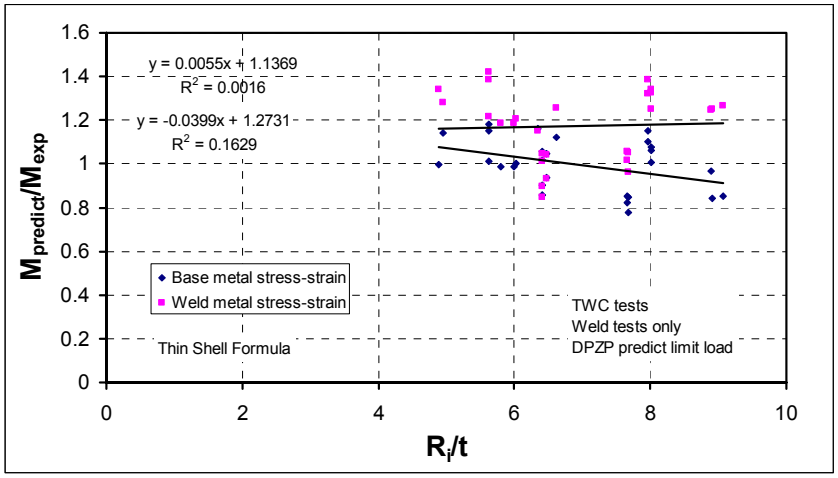


Figure 12

Hence the weld metal strength should not be used in the limit-load crack evaluation procedures, even if the weld metal is tough enough for limit-load applicability.

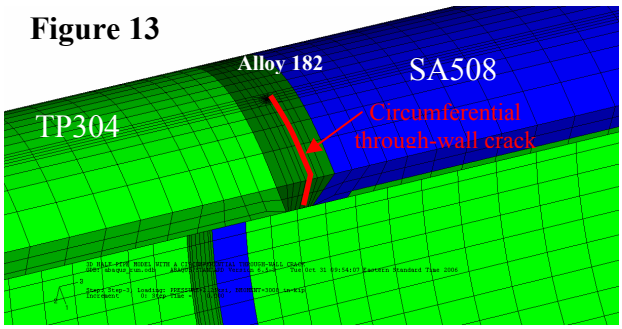
3. EPFM Analysis – When is it needed?

There can be many combinations of material toughness, pipe diameter, and crack type or size that will produce a maximum load-carrying capacity that is less than that predicted by limit-load analyses. To predict that fracture behavior, elastic-plastic fracture mechanics (EPFM) analyses are needed. Prior to showing EPFM analyses for a dissimilar metal weld crack in a pipe, a brief review of different EPFM analyses is given below.

3.1. Idealized Through-Wall-Cracked Pipe EPFM Analyses

There are a number of ways to conduct EPFM analyses for an idealized circumferential through-wall crack in a pipe. The most fundamental way is to conduct finite element analyses that model the cracked pipe with the different materials in the pipe. Modeling a crack in pipe base metal is relatively straight forward, but can be very complex for a crack within a dissimilar metal weld where geometry changes, different material properties in the weld safe end, nozzle/piping and cladding have to be accounted for, as shown in Figure 13. The location of the crack within the weld can also be important, as will be shown later. Other than FE analyses, there are two simplified J-estimation procedures worth noting.

Figure 13

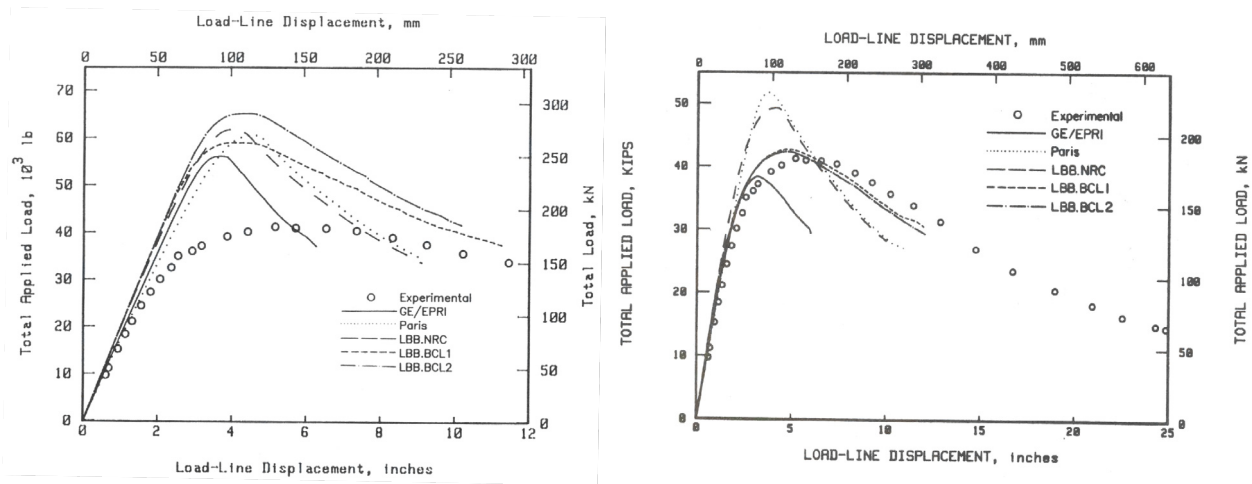


In the 1980's, conducting such FE analyses were very difficult, hence the GE staff first proposed an estimation procedure to determine the applied J for cracks in specimens and structures, including cracks in pipe (Refs. 7, 8, and 9). The method is called the GE/EPRI method and involved developing elastic and fully plastic influence functions from a matrix of FE analyses. The GE/EPRI method can be used to predict the applied J for a large variety of pipe geometries,

materials (using the Ramberg-Osgood relationship), crack sizes, by interpolating between these tabulated elastic and plastic influence functions. *All of these analyses were for cracks in homogeneous pipe, not for cracks in welds.*

Another J-estimation scheme that was analytically rather than numerically developed is the LBB.ENG2 method by Dr. F. Brust of Battelle-Columbus, which is in the NRCPIPE computer code (Ref. 36). This estimation scheme was developed during the NRC's Degraded Piping Program, and improved during the NRC's Short Cracks Program (Refs. 18 and 23). The method involves predicting the global load-displacement (or moment-rotation) response of the cracked pipe, and integrating the energy under the curve to calculate the J applied by using an eta-factor analysis. Again, this method was developed for cracks in a homogeneous material pipe.

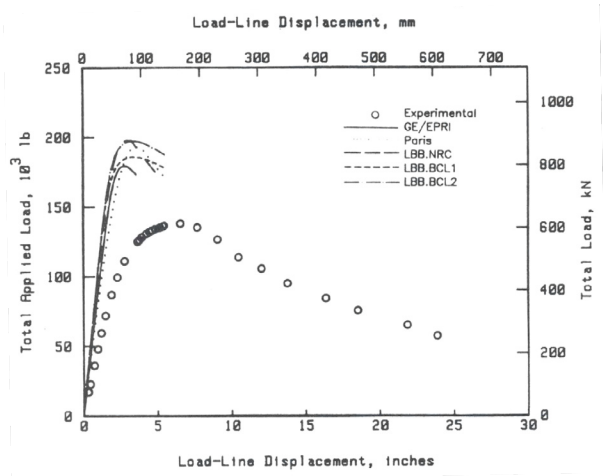
A large number of comparisons were made between the maximum load-carrying capacities predicted from these J-estimation procedures to experimental results for circumferential through-wall-cracked pipe during the various large NRC pipe fracture programs. A couple of cases (Ref. 20) of predictions for cracks in stainless steel weld pipe tests are given next. The first case, shown in Figure 14, is for a 16-inch diameter stainless steel pipe test (4141-3) with the crack in the center of an overmatched weld, i.e., there was a large difference in the weld and pipe stress-strain curves. The predictions in the left figure were made using the weld metal stress-strain curve with the various J-estimation schemes, while the predictions in the right figure were made using the base metal stress-strain curve. Both analyses used the weld metal J-R curve to predict crack growth.



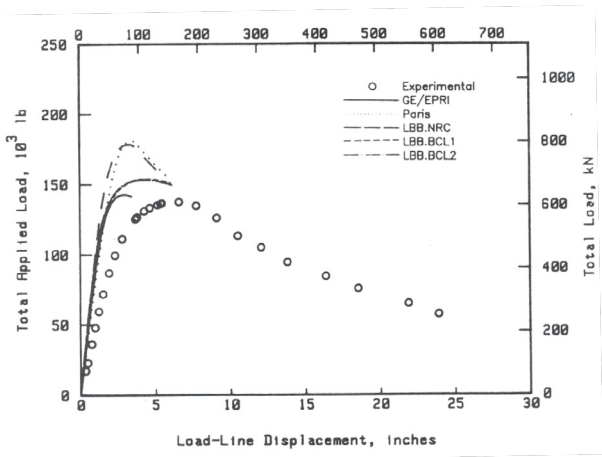
Weld metal stress-strain curve and J_M-R curve ***Base metal stress-strain curve and J_M-R curve***

Figure 14 16-inch diameter pipe test

The second case (also from Ref. 20) is for a 28-inch diameter stainless steel pipe test (4111-5) with the crack in the center of the overmatched weld, i.e., again there was a large difference in the weld and pipe stress-strain curves. The left side of Figure 15 shows the predictions using the weld-metal stress-strain curve in the various J-estimation schemes, while the right side of Figure 15 shows the predictions using the base-metal stress-strain curve. Both analyses used the weld metal J-R curve to predict crack growth.



Weld metal stress-strain curve and J_M-R curve



Base metal stress-strain curve and J_M-R curve

Figure 15 28-inch diameter pipe test

Both of these examples illustrate that using the weld-metal stress-strain curve in the J-estimation schemes drastically overpredicted the experimental maximum load, while using the base metal stress-strain curves gave reasonable predictions of the experimental maximum loads. *This result of using the base metal stress-strain curves for evaluation of cracks in welds is consistent with the limit-load analysis results presented earlier for cracks in high toughness welds.*

It is also important to note for later calculations in this report, that of the five different J-estimation schemes evaluated in the NRC piping research programs, statistical analyses with all of the pipe tests (Reference 1) showed the GE/EPRI method to be the most conservative (average experimental/predicted maximum load ratio of 1.15 with a COV of 11 percent), and *the LBB.ENG2 (called LBB.BCL2 in the above figures) method the most accurate (average experimental/predicted maximum load ratio of 1.04 with a COV of 13 percent) in predicting maximum load.* Slightly different but similar results were obtained if only the pipe tests with cracks in the center of the welds were statistically analyzed. The other methods examined were the Paris/Tada method (Ref. 66), LBB.NRC (Ref. 12), and LBB.ENG1 (called LBB.BCL1 – Ref. 18).

3.2. FEA Results for DMW Case

Cracks in Alloy 82/182 dissimilar metal pipe girth welds present an unusual case that has not been previously considered in the past pipe fracture programs. The unusual aspect is that the base metals on either side of the weld can have drastically different strengths. Consequently, it is not known which base metal strength curve should be used for the most accurate fracture predictions. To address this significant concern, Emc^2 conducted detailed 3D elastic-plastic FE analyses of a surgeline size pipe, with a circumferential through-wall crack in the Alloy 182 weld. Cracks were located in the center of the weld (Figure 13), as well as closer to the stainless steel safe end and closer to the ferritic nozzle (details can be found in draft ASME 2007 PVP paper (Ref. 67) and in the Emc^2 Wolf Creek scoping analysis final report to the NRC – Ref. 4). The actual stress-strain curves for the as-welded Alloy 182 weld metal (Ref. 53), stainless steel safe end and cladding, and A508 nozzle material (or A516 Gr70 for CE/B&W DMWs) were used.

From the FE analyses, the moment versus applied J curves were extracted, see Figure 16. The LBB.ENG2 J-estimation scheme was used to determine the appropriate stress-strain curve needed to match the moment versus applied J curves from the detailed elastic-plastic FE analyses, see Figure 16 for the case of crack in the center of the weld. These results showed that if the crack was in the center of the weld, then the appropriate stress-strain curve for the LBB.ENG2 J-estimation procedure was closer to the stainless steel base metal stress-strain curve than that of the weld or A508 nozzle material, i.e., a weighted average stress-strain curve was calculated which was ¼ of the way from the stainless steel curve when compared to the ferritic nozzle stress-strain curve. For the case of the crack closer to the stainless steel, the stainless-steel base-metal stress-strain curve gave the best predictions in the LBB.ENG2 analysis when compared to the FE results. Additionally, if the crack was in the weld but closer to the ferritic nozzle (i.e., in the buttering) then the average of the A508 and TP304 stress-strain curves gave the best predictions using the LBB.ENG2 analysis. The weld metal stress-strain curve was not used in any of these procedures. Hence, there is some effective stress-strain curve that can be used for DMW cracks, but unless the crack location is known, the stainless-steel base-metal strength should be used in the crack evaluation.

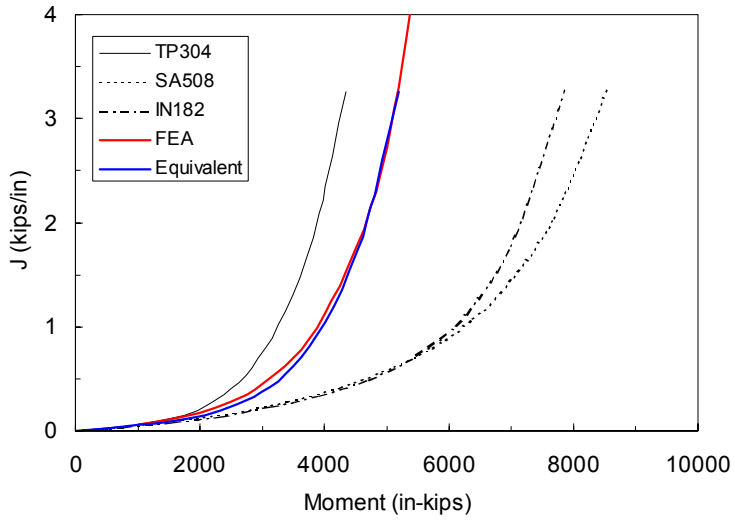


Figure 16

Another interesting aspect from the FE analysis is shown in Figure 17. This figure shows the equivalent plastic strains for a crack in the center of the weld, and illustrates how the plastic zone extends much farther in the adjacent lower strength stainless steel material (left side of the pipe in Figure 17). Because of the plastic zone extending into the stainless steel material, fully plastic limit-load conditions will develop in the stainless safe end before the weld becomes fully plastic. *This is another indication that the stainless steel safe end strength properties should be used in the fracture and limit-load analyses.*

3.3. Z-factor Approach for Alloy 82/182 Weld Metal Cracks

The Section XI IWB-3640 and Appendix C equations account for EPFM fracture behavior in a very simplified, but effective manner. The approach is to use a correction factor on the limit-load solution, where that correction factor is a function of the toughness of the cracked material, as well as the pipe diameter. This approach was first developed by Zahoor and Gamble for the EPRI as the technical basis for the stainless steel SAW crack evaluations (Ref. 2), and later for ferritic

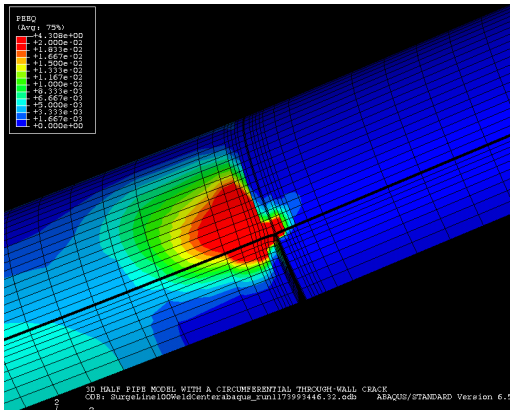


Figure 17

pipe flaw evaluations (Ref. 3). This EPFM correction factor is called a Z-factor, which is simply the thin-shell Net-Section-Collapse predicted maximum load divided by the maximum load determined from the GE/EPRI J-estimation scheme for circumferential through-wall cracks in pipes (Ref. 9). *The base-metal strength was used in the GE/EPRI scheme for Z-factors for welds.* Although the ratio of limit load/EPFM varies with crack length for the through-wall-crack GE analysis, the Z-factor was conservatively taken as the maximum value. This Z-factor changes with pipe diameter, i.e., a Z-factor equation exists as a function of pipe diameter for each material. Even though the Z-factor was developed from a through-wall-crack analysis, it is applied to surface-cracked pipes. From the prior discussion on constraint differences between surface and through-wall-cracked pipes, this is a conservative approach. However, to date a Z-factor for cracks in Alloy 82/182 welds has not been incorporated into the Code.

For the Alloy 82/182 weld metal crack case, Z-factors could be created using the LBB.ENG2 analysis with the appropriate stress-strain curve. This would be less conservative than using the GE/EPRI circumferential through-wall-cracked pipe J-estimation scheme. Assuming the worst case of not knowing where the crack is located, the LBB.ENG2 and limit-load analyses for calculating the Z-factor were performed (Refs. 56 and 67) using the stainless steel base metal strength. The J-R curve used for the Alloy 182 weld metal came from a CE cold-leg DMW, Ref. 53. These calculations were conducted as a function of pipe diameter; see Figures 18 and 19.

Figure 18

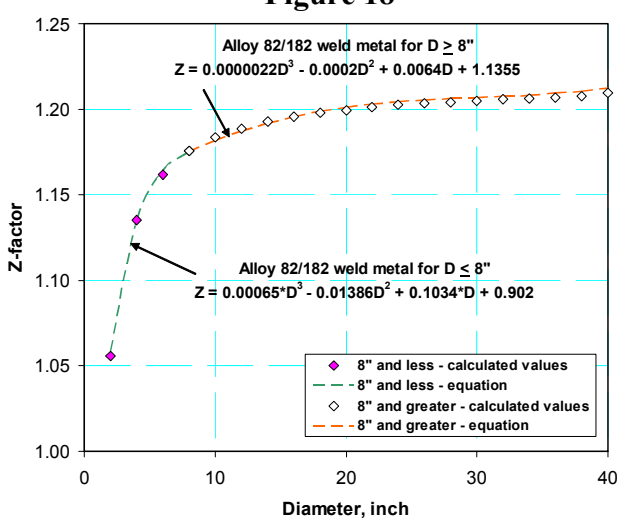
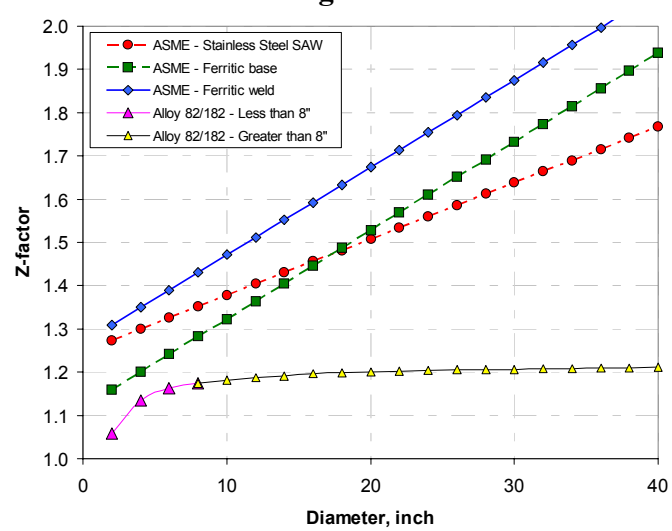


Figure 19



The results show that the Z-factor for Alloy 82/182 is much smaller than the Z-factor values for stainless steel weld metal and ferritic pipe (see Figure 19), but is not small enough that it could be ignored. For the Wolf Creek relief nozzle diameter, the Z-factor is about 1.17, which means that the limit-load calculated maximum moment should be divided by 1.17 to account for the weld metal toughness.

3.3.1. Pipe Test with a Through-Wall-Crack in a DMW

There was one large-diameter pipe test conducted in the NRC Short Cracks program (Ref. 25) where a large circumferential through-wall crack was placed in the fusion line of the Alloy 182 weld between the safe end and an A516 Grade 70 CE cold-leg, see crack location in Figure 20.

This test was on a 36-inch diameter pipe about 3-inches thick. The DMW was made by CE and the pipe was from a cancelled nuclear power plant. The concern at that time was for the integrity of cracks in the ferritic HAZ that might have a lower toughness. The test was done in four-point bending with no internal pressure, but at 550F. In addition, J-R curves were determined from 1T and 3T CT specimens for that crack location and used in the J-estimation scheme analyses.

The experimental and predicted global load-displacement curves were compared in that report (using 1995 methodology, Ref. 25) and are shown in Figure 21. These predictions were made using the different circumferential through-wall-cracked pipe J-estimation schemes. The predictions used the Alloy 182 stress-strain curve and the A516 Grade 70 steel stress-strain curve (since the crack was between these two metals). The predictions using the weld-metal stress-strain curve are on the left, and the predictions using the base-metal stress-strain curve are on the right. Using the weld-metal stress-strain curve overpredicted the experimental maximum loads, and using the A516 Gr 70 base-metal stress-strain curve, the predictions were much closer, but still slightly above the experimental results. With the knowledge from the recent Wolf Creek evaluations (see prior FE results in this report), it is expected that the effective combination of the A516 Gr 70 and stainless-steel stress-strain curves would give even better predictions than the results shown on the right side of Figure 21. Such analyses have not been done yet, but could be done for additional validation.

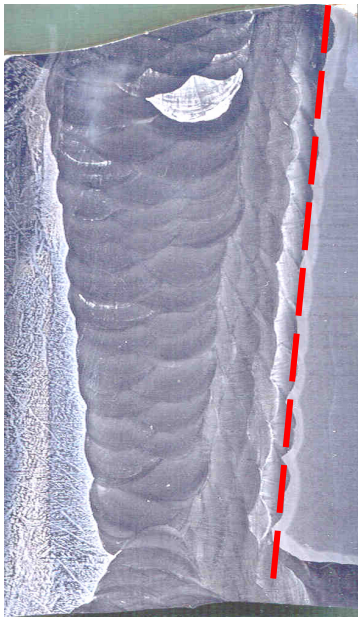
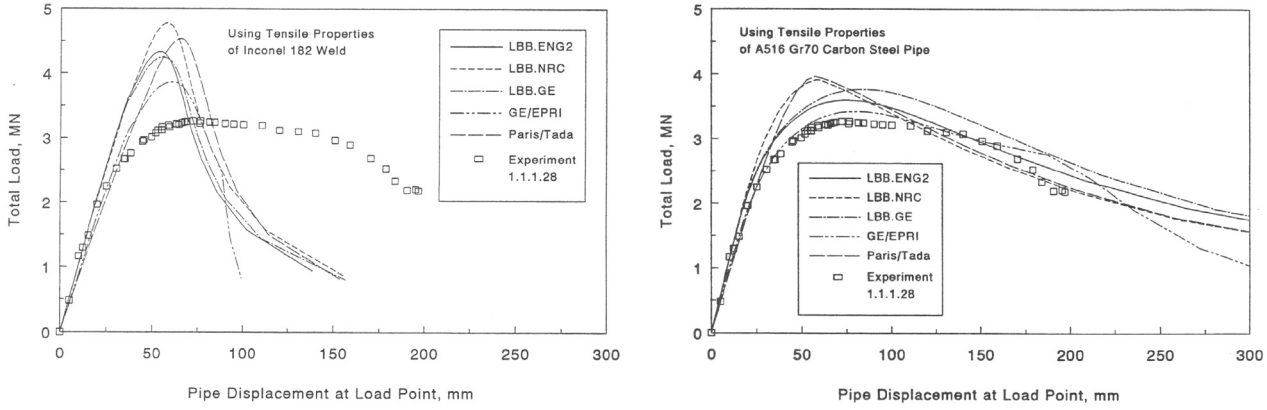


Figure 20 Fusion-line crack location in pipe test



Using weld metal stress-strain curve ***Using base metal stress-strain curve***

Figure 21

3.4. Surface-Cracked Pipe EPFM Analyses

Circumferential surface-cracked pipe EPFM analysis is much more difficult than the analysis of an idealized circumferential through-wall crack. In addition to the added variable of crack depth, the shape of the surface crack also becomes important. A greater complication is that the apparent toughness of the material in the surface-cracked pipe is higher than the toughness measured in a standard ASTM C(T) test due to constraint and anisotropy/orientation effects. The C(T) test is typically taken in the L-C orientation, which represents the crack growing as a circumferential through-wall crack in the pipe. For a circumferential surface-cracked pipe, the orientation of the test specimen should be in the L-R orientation representing crack growth in the radial direction. This orientation would account for material anisotropy which can also affect the toughness value. Ideally single-edge-notched tension (SENT) specimens with the crack in the L-R orientation should be tested to account for constraint and anisotropy effects properly in a surface-cracked-pipe evaluation (Ref. 68). Unfortunately such data seldom exists, so analyses that empirically account for the constraint and anisotropy effects need to be used for more accurate predictions. Without accounting for constraint and anisotropy effects on the material toughness, using a very accurate analysis of the crack-driving force (i.e., from FE analyses) along with the typical L-C orientation C(T) specimen J-R curve will significantly underpredict the maximum-load capability of the surface-cracked pipe. It is relatively easy to conduct appropriate FE analyses, but accounting for the proper material toughness is more difficult.

From the work done in the various NRC piping programs, there are two reasonably accurate circumferential surface-cracked-pipe EPFM analyses. One is empirical. This is the Dimensionless Plastic Zone Parameter analysis (DPZP) that was briefly discussed earlier in this report (Ref. 62). The second is a J-estimation scheme developed by Dr. J. Ahmad during the NRC's Degraded Piping Program. This analysis is called the SC.TNP1 analysis (Ref. 21), and is in the NRCPIPES computer code (Ref. 36). In Reference 1, it shows that the average experimental maximum load divided by the SC.TNP1 predicted maximum loads for seven internal surface-cracked pipe tests with cracks in welds under bending and pressure loading was 1.12 with a COV of 14.9. Hence this procedure was conservative by about 12 percent. The mean and COV values for the DPZP method for the same surface-cracked weld tests was 1.01 with a COV of 8.3 percent. All other EPFM analysis procedures have mean experimental/predicted maximum load ratios of ~1.4 to 1.75, which are too conservative. These other surface-cracked pipe J-estimation procedures have better agreement with FE analyses for the crack-driving force calculation, but the material fracture resistance for the surface-cracked pipe is too low when using the standard C(T) specimen data. The SC.TNP1 analysis inherently mispredicts the crack-driving force by the amount that the C(T) specimen underestimated the material toughness in the surface-crack geometry. This compensating error effect is not totally satisfying, but the analysis worked quite well in predicting all surface-cracked pipe tests, i.e., for 28 surface-cracked pipe tests the average experimental/predicted maximum load ratio is 1.02 with a COV of 13.7 percent (Ref. 1)

For the DMW surface-crack evaluation in the initial Emc^2 Wolf Creek scoping analysis (Ref. 4), the SC.TNP1 J-estimation scheme was used with the stainless steel stress-strain curve (using guidance from the circumferential through-wall-crack FE analysis comparison with the LBB.ENG2 analysis). The SC.TNP1 analysis used the same L-C orientation C(T) J-R curve for the Alloy 182 weld metal as was used in the through-wall-cracked pipe analyses (Ref. 53). This

result predicted that for surface cracks in the Alloy 182 weld metal, limit-load analysis would be appropriate for both the Wolf Creek relief nozzle diameter and the surge-line nozzle diameter. The SC.TNP1 result is consistent with the trend from the empirical DPZP analysis. The toughness of the Alloy 182 weld for the idealized through-wall-cracked pipe case (as measured with C(T) specimens) is slightly lower than what is needed to reach limit-load; however, the surface-crack geometry reduces the constraint (increases the apparent toughness in the surface-crack geometry) so limit-load controls for the surface-cracked pipe with the DMW. *Hence limit-load analyses using the stainless-steel base-metal properties are appropriate for the evaluation of circumferential surface crack in a DMW of a pipe. If the precise location of the DWM crack is known, then the weighted average of the stainless steel safe end and nozzle material strengths suggested earlier might be appropriate to use in the limit-load analysis, but some further validation is warranted if such an assumption is to be used.*

3.5. Complex-Cracked Pipe EPFM Analyses

The geometry of a complex-crack in a pipe was previously discussed and shown in Figures 2 and 6. Such a crack shape could occur for PWSCC as illustrated by industry's recent crack growth analyses as well as the validation analyses conducted by Emc^2, see Figure 22 for calculated crack shape. As noted earlier, this complex-crack geometry, due to the presence of the surface crack, constrains the through-wall-crack plastic zone significantly as compared to a simple idealized through-wall crack. The toughness reduction from this constraint (as determined directly from pipe tests) is illustrated in Figure 6. This toughness reduction factor could be a factor of four on the C(T) specimen J-R curve. *This toughness reduction could be used to calculate a new Z-factor for complex cracks, which would be much greater than that shown for the idealized through-wall crack shown in Figure 18.* We have not done this analysis in this report, but it could be readily done when needed.

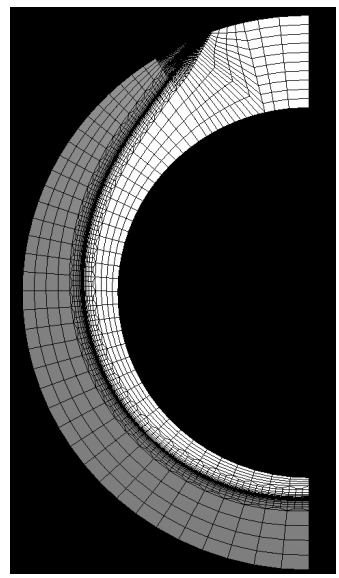


Figure 22

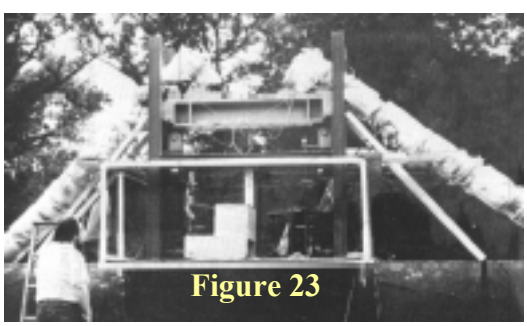


Figure 23

As an additional note, the tearing resistance of a complex-cracked pipe is lowered sufficiently so that limited pipe compliance will force a displacement-controlled (secondary stress) instability that could result in a DEGB (Ref. 11 see Volume 5). Figure 23 shows a 6-inch diameter complex-cracked pipe test that has a relatively short through-wall-crack length, but a DEGB break occurred during the test.

Similar instability behavior can occur in a surface-cracked pipe when the surface crack is very long, see Figure 24. Once the long surface crack starts to tear through the thickness at the center of the crack; it becomes a complex crack, with the same reduction in tearing resistance. *Hence secondary stresses need to be included for stability analysis of a complex-cracked and long surface-cracked pipe.*

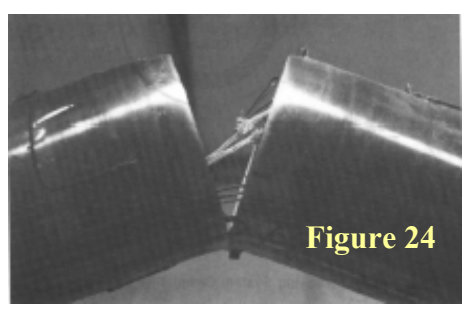


Figure 24

4. Should Secondary Stresses be used in Limit-Load and EPFM?

In piping stress analyses and fracture analyses there are frequently mixed definitions of what a secondary stress is and how it affects pipe failure. In this report, we are defining secondary stresses as those that are global displacement-controlled and not self-equilibrating through the thickness. For instance, thermal expansion and seismic anchor motion produce global secondary stresses; where weld residual stresses are a local residual stress. The R6 approach uses a similar classification, Ref. 63. Based on past pipe fracture tests, for ductile fracture crack stability analyses in nuclear piping steels, weld residual stresses can be neglected (Ref. 11). The few rare cases where weld residual stresses might have to be included are when the toughness is low enough that brittle fracture occurs [linear elastic fracture mechanics (LEFM) applies], e.g., some cast stainless steels that are highly sensitive to thermal aging[2].

Historically, LBB analyses by SRP 3.6.3 require the thermal expansion and SAM stresses to be included as primary stresses in the fracture analyses. The ASME Section XI Code first developed pipe crack evaluation procedures for cracks in wrought stainless steel pipes and their weldments. There was a "gut feeling" by the committee that wrought stainless steel was tough enough that the secondary stresses could be completely ignored. For lower toughness stainless steel butt welds, the secondary stresses should be included but with a safety factor of 1.0, i.e., they were less important than primary stresses.

To address the question of the importance of secondary stresses, some carefully controlled pipe system tests were conducted as part of the IPIRG and BINP international group projects (Refs. 51 and 69). The tests involved a 16-inch diameter pipe loop about 100 feet in total length, where a circumferential surface crack was put in the center of a stainless submerged arc weld. The tests were conducted with subcooled water in the pipe at 550F and 2,250 psig. Thermal expansion stresses were artificially changed at the start of the two tests, which were otherwise identical. A simulated seismic load was put on the pipe system for each experiment, as shown in Figure 25. Both test failed at the same total maximum moment (seismic and thermal expansion together), and hence the thermal expansion stress contributed equally to the fracture process as a primary stresses.

The secondary stress in this pipe system test acted as a primary stress from a fracture viewpoint due to the size of the surface crack ($a/t \approx 0.65$ and $\theta/\pi \approx 0.5$), which localized the plasticity at the crack plane and allowed negligible plasticity in the uncracked pipe loop. The rotations due to the surface crack (up to maximum load) are very small compared to the pipe rotations that can occur due to the thermal expansion stress. *Hence if there is a crack in a pipe system that is large enough that failure of the cracked section will results in elastic-only stresses in the rest of the pipe loop, the secondary stresses will act as a primary stress. This is the case for the Wolf Creek relief nozzle crack being examined by Emc[2] and industry.*

Similar conclusion were also analytically developed for through-wall cracks in pipes, see Ref. 51.

[2] From review of plant specific LBB submittals see Ref. 52.

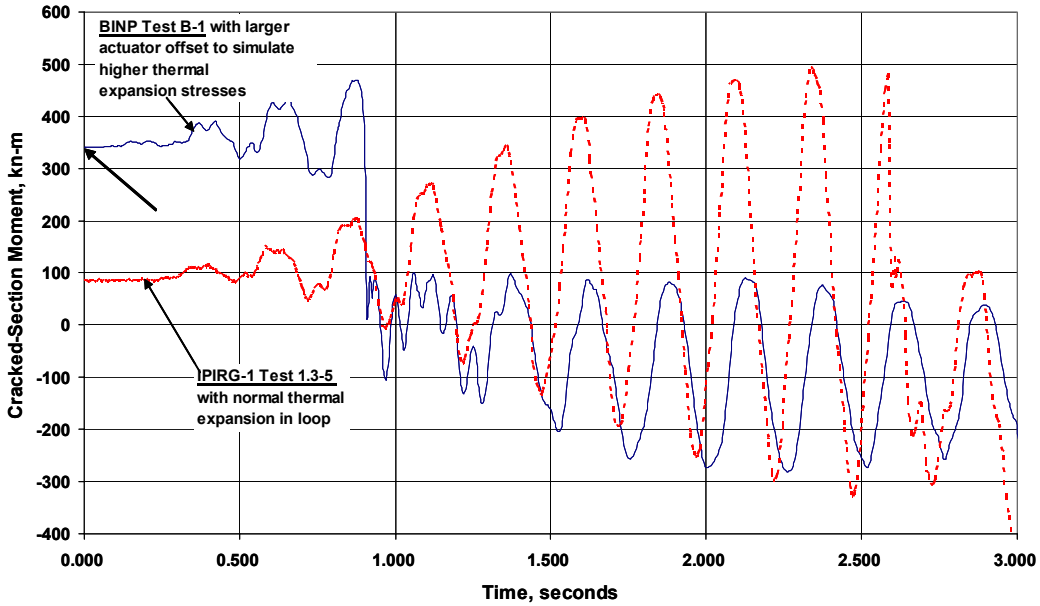


Figure 25

If the crack is smaller and the stresses in the rest of the pipe loop exceed the actual yield of uncracked pipe, there will be a gradual reduction of importance of secondary stresses on the determination of critical crack size. This gradual reduction is sensitive to the material strain-hardening of the pipe steel and the pipe loop configuration (are there single or multiple hinge points forming?).

It is also important to note that this result on secondary stresses and their contribution to fracture are consistent with the "Local Overstrain" warning in NC-3672.6 of Section III of the ASME Code (as well as in ND-3672.6 and B31.1) that says;

> "(b) Local Overstrain. All the commonly used methods of piping flexibility analysis assume elastic behavior of the entire piping system. This assumption is sufficiently accurate for systems in which plastic straining occurs at many points or over relatively wide regions but fails to reflect the actual strain distribution in unbalanced systems in which only a small portion of the piping undergoes plastic strain or in which, for piping operating in the creep range, the strain distribution is very uneven. In these cases, the weaker or higher stressed portions will be subjected to strain concentrations due to elastic follow-up of the stiffer or lower stressed portions. Unbalance can be produced:
>
> (1) …
>
> (2) by local reduction in size or cross section, or local use of a weaker material;
>
> (3) …
>
> Conditions of this type shall be avoided where materials of relatively low ductility are used; if unavoidable…"

Based on these results, it was suggested by G. Wilkowski to the ASME Section XI Working Group on Pipe Flaw Evaluation (presentation at August 8, 2005 meeting) that the approach to handle secondary stresses in pipe fracture should be radically changed. The safety factor for secondary stresses should be a function of the calculated failure stress relative to the yield strength of the pipe-system material. If the calculated failure stress (with no safety factor) is below yield of the uncracked pipe, the secondary stress should have the same safety factor as the primary stresses. It is somewhat less clear how to handle the cases for failure stresses that go above yield of the uncracked pipe, but for very small cracks where a large amount of the pipe system would have to substantially yield to cause failure, then the secondary stress effects can be ignored and the safety factor on the secondary stresses can go to zero. A simple way to handle the effect of secondary stress when the cracked pipe at failure would cause stresses above yield in the pipe system is a linear interpolation of the safety factor on the secondary stresses as the failure stress causes the uncracked pipe stresses to go between yield and the material flow stress. The safety factor on the secondary stress would be equal to the primary stress safety factor at yield (or below yield) and goes to zero when the failure stress causes the uncracked pipe to reach a stress equal to the flow stress. This approach should apply equally to all piping materials; even TP304 stainless steel where secondary stresses are currently ignored.

For the large cracks being considered in the Wolf Creek relief nozzle case (see figure at top of page 16), the failure stresses should be below yield of the uncracked pipe, and hence the secondary stresses should be considered as a primary stress. Since it is unknown if or when the secondary stresses will be completely relieved, it is recommended that they are included in critical crack size analyses.

5. Summary of Issues for Critical Crack Evaluations for DMWs

The results of this technical note show that the follow aspects should be included in the determination of the critical crack evaluation procedures for cracks in dissimilar metal welds.

Limit-Load Evaluations

1. There is very little difference in the predicted maximum moments using a thin-shell or thick-shell Net-Section-Collapse analysis for a circumferential through-wall crack in a pipe, unless the crack length is very long, i.e., greater than 65-percent of the circumference.
2. Experimental results with 237 idealized through-wall-cracked pipe tests in base metal showed virtually no difference in the accuracy of the thin-shell and thick-shell Net-Section-Collapse predicted maximum load-carrying capacity predictions. Given the identical accuracy, the simpler thin-shell Net-Section-Collapse solution should be used. Interestingly, there is a slight trend in the results for both analyses that show that as the pipe R/t ratio decreases, both Net-Section Collapse analyses become slightly conservative.
3. Two aspects that require care in the thin-shell, thick-shell, and Code version of the Net-Section-Collapse analyses are the definition of stresses, and definition of crack length. The Code equations sometimes intermix the thin-shell and thick-shell stress equations, and may even use some conservative equations at times, i.e., they use OD for determining

the axial stress from pressure. A second aspect is in the determination of the crack length. If the crack length is normalized to the pipe circumference, there will be no differences. If absolute measurements of the crack length are made, then it is important to know if they are on the ID, OD, or mean radius.

4. Using limit-load analyses to estimate the criticality of a surface crack by equating the cracked area of the surface crack and to the cracked area of a critical through-wall crack is accurate for surface cracks less than 30-percent of the circumference, but can become very conservative for longer cracks.
5. The Net-Section-Collapse analysis can significantly over predict the maximum load-carrying capacity for surface cracks that are deeper than ~75-percent of the thickness, i.e., for a surface crack with $a/t = 0.8$ and $\theta/\pi = 0.40$, the original Net-Section Collapse solution would over predict the maximum load-carrying capacity by a factor of 2. The Kurihara correction factor approach would have to be used to make reasonable predictions for deep surface cracks of the types being evaluated in the Wolf Creek relief line.
6. Typically, the effects of pressure on the crack faces are not included in Net-Section-Collapse analyses. The crack-face pressure would produce an additional induced moment at the crack plane. In past pipe tests, the axial force from the internal pressure was less than 10 percent of the applied bending stress, so the crack-face pressure effects were negligible compared to the scatter of the data. For the thicker relief valve nozzles, the R/t is small enough and the crack sizes are large enough, that crack-face pressure may become more important. Through-wall cracks have the added complication of a pressure drop through the thickness due to leakage, which may be accounted for in a leak-rate calculation. Additional sensitivity studies are needed to evaluate this effect.
7. The surface-crack Net-Section-Collapse equations in the ASME code are based on a constant depth surface crack. The integral form of the equations can be used to account for any arbitrary crack shape, and there are closed form solutions for elliptical and parabolic shaped surface cracks in the literature. Limited experimental results showed that for the case of a variable depth surface crack, the maximum crack depth could be used with an equivalent length that is equal to the area of the variable depth crack divided by the maximum depth. This equivalent crack size could then be used in the original constant-depth surface-crack Net-Section-Collapse equations to reasonably predict the maximum load.
8. For Net-Section Collapse analyses for cases of a crack in the center of a tough weld, the base metal strength should be used to predict the maximum load-carrying capacity.
9. The applicability of using a limit-load analysis depends on the toughness of the material, the pipe diameter, and the crack geometry, i.e., surface crack, idealized through-wall crack, or complex crack geometries. Surface-cracked pipes are more likely to have failure stresses predicted correctly by the Net-Section-Collapse analysis than the other crack types. The complex crack has the most toughness loss due to constraint and hence their failure stresses should be further below the Net-Section-Collapse predicted failure stress than compared to an idealized through-wall crack.

EPFM Evaluations

10. For an idealized circumferential through-wall crack, existing EPFM J-estimation schemes that were based on homogenous material properties were found to work well in

predicting failure of cracks in the center of welds if the base metal strength was used with the weld metal toughness. Using the weld metal strength significantly overpredicted the maximum load in all the EPFM analyses.

11. In comparison to full-scale circumferential through-wall-cracked pipe tests, the GE/EPRI method was the most conservative and the LBB.ENG2 method was the most accurate in predicting maximum load.
12. For a crack in a DMW, there is the added consideration of having two different base metals on opposite sides of the weld. The strength of A508 nozzle material is significantly greater than the TP304 safe end steel. To evaluate this effect, detailed FE analyses were conducted with cracks at various locations in the weld.
    a. If the crack was closer to the safe end, the stainless steel base metal stress-strain curve could be used in the LBB.ENG2 J-estimation scheme and give good agreement with the FE crack-driving force.
    b. If the crack was close to the nozzle side, then an effective stress-strain curve is the average of the stainless and A508 steel could be used in the LBB.ENG2 J-estimation schemes.
    c. If the crack was in the center of the weld, then the effective stress-strain curve for use in the LBB.ENG2 J-estimation scheme was closer to that of the stainless steel ($1/4^{th}$ of the way from the stainless steel when compared to the A508 steel).
    d. If the crack location cannot be determined, using the stainless steel base metal properties with the EPFM and Net-Section-Collapse analyses would be appropriate.
13. For an idealized through-wall crack, it was found that an elastic-plastic correction factor to the Net-Section Collapse results as a function of pipe diameter (Z-factor relationship developed) can be used. This factor was calculated for the case of the crack closer to the stainless steel base metal. The correction factor for Alloy 182 welds was much smaller than that for stainless steel or ferritic welds in the ASME Code.
14. For a circumferential surface crack, it was determined that limit-load analysis with the stainless-steel base-metal properties should give reasonably accurate results.
    a. If it is desired to account for the surface crack being closer to the higher strength nozzle material, additional analyses would be needed to assess the equivalent stress-strain curve approach as found to exist for idealized through-wall cracks.
15. For a complex crack, EPFM analyses would be needed since the surface crack in the ligament constrains the plasticity and lowers the apparent toughness. Z-factors could be developed for this case if needed. This could be a realistic crack type when looking at industry's recent crack growth analyses.
    a. Complex cracked pipe are much more prone to DEGB failure under displacement-controlled loading, so care should be used in such crack evaluations.

<u>Effect of Secondary Stresses on Pipe Fracture Behavior</u>

16. Carefully conducted full-scale pipe-system experiments with identical surface cracks showed that secondary stresses (thermal expansion and SAM) will act as a primary stress if the crack size is large enough so that the failure stress is below the yield stress in the uncracked pipe system. This is consistent with the ASME Section III Local Overstrain warning.

17. For the large size cracks in the Wolf Creek pressurizer nozzles, it is likely that the failure stress could be below yield of the uncracked pipe (need to account for the nozzle welds being thicker and large diameter in some cases than the piping), so that thermal expansion and SAM stresses may need to be included in the critical crack size evaluation.

6. Recommendations

From the work presented in this technical basis document, there are several recommendations that can be made:

- For circumferential surface-cracked pipe, Net-Section-Collapse analyses are typically appropriate. For idealized circumferential through-wall-cracked and complex-cracked pipe, an EPFM analysis is typically appropriate. However, there are situations where these statements may not be true; therefore, it is recommended that both Net-Section-Collapse analyses and EPFM analyses (either Z-factor, J-estimations scheme, or elastic-plastic finite element analysis) be conducted for all crack shapes. Care should be taken when analyzing deep surface cracks using Net-Section-Collapse analyses, i.e., a correction factor is needed.
- When conducting critical crack size analyses, the base metal flow properties and the weld metal toughness should be employed with the appropriate Net-Section-Collapse and EPFM analyses. The toughness of the material will have to be modified to account for the decrease in toughness in complex-cracked pipes. If a bimetal weld is being analyzed, the lower strength base metal flow strength properties should be used.
- Two aspects that require care in critical crack analyses are the consistent definition of stresses and crack length. It is recommended that great care is taken to assure that consistency occurs in the calculation of stress and crack length.
- Secondary stresses should be included in crack stability analyses if the uncracked pipe is elastic at the failure conditions. As the uncracked pipe stresses move above yield, the effect of secondary stress decreases but is not eliminated. Since it is unknown when or if the secondary stresses are relieved, it is recommended that it be included in all critical crack analyses.

7. Conclusions

This technical basis document was written to provide industry with additional information to evaluate the criticality of circumferential cracks. This document adds additional information to Item 4 from a letter written by the NRC to industry describing concerns over the Phase 1 calculations (from Michele Evans to Alex Marion dated April 4, 2007.) This document describes the large experimental and analytical efforts that have been undertaken to understand and predict the criticality of circumferential cracks in nuclear piping and their associated welds over the last 30 years. This work has been conducted by both the industry and the NRC through large programs which included international participation. Therefore, there is an extremely large database of results and conclusions available in the open literature on this subject. This document was intended to be a reference report on the relevant experimental and analytical results for accurately predicting the critical size of both surface and through-wall-cracked pipes. It was not meant as a comprehensive review of all of the technical issues pertaining to the

criticality of these cracks, but more as a reference document that the reader can use as a guide to finding more technical detail if desired. As part of this document, it was also necessary to give recommendations on the appropriate methodology to use for these analyses based on the wealth of available knowledge.

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