September 23, 1996

APPLICANT: Westinghouse Electric Corporation

FACILITY: AP600

SUBJECT: SUMMARY OF TELEPHONE CONFERENCES TO DISCUSS WESTINGHOUSE AP600 LEAK-BEFORE-BREAK (LBB) AND HIGH ENERGY LINE BREAK OPEN ITEMS

The subject telephone conferences were held on August 27 and 28, 1996, between representatives of Westinghouse Electric Corporation (Westinghouse) and the Nuclear Regulatory Commission Civil Engineering and Geosciences Branch staff and its consultant. The purpose of the telephone conferences was to discuss the status of the open items related to the LBB and high energy line break analyses. The staff provided a status of its review in a letter dated August 20, 1996. To facilitate Westinghouse's preparation for the telephone conferences, a facsimile of the status was sent prior to the receipt of the mailed copy. Attachment 1 is the open item status as a result of the telephone conferences. Attachment 2 is part of NUREG-6443, "Deterministic and Probabilistic Evaluations for Uncertainty in Pipe Fracture Parameters in Leak-Before-Break and In-Service Flaw Evaluations," which was sent by facsimile to Westinghouse after the telephone conferences in reference to request for additional information (RAI)# 210.228.

original signed by:

Diane T. Jackson, Project Manager
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Office Of Nuclear Reactor Regulation

Docket No. 52-003

Attachments: As stated

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DOCUMENT NAME: A:ECG8 27T.MIN (8H AP600 DISK) *See previous concurrence

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Open Items (OIs) Discussed in August 27 and 28, 1996, Telephone Conferences

OI 3.6.3.6-1 (OITS# 615)
Westinghouse will send a draft markup of standard safety analysis report (SSAR) 3.6.4.2. Action Westinghouse

OI 3.6.3.6-3 (OITS# 617)
The staff expressed a concern regarding the designer's use of Westinghouse document GW-N1-001 instead of the SSAR. Westinghouse stated that the document and the SSAR would be consistent. The staff stated that this document would be reviewed for the audit. Action Westinghouse/Action NRC

OI 3.6.3.4-1 (OITS# 608)

3.6.3.2

a) The staff expressed a concern regarding the application of leak-before-break (LBB) to class 2 and 3 piping. Westinghouse will send a request for additional information (RAI) response explaining the significance of the application of LBB. Action Westinghouse

b) The staff requested clarification on SSAR Section 3.6.3.2 regarding how preservice inspection and in-service inspection will provide for the integrity of LBB candidate piping systems. Westinghouse will review these sections and provide a draft markup. Action Westinghouse

3.6.3.3

c/d) The staff requested clarification on SSAR Section 3.6.3.3 regarding how the bounding analysis satisfies LBB acceptance criteria. Westinghouse will review these sections and provide a draft markup. Action Westinghouse

3B.1

e) Resolved

3B.2

f) The staff expressed a concern regarding the water chemistry. After discussions with Westinghouse, the staff will review the additional information. Action NRC

g) Westinghouse will add an explanation on the limiting water hammer load and the pressurizer safety valve discharge load to the footnote on SSAR p. 3B-17. Action Westinghouse

h) The staff asked if fatigue was considered for class 2 and 3 piping. Westinghouse stated they would review their calculation and check if fatigue was included in the "f" factor and revise the SSAR accordingly. Action Westinghouse

i) The staff expressed a concern regarding dynamic strain aging effects. After discussions, Westinghouse will provide an explanation in SSAR 3B.2.5. Action Westinghouse

j) Westinghouse stated that there now are no unisolatable section in the AP600. They will change its SSAR to reflect the change. Action Westinghouse

k) Westinghouse will include a statement regarding their evaluation on creep fatigue and indirect causes and cleavage type failure. Action Westinghouse

Attachment 1

3B.3

l) After discussions with Westinghouse, this concern is resolved. Resolved

m) Westinghouse will revise the SSAR to reflect that Westinghouse uses a margin of 1 on load by using an absolute sum. Action Westinghouse

n) After discussions with Westinghouse, this item is resolved. Resolved

o) Westinghouse will clarify the definition. Action Westinghouse

p) Westinghouse will clarify the information on stainless steel and ferritic steel regarding the determination of the high bending stress. Action Westinghouse

q) Westinghouse explained to the staff that the Y and Z axis are lateral to the pipe axis. Westinghouse will clarify the designation in the SSAR. Action Westinghouse

3B.4

r) Westinghouse will revise the SSAR 3B.4 to include class 3 for stainless steel because the distinction is a function of the material not the code class. The staff will discuss internally the need for spot radiography on certain lines. Action Westinghouse/Action NRC

s) Westinghouse will change the title of SSAR 3B.4 to better reflect the text. Action Westinghouse

3B.5

t) Westinghouse will clarify the inspection differences for ASME code class 1, 2,and 3 piping systems. Action Westinghouse

3B.6

u) Westinghouse will clarify the differences in fabrication requirements ASME code class 1, 2,and 3 piping systems. Action Westinghouse

3B.7

v) The staff expressed its concern regarding water hammer and the application of LBB for feedwater lines. The staff needs further internal discussions. Action NRC

3B.8

w) The staff expressed its concern regarding water hammer and the application of LBB for feedwater lines. The staff needs further internal discussions. Action NRC

Tables: Westinghouse informed the staff that the automatic depressurization system (ADS) stage 1 (4-inch pipe) would no longer be a candidate for LBB application. Westinghouse will revise the SSAR to reflect this change. Westinghouse will also expand tables 3B.1 and 3B.2 to include line sizes and material. Action Westinghouse

Bounding Curves: The staff identified six bounding curves to review for the audit. One of these lines was the ADS stage 1 (no longer a LBB candidate). The staff will choose a replacement.

OI 3.6.3.4-2 (OITS# 609)
Westinghouse will clarify SSAR 3.6.3.3 and SSAR Tables 3B.1 and 3B.2. Action Westinghouse

OI 3.6.3.4-1 COL
The staff expressed the concern that the COL should verify piping stresses based on as-built configuration and material properties. Westinghouse will

consider this concern and determine how to address it. In addition COL needs to perform a materials test for ferritic LBB piping (feedwater and main steam). Action Westinghouse

OI 3.6.3.5-2
Westinghouse will revise the SSAR as noted in 3.6.3.4-1 above. Action Westinghouse

OI 3.6.3.6-3
The staff will review Westinghouse document GW-N1-001 at the audit. Westinghouse will ensure this document and the SSAR are consistent.
Action Westinghouse/Action NRC

OI 3.6.3.6-6
Westinghouse submitted a WCAP on testing at Oregon State University. Westinghouse will provide the WCAP number. The staff will review the pertinent information in the report. Action Westinghouse/Action NRC

RAI 210.228
The staff expressed a concern regarding the bending stress in small diameter pipes. This issue is discussed in NUREG-6443, "Deterministic and Probabilistic Evaluations for Uncertainty in Pipe Fracture Parameters in Leak-Before-Break and In-service Flaw Evaluations," issued in June 1996. Westinghouse did not have a copy of this NUREG. Action NRC

Subsequent to the telephone conference, the staff faxed several pages for reference until Westinghouse could obtain a copy of the NUREG. After Westinghouse has reviewed this document, a telephone conference or meeting will be scheduled. Action Westinghouse

RAI 210.215
Westinghouse revised the SSAR in Revision 9. Resolved

13) OI# 3.6.2-1 (OITS# 592)
Westinghouse needs a cross reference SSAR information. Action Westinghouse

14) RAI# 210.225
The staff required clarification on the revisions to SSAR Table 3.6-2.
Resolved

15) RAI# 210.40
Westinghouse and the staff discussed the break exclusion zone on the startup feedwater line. Action Westinghouse

Subsequent to the telephone conference Westinghouse sent larger isometric drawings of the piping. The staff will review the drawings and this item will be discussed at a later time. Action NRC

16) OI# 3.6.2.3-1 (OITS# 595)
Westinghouse will describe the pipe rupture hazard analysis in the SSAR.
Action Westinghouse

17) OI# 3.6.2.3-2 (OITS# 596)
Due to staff review of the Westinghouse information this item is resolved. Resolved

18) OI# 3.6.2.3-5 (OITS #599) - Separating structures
The staff stated they would better explain the staff's position. Action NRC

Subsequent to the telephone conference, the staff discussed the issue internally and provides the evaluation as follows:

(Reference Item 8 in the enclosure to letter from Jackson to Liparulo dated April 10, 1996). In a conference call with Westinghouse on August 28, 1996, the staff agreed to provide Westinghouse with a clarification of the staff's position on this issue. This guideline, which is currently in standard review plan (SRP), Section 3.6.2, BTP MEB 3-1, Subpart B.1.c.(4), has been in SRP 3.6.2 since the original version was published in 1975. Final safety analysis reports (FSARs) for plants that have been granted operating licenses since that time have commitments to this guideline. In a letter from William Kerr to Victor Stello dated June 9, 1987, the NRC Advisory Committee on Reactor Safeguards (ACRS) provided the staff with comments relative to a proposed revision to SRP 3.6.2, which eliminated the criteria for postulating arbitrary intermediate pipe ruptures. In this letter, the ACRS stated that it agreed with the proposed revision, provided that the guidance in BTP MEB 3-1, Subpart B.1.c.(4) be retained in the SRP. On June 19, 1987, Generic Letter 87-11 released Revision 2 of BTP MEB 3-1, which complied with the ACRS request. Recent examples of acceptable implementation of this guideline for piping systems not qualified for LBB can be found on page 3-35 of NUREG-1503, "Final SER Related to the Certification of the ABWR Design," and in the last paragraph in Section 3.6.2.1.1 of the CE System 80+ Design Control Document (DCD). This same paragraph in the System 80+ DCD also contains acceptable implementation for piping systems which are qualified for LBB. Westinghouse is requested to revise the AP600 SSAR to provide similar commitments. Action Westinghouse

NUREG/CR-6443
BMI-2191

Deterministic and Probabilistic Evaluations for Uncertainty in Pipe Fracture Parameters in Leak-Before-Break and In-Service Flaw Evaluations

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Attachment 2

the off-centered crack was 50-degrees off the bending plane. This 10 percent difference is considered insignificant.

3.5 Effect of Restraint of Pressure Induced Bending in a Piping System on LBB

Another factor not generally considered in LBB analysis is that there is a restraint of pressure induced bending for a crack in a piping system. This effect was first observed in IPIRG-1 pipe system Experiment 1.3.7, where the calculated critical crack size, considering pressure loading alone, was 64 percent of the circumference, but the observed crack length at instability was 95 percent of the pipe circumference. This difference in crack sizes was explained by the effect of restraint of pressure induced bending. That is, the critical crack length solutions (EPFM and Net-Section-Collapse analyses) for a circumferential crack in a pipe under axial tension assume that the ends of the pipe are free to rotate. With the free rotation, there is an induced bending from axial forces times an eccentricity equal to the distance from the center of the crack plane to the center of the pipe. In a pipe system, this induced bending can be restrained and then the load-carrying capacity increases. This difference for the Net-Section-Collapse analysis is illustrated in Figure 3.12. Hence, there is some additional load-carrying capacity for a through-wall crack in a pipe due to this effect.

One factor briefly investigated in Reference 3.15, was that the restraint of induced bending also affects the crack-opening displacement even under elastic loading. In this case, the COD is less than that calculated by typical LBB analyses that assume the pipe is free to rotate under pressure loading. The reduction of the COD was calculated by elastic analysis in Reference 3.15, and was found to be affected by the length of the through-wall crack, and the location of the crack from a restrained location, see Figure 3.13. This reduction in the COD is detrimental to LBB acceptance, but is not very significant for short crack lengths.

Because of the trade-offs of the effects on restraint of pressure induced bending on COD versus maximum loads, sample deterministic LBB calculations were made. Probabilistic calculations are also discussed later in this report. The deterministic calculations made involved 114.3 and 711.2 mm (4.5 and 28 inch) outside pipe diameters. The pipe diameter was varied because the LBB crack size is a larger percent of the circumference for a smaller diameter pipe, and hence the restraint of bending is more significant for the small diameter pipe as can be inferred from Figure 3.13.

Calculations of the leakage crack size were made with and without the restraint of the pressure using the COD restraint values in Figure 3.13. Using the normalized restraint length of 1.0 represented the case of a crack close to a nozzle or elbow. The following conditions were used in this analysis:

- The SQUIRT Code Version 2.4 was used with the IGSCC crack default parameters.
- The R_m/t ratio was 6 for the 114.3 mm (4.5 inch) and 10 for the 711.2 mm (28 inch) pipe.
- The pressure was 15.51 MPa (2,250 psi) and the temperature was 288 C (550 F).

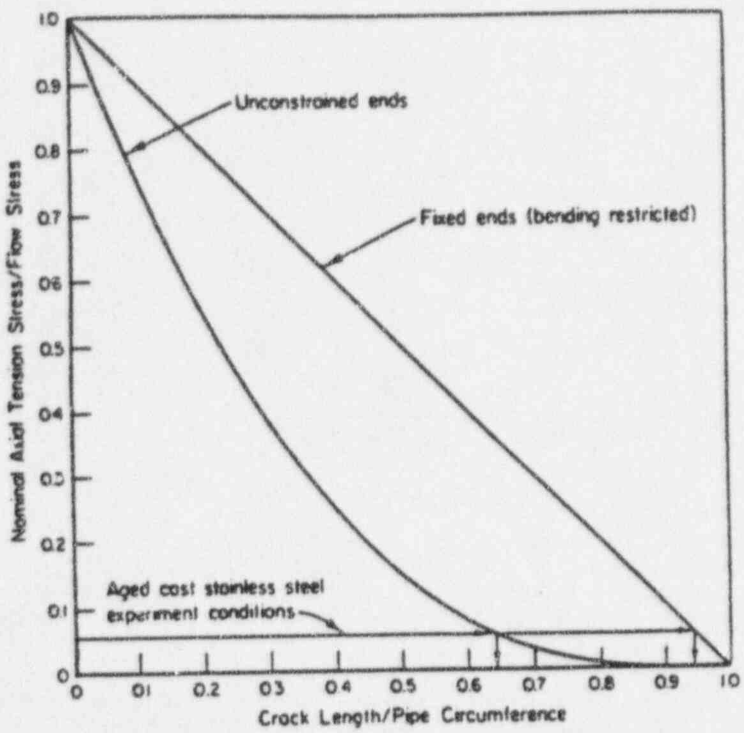

Figure 3.12 Net-Section Collapse analyses predictions, with and without considering induced bending, as a function of the ratio of through-wall-crack length to the pipe circumference and comparison to IPIRG-1 Experiment 1.3-7 crack length at DEGB

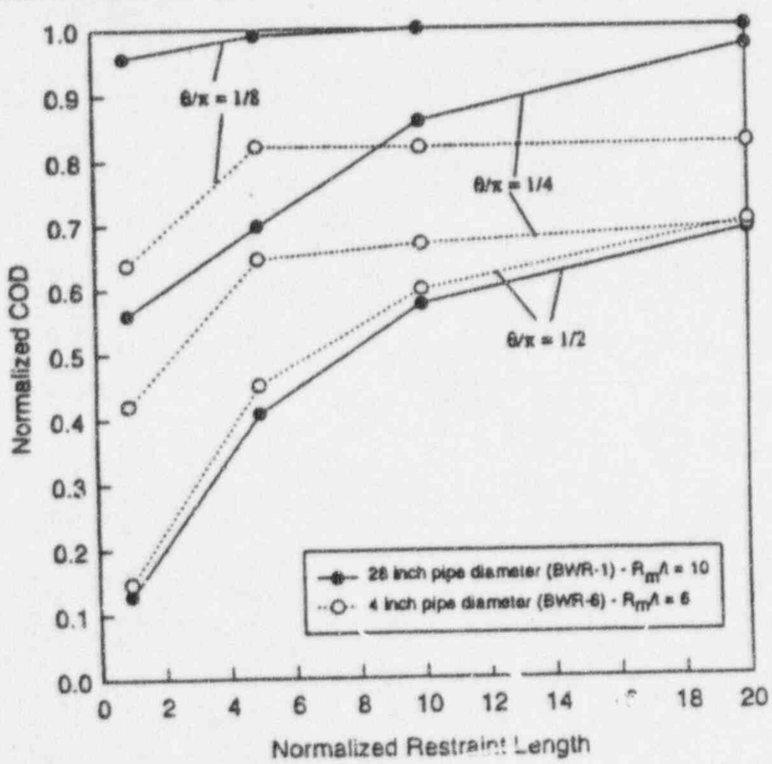

Figure 3.13 Effects of fully restrained bending conditions from crack location on COD normalized by the unrestrained COD

- A bending stress chosen to give a total pressure and bending stress of 50 percent of the Service Level A maximum allowable stress from ASME Section III Article NB-3650 for TP304 pipe was used.

Initial calculations were made with a leak rate of 37.8 liters per minute (10 gpm). This was to correspond to a 3.78 l/min (1.0 gpm) leak times a safety factor of 10. Analyses were successfully conducted for the large diameter pipe, but solutions could not be obtained for the small diameter pipe. The leak rate was subsequently reduced to 1.89 l/min (0.5 gpm) and a solution for both the large and small diameter pipes were obtained. Table 3.3 shows the difference in the through-wall-crack lengths.

Table 3.3 Differences in leakage flaw sizes due to restraint of pressure induced bending

Outside Pipe Diameter		Leakage Crack Length, θ/π	
mm	inches	Restrained	Unrestrained
114.3	4.5	0.7250	0.2360
711.2	28.0	0.0219	0.0219

The next step in the deterministic LBB analysis was to assess the effect of restraint of pressure induced bending on the maximum load-carrying capacity. To do this, the LBB.ENG2 analysis procedure, Ref. 3.17, was modified to eliminate the induced bending from the axial tension stress component. (A special modification of NRCPIPE Version 3.0 was used in these calculations.) Hence, maximum load calculations were made in the unrestrained and restrained conditions for the corresponding leakage cracks. These calculations assumed the following:

- The crack is centered on the bending plane,

- The average stress-strain curve properties for TP304 stainless steel base metal were used from the statistical analysis in Appendix B of Reference 3.13, as were previously given in Equation 3-3, and

- The crack was assumed to be in the weld, hence the mean minus one standard deviation J-R curve for a stainless steel SAW weld was used, see Equation 3-4.

The results of the maximum load calculations are shown in Table 3.4.

Table 3.4 Differences in maximum stresses[(a)] for LBB analyses due to restraint of pressure induced bending

Outside Pipe Diameter		
mm	inches	Restrained/Unrestrained Maximum Stresses
114.3	4.5	0.1129
711.2	28.0	1.007

(a) Maximum stress = nominal bending plus tension stresses.

These results showed that the effects of the restraint of pressure induced bending on the maximum load was insignificant for the large diameter pipe. However, for the small diameter pipe, the effect was significant. This comes about because: (1) the difference in the leakage crack length was negligible for large diameter pipe with a short crack, and (2) for the small diameter pipe the effect on the leakage crack length is very large and the higher load-carrying capacity for the restraint of pressure induced bending loads offers little compensation for the large crack size. This result is significant in regard to application of LBB to smaller diameter pipe. The trend for other intermediate pipe sizes is not obvious.

3.6 Effect of Weld Residual Stresses on LBB Analysis

Another factor that has not been given much attention in LBB analysis is the effect of weld residual stresses. Residual stresses could potentially affect the maximum load-carrying capacity as well as the crack-opening displacement. For nuclear piping, carbon steel welds less than 38.1-mm (1.5-inches) thick are typically not stress relieved. Austenitic pipe occasionally have solution-annealed welds, if the whole pipe subassembly can be heat-treated, but there are tie-in welds that would not be solution annealed.

Work in the Degraded Piping Program - Phase II on as-welded and solution-annealed stainless steel SAWs with circumferential cracks, showed that there were no detrimental effects from the residual stresses on the fracture behavior (crack initiation and maximum loads) of the as-welded pipes, Ref. 3.18. Interestingly, the solution-annealed pipes actually had lower maximum loads than the as-welded pipes with identical cracks. This is believed to be due to the lowering of the yield strength of the weld metal from the solution annealing. (See Reference 3.19 for additional analyses accounting for weld metal strength properties in fracture analyses.)

In References 3.15 and 3.20, the effects of residual stress on the crack-opening displacement were investigated. These analyses showed that with thinner pipe (less than 25-mm [1-inch] thick), the tension-compression residual stress fields through the thickness caused a significant rotation of the crack faces. For thicker welds, the residual stress field may be tension-compression-tension through the thickness, and the resulting rotation of the crack faces is much smaller. The magnitude of the crack-face rotation relative to the crack-opening displacement from the applied loads would determine the effect on leak rates. The crack-face rotation from the residual stresses would make the crack-opening displacement on the inner surface larger, and the crack-opening displacement on the outside surface smaller. The average crack-opening displacement would be the same, unless the crack faces rotated enough to touch.

One question is what would be the effect of the crack-face rotation on leak rates. Unpublished data from Nuclear Electric* showed that converging and diverging crack faces gave the same leakage. This information suggests that the crack-face rotation is not important on the leak rate unless the crack faces touch. This observation has been substantiated with calculations using the SQUIRT leak-rate computer code.

Typically, LBB analyses calculate the center-crack-opening displacement and use the assumption of an elliptical crack-opening profile. Finite element analyses by many investigators have shown that the elliptical profile is a good approximation (Ref. 3.15). Hence, it is quite possible that the residual stresses

* Results from Mr. T. Chivers to Dr. G. Wilkowski.

6.0 SUMMARY AND CONCLUSIONS

The following summarizes the objectives, results, and presents conclusions from both the deterministic and probabalistic studies. These results are organized by the technical aspect being evaluated. In most cases there are both deterministic and probabilistic results. The deterministic analyses were conducted independently of the probabilistic analysis, which offered the opportunity to validate conclusions from each of these studies. At the end of this section, the relative significance of these various technical aspects are ranked.

6.1 Uncertainty Analyses Relative to LBB

6.1.1 Evaluation of Different Crack Morphology Default Values

The objective in this effort was to assess any differences in default crack morphology parameters between PICEP Version 4.0, SQUIRT Version 2.3, and SQUIRT Version 2.4. This evaluation was done only in a deterministic manner. The SQUIRT Version 2.3 default values were typical values from an experiment, but no special attempt was made to define these values. The basis of the PICEP default values is not well documented. It is believed that the IGSCC values come from an EPRI/Battelle leak-rate program, but the basis of the corrosion-fatigue crack morphology default values could not be traced. The SQUIRT 2.4 default crack morphology parameters are the mean values from statistical evaluation of cracks removed from service as documented in Reference 6.1. The crack morphology parameters in these analyses are the surface roughness and the number of turns per unit of thickness. Cracks resulting from both IGSCC and corrosion-fatigue mechanisms were considered.

The calculated crack lengths using both SQUIRT versions and PICEP Version 4.0 default crack morphology parameters for IGSCC cracks were very close. However, it should be noted that the default values are mean values and there is a high statistical variability for IGSCC crack morphology parameters. This is due to the fact that typical wrought stainless steel piping products will have grain sizes of 3 to 6[*]. Using ASTM Standard E112 to convert grain size numbers to physical dimensions gives a range of grain sizes that vary by a factor of 2.77 in average "diameter". Consequently, roughness and number of turns will vary proportionally to this change in grain size for an IGSCC.

The calculated crack lengths for a given leak rate using the corrosion-fatigue crack default parameters had a larger difference. These resulted in a 16 to 40 percent larger crack length, for the 18.9 liters per minute (5 gpm) leak, when using SQUIRT 2.3 default parameters compared with PICEP or SQUIRT 2.4. The new SQUIRT Version 2.4 statistical default values resulted in crack lengths of 4 to 12 percent larger values than crack lengths calculated using the PICEP default values at the 18.9 liters per minute (5 gpm) leak rate. All of these differences were less for the 1.89 l/min (0.5 gpm) leak.

* Information from Dr. H. Mehta of GE Nuclear Energy Operations.

6.1.2 Evaluation of COD Dependant and Independent Crack Morphology Models for Tight Crack Leak Rate Analyses

The objective of this analysis was to assess the effect of using a COD-dependent crack morphology model to alleviate problems in leak-rate calculations for tight cracks. This analysis was only conducted in a deterministic manner.

One of the major concerns with tight cracks comes from limitations on the friction factor equations used in all leak-rate codes. Experimental data exist over a limited range for these friction factor equations, and extrapolating them to lower values was found to give erroneous numerical solutions. In fact, at low COD values a critical term in the friction-factor equation becomes negative which contributes to the leak-rate going to zero and then increasing again with even smaller COD values. The COD-dependant crack morphology model circumvents the friction-factor problem by increasing the number of turns in the flow path and reducing the surface roughness, i.e., the local roughness is that of a grain boundary for an IGSCC. By doing this, it was found that the COD-dependent crack-morphology model gave leak rates which could be a factor of four below the standard COD-independent crack-morphology models when the friction-factor equation lower limit was reached.

For the case studied, the improved model gave the same results as the standard model for leak rates greater than 7.56 l/min (2 gpm), had some improvement for leak rates from 4.5 to 3.5 l/min (0.93 to 1.2 gpm), and gave very significantly different results for leak rates less than 3.5 l/min (0.93 gpm). These leak rates are within the range of leak rates of interest for LBB analyses, but without the safety factor of 10 used in the NRC SRP 3.6.3. If deterministic calculations are made with the safety factor of 10 on leak rates for LBB analyses, then the current COD-independent models and the COD-dependent model give the same result. If the safety factor is not used in the analyses (i.e., in probabilistic analyses), or much lower leak rates are of interest, then the new COD-dependent crack-morphology model can provide more accurate leak-rate predictions.

6.1.3 Changes of Normal Operating and N+SSE Stress Levels on Failure Probability

LBB analyses could be conducted with either a conservative deterministic analysis, or with a probabilistic analysis. Deterministic LBB analyses typically involve a two-step calculation. First, a flaw size corresponding to a given leak rate (with some safety factor on the leak rate) is determined at the normal operating stresses. The second step is that flaw size is used to calculate if the flaw is stable at the expected SSE loads. In this second step, safety factors may be applied to either the leaking crack length or the SSE loads, and the worst case material properties are used.

There are many variables in an LBB analysis and some of these have some statistical variation. To assess this variability on the likelihood of a failure, probabilistic analyses were conducted. The term conditional probability of failure (CPOF) is frequently used in probabilistic work and means two things. First, there are some important conditions or assumptions in the analysis. For example, in the calculations conducted in this report, it was assumed that an SSE load would occur with a probability of 1.0. The probability of occurrence of an SSE event occurring is a site-specific probability. If this probability is known it could be multiplied times our CPOF value to obtain the failure probability in more absolute terms, i.e., to "decondition" the analysis. Another condition is that the leakage at a given rate would occur and be detected with a probability of 1.0. Subcritical crack growth analyses could be conducted to determine the probability of a leaking crack occurring, and the reliability of the leak detection equipment could be determined. Again, this probability times our CPOF would further "decondition" the analyses. In reality, all probabilistic analyses are conditional or have some inherent assumptions in the deterministic analyses or analysis logic.

The second important aspect of the term CPOF is the meaning of the word failure. The failure criterion in this probabilistic analysis is normal plus SSE stresses equaling or exceeding the maximum load-carrying capacity of the through-wall-cracked pipe. This is consistent with the U.S. NRC LBB analysis procedures. In actuality, if some of these stresses are secondary stresses, it is possible that the cracked pipe may not experience a double-ended guillotine break failure, i.e., there will only be a large leak. Also if the stresses are dynamic and cyclic, the crack may start to grow, but the cyclic loads may decrease fast enough to arrest unstable crack growth. Additionally, the analyses use elastic uncracked pipe stress values, where the presence of the crack and plasticity from the crack may truncate the magnitude of the seismic moments. In the present work, a plasticity correction factor was used to reduce the elastic pipe stresses (Ref. 6.1). All of these considerations could be used to refine the deterministic "failure" analyses and hence to further "decondition" the CPOF values in the analyses. This would make the CPOF values more realistic. Unfortunately, such improvements make the probabilistic model much more complicated than could be undertaken within the scope of this analysis.

With the above limitations on the conditions and definitions of "failure" in mind, the objective of this study was to expand the original probabilistic results from Reference 6.1 to a larger range of normal operating stresses as well as a larger range of N+SSE stresses. This was only a probabilistic study, where the safety factors on leak rate, crack length, and SSE loads were not used because their uncertainties were explicitly modeled by probability distributions. Additionally, these CPOF values were used as baseline values for additional probabilistic analyses where the importance of other technical issues were evaluated in this report.

From the results of the probabilistic analysis of ten different PWR and BWR piping systems, it was found that the normal operating stresses have a more profound effect on the conditional probability of failure than the level of the SSE stresses in the LBB analyses. Any uncertainty in the normal operating stresses can lead to large variations in the predicted conditional probability of failure. The change in the failure probabilities for normal operating stresses from 0.25 to 1.0 of Service Level A limits was 6 to 9 orders of magnitude (depending on the leak rate).

For a fixed normal operating stress, any increase in the N+SSE stress above the ASME Service Level B maximum limits to ASME Service Levels C or D maximum limits will also increase the conditional probability of failure, but these changes in the conditional probability of failure were much smaller (up to 3 orders of magnitude change) than changes due to the normal operating stresses. At first it was expected that the CPOF values of the Service Level D N+SSE stresses should approach 1.0. However, due to the use of actual strengths (rather than Code Strengths) and a correction for plasticity on the elastic stresses, the Service Level D CPOF values were much lower.

One major implication from this work is that the requirement for conducting an LBB analysis may need to be reconsidered. For instance, NRC SRP 3.6.3 for LBB analyses requires the plant operator to "Identify the location(s) at which the highest stresses coincident with the poorest material properties occur..." It was shown that the conditional failure probabilities are the highest when the normal operating stresses are low, and that a location with lower N+SSE stresses and low normal operating stresses would have a higher failure probability than a location with higher normal operating stresses and higher N+SSE stresses. Hence, the LBB criterion needs to be more specific on what stresses are the highest, i.e., either the normal operating stresses or normal plus SSE stresses. Since a crack is more likely to occur with high normal operating stresses, one logical choice is to select the locations with the highest normal operating stresses for LBB analyses.

With regard to the current LBB procedure, it is somewhat counterintuitive to good design practice that one can more readily satisfy LBB if the normal operating stresses are high. Good design practice would like to have low normal operating stresses so that cracking problems do not occur and one would have a safer plant. Yet with the low normal operating stresses, it is difficult to satisfy LBB because for the typical LBB leak rates, the crack size is very large at low normal operating stresses. As a result, satisfying the fracture criterion at normal plus SSE loads is difficult. A basic philosophy difference exists here that is not easy to reconcile.

6.1.4 Dynamic and Cyclic Loads History Effect on Load-Carrying Capacity of Through-Wall-Cracked Pipe for LBB Fracture Analyses

The objective of this effort was to assess the significance of toughness changes due to cyclic and dynamic load effects on LBB fracture load predictions. These dynamic and cyclic effects have been found to affect the toughness of nuclear piping steels in the IPIRG programs. Deterministic and probabilistic analyses were conducted on this technical aspect.

From the deterministic through-wall-cracked pipe analyses, the results show that the predicted effects of cyclic loading using both the LBB.NRC and GE/EPRI J-estimation schemes are more severe than the existing through-wall-cracked cyclic-loaded pipe test data. Additionally, it was found that the Z-factor approach in SRP 3.6.3 would underpredict the maximum loads if the flaw size effects are taken into account in a detailed EPFM analysis, particularly for pipe diameters larger than 254 mm (10 inches).

The results of the probability analyses show that the conditional failure probability will increase when the dynamic and cyclic loading effects are included via correction factors on the fracture toughness. The magnitude of their resultant effect will, however, depend on the values of correction factors, which in turn are strongly dependent on the quasi-static yield-to-ultimate strength ratio. Based on the results of analyses of some specific pipes, the dynamic and cyclic loading rate can affect the prediction of the conditional failure probability for both austenitic and ferritic pipes. Analyses were not conducted for welds, where there may actually be an improvement in the toughness due to the combined effects of dynamic and cyclic loading.

The probabilistic results are consistent with the deterministic calculations, but the existing experimental data suggest the LBB.NRC and GE/EPRI EPFM analyses overpredict the detrimental effects of cyclic and dynamic loading for through-wall-cracked pipes.

6.1.5 Evaluation of the Effect of Off-Centered Cracks for LBB Evaluations

The objective of this investigation was to assess the effect of having a leaking crack off the center of the bending plane at normal operating conditions, but centered on the bending plane for N+SSE loading. Reference 6.1 gives some prior results. These analyses were conducted in both deterministic and probabilistic evaluations.

The deterministic calculations for the effects of off-centered cracks during leakage of 3.8 liters per minute (1 gpm) on the maximum load-carrying capacity for LBB evaluations showed that there was not a very large difference in the crack lengths between on-centered and off-centered cracks for a given leak rate until the center of the crack was more than 50 degrees off the center of the bending plane.

Further deterministic analyses of the change in the maximum load-carrying capacity relative to the centered leaking crack case showed that the maximum load capacity of the off-centered crack (under normal operating conditions) was less than 10 percent lower than the centered crack maximum load when the middle of the off-centered crack was 50-degrees off the bending plane. This 10 percent difference is considered insignificant.

From the probabilistic analysis, it was found that if the center of the crack is allowed to vary randomly by ±90 degrees, then the conditional failure probability increased moderately. The change in the conditional probabilities of failure due to the cracks being centered or off centered was roughly equal to the failure probability change of a centered crack experiencing Service Level D stresses rather than Service Level B stresses. The random crack locations with the center being offset more than 50 degrees caused the change in the conditional failure probabilities.

6.1.6 Evaluation of the Effect of Restraint of Pressure Induced Bending on LBB Evaluations

The objective of this evaluation was to assess the effect of the restraint of induced bending from axial stresses in a pipe system. Typical fracture mechanics analyses assume that the ends of a pipe under pressure loading are free to rotate. However, in a pipe system, the attached piping restrains this rotation. This restraint of pipe rotation at the crack plane has two effects. First, it increases the maximum load-carrying capacity. Second, it reduces the crack-opening displacement for leak-rate analyses. These two restraint effects (leak rate versus failure load changes) compete when conducting an LBB analysis.

Both deterministic and probabilistic analyses were conducted to assess the impact of the restraint of pressure-induced bending. In this analysis, it was assumed that a crack was close to a nozzle. The deterministic results showed that the effects on maximum load were insignificant for large-diameter pipe. However, for small-diameter pipe, the effect was tremendous, i.e., the maximum load under the restrained conditions dropped to 11 percent of the unrestrained maximum load. This comes about because: (1) the short crack length in the large diameter pipe made both the restraint effects on the COD and the restraint effect in increasing the maximum loads negligible, and (2) for the small diameter pipe, the effect of restraint on the COD made the leaking crack length very large but the higher load-carrying capacity for the restraint of pressure induced bending loads offers little compensation for the large crack size. This result is significant in regard to application of LBB to smaller diameter pipe.

The probabilistic calculations involved only a large diameter pipe analysis. These results showed that due to the increase in the failure load, the estimated conditional failure probability for a restrained condition was actually slightly lower. This is consistent with the deterministic calculations. Probabilistic calculations for the small diameter pipe case were not conducted.

6.1.7 Evaluation of the Effect of Residual Stresses on Leak-Rate Analyses for LBB

The objective of this analysis was to assess the effect of weld residual stresses on leak-rate analyses for LBB evaluations. Deterministic and probabilistic analyses were conducted on this topic.

Past work during the Degraded Piping Program on as-welded pipe and solution-annealed welds with identical cracks showed that solution annealing to eliminate residual stresses did not improve the load-carrying capacity, and in fact, the solution annealing lowered the fracture loads (probably because the strength of the weld metal was lowered by the solution annealing). Hence, this past work showed that residual stresses in a low toughness stainless steel SAW did not affect the maximum load-carrying capacity. For the present investigation, the effects of residual stresses was only considered for leaking cracks at normal operating stress levels. Results from this program, including work by Brickstad and Moberg of SAQ from an IPIRG-2 round-robin problem (Ref. 6.2), and other concurrent efforts at Battelle (Ref. 6.3) are summarized.

The deterministic results of the effects of weld residual stresses on LBB showed that weld residual stresses can significantly affect the leak rate for pipes welded with tension-compression residual stress fields through the thickness. This is more likely to occur with thinner pipe and hence smaller diameter pipe. The most significant effect on leak rate seemed to be from the effective shortening of the crack length due to the crack-face rotations pinching off the crack opening at the ends of the flaw. An effective countermeasure to this would be to stress-relieve the welds or hydro test to a high enough level to reduce the residual stress fields. Either of these countermeasures would help to mitigate subcritical crack growth as well, but the high-pressure hydro testing would not lower the weld metal strength giving the pipe a higher load-carrying capacity for fracture resistance.

The probabilistic results accounted for residual stresses only by the rotation of the crack faces. The effect of pinching off of the crack opening at the ends of the crack was neglected until the center of the crack was also closed by the residual stress rotation of the crack faces. The results showed significant effects when the crack opening was completely pinched off for the thinner pipe case, but negligible effects of just having the crack faces rotate. Accounting for the crack being pinched off at the ends would change the probabilistic results.

In summary, the residual stress effects were negligible for the thick pipe case, but were highly significant for the thin [less than 25 mm (1 inch) thick] case. Cases between the thin-wall and thick-wall pipes were not addressed in this limited study.

6.2 Uncertainty Analyses Relative to In-Service Flaw Evaluations

6.2.1 Dynamic and Cyclic Loads History Effect on Load-Carrying Capacity of Surface-Cracked Pipe for In-Service Flaw Evaluations

The objective of this effort was to assess the significance of toughness changes due to cyclic and dynamic load effects on surface-cracked pipe predictions for in-service flaw evaluation. Deterministic and statistical analyses were independently conducted on this technical aspect.

The results of the deterministic calculations for TP304 stainless steel base metal were illustrated by calculating the limit load normalized by the EPFM load as a function of the pipe diameter. The EPFM analysis in this case was the SC.TNP1 analysis which has been found to be the most accurate in predicting experimental maximum loads. This normalized load ratio is equivalent to the ASME Z-factor.

The analyses support the conclusion that failure is essentially a limit-load failure for stainless steel base metal pipes of typical size for nuclear plants under monotonic loading. However, for the cyclic/dynamic loading case, failure loads dropped below the limit load. The results showed that the EPFM load-carrying capacity for surface cracks can be reduced by 20 to 30 percent for stainless steel pipes under cyclic dynamic loading compared to quasi-static loading. This calculated effect was validated with experimental results.

The importance of this finding is that an EPFM analysis (i.e., a Z-factor analysis) for stainless steel pipes under N+SSE loading may be needed, but not for normal operating or operating basis earthquake conditions where the cyclic loads are small. The change in load-carrying capacity under cyclic/dynamic loading is significant for N+SSE loads where the ASME applied safety factor is 1.39, and hence a reduction of 20 to 30 percent in load-carrying capacity erodes that margin considerably.

The statistical results were first evaluated by comparing mean loads with and without the effects of cyclic/dynamic loading on the toughness. These results suggest that the effect of cyclic/dynamic loading on the maximum loads was to reduce the maximum loads by about 4 and 10 percent for A516 Grade 70 and TP304 cases, respectively. Interestingly, from the separate deterministic analysis conducted on the TP304 stainless steel pipe with the same pipe diameter, a reduction in maximum loads of about 20 percent was observed. This appears to be an inconsistency between the deterministic and statistical results, so the initial inputs were carefully examined. The deterministic analyses used a stainless steel pipe that had a lower yield-to-ultimate strength ratio than the average value used in the statistical analysis. Hence, the dynamic/cyclic toughness correction was lower in the deterministic analyses than the mean values from the statistical analyses. Thus, the apparent inconsistency can be explained.

To improve such statistical analysis in the future, the yield-to-ultimate strength ratios need to be statistically modeled (with the proper cross-correlation coefficients) and then used to determine a statistical toughness correction due to cyclic and dynamic effects, rather than keeping the toughness correction as a deterministic constant. This would help to better define reasonable bound on dynamic/cyclic toughness corrections for a class of materials.

Results from the deterministic and statistical analyses show that the effect of the yield-to-ultimate strength ratio is an important parameter in determining the corrections to the toughness and the subsequent effects on the load-carrying capacity. An implication from this is that specifing material with a higher yield-to-ultimate strength would be less susceptible to cyclic degradation. Examples of such materials are low alloy piping steels such as used in German or Japanese PWR piping.

6.2.2 Effect of Uncertainty in UT Flaw Sizing for In-Service Flaw Evaluations

This analysis was conducted to assess the sensitivity of UT flaw sizing variability on the maximum-load capacity of circumferentially surface-cracked pipe. The UT flaw sizing variability data came from 1989 EPRI round-robin results on stainless steel piping. Consistent with the EPRI data, analyses were conducted only on stainless steel pipe, and in particular, they were conducted only for a 28-inch nominal diameter pipe case. This was a statistical analysis where the mean and standard deviations of the UT flaw sizing were varied as a function of flaw depth. Comparisons based on the mean values are described first. The mean value comparison is essentially a deterministic evaluation. Second, comparisons were made involving the standard deviation normalized by the mean value (the coefficient of variance, COV). The COV values are important if a deterministic analysis was to consider using some conservative bound on a mean value to give a higher reliability. Frequently, mean minus one or two standard deviation values are used in bounding deterministic analyses.

The comparison of the mean values of the maximum moments using the UT flaw depth with the moment using the actual flaw depth (deterministic comparisons) showed that the calculated moment accounting for the UT flaw sizing inaccuracy was slightly lower for a/t values of less than 0.35, and then increased for larger a/t values. This trend is consistent with the mean UT flaw depth accuracy trend, i.e., as the flaw depth increases the accuracy gets worse. The magnitude of the moment ratios changes with the flaw a/t, θ/π, and J-estimation scheme used. The SC.TNP1 analysis method, which has been found to give the best agreement with experimental maximum loads, shows that the maximum overprediction of the actual loads range from close to zero percent (for short flaw lengths of any depth) to about 35 percent for the deepest and longest flaw evaluated.

The coefficient of variance (COV) is a measure of the statistical variability of a parameter. If the COV or standard deviation is small, then one might not need to apply a large safety factor to accommodate uncertainty. Conversely, a large COV may make a larger safety factor desirable. Good surface-cracked or through-wall-cracked pipe J-estimation schemes have a COV value around 10 percent for the accuracy of maximum load predictions. The COV values for the UT flaw sizing were found to be 40 to 80 percent, depending on the flaw depth. Shallower flaws had higher COV values than deeper flaws.

A comparison of the COV values from the maximum-load statistical predictions showed that the COV values from the predictions of the maximum loads using the UT flaw sizing variability increase slightly as the flaw depth and lengths became larger. The COV values of the maximum loads due to UT variability were from 11 to 22 percent for the most accurate J-estimation scheme used (the SC.TNP1 analysis). This is a considerably lower COV range than the UT flaw sizing COV of 40 to 80 percent. This reflects some insensitivity in the fracture analyses to flaw depth variability. The larger UT flaw sizing COV was greater for ***shallower*** a/t values. However, the maximum load COV values were greater for ***deep*** and long flaws.

This diverse trend of larger COV values for shallow a/t flaw depths from UT (from the EPRI UT round-robin results) versus the maximum load COV values being larger for deep flaws comes from the fact that the maximum loads are more sensitive to deep flaws than shallow flaws. This is especially true for flaws that are longer. For small flaw lengths, the maximum moments are exceedingly insensitive to crack depth, especially in the Net-Section-Collapse and the SC.TNP1 analyses. Hence, for a short flaw a large variability on flaw depth will result in a small variability on maximum load, and therefore the short flaw maximum loads are more sensitive to material property variations than UT flaw sizing uncertainty.

Results such as these could be used in justifying variable safety margins for UT flaw sizing. For instance, the safety factor need not be as high for shallow flaws even though the COV is highest for them. Similarly, if the flaw length is short, the safety factor could be less than for a long flaw.

6.3 Ranking of Significance of Various Factors Investigated

The significance of the various technical aspects investigated was ranked in importance of how these technical aspects may change results relative to current analysis methodologies. Table 6.1 shows this ranking for both the deterministic and probabilistic results for technical aspects that affect LBB evaluations. Table 6.2 shows this ranking for technical aspects that affect in-service flaw evaluations.

Tables 6.1 and 6.2 also shows a key table number or figure number from the report that was used in establishing the significance of the technical aspect investigated.

These rankings are in the categories of very low, low, medium, high, and very high. An example of a very high ranking is the case of restraint of pressure induced bending on LBB, where for small diameter pipe the difference in the failure loads was a factor of 9 which was much greater than the maximum load safety factor of $\sqrt{2}$ used in LBB analyses. An example of the very low rating is the case of residual stresses on leak-rate analyses for a thick-walled pipe. Here the effects were essentially negligible, except at extremely low operating stresses thought to be lower than practical.

As a final remark, we would like to note that in some cases, it appeared from our initial review that the significance of the deterministic and probabilistic analyses did not agree. Upon further review, however, it was found that most of the deterministic and probabilistic analyses agreed on the significance of a technical aspect. The cases where there were differences in the significance of a technical aspect were found to be due to:

1. The deterministic model being more sophisticated than the model used in the probabilistic analysis. The effect of residual stresses on leak rates was such a case.

2. The material property input not being the same in the deterministic and probabilistic analyses. The effects of cyclic and dynamic loading toughness and load-carrying capacity was such a case.

3. What appeared to be a significant effect over a small range was thought to be less important from a deterministic view, but that same factor gave a major change in conditional failure probabilities. The effect of an off-centered crack on LBB being significant only if the crack was off-centered by more than 50 degrees was such a case.

All of these differences were closely evaluated to make our final ranking.

Table 6.1 Ranking of various technical aspects investigated that affect LBB evaluations

Technical Aspect Investigated	Comments	Significance	Key Table or Figure
Evaluation of different crack morphology default values	For IGSCC	Low	Figure 3.6a
	For corrosion fatigue	Medium	Figure 3.6b
Evaluation of COD dependant and independent crack morphology models for tight crack leak rate analyses	Leak rates > 7.56 l/min (2 gpm)	Low	Figure 3.9a
	3.5 l/min (0.926 gpm) <Leak rate < 4.5 l/min (1.2 gpm)	Medium	Figure 3.9b
	Leak rate < 3.5 l/min (0.926 gpm)	High	Figure 3.9b
Changes of normal operating and N+SSE Stress levels on failure probability	Low normal operating stresses	High	Figures 4.1 - 4.12
	High N+SSE stresses	Medium	Figures 4.1 - 4.12
Dynamic and cyclic loads history effect on load-carrying capacity of through-wall-cracked pipe for LBB fracture analyses	Experimental results show analyses too conservative. (Low cycle fatigue crack growth not evaluated.)	Low	Figure 3.4a
Evaluation of the effect of off-centered cracks for LBB evaluations	Cracks off centered < 50 degrees	Low	Figure 3.11
	Cracks off centered > 50 degrees	Medium	Figure 3.11
	Statistically varying off-center angle	Medium	Figures 4.13 - 4.18
Evaluation of the effect of restraint of pressure induced bending on LBB evaluations	Large diameter	Very low	Table 3.4
	Small diameter	Very High	Table 3.4
Evaluation of the effect of residual stresses on leak-rate analyses for LBB	Thin-walled pipe (i.e., tension to compression stresses through the thickness) at low operating stresses	High to very high	Figure 3.16
	Thin-walled pipe (i.e., tension to compression stresses through the thickness) at high operating stresses	Low	Figure 3.16
	Thick-walled pipe (i.e., tension to compression to tension stresses through the thickness) at typical operating stresses.	Very low	Figure 3.16

Table 6.2 Ranking of various technical aspects investigated that affect in-service flaw evaluations

Technical Aspect Investigated	Comments	Significance	Key Figure
Dynamic and cyclic loads history effect on load-carrying capacity of surface-cracked pipe for in-service flaw evaluations	Low yield-to-ultimate strength materials	Medium	Figure 3.1
	High yield-to-ultimate strength materials	Low	Figures 3.1a - 3.1b
Effect of uncertainty in UT flaw sizing for in-service flaw evaluations	$a/t < 0.25$	Low	Figures 5.6 - 5.7
	$0.25 < a/t < 0.5$	Medium	Figures 5.6 - 5.7
	$a/t > 0.5$	High	Figures 5.6 - 5.7

6.4 References

6.1 Rahman, S., Ghadiali, N., Paul, D., and Wilkowski, G., "Probabilistic Pipe Fracture Evaluations for Leak-Rate Detection Applications," NUREG/CR-6004, April 1995.

6.2 Rahman, S., Olson, R., Rosenfield, A., and Wilkowski, G., "Summary of Results from the IPIRG-2 Round-Robin Analyses," NUREG/CR-6337, January 1996.

6.3 Rahman, S., Dong, P., Wilkowski, G. M., Brickstad, B., Moberg, F., "Effect of Weld Residual Stresses on the Crack-Opening-Area Analysis of Pipes for LBB Applications," *Proceedings of LBB'95 Conference*, Lyon France, October 1995.