

# Application of Degraded Piping Program Results to Leak-Before-Break and In-Service Flaw Assessment Criteria

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## ABSTRACT

This paper summarizes the significance of the U.S. NRC's Degraded Piping Program - Phase II for pipe fracture evaluations. This was a 5 year program that ended in January of 1989. The intent of this program was to experimentally validate and enhance available analytical methods for evaluating the mechanical behavior of nuclear power plant piping containing circumferentially oriented defects.

Included in this paper are discussions of: (1) the significance of program results to LBB and in-service flaw acceptance criteria, (2) the importance of material characterization and observations of failure modes in flaw evaluation procedures, and (3) areas in which additional study is needed for improved piping integrity.

## 1.0 INTRODUCTION

At the beginning of the Degraded Piping Program - Phase II, the fracture mechanics analyses for pipe were quite limited, and additional data were needed for verification of these analyses:

- (a) the net-section collapse (limit-load) analysis for circumferentially cracked pipe was developed and verified only on small diameter stainless steel pipe (Refs. 1-2),
- (b) the EPRI/GE J-estimation elastic-plastic fracture mechanics analysis was developed, but had little verification (Ref. 3),
- (c) the NRC.LBB analysis method (Ref. 4) was under development but not published at that time,
- (d) the material property data available on nuclear piping materials were very limited (Refs. 5-6), and
- (e) the pipe fracture data available on nuclear piping materials were inadequate (Ref. 6).

The technical advancements from this program (Ref. 7) have been used to assess LBB fracture analyses and in-service flaw acceptance criteria. LBB developments include evaluation of J-estimation schemes for through-wall circumferentially cracked pipe, and for generation of experimental data to verify crack-opening areas for leak-rate predictions. In-service flaw evaluation

criteria included assessments of the ASME Section XI IWB-3640 austenitic flow evaluation procedure (Ref. 8) and the IWB-3650 ferritic flow evaluation procedure (Ref. 9). This effort involved assessment of the inherent safety factors in the ASME analyses and development of fracture toughness data for establishing reasonable lower bound material properties in the ASME analyses.

## 2.0 SIGNIFICANCE OF PROGRAM RESULTS FOR LBB FRACTURE ANALYSES

The program results can be characterized as efforts that support or validate either leak-before-break (LBB) fracture analyses or in-service flow evaluation criteria, i.e., ASME Section XI criteria. The significance to current LBB fracture analyses and possible future applications is also discussed in this section.

### SIGNIFICANCE FOR CURRENT LBB ANALYSES

Results from this program directly support the fracture mechanics analyses used in the LBB analysis procedures developed in NRC's Draft Standard Review Plan 3.6.3 (Ref. 10). Some of these findings may be summarized as follows:

Limit-Load Evaluations Limit-load analyses can be used for high toughness small and intermediate diameter pipe. However, elastic-plastic fracture mechanics analyses are generally needed for large diameter or lower toughness pipe. A screening criterion, see Figure 1, was developed to facilitate identification of the appropriate analysis technique. The program results showed that high toughness is not enough to guarantee that limit load will be reached. If the pipe diameter is large enough, even wrought stainless steel may not reach limit load (Ref. 7).

Circumferential Through-Wall Cracked Pipe Elastic-Plastic Analyses Two elastic-plastic fracture J-estimation methods had been developed in this program for circumferential through-wall-cracked pipe (Ref. 11). These methods are called LBB.GE and LBB.ENG, and were found to be slightly conservative, yet reasonably accurate methods to predict maximum load. Results of comparisons to experimental data are shown in Tables 1 and 2. The GE/EPRI method gave the lowest predictions; the Paris and LBB.NRC methods gave the highest predictions of load. The results suggest the use of either the LBB.GE or LBB.ENG methods for LBB fracture analyses. These methods are included in a computer code called NRCPIPE which was developed in this program.

Evaluation of Cracks in Welds For welds, it is generally more conservative to use the base metal stress-strain curve in the load predictions rather than the weld metal strength (Ref. 12). This procedure is illustrated in Figure 2. Some improvements could be made in developing an effective stress-strain curve, perhaps using a rule-of-mixtures, for consistency in the fracture and crack-opening-area analyses for LBB. Limited data show that if a thinner weld is used to determine the fracture toughness of a stainless steel flux (SAW or SMAW) weld, then the fracture toughness curve will be much higher than for a thicker stainless steel weld (Ref. 12). This is mainly due to the welding procedure where a high toughness TIG weld is used for the first two passes in a stainless steel weld. Hence, one should not use toughness data from thin stainless steel flux welds to evaluate pipe with thicker stainless steel flux welds.

Numerical Analyses of Circumferentially Through-Wall Cracked Pipe The results show that generally finite element predictions of loads and displacements for a circumferentially through-wall-cracked pipe in bending are generally lower than experimental results (Ref. 13). Consequently, such analyses are expected to be conservative when used for licensing and regulatory purposes.

Effect of Complex-Crack Geometries on Crack Stability A complex-crack geometry is a long surface crack where the crack has penetrated the thickness for a short length. Results from complex-cracked pipe experiments show that even a shallow surface crack adjacent to a through-wall crack can significantly lower the apparent fracture resistance of the pipe (Ref. 14), see Figure 3. Further sensitivity studies are needed to assess if this reduction could significantly erode the margin of safety in LBB fracture analyses.

### POSSIBLE APPLICATIONS OF LBB

Some possible applications to future LBB analyses are summarized as follows:

Improve Crack Stability Calculations Predictions of crack stability can be made using the LBB.ENG or LBB.GE methods for combinations of load-controlled and displacement-controlled stresses. These methods, when used in an energy balance analysis, can estimate not only the start of an instability, but also the arrest of a crack.

Surface Crack Stability Current LBB analyses postulate a through-wall crack and determine if the crack can be detected by leakage at normal operating conditions and still be stable at emergency and faulted loads. Current analyses do not consider surface crack stability at normal loads. Rather, the surface crack is considered to break through the thickness at emergency and faulted loads. This crack could either remain stable or result in a double-ended guillotine break (DEGB). Development of surface crack stability criteria at normal loads would give further credence to the current LBB methodology.

Replacement for DEGB Criteria Should the development of an alternative criterion to the DEGB be desired in the future, the methodology in this program could be used to estimate the maximum credible leakage area. This methodology could be used for equipment qualification relief, subcompartment flooding criterion, improved pipe support analyses for thrust loads, and more realistic predictions of depressurization loads for reactor pressure vessel core supports.

### 3.0 SIGNIFICANCE FOR IN-SERVICE FLAW ACCEPTANCE CRITERIA

Some of the program results that contributed to current in-service flaw evaluation criteria are summarized as follows:

Evaluation of ASME Austenitic Pipe Flaw Criteria The ASME IWB-3640 criteria were validated for cracks in wrought stainless steel, cast stainless steel with ferrite numbers less than 20, GTAW and flux welds. In general, the criteria do not provide a minimum safety factor for all the experimental data, but the safety factors are met for more than half of the data developed. It appears that the flux weld criteria for SAW and SMAW stainless steel welds could be combined into a single criterion (Ref. 12).

Fusion Line Toughness A limited amount of heat-affected-zone data (Ref. 12) showed that there is a potential for lower toughness along the fusion line of stainless steel welds (see the crack tip opening angle in the fusion line crack Specimen A8-5 in Figure 4). Since stress corrosion cracks frequently grow to the fusion line, this observation needs further investigation.

Fracture of Stainless-Steel Weld-Overlaid-Repaired Pipe The net-section collapse and IWB-3640 analyses were found to be satisfactory for weld overlays made by TIG welding on stainless steel pipe (Ref. 7).

Inherent Safety Factors in the ASME Pipe Flaw Evaluation Criteria The plastic-zone screening criterion developed in this program showed that the maximum loads for through-wall cracked pipe are more sensitive to toughness than are surface-cracked pipe (Ref. 7). For low toughness pipe materials, the ASME Section XI acceptance criteria for surface cracks are based on approximate through-wall cracked pipe analyses; hence, they contain an inherent safety factor.

ASME Ferritic Pipe Criteria The results of this program were used in the development and verification of the ASME IWB-3650 analysis procedure for ferritic pipe. These results show that the procedure meets the advertised safety factor. This analysis could be improved by using an actual surface-crack J-estimation scheme, such as SC.TKP (Ref. 15), to better assess the load-carrying capacity for finite-length surface-cracked pipe.

Numerical Analyses of Circumferentially Surface-Cracked Pipe Finite element analyses of a surface-cracked pipe experiment showed that for the circumferential surface crack case, the size of the finite element mesh is important. Moreover, such an analysis may tend to overpredict actual loads. The magnitude of the overprediction was not pursued in this program, because the analyses were carried out only to crack initiation and not to maximum load.

#### 4.0 SIGNIFICANCE OF MATERIAL CHARACTERIZATION EFFORTS AND OTHER OBSERVATIONS THAT MAY AFFECT FLAW ACCEPTANCE PROCEDURES

Some additional findings from this program that affect the LBB fracture or in-service flaw evaluation procedures can be summarized as follows:

Material Property Data Base Over 150 tensile tests and 175 fracture toughness tests (J-R curves) have been conducted in this program. These data have been incorporated into the NRC PIFRAC piping material property data base (Ref. 16). They have been useful in establishing generic bounds on the toughness of piping materials. Additional data are needed for ferritic welds and for fusion line areas of both ferritic and austenitic welds.

Toughness of ERW Pipe One interesting fact uncovered is that A333 Grade 6 pipe can be made either by seamless methods or by electric resistance welds (ERW). The toughness of ERW weld can typically be one-tenth to one-third of the lower bound toughness used in the IWB-3650 procedure for ferritic steels (Ref. 17). Further investigation is needed to assess if such welds are actually used, and to assess their behavior at LWR temperatures. These results could then affect the ASME IWB-3650 analysis procedure.

Data for Probabilistic Analyses The reproducibility of tensile test results was assessed in a round-robin effort with NRC contractors. While reasonable consistency of results was observed among contractors, sensitivity studies on the predictions of the J-estimation schemes would be worthwhile. These data, along with the rest of the material property data base, would be useful in future probabilistic fracture mechanics analyses.

Extrapolation of Crack Growth Resistance Curves from Small Specimens Three extrapolation methods for crack growth resistance curves were assessed in this program. All of these methods used the J-integral based parameter. The NUREG 1061 Volume 3 method (Ref. 18) was found to be too restrictive. A recently developed method from other NRC efforts, involving a power-law extrapolation of the deformation theory J-R curve, gave reasonable and slightly conservative results when used with most pipe fracture estimation schemes (Ref. 7), see results in Table 1. Another proposed fracture parameter is the modified J or  $J_M$ -R curve proposed by Ernst (Ref. 19). The linear extrapolation of the  $J_M$ -R