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Application of xLPR to Small Diameter Piping Nozzles with Dissimilar Metal Butt Welds Susceptible to Primary Water Stress Corrosion Cracking

Application of xLPR to Small Diameter Piping Nozzles with Dissimilar Metal Butt Welds Susceptible to Primary Water Stress Corrosion Cracking

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ABSTRACT

10CFR50, Appendix A, General Design Criteria 4 (GDC-4) requires that structures, systems, and components important to nuclear power plant safety are protected from the dynamic effects of pipe ruptures unless it can be demonstrated that the probability of rupture is extremely low. To demonstrate low probability of rupture, deterministic leak-before-break (LBB) analysis (based on margins on leak rate and critical flaw size) as described in Standard Review Plan (SRP) 3.6.3 has been used by the nuclear industry in lieu of probabilistic methods. The LBB deterministic margins are generally met for large diameter piping (NPS 10 and greater) using a traditional leak rate detection (LRD) of 1.0 gpm. For smaller diameter piping, it is generally difficult to meet the required margins using LRD of 1.0 gpm, necessitating crediting a lower LRD capability. It becomes even more challenging for smaller diameter piping in the presence of primary water stress corrosion cracking (PWSCC) because the available margin is further reduced due to the PWSCC morphology. An alternative approach is to employ probabilistic methods to determine the probability of rupture as required by GDC-4 and compare it to an appropriate probabilistic acceptance criterion. Recent release of the Extremely Low Probability of Rupture (xLPR) software has made the use of such a probabilistic approach possible.

In this report, a feasibility study was performed using xLPR to investigate whether low probability of rupture can be demonstrated for a typical small diameter piping nozzle with a dissimilar metal (DM) butt weld that is susceptible to PWSCC. This study assumes a small surface crack and grows this crack to determine if rupture occurs and whether by a through-wall crack or a surface crack. Several sensitivity studies were performed to investigate the effects of key input variables on the rupture probabilities.

The study has shown that it is feasible to justify low probability of rupture for small diameter DM welds susceptible to PWSCC. However, the weld residual stress (WRS) distribution used in the evaluation has strong influence on the probability of rupture. The study has also shown the limitations in applying the deterministic LBB approach on a broader basis to small diameter DM welds in the presence of PWSCC because rupture by surface cracks instead of through-wall cracks cannot be summarily dismissed which challenges a fundamental assumption in deterministic LBB with SRP 3.6.3.

Keywords

Deterministic fracture mechanics (DFM)
Extremely Low Probability of Rupture (xLPR) software
Leak-before-break (LBB)
Probabilistic fracture mechanics (PFM)

EXECUTIVE SUMMARY

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KEY RESEARCH QUESTION

Can probabilistic fracture mechanics (PFM) evaluations using the Extremely Low Probability of Rupture (xLPR) software be used to demonstrate an extremely low probability of failure for small diameter piping nozzles with dissimilar metal (DM) butt welds susceptible to primary water stress corrosion cracking (PWSCC)?

RESEARCH OVERVIEW

A representative pressurizer spray line that contains a DM butt weld was considered in this evaluation. Evaluations were performed using the current deterministic approach in NUREG-1061, Vol. 3 and Standard Review Plan (SRP) 3.6.3 followed by a corresponding crack geometry using a PFM approach with xLPR. The PFM evaluations also included sensitivity studies of two different weld residual stress (WRS) distributions. Because most of these PWSCC susceptible welds for small diameter piping have been mitigated by weld overlay (WOL), the effect of this mitigation technique on the probability of rupture was also investigated. Finally, a scenario considering the presence of multiple circumferential flaws that have coalesced to form a long circumferential surface flaw is also investigated for small diameter DM butt welds for several crack lengths ranging from 180° to 270°.

KEY FINDINGS

- The deterministic leak-before-break (LBB) evaluation of small diameter nozzles demonstrated that a very sensitive leak-rate detection (LRD) system is required to meet the SRP 3.6.3 requirement (a factor of 10 on leak rates and a factor of 2 on crack size) whereas using probabilistic evaluations, a low probability of rupture (<1E-06) can be demonstrated with an LRD as high as 5 gpm (probability of rupture, 1.05E-06 for 10 gpm LRD, was slightly higher than acceptance criteria). This demonstrates that deterministic LBB evaluation using SRP 3.6.3 is very conservative for small diameter nozzles.

- The WRS distribution influences the probability of rupture. For an LRD range of 0.1–10 gpm, the probability of rupture per year for one WRS case was on the order of 4.6E-06, which is slightly above the applied acceptance criteria of 1E-06 whereas it is two orders of magnitude lower for another WRS case for an LRD range of 0.1–5 gpm and slightly above the acceptance criteria for 10 gpm (1.05E-06).
- With an initial surface crack as a starting point, ruptures occurred mainly by surface cracks growing in the circumferential direction. Although the overall probability of occurrence was reasonably low, this goes against the assumption of a through-wall flaw in deterministic LBB evaluations. This behavior occurred with both unmitigated WRS distributions considered in the study.
- When mitigated by WOL, the probability of rupture is essentially zero for these small diameter nozzle DM welds regardless of which of the two WRS distributions is used.
- The case of multiple flaws that have coalesced into a long circumferential flaw was also evaluated with various combinations of WRS, LRD, and in-service inspection (ISI). Even with a 270^{o} long circumferential surface crack, when mitigated in combination with LRD and ISI, the probability of rupture is well below the acceptance criteria.

WHY THIS MATTERS

Although several studies were performed for large and intermediate diameter piping, there are relatively small diameter piping systems for which LBB has not been applied because the current deterministic approach requires very low LRD capabilities to meet the required margins in SRP 3.6.3. This study has shown that it is feasible to justify low probability of rupture for small diameter DM welds susceptible to PWSCC using a probabilistic approach with xLPR. However, the WRS distribution used in the evaluation has strong influence on the probability of rupture. Once WOL mitigation has been applied, low probability of rupture can be demonstrated regardless of the original DM weld WRS distribution. The study has also shown the limitations in applying the deterministic LBB approach on a broader basis to small diameter DM welds in the presence of PWSCC, because rupture by surface cracks instead of through-wall cracks cannot be summarily dismissed which challenges a fundamental assumption in deterministic LBB with SRP 3.6.3.

HOW TO APPLY RESULTS

This feasibility study for select small diameter piping demonstrated that the intent of GDC-4 can be met despite the presence of an active degradation mechanism because the calculated probabilities of rupture for these systems are below the proposed acceptance criteria. However, the WRS distribution used in the evaluation has strong influence on the probability of rupture. Moreover, because ruptures by surface cracks appear possible and become dominant at most relevant LRD limits, the deterministic concept of LBB should be cautiously applied to small diameter piping nozzles in the presence of PWSCC. Once mitigated by WOL repair, low probability of rupture can easily be demonstrated regardless of the original DM weld WRS distribution. More studies that include additional small diameter piping nozzles and associated WRS distributions should be performed before general conclusions can be reached.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- The Extremely Low Probability of Rupture (xLPR) Probabilistic Fracture Mechanics Code, Version 2.2 (EPRI 3002023872) was released by EPRI in 2023. This state-of-the-art PFM code models failure probabilities associated with nuclear power plant piping system components subject to active degradation mechanisms.
- Extremely Low Probability of Rupture Version 2 Probabilistic Fracture Mechanics Code (EPRI 3002013307/NUREG-2247).

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IMPLEMENTATION CATEGORY: Reference – Technical Basis

ACRONYMS AND VARIABLES DEFINITIONS

a	flaw depth, mm (in.)
α	power law constant
ASME	American Society of Mechanical Engineers
B&W	Babcock and Wilcox
β	stress intensity factor exponent for crack growth
β_0, β_1	POD model parameters
BWR	boiling water reactor
c	Flaw half length, mm (in.)
CE	Combustion Engineering
CFR	Code of Federal Regulations
DFM	deterministic fracture mechanics
DM	dissimilar metal
EPFM	elastic-plastic fracture mechanics
EPRI	Electric Power Research Institute
FAC	flow-accelerated corrosion
GDC	general design criteria
gpm	gallons per minute (lpm)
ID	inside diameter, mm (in.)
IGSCC	intergranular stress corrosion cracking
ISI	in-service inspection
K	stress intensity factor, MPa√m (ksi√in)
LBB	leak-before-break
LEAPOR	leak analysis of piping – Oak Ridge
LRD	leak rate detection
M_f	limit moment corresponding to fully plastic conditions, N-mm (lbf-ft)
MRP	Materials Reliability Program
MSIP®	mechanical stress improvement process
N	number of realizations
NO	normal operating
NPS	nominal pipe size
NSSS	nuclear steam supply system

OD	outside diameter, mm (in.)
P_f	probability of failure
$P_{f\|TWC}$	conditional probability of failure given a through-wall crack
PFM	probabilistic fracture mechanics
POD	probability of detection
P_{sc}	probability of surface crack rupture
P_{TWC}	probability of a through-wall leaking crack
PWR	pressurized water reactor
PWSCC	primary water stress corrosion cracking
Q_g	thermal activation energy for crack growth, kJ/mol (kcal/mole)
R_m	mean radius, mm (in.)
RVIN	reactor vessel inlet nozzle
RVON	reactor vessel outlet nozzle
SCC	stress corrosion cracking
σ_f	flow stress, MPa (ksi)
SRP	Standard Review Plan
SSE	safe shutdown earthquake
t	thickness, mm (in.)
θ	half through-wall flaw angle, radians
US NRC	United States Nuclear Regulatory Commission
WOL	weld overlay
WRS	weld residual stress
x	crack depth, mm (in.)
xLPR	Extremely Low Probability of Rupture software

CONVERSION FACTORS

Length	1 inch = 25.4 mm = 0.0254 m
Pressure	1 ksi = 1000 psi = 6.895 MPa
Stress intensity factor	1 ksi$\sqrt{\text{in}}$ = 1.0988 MPa$\sqrt{\text{m}}$
Temperature (absolute)	°C = (°F – 32)(5/9)
Temperature (difference)	°C = °F(5/9)
Moment	1 N-mm = 7.4x10^{-4} lbf-ft
Flow	1 gpm = 3.79 liters per minute (lpm)

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1 INTRODUCTION

1.1 Background

10CFR50, Appendix A, General Design Criteria 4 (GDC-4) [1] requires that structures, systems, and components important to nuclear power plant safety are protected from the dynamic effects of pipe ruptures unless it can be demonstrated that the probability of rupture is extremely low. Such analyses are required to be reviewed and approved by the U.S. Nuclear Regulatory Commission (NRC). GDC-4 states:

Environmental and dynamic effects design bases. Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. These structures, systems, and components shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit. ***However, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping.***

GDC-4 requires demonstration of low probability of rupture of the piping system; however, at the time of this regulation, the state of probabilistic fracture mechanics (PFM) was not sufficiently advanced to address this requirement in a probabilistic framework. Consequently, a simple deterministic fracture mechanics analysis known as *leak-before-break (LBB)* was adopted as a substitute to demonstrate the low probability of rupture requirement in GDC-4 by U.S. utilities. Current LBB evaluations apply deterministic fracture mechanics principles to demonstrate that flaws in high-energy fluid systems will grow predominantly in the through-wall direction and leak so that the leakage can be detected by the plant leakage detection system long before the through-wall flaw reaches critical flaw length. To aid in the application of LBB, two documents were published by NRC. The first is NUREG-1061, Volume 3 [2], which provides technical guidelines on the application of LBB; the second is Standard Review Plan (SRP) 3.6.3 [3], which provides the criteria by which the NRC will evaluate LBB submittals. SRP 3.6.3 was first published in 1987 but has gone through two revisions, with the latest in 2007 addressing issues related to primary water stress corrosion cracking (PWSCC), which was identified within relevant piping systems in the early 2000s.

As is typical for a deterministic analysis, the approach in SRP 3.6.3 applies assumptions and margin terms that are generally judged to be rather conservative. To apply LBB, SRP 3.6.3 requires that there should be essentially no degradation mechanisms present in the piping system that can cause a flaw to develop in the first place. As such, systems susceptible to degradation mechanisms such as stress corrosion cracking (SCC), water hammer, flow-accelerated corrosion (FAC), or cleavage are excluded from LBB applications. Initially, large diameter piping in the main loop of pressurized water reactors (PWRs) were thought to be free of these mechanisms and, therefore, LBB was applied to these systems and approved by the U.S. NRC. To date, LBB has not been applied to BWRs because of concerns with SCC in the stainless steel recirculation piping. To apply LBB, a factor of 10 is required to be applied on the leakage detection limit of the plant because of uncertainties in the analytical models for leak rate determination. Furthermore, it is required that a margin of two exist between the through-wall critical flaw length and the leakage flaw length. The critical flaw length is the through-wall flaw length that results in rupture, and the leakage flaw length is the through-wall flaw length that produces a particular leakage flow rate. The leakage flaw size is determined using normal operating (NO) stresses while the critical flaw size is determined using the NO stresses plus safe shutdown earthquake (SSE) stresses. A traditional leakage detection limit of 1.0 gallon per minute (gpm) has often been used in the determination of the leakage flaw sizes in LBB evaluations. The factors of 10 on leakage and 2 on the critical flaw size–to–leakage flaw size, although appearing to be reasonably conservative, have no formal technical basis.

Following the identification of PWSCC in PWR dissimilar metal (DM) piping butt welds in the early 2000s, the technical bases for LBB submittals for PWRs with Alloy 82/182 welds were called into question because such a degradation mechanism is not permitted for the application of LBB. These are typically DM butt welds in nozzle-to-safe-end or nozzle-to-piping welds in PWRs. Although an evaluation performed in MRP-140 [4] indicated that despite the presence of PWSCC, LBB margins for most DM welds were maintained for large diameter piping (12-inch and greater) and that the issue was not an immediate concern, a more robust and comprehensive approach was needed to address the GDC-4 requirements. As such, in 2009, the NRC Office of Regulatory Research and EPRI signed a memorandum of understanding [5] to develop a PFM approach to demonstrate the low probability of rupture requirement in GDC-4 even in the presence of PWSCC. This led to the Extremely Low Probability of Rupture (xLPR) program [6, 7], publicly released in 2020. After several years of subsequent collaborative xLPR application effort between EPRI and NRC, the NRC Office of Regulatory Research issued two reports detailing evaluation of the probability of rupture of PWSCC-susceptible DM butt welds representative of the U.S. PWR fleet in lines previously approved for LBB by the NRC [8, 9]. In the first report, reactor vessel outlet nozzle (RVON) and reactor vessel inlet nozzle (RVIN) DM welds of a Westinghouse four-loop plant were evaluated [8]. In the second report, the remaining piping systems that have been currently approved for LBB encompassing plants of all three U.S. PWR nuclear steam supply system (NSSS) vendors (Westinghouse, Combustion Engineering [CE], and Babcock and Wilcox [B&W]) were evaluated [9]. The evaluations indicated that for these relatively large line sizes, the probability of rupture is indeed extremely low and therefore meets the intent of GDC-4. However, it is important to note that this represents a research conclusion and, as of this writing, a formal regulatory position is still pending.

However, there are relatively small diameter piping systems for which LBB has not been applied because the current deterministic approach requires very low leak rate detection (LRD) capabilities to meet the required margins in SRP 3.6.3. In a recent study [10], LBB margins were determined for small diameter stainless steel piping (Sch. 160) for a range of NPS 2 to 12 using the deterministic LBB procedure described in SRP 3.6.3. It was reported that when applying the SRP 3.6.3 margin of 10 on leakage, the traditional LRD limit of 1.0 gpm can be met for NPS 10 and above. The 1.0 gpm leak detection limit can also be met for NPS 8 and NPS 6 piping under certain stress combination conditions. However, for NPS 4 and below, the traditional 1.0 gpm leak detection limit cannot be met, and a lower LRD limit is necessary to meet the LBB margin of 2.0. Since NPS 8 lines are less common, the focus of this report will be on NPS 6 and smaller lines. To apply LBB to NPS 6 and smaller lines and meet SRP 3.6.3 margins, a lower LRD limit must be applied and may be justified with the current PWR leak detection programs. However, an alternative is to apply a probabilistic approach using a software tool such as xLPR to determine the probability of rupture with various LRD limits.

1.2 Objective

The objective of this report is to present the findings of feasibility studies for a small diameter piping nozzle with a DM butt weld susceptible to PWSCC involving both deterministic LBB using the SRP 3.6.3 approach and probabilistic methods using xLPR to determine whether LBB behavior can be demonstrated for these nozzles. To achieve this objective, the report is organized as follows:

- Section 2 presents the basic elements of deterministic and probabilistic LBB.
- Section 3 discusses the selection of the small diameter DM nozzle weld used in the feasibility study as well as other relevant input parameters used in the deterministic and probabilistic LBB evaluations.
- In Section 4, deterministic LBB evaluation using the SRP 3.6.3 method is presented to provide benchmark results for comparison with the probabilistic results.
- In Section 5, probabilistic evaluations using xLPR are presented. The effect of the through-wall weld residual stress (WRS) distribution associated with the fabrication of the DM weld was investigated through a sensitivity study involving two different WRS distributions. Because most of these PWSCC-susceptible welds for small diameter piping have been mitigated by weld overlay (WOL), the effect of this mitigation technique on the probability of rupture was also investigated. Finally, a scenario considering the presence of multiple circumferential flaws that have coalesced to form a long circumferential surface flaw is also investigated for small diameter DM butt welds for several initial crack lengths ranging from 180^o to 270^o.
- Section 6 provides a summary and conclusions from the feasibility study as well as recommendations for future work.
- References used throughout the report are provided in Section 7.

An abridged summary of this work was originally published in the following ASME paper: “Application of Leak-Before-Break to Small Diameter Piping Nozzles With Dissimilar Metal Butt Welds Susceptible to PWSCC Using xLPR,” by Nat Cofie, Dilip Dedhia, Gary Dominguez, Mo Uddin, Craig Harrington, Nate Glunt, and Do Jun Shim, Paper No: PVP2022-86180 [29].

2 ELEMENTS OF DETERMINISTIC AND PROBABILISTIC LBB

2.1 Elements of Deterministic LBB

The basic assumption in LBB is that when a flaw develops in a fluid piping system, it will grow in the through-thickness direction and become a through-wall crack before growing around the circumference. Under such a scenario, the plant's leak detection system will be able to detect the crack long before it reaches the critical through-wall crack length. Therefore, for LBB evaluations, the leak detection system is essential. Relevant leak detection guidance, independent from LBB considerations, has been provided by the NRC in Regulatory Guide 1.45 [11] so that the systems are reliable, diverse, and sensitive and therefore also support LBB. The framework for performing deterministic LBB is provided in SRP 3.6.3 [3] and NUREG-1061, Volume 3 [2]. The essential elements are as follows:

- Address the limitations imposed in Section 5.1 of NUREG-1061, Vol. 3 on the use of LBB for high-energy piping. LBB is not considered applicable to systems if operating experience indicates particular susceptibility to failure from the effects of corrosion (for example, intergranular stress corrosion cracking [IGSCC] or FAC), water hammer, or low and high cycle (that is, thermal, mechanical) fatigue.
- Determine loads and stresses. The loads to be used in LBB evaluations include normal operating loads (pressure, dead weight, and thermal) for leakage determination and normal plus safe shutdown earthquake (SSE) loads for critical flaw size determination.
- Determine material properties to be used in the LBB evaluation. Key material properties include stress-strain curve parameters and material toughness for elastic-plastic fracture mechanics (EPFM) evaluations. For limit load analysis, the important material property is the flow stress (average of yield and ultimate stress). Specific requirements for determination of the material properties are provided in NUREG-1061, Vol. 3.
- Determine critical flaw size based on fracture mechanics using either the EPFM J-integral/tearing modulus approach or net section collapse (limit load) analyses. The critical flaw size is the flaw size at which failure or instability occurs based on the applied loading.
- Determine the flaw size that will result in a particular leakage rate (usually 1 gpm with a margin of 10 applied according to NUREG-1061, Vol. 3), referred to as the *leakage flaw size*.
- Determine the margin between the critical flaw size and the leakage flaw size. NUREG-1061, Vol. 3 recommends a margin of two between the critical flaw size and the leakage flaw size.
- There is an additional requirement of margin in loads so that if the algebraic summation method is used to combine the loads, the critical crack size based on a factor of $\sqrt{2}$ on loads must exceed the leakage flaw size. The factor of $\sqrt{2}$ can be reduced to 1.0 if faulted loads are combined by the absolute summation method [2].

- LBB for the piping system is demonstrated if adequate margin exists between the leakage flaw size and the critical flaw size and if there is an adequate inspection interval to supplement the LBB evaluation.
- Demonstrating that the piping system is not subject to mechanisms that can cause flaw initiation and growth provides defense in depth for showing extremely low probability of rupture using a deterministic approach. Although fatigue was generally considered as a potential degradation mechanism for subcritical crack growth evaluations, following the identification of PWSCC in PWR DM piping butt welds, PWSCC is considered a potential degradation mechanism in the present study.

2.2 Elements of Probabilistic LBB

In the present study, PFM evaluations were performed using xLPR software version 2.1 [12]. Development of the xLPR methodology and the corresponding software tool involved many challenging technical decisions, modeling judgments, and sensitivity analyses. This program has been described extensively elsewhere [6, 7, 8, 9, 13]; therefore, it is only briefly summarized herein. Version 2.1 of xLPR was developed under a Software Quality Assurance Program [14] that fulfills the software work practice requirements of ASME NQA-1-2008 (including Addenda 2009) Quality Assurance Requirements for Nuclear Facility Applications, Part I Requirements 3 and 11 and Part II Subpart 2.7 [15].

Unlike the deterministic approach in which conservative input values are used, with predetermined margins to perform crack stability evaluations, a probabilistic approach uses statistical distributions of the input variables to determine the probability of failure and other relevant quantities of interest. The xLPR software embodies the full range of physical phenomena necessary to evaluate both fatigue and PWSCC degradation modes from crack initiation through failure. These models are implemented in a modular form and linked by a probabilistic framework that contains the execution logic, exercises the individual modules as required, and performs necessary administrative and bookkeeping functions. A high-level flowchart for xLPR Version 2.1 is shown in Figure 1.

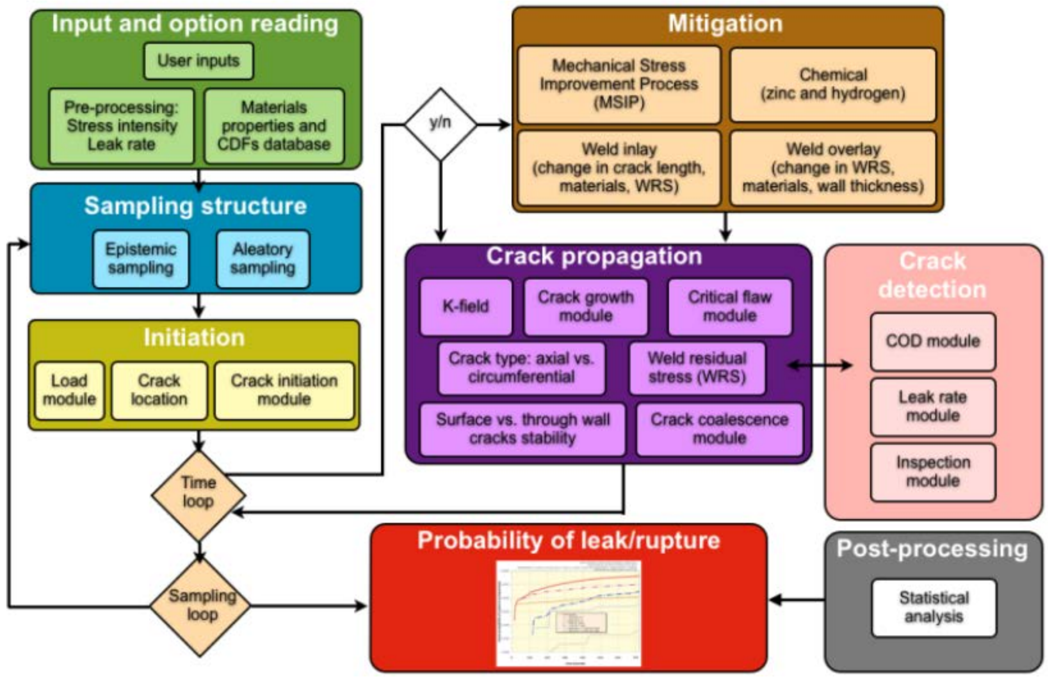

Figure 1. High-Level xLPR Version 2.1 Flowchart

As indicated in the flowchart, the program can also address several mitigation techniques such as mechanical stress improvement process (MSIP®) and weld overlay (WOL) that have been used by industry to mitigate PWSCC.

2.2.1 Sampling Method and Treatment of Uncertainties

Monte Carlo simulation is used in the PFM evaluations to compute failure probabilities in xLPR. In the Monte Carlo simulation, many variables may be treated as random with statistical distributions selected based on prior knowledge (such as normal, log-normal, Weibull, exponential, and so on). A realization in the simulation involves one deterministic evaluation in which the important variables have been randomly selected. Many realizations (possibly in the millions) are performed to develop the statistical distribution of the outcome from which the probability of failure is determined.

Characterization of the contribution of uncertainty to the results is essential for performing Monte Carlo simulation. Uncertainty is broadly categorized in two ways—the result of either inherent randomness or incomplete knowledge. Uncertainty that results from random scatter in nature is termed *aleatory* uncertainty. In this case, the probability of obtaining each outcome can be measured or estimated, but the precise outcome in any particular instance is not known in advance. Like a scenario such as rolling dice, obtaining more data will not help reduce the variability. Uncertainty resulting from a lack of knowledge is termed *epistemic* uncertainty. Unlike aleatory uncertainty, gathering more data can be helpful in reducing epistemic variability.

Within xLPR, inputs can generally be designated as constants or uncertain, with the latter represented as distributions. Uncertain inputs may be further classified by the user as either aleatory or epistemic. The software is structured so that the sampling of these two types of uncertainties is performed by two nested loops, as shown in Figure 2. The epistemic uncertainty is sampled in the outer loop and, for each epistemic realization, a user-specified number of aleatory samples is performed in the inner loop. Therefore, the total sample size is equal to the epistemic sample size multiplied by the aleatory sample size. This separation of uncertainty types can be leveraged to inform decisions, such as to initiate additional materials testing to reduce epistemic uncertainties in materials properties determined to control aspects of a problem. However, in this present work, such understandings are not the focus and thus uncertainty separation would unnecessarily add computational complexity. Therefore, for the analyses presented herein, all random inputs were set as epistemic with a single-loop aleatory realization, and the number of epistemic realizations varied from 400,000 to 800,000. In addition, sensitivity studies were performed on the key inputs.

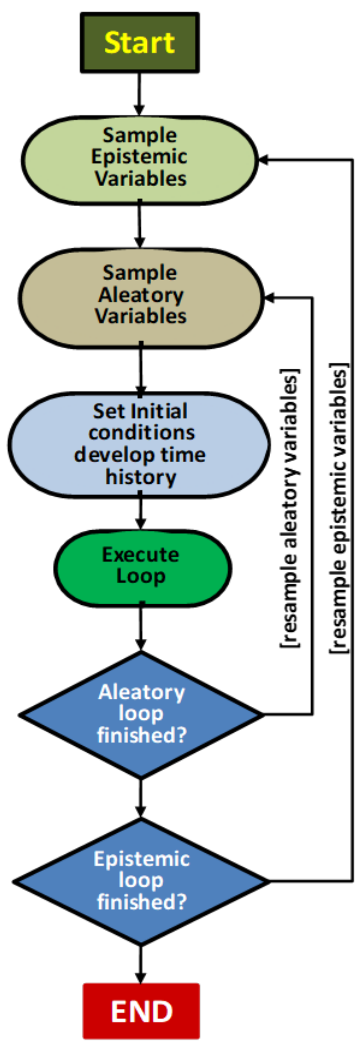

Figure 2. Schematic of the xLPR Code Looping Structures Used to Appropriately Account for Epistemic and Aleatory Uncertainties

2.2.2 Degradation Mechanisms

PWSCC is the only degradation mechanism considered in the present study. Fatigue crack initiation and growth were not considered because the crack growth would be dominated by PWSCC in the DM butt welds.

The PFM evaluations assumed a pre-existing single PWSCC flaw in the DM butt welds with no additional initiation during the evaluation period. Although it could be more realistic to include initiation, only pre-existing flaws were used because the purpose of this work is to investigate LBB behavior, which in the deterministic approach assumes the presence of a through-wall flaw. Therefore, in the PFM evaluations, a statistical distribution of initial flaw sizes at the beginning of evaluation is used along with in-service inspections at specified intervals.

2.2.3 Flaw Orientations

In this study, only circumferential flaws are considered. This is because in many deterministic LBB evaluations, it has been established that circumferential flaws are more limiting than axial flaws [10].

2.2.4 Mitigations and Leak Detection

Application of MSIP® or WOL changes the original DM weld through-wall residual stress distribution (typically tensile on the inner half of the thickness) to a more favorable state (typically compressive on the inner half of thickness) to mitigate PWSCC. In this evaluation, because most of these PWSCC-susceptible welds for small diameter piping have been mitigated by WOL, the mitigating effects of only WOL on the resulting probability of rupture are considered.

As discussed in Section 1.1, for small diameter piping, leak rate detection (LRD) lower than the traditional 1.0 gpm may be required. In this study, LRD in the range of 0.1 to 10 gpm is considered.

2.2.5 Number of Realizations

The outcome of a Monte Carlo simulation is itself a random variable. To accurately define the answer, many trials with many failures are required. Even with high failure probabilities, the confidence interval on the "answer" may be wide. This is referred to as *error associated with sample size* in Section 5.2.5 of Reference [16]. The percent error is estimated as:

$$\%\ \text{Error} = 200\sqrt{\frac{1-p_f}{N\times p_f}} \qquad \text{Eq. 1}$$

where,

N is the number of realizations

p_f is the probability of failure.

There is a 95% chance that the error in the estimated probability will be less than that given in Equation 1.

In the current work, up to 800,000 realizations were used for the PFM evaluations for circumferential flaws. The lowest probability of rupture to meet 1E-06 after 80 years would be 8E-05, and the estimated error for 800,000 realizations using Equation 1 would be 25%.

2.2.6 Calculation of Leak and Rupture Probabilities

From the PFM evaluations, probabilities of leak and rupture (per year) were calculated. In xLPR, *leak* is defined as when a surface flaw transitions to a through-wall flaw (at crack depth of 95% of wall thickness according to the crack transition module in xLPR) and *rupture* is defined as when the flaw becomes unstable.

3 DETERMINISTIC AND PROBABILISTIC INPUT PARAMETERS

3.1 Selection of Small Diameter Nozzle

A typical inventory of small diameter piping systems found in the plants of the three U.S. NSSS vendors is shown in Table 1. Typical dimensions of the DM welds for the nozzles of these piping systems are shown in Table 2. As shown, these piping systems range from NPS 1.5 to NPS 6. Common among all the NSSS vendors are the pressurizer safety and relief nozzles. These are not connected to any primary system piping and therefore are of little interest from an LBB perspective. The safety injection systems for the Westinghouse plants are stainless steel piping, which does not typically contain DM welds. For the CE plants, the safety injection lines typically contain a DM weld. For this study, the pressurizer spray line—which falls in the middle of the dimensions of the piping systems shown in Table 2 and typically contains a DM weld—was selected. Because of a limitation of pipe thickness-to-diameter ratio in xPLR, dimensions close to the Plant E spray nozzle were selected as given by the row “xPLR” in Table 2. The pressurizer spray line is also at high temperature connected directly to the pressurizer. Therefore, relatively higher PWSCC crack growth would be expected.

Table 1. Inventory of small diameter lines/components in PWR fleet

B&W Plants	CE Plants	Westinghouse Plants
1.5" Drain Lines 2.5" Letdown/Drain Lines 2.5" HPI/Makeup 2.5" Spray Line Safety/Relief Valves	2" Drain Lines 2" Letdown Lines 2" Charging Lines 3" Spray Line 6" Safety Injection Line Safety/Relief Valves	1.5" Boron Injection Lines 2" Drain Lines 3" Letdown/Drain Lines 3" Charging Lines 4" Pressurizer Spray Line 6" Safety Injection Lines Safety/Relief Valves

Table 2. Dimensions of small diameter DM welds in PWRs

Plant	Component	OD in. (mm)	ID in. (mm)	Thickness in. (mm)
A	Safety Valve Nozzle	5.25 (133.4)	3 (76.2)	1.125 (28.6)
B	Relief Nozzle	5.25 (133.4)	3 (76.2)	1.125 (28.6)
B	2½ inch Pressurizer Relief Nozzle	4.5 (114.3)	2.5 (63.5)	1.0 (25.4)
C	Safety/Relief Valve Nozzle	4.5 (114.3)	2.5 (63.5)	1.0 (25.4)
D	Spray Nozzle	5.146 (130.7)	3.625 (92.1)	0.761 (19.3)
D	Safety Valve Nozzle	6.812 (173.0)	5.554 (141.1)	0.629 (16.0)
E	Spray Nozzle	5.32 (135.1)	3.44 (87.4)	0.94 (23.9)
xLPR	Spray Nozzle	5.64 (143.3)	3.76 (95.5)	0.94 (23.9)
E	Safety Valve Nozzle	8 (203.1)	4.937 (125.4)	1.532 (38.9)

3.2 Details on Input Parameters

Table 3 summarizes the constant and random inputs that are used in the deterministic and probabilistic LBB evaluations in this report. Details on each of these input variables are provided in subsequent subsections.

Table 3. Input variables and type

Variable	Variable Type
Pipe Dimensions	Constant
Weld Width	Constant
Piping Stresses	Constant
Weld Residual Stresses	Random
Operating Temperature	Constant
Material Properties	Random
Number of Flaws	Constant
Initial Flaw Size Distribution	Random
PWSCC Growth Rate	Random
Hydrogen Concentration	Constant
POD Curves	Random
ISI	Constant

3.2.1 Pipe Dimension and Material Properties

The dimensions of the selected spray nozzle are highlighted in Table 2 with an outer diameter of 5.64 in. (143.3 mm) and a thickness of 0.94 in. (23.9 mm).

Material properties such as yield strength, ultimate strength, and elastic modulus are obtained from the material library of xLPR Ver. 2.1 [12] as shown in Table 4.

Table 4. Material properties

Material Property	Dist.	Probabilistic Parameters						Deterministic Parameters
		Alloy 82/182 (Weld)		SA-508 CS (Left Pipe)		316 SS (Right Pipe)		Weld Center
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	-
Yield Strength, MPa (ksi)	Log-normal	316.5 (45.9)	55.0 (8.0)	399 (57.9)	68 (9.9)	197.1 (28.6)	54 (7.8)	277.8 (40.3)
Ultimate Strength, MPa (ksi)	Log-normal	543.4 (78.8)	26.8 (3.9)	629 (91.2)	38 (5.5)	440.4 (63.9)	67 (9.7)	515.6 (74.8)
Elastic Modulus, MPa (ksi)	Normal	196,800 (28,542)	29,520 (4,281)	174,960 (25,376)	26244 (3,806)	176,670 (25,624)	26,490 (3,842)	175,944 (25,518)

3.2.2 Normal Operating Conditions and Stresses

Typical normal operating pressure and temperature for these nozzles are 15.5 MPa (2250 psig) and 326.7°C (620°F), respectively. Consistent with SRP 3.6.3, for leak rate calculation, the normal operating loads consisting of pressure, deadweight, and thermal expansion stresses are used. To assess stability, SSE is added to the normal operating loads. The loads for these small diameter nozzles are taken from a plant-specific CE pressurizer spray nozzle, and the corresponding stresses are shown in Table 5.

Table 5. Load types and stresses

Load	Type	Stress, MPa (ksi)
Internal Pressure	Membrane	23.27 (3.38)
Crack Face Pressure[1]	Membrane	15.51 (2.25)
Deadweight	Membrane	-0.35 (-0.05)
	Bending	1.47 (0.21)
Thermal Expansion	Membrane	-0.14 (-0.02)
	Bending	7.55 (1.1)
SSE	Membrane	0.30 (0.04)
	Bending	35.99 (5.22)

[1] Crack face pressure is conservatively assumed to be equal to the operating pressure.

3.2.3 Weld Residual Stresses

Most PWSCC flaws found in DM butt welds have been at locations of high tensile residual stresses near the wetted surface. Such stresses are typically a result of either the weld joint geometry or in-process weld repairs, especially weld repairs of the inside diameter surface. Because WRS is widely recognized as a significant factor in the occurrence of PWSCC, the choice of WRS distribution for the evaluation is a key component of the analysis. In addition, many of these PWSCC-susceptible welds have been mitigated by stress improvement techniques—therefore, selection of a representative WRS distribution for mitigated welds is equally important.

3.2.3.1 Unmitigated Welds

Two WRS distributions are considered as shown in Figure 3. The first distribution (black line) was derived from that included in MRP-106 for the 5-in. safety relief nozzle [17], which was developed by modeling the original dissimilar metal weld followed by a 25% depth OD weld repair. The second distribution (red line) corresponds to a plant-specific weld residual stress analysis of the CE-plant spray nozzle that involved simulating the original dissimilar metal weld, followed by a 50% depth pre-service ID weld repair. The trend of both WRS distributions is similar except that the plant-specific one has higher tensile stresses at the inside surface of the pipe. Both distributions are considered in this study to provide additional insight into the role of WRS on failure probabilities.

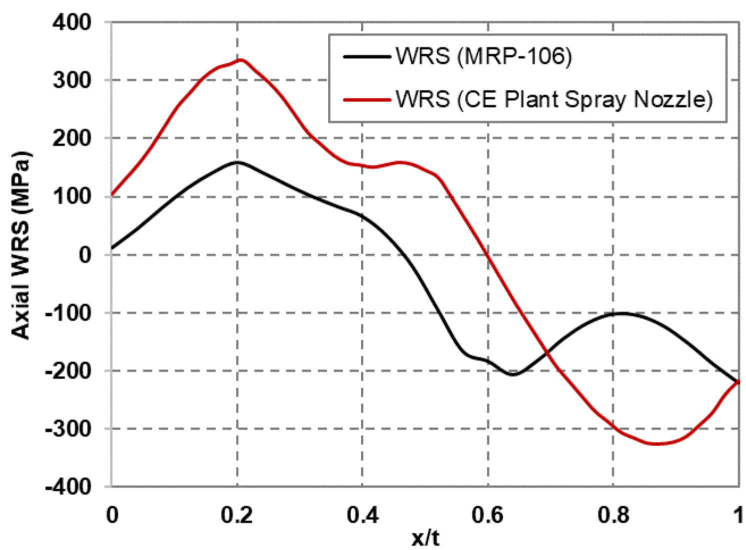

Figure 3. Unmitigated axial WRS distribution

3.2.3.2 Mitigated Welds

Stress mitigation is applied to slow the growth of PWSCC by creating more favorable compressive weld residual stresses near the inside surface of the pipe. Two types of mitigation have typically been applied to PWSCC-susceptible welds in PWRs: the mechanical stress improvement process (MSIP®) and WOL. Although MSIP® is typically applied on larger diameter piping DM welds, the more commonly applied stress mitigation technique for small diameter DM welds is WOL.

To that end, two WRS distributions reflecting WOL mitigation are considered as shown in Figure 4. WOL-WRS-1 corresponds to an earlier generation weld residual stress analysis in which the original dissimilar metal weld was not simulated. Rather, the analysis started with a stress-free state, and a pre-service repair weld of 50% thickness was simulated in the evaluation followed by a WOL. WOL-WRS-2 corresponds to a later generation residual stress analysis, which involved simulation of the original dissimilar metal weld followed by a 50% pre-service weld repair and then the WOL. As can be seen in Figure 4, both processes resulted in desirable compressive residual stress on the inner half of the DM butt weld although the distributions are different. The outer half where the distribution resulted in tensile stresses are very similar. Both distributions are considered in this evaluation.

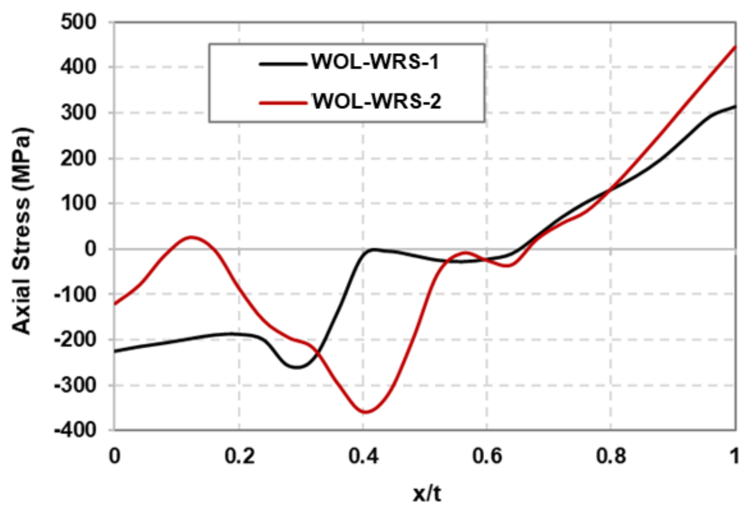

Figure 4. Mitigated axial WRS distribution

3.2.4 Initial Flaw Size Distribution

The initial crack size distribution parameters are obtained from Section 2.4.3 of Reference [18]. For crack depth, a lognormal distribution with a median of 1.5 mm (0.059 in.), a ln(σ) of 0.35, and a lower truncation limit of 0.5 mm (0.02 in.) are used. For crack length (2c), a lognormal distribution with a median of 4.8 mm (0.189 in.) and a ln(σ) of 0.8 are used. The parameters are shown in Table 6.

Table 6. Initial flaw size distribution input

Global ID	Property Name	Unit	Data Source*	Distribution Type	Median	Shape Parameter	Min. Cutoff	Max. Cutoff
1210	Initial Flaw Full-Length (Circ)	m	Epistemic	LOGNORM	0.0048	2.226	-	-
1212	Initial Flaw Depth (Circ)	m	Epistemic	LOGNORM	0.0015	1.419	0.0005	0.0635

3.2.5 PWSCC Growth Rate

For this study, the crack growth rate data of MRP-115 [19] are used as shown in Table 7. A more recent reassessment of crack growth rate data for Alloy 82/182—including additional test results—has been published in MRP-420, Revision 1 [20] that generally showed a reduced crack growth rate. However, for this current study, the crack growth rate data of MRP-115 are used to be consistent with previous studies [8, 9]. Using crack growth rate data from MRP-115 would provide conservative results compared to those using data from MRP-420.

Table 7. xLPR input for MRP-115 PWSCC crack growth rate

Property Name	Unit	Data Source	Deterministic Value	Distribution	Mean (Normal) or Median (Log Normal)	Std. Deviation (Normal) or Shape Parameter (Log Normal)
Power Law Constant, α	(m/s) $(MPa\text{-}m^{0.5})^{\beta}$	Constant	2.01E-12	DISCRETE	-	-
Power Law Exponent, β		Constant	1.6	DISCRETE	-	-
SIF Threshold, K_{th}	$MPa\text{-}m^{0.5}$	Constant	0	DISCRETE	-	-
Activation Energy, Q_g	kJ/mol	Aleatory	104	NORMAL	104	20
Comp-to-Comp Variable Factor, f_{comp}		Aleatory	1	LOGNORM	1	1.632
Within-Comp Variable Factor, f_{flaw}		Aleatory	1	LOGNORM	1	1.454
Peak-to-Valley ECP Ratio - 1, P-1		Aleatory	91.84	LOGNORM	91.8	15.64
Charact Width of Peak vs ECP, c	mV	Aleatory	18.2	NORMAL	18.2	5.5
Factor of Improvement, IF		Constant	1	DISCRETE	-	-
Reference Temperature	°C	Constant	325	DISCRETE	-	-

3.2.6 Inspection Scenarios

The inspection schedules for DM welds provided in ASME Section XI Code Case N-770-7 [21] are different for mitigated and unmitigated welds. However, for comparison purposes, a typical ASME Section XI inspection schedule of one inspection in every 10 years is used in all analyses in this study.

3.2.7 POD Curves

Simulating the inspection of welds requires a model for probability of detection (POD) of a flaw during examination of the weld. The model for POD in xLPR is the logistic model, which expresses the probability of detection of an existing flaw of size *x* as follows:

$$\mathrm{POD}(x) = \frac{e^{\beta_0+\beta_1 x}}{1+e^{\beta_0+\beta_1 x}} \quad \text{Eq. 2}$$

where *x* is the crack depth normalized by the wall thickness (a/t).

The parameters β_0 and β_1 are obtained from the xLPR User's Manual [12] in E.12-2. These are summarized in Table 8.

Table 8. Summary of POD Parameters for Circumferential Crack

Category	β_0	β_1	$\sigma\beta_0$	$\sigma\beta_1$	$\rho(\beta_0, \beta_1)$
Small Diameter Pipe Nozzle (102–152 mm)	2.69	0	0.09	0	0

3.2.8 Leak Rate Detection

Leak rate detection (LRD) plays an important role in LBB. In the deterministic LBB evaluation according to SRP 3.6.3, LRD of 1.0 gpm is typically used, consistent with most licensee Technical Specification requirements that allow for up to 1 gpm of unidentified leakage. For small diameter stainless steel piping in the range of NPS 4 to NPS 6, it was shown in Reference [10] that an LRD range of 0.1 gpm to 0.5 gpm is required to meet the SRP 3.6.3 LBB margin of 2.0 with a factor of 10 on leakage crack size. It is relevant to note that a few plants have been able to justify a leak detection limit as low as 0.25 gpm, which allowed them to qualify NPS 6 stainless steel piping for LBB [22, 23] using the deterministic SRP 3.6.3 approach. As has been stated in NRC Regulatory Guide 1.45, Revision 1 [11], "Since the 1970s, improvements have occurred in the available instruments and methods for monitoring leakage, as well as in the overall understanding of the capabilities of those instruments and methods. Plants have used leakage monitoring methods that can detect flow rates lower than 0.05 gal/min (0.19 L/min)." To assess sensitivity to this parameter, an LRD range of 0.1 gpm to 10 gpm is considered in this study.

4 DETERMINISTIC LBB EVALUATION USING SRP 3.6.3

Although the focus of this report is on the application of a probabilistic approach to demonstrate LBB behavior in small diameter nozzle DM welds, a deterministic LBB analysis using the SRP 3.6.3 approach is presented in this section to provide a benchmark comparison. To apply LBB according to SRP 3.6.3, a factor of 10 is required to be applied on the LRD limit of the plant to account for uncertainties in the analytical models for leak rate prediction through cracks. Furthermore, it is required that a margin of two exist between the through-wall critical flaw length and the leakage flaw length. The critical flaw length is the through-wall flaw length that results in rupture, and the leakage flaw length is the through-wall flaw length that produces leakage at the LRD detection limit with a factor of 10. The leakage flaw size is determined using normal operating (NO) stresses; the critical flaw size is determined using the NO stresses plus safe shutdown earthquake (SSE) stresses. The traditional LRD limit of 1.0 gallon per minute (gpm) applied in the determination of the leakage flaw size in LBB evaluations—when compounded by the prescribed factor of 10—leads to an evaluated leakage of 10 gpm in deterministic LBB evaluations.

Using the SRP 3.6.3 procedure, the critical through-wall crack lengths and leakage flaw lengths and the corresponding LBB margins were determined using the input parameters such as pipe dimension, material properties (Table 4), and stresses (Table 5) discussed previously.

Limit load analysis was used to determine the critical through-wall flaw length using Equation A-13 provided in Appendix A of NUREG-1061, Vol. 3 [2] as given by:

$$M_f = 4\sigma_f {R_m}^2 t \left(cos\gamma - \frac{1}{2} sin\theta\right) \qquad \text{Eq. 3}$$

where:

M_f = the limit moment corresponding to fully plastic conditions, N-mm
R_m = mean radius, mm
t = pipe thickness, mm
θ = half through-wall flaw angle, radians
σ_f = flow stress, MPa

$$\gamma = \frac{\theta}{2} + \left(\frac{\pi}{2}\right)\frac{\text{Axial Load}}{2\pi R_m \sigma_f t} \qquad \text{Eq. 4}$$

The critical through-wall flaw length is found to be 198 mm (53% of the circumference).

To determine the leakage flaw sizes, the crack opening displacement was calculated using the formulations in References [24] and [25], and the leakage flaw sizes were determined using the software program LEAPOR [26] developed under the xLPR program. The leak rate as a function of crack length is shown in Figure 5. The leakage at the critical crack length is 15 gpm; however, it is only 0.7 gpm at half critical length.

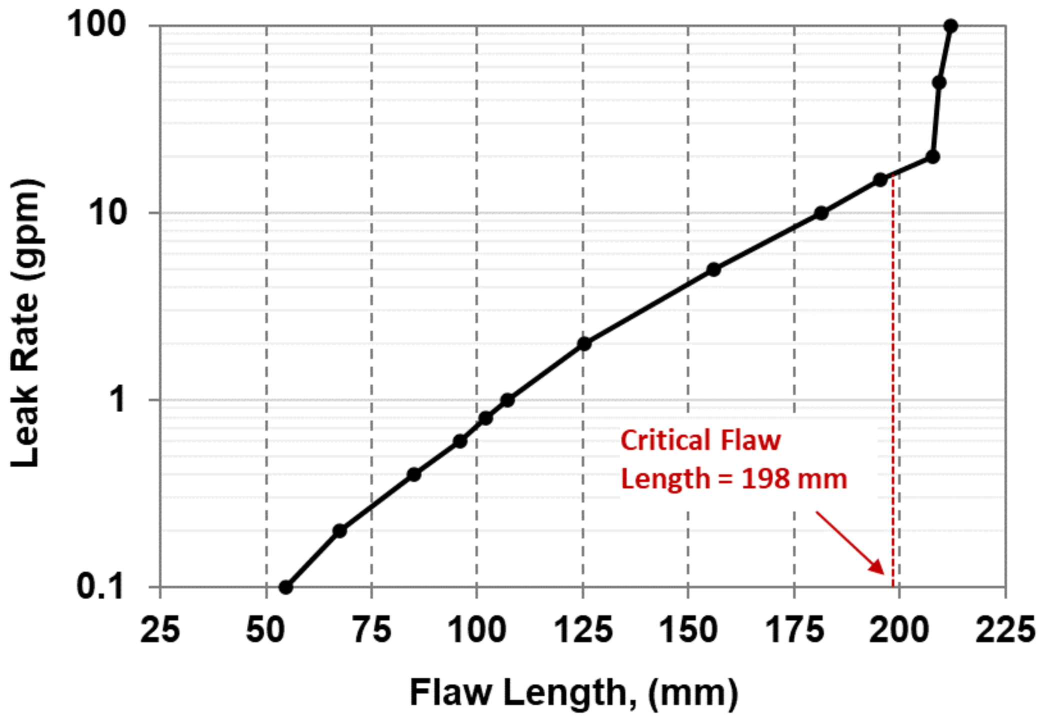

Figure 5. Leak rate vs. flaw length

The LBB margin is determined by calculating the ratio of the critical through-wall flaw length to the leakage flaw length. A summary of margins at various LRDs is shown in Table 9 and Figure 6. With a traditional LRD of 1.0 gpm (that is, evaluated leak rate of 10 gpm), this small diameter nozzle does not meet the criteria (a factor of 2.0)—but it meets the criteria when LRD threshold is reduced to 0.07 gpm (that is, evaluated leak rate of 0.7 gpm). Therefore, although the deterministic LBB approach using SRP 3.6.3 can be applied to small diameter nozzle DM welds, it requires a significantly lower LRD capability (in this case, 0.07 gpm) compared to the traditional LRD of 1.0 gpm that has been typically used in deterministic LBB evaluations.

Table 9. Deterministic LBB margins at various LRDs

LRD (gpm)	Evaluated Leak Rate (gpm)	Deterministic LBB Margin
1	10.0	1.1
0.1	1.0	1.9
0.07	0.7	2.0
0.01	0.1	3.6

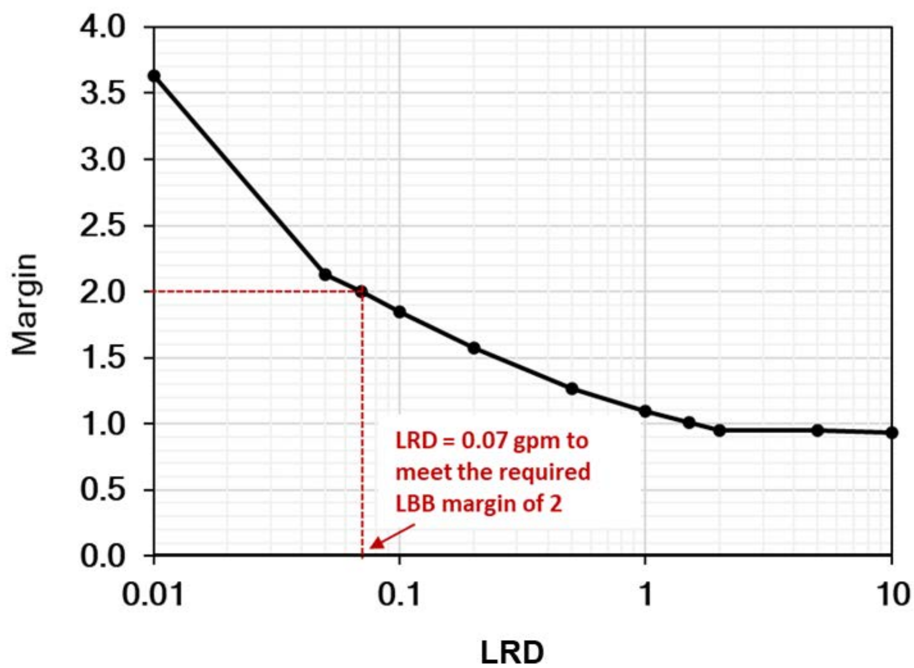

Figure 6. Variation of LBB margin with LRD (SRP 3.6.3 approach)

5 PROBABILISTIC EVALUATION USING xLPR

Because the deterministic LBB approach using SRP 3.6.3 requires a significantly lower LRD capability for small diameter nozzle DM welds, an alternative approach would be to apply a probabilistic LBB approach such as xLPR to small diameter nozzle DM welds to investigate the LRD limit at which, without a factor of 10 on LRD, an extremely low probability of failure can be obtained for these welds. As such, an LRD range of 0.1 gpm to 10 gpm is considered in this study. Use of the xLPR approach also provides the opportunity to investigate the effects of several input parameters such as a surface flaw, WRS distributions from fabrication of the original DM butt weld, and WRS resulting from application of mitigation techniques such as WOL. These are typically not considered in the deterministic LBB approach in which a through-wall flaw is assumed.

To that end, probabilistic evaluations using xLPR were performed for the selected pressurizer spray piping nozzle to determine the probability of failure for various LRD values. Additional sensitivity studies were performed that include the two different WRS distributions, long coalesced circumferential surface cracks, and PWSCC mitigation. Very long circumferential cracks that may cause surface crack ruptures and escape leak detection may grow from a single initiation or develop when multiple cracks coalesce. To gain additional insights into the probability of occurrence for the latter, evaluations on several crack lengths ranging from 180^o to 270^o were performed. Because most of these PWSCC-susceptible welds for small diameter piping actually in-service had been mitigated by WOL, the effect of mitigation on the probability of rupture was also investigated.

5.1 Acceptance Criterion for Probabilistic Evaluation

The acceptance criterion recommended by the Acceptance Group of the xLPR project for a probabilistic analysis of an individual plant is that the total failure frequency of all exempted, high-energy piping welds susceptible to PWSCC within all environmental zones that contain safe shutdown equipment shall be less than 1E-06 failures per year. Actions that result in absolute plant piping failure frequencies less than 1E-06 failures per year would be permissible [27]. This was used by the NRC Office of Regulatory Research as the acceptance criterion in the evaluations documented in References [8, 9] and is likewise used in this study.

5.2 Probabilistic Approach Using xLPR

The purpose of determining the probability of failure of a postulated through-wall crack is that it is reasonably analogous to the SRP 3.6.3 approach, which assumes the non-mechanistic presence of a critical through-wall flaw. To determine the probability of failure for such a flaw, one might simulate a through-wall flaw in xLPR and then grow that flaw to an LRD limit and then on to rupture. However, greater insights can be obtained by starting with a surface flaw, growing it to a through-wall flaw, and then determining the probability of occurrence of reaching a given LRD limit or of rupture. In this case, the probability of rupture for a through-wall flaw can be determined from the relationship:

$$P_f = P_{TWC} \times P_{f|TWC} + P_{SC} \quad \text{Eq. 5}$$

where:

P_f is the probability of failure

P_{sc} is the probability of surface crack rupture

P_{TWC} is the probability of a through-wall leaking crack

$P_{f|TWC}$ is the conditional probability of failure given a through-wall crack

Using Equation 5, simulations involving a surface flaw grown to a through-wall flaw (defined by a given detectable leakage rate) and then to rupture can be used to calculate the conditional probability of a failure ($P_{f|TWC}$). All the cases with surface flaws that result in through-wall flaws can be used to determine the parameter (P_{TWC}) at various selected leakage rates. The parameters P_f and P_{sc} are determined from the number of total ruptures and number of only surface crack ruptures, respectively.

5.2.1 Case Studies

5.2.1.1 Single Flaw

A single surface flaw is assumed for the analysis, which can grow either predominantly in the length direction to remain as a long surface flaw or in the depth direction to become a transitioning through-wall flaw and eventually to an idealized through-wall flaw of some length. This represents a more realistic case compared to the simple SRP 3.6.3 assumption of a through-wall flaw; however, the results from this case can also be used to determine the probability of failure of a postulated through-wall flaw (using Equation 5).

First, simulations were performed for this case using the unmitigated WRS distributions shown in Figure 3. Each xLPR run directly provides the following:

- Probability of leak (probability of through-wall flaw) (P_{TWC})
- Probability of rupture with LRD (P_f)
- Probability of surface crack rupture (P_{sc})

Using xLPR, simulations were performed with 800,000 realizations for various LRDs ranging from 0.1 gpm to 10 gpm for the two unmitigated WRS distributions discussed in Section 3.2.3.1 (shown in Figure 3). The results are summarized in Table 10 and Table 11. As seen in these tables, rupture was mainly by surface cracks for the MRP-106 WRS distribution for the entire range of LRD; for the CE Spray Nozzle WRS distribution case, rupture was mainly by surface cracks for LRD of 1–5 gpm range (only one rupture in 800,000 realizations)—but it was mainly by through-wall crack rupture for LRD of 10 gpm. The cumulative probability of surface crack rupture for the CE Spray Nozzle WRS case is about two orders of magnitude lower than the

MRP-106 WRS case. This is because virtually all consequential cracks grow through-wall for the CE Spray Nozzle WRS (P_{TWC} = 0.999), and the leaks are detected—preventing through-wall ruptures. The probability of leak for the MRP-106 WRS case is low (0.631), leading to higher surface crack ruptures. The reason for higher surface crack ruptures for the MRP-106 WRS case is described later in this section.

Although LRD does not affect the probability of surface crack ruptures, it does affect the probability of rupture with the presence of through-wall cracks. For the LRD range of 1 gpm to 5 gpm, all leaks were detected, leading to zero through-wall crack ruptures for both WRS distributions—all failures were by surface crack rupture. Therefore, the total probability of rupture remained the same over the LRD range of 1 gpm to 5 gpm. However, at 10 gpm LRD, all leaks were not detected prior to rupture; therefore, the failures were due to a combination of surface and through-wall crack ruptures for both WRS distributions, even though the magnitudes were different. For example, in the CE Spray Nozzle WRS case (Table 11), there was only one surface crack rupture with 66 through-wall crack ruptures in 80 years compared to 281 surface crack and 18 through-wall crack ruptures for the MRP-106 case (Table 10).

On a per-year basis, the probability of rupture for the MRP-106 WRS distribution for LRDs between 0.1 gpm and 10 gpm is on the order of 4E-06, which is slightly higher than the acceptance criteria of 1E-06. However, the probability of rupture per year for the CE spray nozzle for LRDs between 0.1 gpm and 5 gpm is on the order of 1.5E-08 (which is two orders of magnitude below the acceptance criteria) and 1.05E-6 for 10 gpm (which is slightly higher than the acceptance criteria). This confirms the influence of WRS distribution on the analysis for this small pipe diameter nozzle. Nevertheless, even in the case of the MRP-106 WRS distribution, the probability of rupture is very close to the acceptance criteria—which demonstrates the low probability of rupture for the small piping nozzle DM welds.

However, when compared with the results from deterministic LBB evaluation (Section 4.0), an LRD of 0.07 gpm is required to meet the SRP 3.6.3 requirement (a factor of 10 on leak rates and a factor of 2 on crack sizes) whereas using probabilistic evaluations, a low probability of rupture (<1E-06) can be demonstrated with an LRD as high as 5 gpm (probability of rupture, 1.05E-06 for 10 gpm LRD, was slightly higher than acceptance criteria). This demonstrates that deterministic LBB evaluation using SRP 3.6.3 is very conservative for small diameter nozzles. Moreover, because ruptures by surface cracks appear possible and become dominant at most relevant LRD limits, the deterministic concept of LBB should be cautiously applied to small diameter piping nozzles in the presence of PWSCC. Through-wall crack ruptures tend to occur only when the LRD is high and as a result, leaks are allowed to grow to high rates (10 gpm) before detection is credited—corresponding to through-wall crack lengths approaching the critical flaw length. However, ruptures by surface cracks are still occurring at these high LRDs.

Table 10. xLPR results from 800,000 realizations with MRP-106 WRS distribution

LRD (gpm)	Cumulative Probability of Leak after 80 Years. P_{TWC}	Cumulative Probability of Rupture After 80 Years, P_f (Cumulative Number of Ruptures)	Cumulative Probability of Surface Crack Rupture After 80 Years, P_{sc} (Cumulative Number of Ruptures)	Cumulative Conditional Probability of Rupture After 80 Years, $P_{f\|TWC}$ (Cumulative Number of Ruptures)	Probability of Rupture per Year (Number of Ruptures)	Conditional Probability of Rupture per Year (Number of Ruptures)
0.1	0.631	3.33E-04 (266)	3.33E-04 (266)	N/A	4.16E-06 (3)	N/A
1	0.631	3.33E-04 (266)	3.33E-04 (266)	N/A	4.16E-06 (3)	N/A
5	0.631	3.51E-04 (281)	3.51E-04 (281)	N/A	4.39E-06 (4)	N/A
10	0.631	3.74E-04 (299)	3.51E-04 (281)	3.65E-05 (29)	4.68E-06 (4)	4.56E-07 (<1)

Table 11. xLPR results from 800,000 realizations with CE spray nozzle WRS distribution

LRD (gpm)	Cumulative Probability of Leak after 80 Years. P_{TWC}	Cumulative Probability of Rupture After 80 Years, P_f (Cumulative Number of Ruptures)	Cumulative Probability of Surface Crack Rupture After 80 Years, P_{sc} (Cumulative Number of Ruptures)	Cumulative Conditional Probability of Rupture After 80 Years, $P_{f\|TWC}$ (Cumulative Number of Ruptures)	Probability of Rupture per Year (Number of Ruptures)	Conditional Probability of Rupture per Year (Number of Ruptures)
0.1	0.999	1.25E-06 (1)	1.25E-06 (1)	N/A	1.56E-08 (0)	N/A
1	0.999	1.25E-06 (1)	1.25E-06 (1)	N/A	1.56E-08 (0)	N/A
5	0.999	1.25E-06 (1)	1.25E-06 (1)	N/A	1.56E-08 (0)	N/A
10	0.999	8.37E-05 (67)	1.25E-06 (1)	8.25E-05 (66)	1.05E-06 (1)	1.03E-06 (1)

For the small diameter nozzle considered in this study, a representative case of surface crack rupture was further investigated to understand the reasons for which such behavior might occur. Figure 7 shows the stress intensity factor (K) distribution for the two WRS distributions as a function of wall thickness. Only WRS loadings are applied in these cases. The K at both the deepest point and the surface of the semi-elliptical flaw are plotted. Overall, the K values are lower for the MRP-106 WRS case, which explains the lower leak probabilities (P_{TWC} = 0.631) compared to the CE Spray Nozzle WRS case (P_{TWC} = 0.999). On the other hand, the cumulative rupture probabilities are higher for the MRP-106 case, mainly because of surface crack ruptures. In the case of the CE Spray Nozzle WRS, virtually all consequential cracks grow through-wall, and the leaks are detected—preventing through-wall ruptures. For the MRP-106 WRS, the K at the deepest point goes negative, either slowing down or arresting the cracks depending on the loading configuration. However, the K at the surface point is always positive, which will continue to grow the surface length of the crack, eventually leading to surface crack ruptures. However, for higher LRD (for example, 10 gpm), cracks are allowed to grow before detection occurs, which leads to through-wall crack ruptures for both WRS distributions. These observations suggest that both the magnitude and the distribution of WRS play a key role in determining this behavior of surface crack ruptures vs. through-wall crack ruptures.

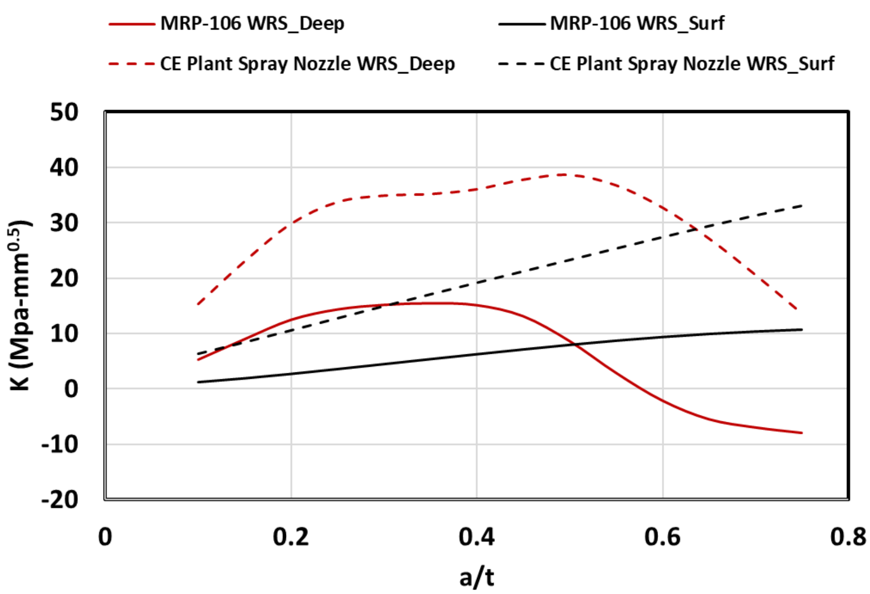

Figure 7. Stress intensity factor distribution for MRP-106 and CE spray nozzle WRS distributions

5.2.1.2 Single Flaw with Mitigation

Because most of the small diameter nozzle DM welds have been mitigated, using a mitigated WRS distribution would represent a more realistic probabilistic evaluation case for these welds. The preferred stress mitigation technique for the small diameter piping is typically WOL, and the two post-weld overlay WRS distributions considered in this study are shown in Figure 4. For all LRD cases, no ruptures involving a single crack were observed in 800,000 realizations when WOL had been applied.

5.2.1.3 Multiple and Long Circumferential Flaws

The evaluations described so far considered the case of a single circumferential flaw. The case of multiple crack initiation sites resulting in multiple circumferential flaws was also investigated. Rather than treating this case as multiple individual flaws, a conservative case was considered in which all the flaws coalesced to form one long circumferential flaw. This scenario is therefore investigated for several initial crack lengths ranging from a 180° to 270° flaw. The effects of mitigation and in-service inspection are also considered with these cracking configurations. The results of the evaluation are summarized in Table 12.

Table 12. xLPR results from 400,000 realizations for very long circumferential cracks with 0.1–1.0 gpm LRD

Case	WRS (Mitigated or Unmitigated)	Cumulative Probability of Leak After 80 Years, P_{TWC}	Cumulative Probability of Rupture with LRD After 80 Years, $P_{f\|LRD}$ (Cumulative No. of Ruptures)	Cumulative Probability of Surface Crack Rupture with LRD After 80 Years with LRD, P_{sc} (Cumulative No. of Ruptures)	Cumulative Probability of Rupture with LRD and ISI After 80 Years, $P_{f\|LRD-ISI}$ (Cumulative No. of Ruptures)	Probability of Rupture per Year with LRD (Cumulative No. of Ruptures)	Probability of Surface Crack Rupture with LRD per Year (Cumulative No. of Ruptures)	Probability of Rupture per Year with LRD and ISI After 80 Years (Cumulative No. of Ruptures)
MRP-106 WRS 180° Flaw	Unmitigated	0.91	8.75E-04 (350)	8.75E-04 (350)	4.15E-05 (17)	1.09 E-05 (4)	1.09E-05 (4)	5.19E-07 (~0)
CE Spray Noz WRS 180° Flaw	Unmitigated	1	0	0	0	0	0	0
WOL WRS-1 (1) 180° Flaw	Mitigated	0	0	0	0	0	0	0
WOL WRS-2 (1) 180° Flaw	Mitigated	2.5E-06	0	0	0	0	0	0
WOL WRS-2 (1) 270° Flaw	Mitigated	0	2.50E-06 (1)	2.50E-06 (1)	2.02E-13 (~0)	3.13E-08 (~0)	3.13E-08 (~0)	2.53E-15 (~0)

With LRD of 0.1–1.0 gpm and a 180° crack for 400,000 realizations, failures were by surface crack ruptures for the MRP-106 WRS whereas there was no failure for the CE Spray Nozzle WRS. This is consistent with the single surface flaw case in which the CE Spray Nozzle WRS and K distributions caused all cracks to grow through-wall (P_{TWC} = 1), leading to no surface crack rupture—and the leaks were detected by LRD before rupture. However, the MRP-106 WRS and K distributions caused some cracks to form very long surface cracks (P_{TWC} = 0.91), leading to surface crack rupture before detection by LRD. There was no through-wall crack rupture for either WRS distribution. It is also important to note that the results remain the same over the entire range of 0.1 gpm to 1.0 gpm LRD. This is because all leaks for 180° cracks were greater than 1 gpm, which were all detected by 0.1–1.0 gpm LRD. Another observation is that with ISI, the four total ruptures observed for 0.1–1.0 gpm LRD decreased to zero total ruptures.

When mitigation by WOL is applied, the probability of having a leaking crack and probability of through-wall and surface crack ruptures are zero (or close to zero) for a 180° flaw. Even for a 270° flaw, the probability of rupture per year with LRD only is 3.1E-08 and decreases to 2.5E-15 with LRD and ISI.

6 SUMMARY AND CONCLUSIONS

A feasibility study has been presented in this report to investigate the application of both deterministic and probabilistic LBB evaluations to small diameter piping nozzle DM welds susceptible to PWSCC. The deterministic LBB evaluations were performed according to the requirements of SRP 3.6.3; the probabilistic evaluations were performed using the xLPR program. Typical deterministic and probabilistic inputs were used in the evaluation. The probabilistic evaluations considered a single initial surface crack as well as the case of multiple cracks that are assumed to have coalesced to form one long circumferential crack. Two unmitigated WRS distributions were considered (MRP-106 WRS distribution and a plant-specific CE Spray Nozzle WRS distribution). The effect of mitigation by WOL was also addressed by considering two different WOL WRS distributions. A summary of this feasibility study is also presented in Reference [29].

From this study, the following observations are noted:

- The deterministic LBB evaluation of a representative small diameter nozzle demonstrated that an LRD of 0.07 gpm is required to meet the SRP 3.6.3 requirement (a factor of 10 on leak rates and a factor of 2 on crack sizes). This LRD is extremely low compared to the traditional LRD of 1.0 gpm typically used in LBB evaluations. Although the sensitivity to leak detection has increased over time at plants, it is believed that this LRD limit will pose some challenges to plants in demonstrating LBB using the deterministic approach. However, using probabilistic evaluations with xLPR, a low probability of rupture (<1E-06) can be demonstrated (for CE spray nozzle WRS case) with an LRD as high as 5 gpm (probability of rupture, 1.05E-06 for 10 gpm LRD, was slightly higher than acceptance criteria). This demonstrates that deterministic LBB evaluation using SRP 3.6.3 is very conservative for small diameter nozzle DM welds.
- In the probabilistic approach using xLPR, the WRS distribution influences the probability of rupture. For an LRD range of 0.1 gpm to 10 gpm, the probability of rupture per year for the MRP-106 WRS case was on the order of 4.6E-06, which is above the applied acceptance criteria of 1E-06—whereas it is two orders of magnitude lower (1.5E-08) for the CE Spray Nozzle WRS for an LRD range of 0.1 gpm to 5 gpm and slightly above the acceptance criteria for 10 gpm (1.05E-06). Therefore, the WRS distribution has a considerable effect in promoting surface crack rupture and thus there should be a strong technical basis for WRS distributions selected for a given analysis.
- With an initial surface crack as a starting point, ruptures occurred mainly by surface cracks growing in the circumferential direction. Although the overall probability of occurrence was reasonably low, this goes against the assumption of a through-wall flaw in deterministic LBB evaluations. This behavior occurred with either of the unmitigated WRS distributions considered in the study.
- When mitigated by WOL, the probability of rupture is essentially zero for these small diameter nozzle DM welds, regardless of which of the two WRS distributions is used.

Therefore, a potential way to demonstrate LBB for these small nozzle DM welds is to apply WOL mitigation.

- The case of multiple flaws that have coalesced into a long circumferential flaw was also evaluated with various combinations of WRS, LRD, and ISI. Even with a 270^{o} long circumferential surface crack, when mitigated in combination with LRD and ISI, the probability of rupture is well below the acceptance criteria.

This study has shown that it is feasible to justify low probability of rupture for small diameter DM welds susceptible to PWSCC using a probabilistic approach with xLPR. However, without mitigation, the WRS distribution used in the evaluation has strong influence on the probability of rupture. The study has also shown the limitations in applying the deterministic LBB approach on a broader basis to small diameter DM welds in the presence of PWSCC, because rupture by surface cracks instead of through-wall cracks cannot be summarily dismissed which challenges a fundamental assumption in deterministic LBB with SRP 3.6.3.

More studies that include additional small diameter piping nozzle DM welds and associated WRS distributions should be performed before general conclusions can be reached. WRS distributions presented in MRP-216 Rev. 1 [28] for some small diameter nozzle DM welds can be used as a starting point for continued studies to determine the effects of WRS distributions.

This study considered PWSCC as the active degradation mechanism. It is also recommended as future work that additional studies be performed to determine whether the same observations can be made with fatigue crack growth as the degradation mechanism.

7 REFERENCES

1. U. S. Nuclear Regulatory Commission, 10 CFR Part 50, General Design Criterion 4, "Modification of Requirements for Protection Against Dynamic Effects of Postulated Pipe Rupture," Federal Register, Vol. 52, No. 207, October 27, 1987.
2. NUREG-1061, Volume 3, "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee – Evaluation of Potential for Pipe Breaks," prepared by the Piping Review Committee, NRC, November 1984.
3. U.S. Nuclear Regulatory Commission; Standard Revision Plan; Office of Nuclear Reactor Regulation, "Section 3.6.3, Leak-Before-Break Evaluation Procedure," NUREG-0800, August 2007.
4. *Materials Reliability Program: Leak-Before-Break Evaluation for PWR Alloy 82/182 Welds (MRP-140)*. EPRI, Palo Alto, CA: 2005. 1011808.
5. NRC and EPRI, "Addendum to Memorandum of Understanding between U.S. Nuclear Regulatory Commission and Electric Power Research Institute on Cooperative Nuclear Safety Research—Extremely Low Probability of Rupture (xLPR)." October 22, 2009.
6. *Extremely Low Probability of Rupture Version 2 Probabilistic Fracture Mechanics Code*. EPRI, Palo Alto, CA: 2021. 3002013307.
7. NUREG-2247, "Extremely Low Probability of Rupture Version 2 Probabilistic Fracture Mechanics Code," U.S. Nuclear Regulatory Commission, August 2021, ADAMS Accession No. ML21225A736.
8. C. J. Sallaberry, R. Kurth, E. Kurth-Twombly, and F. W. Brust, "Probabilistic Leak-Before-Break Evaluation of a Westinghouse Four-Loop Pressurized-Water Reactor Primary Coolant Loop Piping using the Extremely Low Probability of Rupture Code," U.S. NRC Technical Letter Report TLR-RES/DE/REB-2021-09, August 13, 2021, ADAMS Accession Number ML21217A088.
9. C. J. Sallaberry, R. Kurth, E. Kurth-Twombly, and F. W. Brust, "Probabilistic Leak-Before-Break Evaluations of Pressurized Water Reactor Piping Systems Using the Extremely Low Probability of Rupture Code," U.S. NRC Technical Letter Report TLR-RES/DE/REB-2021-14-R1, April 2022, ADAMS Accession Number ML22088A006.
10. N. G. Cofie, D. Dedhia, and D. Shim, "Application of Leak-Before-Break to Small Diameter Stainless Steel Piping in PWRs," PVP2021-62368, Proceedings of the ASME 2021 Pressure Vessels and Piping Conference, PVP2021, July 13–15, 2021, Virtual.
11. U.S. NRC Regulatory Guide 1.45, "Guidance on Monitoring and Responding to Reactor Coolant System Leakage," Revision 1, May 2008.
12. User Manual for xLPR Version 2.1, xLPR-UM-2.1, Version 1.0, May 2020.

13. NRC, NUREG-2110, “xLPR Pilot Study Report,” May 2012, ADAMS Accession No. ML12145A470.
14. xLPR-SQAP, “xLPR Software Quality Assurance Plan,” Version 5.0, September 2014.
15. ASME NQA-1a-2009, “Addenda to ASME NQA-1-2008, Quality Assurance Requirements for Nuclear Facility Applications, relative to software (Part I, Requirements 3 and 11 and Part II, Subpart 2.7).”
16. A. H-S. Ang and W. H. Tang, Probability Concepts in Engineering and Design, Vol. II: Decision, Risk and Reliability, John Wiley & Sons, 1984.
17. *Materials Reliability Program: Welding Residual and Operating Stresses in PWR Alloy 182 Butt Welds (MRP-106).* EPRI, Palo Alto, CA: 2004. 1009378.
18. xLPR-SRD-CI-SCC, xLPR Software Requirements Description for Crack Initiation - PWSCC, Version 3.1, March 2014.
19. *Materials Reliability Program: Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82/182 and 132 Welds (MRP-115)*, EPRI, Palo Alto, CA: 2004. 1006696.
20. *Materials Reliability Program: Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials and Alloy 82, 182, and 132 Welds (MRP-420, Revision 1)*. EPRI, Palo Alto, CA: 2018. 3002014244.
21. ASME Boiler and Pressure Vessel Code Case N-770-7, “Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated With UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities,” Section XI, Division 1, Approval Date: December 4, 2020.
22. Letter from G. S. Vissing (USNRC) to R. C. Mecredy (Rochester Gas and Electric Corporation), “Staff Review of the Submittal by Rochester Gas and Electric Company to Apply Leak-Before-Break Status to Portions of the R. E. Ginna Nuclear Power Plant Residual Heat Removal System Piping (TAC No. MA0389),” February 25, 1999.
23. Letter from J. G. Lamb (USNRC) to T. Coutu (Nuclear management Company, LLC), “Kewaunee Nuclear Power Plant – Review of Leak-Before-Break Evaluation for Residual Heat Removal, Accumulator Injection Line and Safety Injection System (TAC No. MB 1301),” September 5, 2002.
24. M. L. Benson, B. A. Young, D. J. Shim, and F. W. Brust, “Crack Opening Displacement Model for Through-Wall Axial Cracks in Cylinders,” PVP2013-98008, Proceedings of the ASME 2013 Pressure Vessels and Piping Conference, PVP2013, July 14–18, 2013, Paris, France.
25. B. A. Young, R. J. Olson, and M. Kerr, “Advances in COD Equations: Circumferential Through-Wall Cracks,” PVP2012-78181, Proceedings of the ASME 2012 Pressure Vessels and Piping Conference, PVP2012, July 15–19, 2012, Toronto, Ontario, Canada.

26. P. T. Williams, B. R. Bass, T. L. Dickson, and H. B. Lasky, "LEAPOR – A Computer Code for Leakage-Rate Calculations for Cracks in Cooling Water Piping Systems." PVP2017-65263, Proceedings of the ASME 2017 Pressure Vessels and Piping Conference, July 16–20, 2017, Waikoloa, Hawaii, USA.

27. Letter from B. E. Thomas (U.S. NRC) to J. W. Lubinski (U.S. NRC), Acceptance Criteria to Use with xLPR Code, Version 2.0, dated November 7, 2016, ADAMS Accession Number ML16271A436.

28. *Materials Reliability Program: Advanced FEA Evaluation of Growth of Postulated Circumferential PWSCC Flaws in Pressurizer Nozzle Dissimilar Metal Welds (MRP-216, Rev. 1): Evaluations Specific to Nine Subject Plants.* EPRI, Palo Alto, CA: 2007. 1015400.

29. N. Cofie, D. Dedhia, G. Dominguez, M. Uddin, C. Harrington, N. Glunt, and D. J. Shim, "Application of Leak-Before-Break to Small Diameter Piping Nozzles with Dissimilar Metal Butt Welds Susceptible to PWSCC Using xLPR," PVP2022-86180, Proceedings of the ASME 2022 Pressure Vessels and Piping Conference, July 17–22, 2022, Las Vegas, NV, USA.

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