2024 TECHNICAL REPORT

Materials Reliability Program: xLPR Estimation of PWR Loss-of-Coolant Accident Frequencies (MRP-480)

PREPARED UNDER THE NUCLEAR QA PROGRAM

Materials Reliability Program: xLPR Estimation of PWR Loss-of-Coolant Accident Frequencies (MRP-480)

3002023895

Final Report, February 2024

EPRI Project Manager
N. Glunt

All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

YES ✓ NO

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Dominion Engineering, Inc.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Together…Shaping the Future of Energy®

ACKNOWLEDGMENTS

The following organization, under contract to EPRI, prepared this report:

Dominion Engineering, Inc.
12100 Sunrise Valley Drive, Suite 220
Reston, VA 20191

Principal Investigators
M. Burkardt
G. Schmidt

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Materials Reliability Program: xLPR Estimation of PWR Loss-of-Coolant Accident Frequencies (MRP-480). EPRI, Palo Alto, CA: 2024. 3002023895.

ABSTRACT

The nuclear power industry is performing research and development through EPRI to investigate the acceptability of increasing nuclear fuel burnup limits to 75 GWd/MTU peak rod average burnup. The research addresses the potential for fuel fragmentation, relocation, and dispersal (FFRD) in high-burnup fuel during design basis accidents. A key factor in this research is the probability of loss-of-coolant accidents (LOCAs) as a function of line size, as well as the probability that leakage as a precursor to a LOCA will be detected in sufficient time to allow for reactor shutdown and reduction of decay heat generation before a LOCA occurs.

NUREG-1829, Vol. 1, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process" (published in April 2008) developed LOCA frequency estimates for pressurized water reactors (PWRs) and boiling water reactors that were based on an expert elicitation process. These LOCA frequency estimates can provide risk insights in addressing FFRD. This report applies the Extremely Low Probability of Rupture (xLPR) code to develop analytically derived LOCA frequency estimates for PWRs to complement and compare against those in NUREG-1829. Additionally, the xLPR code provides a statistical distribution describing the time between detectable leakage and LOCA. The results for time between detectable leakage and rupture were also investigated for further context.

Keywords

Fatigue
Fuel fragmentation, relocation, and dispersal
Loss-of-coolant accident (LOCA)
Primary water stress corrosion cracking
xLPR

Deliverable Number: 3002023895

Product Type: Technical Report

Product Title: Materials Reliability Program: xLPR Estimation of PWR Loss-of-Coolant Accident Frequencies (MRP-480)

PRIMARY AUDIENCE: Probabilistic fracture mechanics (PFM) technical staff and regulators.

SECONDARY AUDIENCE: Pressurized water reactor (PWR) plant owners, utilities, licensees, and engineering experts.

KEY RESEARCH QUESTION

This work was performed to further validate the expert elicitation-based loss-of-coolant accident (LOCA) frequency estimates for PWRs within NUREG-1829 by applying PFM analyses using the Extremely Low Probability of Rupture (xLPR) code. This improves confidence in the LOCA frequency estimates for future applications. Moreover, xLPR results were further analyzed to provide a statistical distribution describing the time between detectable leakage and LOCA.

RESEARCH OVERVIEW

The xLPR code was used to perform a PFM evaluation of all PWR line sizes represented in NUREG-1829 within the scope of interest. For each line, a base case and several sensitivity cases were developed. The sensitivity cases were defined considering inputs known to have an influence on xLPR results, as well as modeling decisions made during input development. Prior xLPR analysis case results were leveraged where possible and supplemented with additional xLPR analysis cases as needed to cover the remaining piping systems of interest.

KEY FINDINGS

- This report summarizes lines selected for evaluation, xLPR analysis cases run, applicable degradation mechanisms, and analysis results.
- Results from xLPR considering PWSCC and fatigue provide valuable information regarding conservatism or non-conservatism of the NUREG-1829 LOCA frequencies in the context of the material degradation mechanisms considered in xLPR.
- Ruptures did not occur when evaluating in-service inspection (ISI) or leak rate detection (LRD) in all base cases and all but three sensitivity cases. When interpreted as LOCA frequencies, these 80-year results are on a similar or lower order of magnitude than NUREG-1829. Notably, the three sensitivity cases that led to isolated realizations ending in ruptures with ISI or LRD included modeling assumptions which are not representative of current plant conditions and operations.
- The time between detectable leakage and LOCA was calculated for the xLPR analysis cases considered. This output provided an important understanding of the likelihood for leakage to be detected in sufficient time to shut down the reactor and reduce decay heat generation prior to LOCA occurring. Depending on the analyzed component, this investigation showed that either LOCAs did not occur, substantial time (lower bound 95/95 one-sided tolerance intervals of at least 19 months) existed between detectable leakage and LOCA, or that when ISI is credited any resulting LOCA scenarios are highly unlikely (annual frequency of occurrence on the order of 1E-12 yr^{-1}).

WHY THIS MATTERS

The nuclear power industry is performing research and development through EPRI to investigate the acceptability of increasing nuclear fuel burnup limits to 75 GWd/MTU peak rod average burnup. Research includes addressing the potential for fuel fragmentation, relocation, and dispersal (FFRD) in high burnup fuel during design basis accidents. Key inputs to this research are the probability of LOCAs as a function of line size, and the probability that leakage as a precursor to a LOCA will be detected in sufficient time to allow for reactor shutdown before a LOCA occurs.

HOW TO APPLY RESULTS

This report provides information regarding xLPR-estimated LOCA frequency as a function of line size, time between detectable leakage and LOCA, as well as time between detectable leakage and rupture. These outputs improve confidence in the expert-elicitation based NUREG-1829 (ML082250436) LOCA frequency estimates. LOCA frequency and time from detectable leakage to LOCA outputs estimated using xLPR are applied as inputs for an alternative licensing strategy (ALS) to address FFRD.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- xLPR v2.2 (3002023872) is a probabilistic fracture mechanics code developed cooperatively by EPRI and the U.S. Office of Nuclear Regulatory Research; it is applied to leak-before-break (LBB) analysis.
- EPRI 3002018457 describes an ALS to address FFRD, which includes analytical support by applying the xLPR code.
- NUREG-1829 (ML082250436) developed LOCA frequency estimates for pressurized water reactors and boiling water reactors that were based on an expert elicitation process.
- The xLPR Piping System Analysis (ML21217A088) documents xLPR analyses of representative reactor vessel outlet and inlet nozzle welds in a Westinghouse four-loop PWR and includes an extensive set of sensitivity studies.
- The xLPR Generalization Study (ML22088A006) documented xLPR analyses of other piping systems containing Alloy 82/182 dissimilar metal piping butt welds. The xLPR Generalization Study included a reduced set of sensitivity studies per analyzed component, as informed by results from the xLPR Piping System Analysis work.

EPRI CONTACTS: Nate Glunt, Principal Technical Leader, nglunt@epri.com; Craig Harrington, Technical Executive, charrington@epri.com

PROGRAM: Pressurized Water Reactor Materials Reliability Program (MRP), P41.01.04

IMPLEMENTATION CATEGORY: Reference – Technical Basis

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

ACRONYMS

ADAMS	Agencywide Documents Access and Management Systems (U.S. NRC)
ALS	alternative licensing strategy
ASME	American Society of Mechanical Engineers
ATF	accident-tolerant (advanced technology) fuel
B&W	Babcock & Wilcox
BWR	boiling water reactor
BWRVIP	Boiling Water Reactor Vessel and Internals Project
CASS	cast austenitic stainless steel
CE	Combustion Engineering
CFR	Code of Federal Regulations
CGR	crack growth rate
CL	cold leg
COD	crack opening displacement
CRDM	control rod drive mechanism
CTM	crack transition module
CVCS	chemical volume control system
DMW	dissimilar metal weld
DN	diamètre nominal
DVI	direct volume injection
EFPY	effective full-power years
EPRI	Electric Power Research Institute
FFRD	fuel fragmentation, relocation, and dispersal
HAZ	heat-affected zone
HL	hot leg
ICI	in-core instrumentation
ID	inner diameter

ISI	in-service inspection
KPW	K calculator for part-through-wall cracks
KTW	K calculator for through-wall cracks
LBB	leak-before-break
LEAPOR	Leak Analysis of Piping Oak Ridge
LBLOCA	large-break loss-of-coolant accident
LOCA	loss-of-coolant accident
LRD	leak rate detection
LTCP	low temperature crack propagation
MDM	materials degradation matrix
MRP	Materials Reliability Program
MSIP	mechanical stress improvement process
NPS	nominal pipe size
NRC	Nuclear Regulatory Commission
PFM	probabilistic fracture mechanics
POD	probability of detection
PREN	pitting resistance equivalent number
PSL	pressurizer spray line
PWR	pressurized water reactor
PWSCC	primary water stress corrosion cracking
PZR	pressurizer
QoI	quantity of interest
RCP	reactor coolant pump
RCS	reactor coolant system
RH	reactor head
RHR	residual heat removal
RVIN	reactor vessel inlet nozzle
RVON	reactor vessel outlet nozzle
SCC	stress corrosion cracking
SGIN	steam generator inlet nozzle
SGON	steam generator outlet nozzle

SIS	safety injection system
SQA	software quality assurance
SRV	safety relief valve
SSE	safe shutdown earthquake
TIFFANY	Thermal stress Intensity Factors For ANY coolant history
TLR	Technical Letter Report
TW	through-wall
TWC_fail	circumferential through-wall crack stability
WRS	weld residual stress
xLPR	Extremely Low Probability of Rupture

UNIT CONVERSION FACTORS

1 inch	25.4 mm
1°F	1.8°C + 32
1 Δ°F	1.8 Δ°C
1 ksi	1000 psi = 6.895 MPa
1 ksi$\sqrt{\text{inch}}$	1.099 MPa$\sqrt{\text{m}}$
1 lbf/inch	0.1751 N/mm 0.1751 kJ/m^2 0.1751 MPa·mm
1 gpm	3.8 lpm

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Background

NUREG-1829, Vol. 1, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process" [1] was published by the U.S. Nuclear Regulatory Commission (NRC) in April 2008. One stated purpose of the report is as follows:

> "Current requirements consider pipe breaks in the reactor coolant pressure boundary, up to and including breaks equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system. One aspect of this risk-informing activity is to evaluate the technical adequacy of redefining the design-basis break size (the largest pipe break to which 10CFR50.46 [which specifies acceptance criteria for emergency core cooling systems] applies) to a smaller size that is consistent with updated estimates of pipe break frequencies."

To support this purpose, NUREG-1829 developed LOCA frequency estimates for pressurized water reactors (PWRs) and boiling water reactors (BWRs) that were based on an expert elicitation process. As stated in NUREG-1829, the expert elicitation process required experts to "consolidate operating experience and insights from probabilistic fracture mechanics (PFM) studies with knowledge of plant design, operation, and material performance. This process is well-recognized for quantifying phenomenological knowledge when data or modeling approaches are insufficient."

The Extremely Low Probability of Rupture (xLPR) code [2], developed cooperatively by EPRI and the U.S. Office of Nuclear Regulatory Research, provides substantive new analytical capabilities that may now be applied to further validate the results and conclusions reflected in NUREG-1829. While the larger interest for this present work is to complete a broadly applicable comparison to NUREG-1829, the impetus behind the initial effort is more narrowly focused.

Separately, the nuclear power industry is performing research and development through the Electric Power Research Institute (EPRI) to investigate the acceptability of increasing nuclear fuel burnup limits to 75 GWd/MTU peak rod average burnup. These activities apply to current fuel designs, as well as accident-tolerant fuel/advanced-technology fuel (ATF) near-term concepts. The research addresses the emerging finding that high burnup fuel pellets could fragment, relocate axially, and possibly disperse outside of the fuel rod during a postulated design basis accident such as a LOCA [3]. These phenomena are collectively termed *fuel fragmentation, relocation, and dispersal* (FFRD). The conventional approach for satisfying technical and regulatory requirements for issues such as FFRD relies on fuel testing and measurements that are then incorporated into a semi-empirical model subject to NRC review. The limited test facilities and challenges in obtaining high burnup fuel for testing create schedule and regulatory risks. An alternative licensing strategy (ALS) to address FFRD is described in EPRI report 3002018457 [4], which includes analytical support of this licensing effort by application of the xLPR code [2].

Further validation of the expert elicitation-based LOCA frequency estimates within NUREG-1829 is desired using probabilistic fracture mechanics analyses performed with xLPR to improve confidence of their application in high burnup fuel licensing. Moreover, insights gained from xLPR analyses about the time between detectable leakage and LOCA will directly support the licensing effort. Key xLPR outputs investigated through this report, which are inputs for the ALS, are:

1. The probability of LOCAs (e.g., pipe ruptures) as a function of line size, and
2. An assessment of time between detectable leakage and the occurrence of a LOCA event (which occurs as a precursor to rupture) to demonstrate that sufficient time exists to allow for reactor shutdown and the reduction of decay heat generation, and thereby likely preclude progression to a LOCA event.

While the ALS is an immediate driver for the investigation into NUREG-1829 LOCA frequency results and time between detectable leakage and LOCA, it should be noted that the results herein are intended to be generic and of use to other projects. The aspects of this report with specific interest to the ALS will be identified throughout.

1.2 Objectives

The objective of this work was to use xLPR to develop analytically derived LOCA frequency estimates to both complement and compare against similar estimates presented in NUREG-1829 for a range of PWR piping systems and line sizes, and to rigorously investigate the time between detectable leakage and LOCA.

1.3 Scope

This work focused on piping welds for all PWR piping systems from NUREG-1829 with line size greater than NPS 6 (DN 150) at reactor coolant system (RCS) primary operating temperature and pressure. For the purposes of ALS for FFRD, only the analyses focused on the primary loop reactor coolant system piping welds are assumed relevant. Fuel cladding rupture simulations are expected to demonstrate that LOCAs in smaller lines do not lead to cladding rupture for high burnup fuel and therefore do not result in fuel dispersal. Maximum piping sizes considered in the fuel cladding rupture calculations are documented in Westinghouse Letter NSD-EPRI-23-4 [5]. While these analyses are not complete at the time of the publishing of this report, it is assumed that these analyses will be successful in demonstrating that FFRD is not a concern for all lines smaller than the primary loop reactor coolant system piping.

By design, xLPR analyses consider one weld at a time. All cases modeled either an Alloy 82/182 dissimilar metal weld, or a genericized representative similar-metal weld. The most limiting configuration between these two options was chosen for each individual line modeled depending on the corresponding materials and relevant material degradation mechanisms. This evaluation was limited to PWRs.

1.4 Approach

The xLPR code was used to perform a PFM evaluation of all line sizes represented in NUREG-1829 that are within the scope defined in Section 1.3. For each line, a base case and several sensitivity cases were developed. The sensitivity cases were defined considering inputs known to have influence on xLPR results, as well as modeling decisions made during input development, and typically reflected more challenging conditions.

xLPR analysis cases were developed applying fatigue (driven by plant transients and not local thermal fluctuations or vibration) and/or primary water stress corrosion cracking (PWSCC) (for the case of the Alloy 82/182 welds) as the material degradation mechanisms. xLPR analysis cases either modeled individual or multiple flaws present at the start of the simulation or used initiation models to calculate the time to flaw initiation. In either case, flaws of engineering scale were modeled in xLPR. Sensitivity cases were also included to model alternate inputs for parameters such as geometry, loading, weld residual stress profiles, or initial flaw sizes.

The key outputs of this effort were LOCA frequency and the time between detectable leakage and LOCA. Time between detectable leakage and rupture results were also investigated for further context.

1.5 Report Organization

This report is organized as follows:

- **Lines Selected for Evaluation (Section 2).** Section 2 details the considerations involved in selecting lines for evaluation in this study, including leveraging of previous studies.
- **xLPR PFM Evaluation (Section 3).** Section 3 provides the main details about xLPR cases run and xLPR cases leveraged from other studies. This section describes the output quantities of interest, and documents benchmarking between different xLPR versions used.
- **Analysis of PFM Results (Section 4).** Section 4 provides comparison against NUREG-1829 estimates, analysis of time from detectable leakage to LOCA, analysis of time from detectable leakage to rupture, and discusses this work in the context of Regulatory Guide 1.245.
- **Investigation into Applicable Degradation Mechanisms (Section 5).** Section 5 discusses applicable degradation mechanisms, including those not directly evaluated in the xLPR studies.
- **Conclusions (Section 6).** Section 6 provides the conclusions of this report.
- **References (Section 7)**. Section 7 lists the references that are cited in this report.
- **Template for Run Description Forms (Appendix A).** Appendix A provides a template for documentation of inputs and other run details.
- **Additional xLPR Analysis Cases (Appendix B).** Appendix B provides details on the additional xLPR analysis cases that were executed for this effort, including discussion of base cases, sensitivity cases, and results.
- **Description of xLPR Runs (Appendix C).** Appendix C contains a description of all new xLPR runs executed for this report. Full xLPR run details including inputs are stored in the EPRI electronic document repository and can be shared upon request.

2
NUREG-1829 LOCA FREQUENCIES AND XLPR CASE SELECTION FOR EVALUATION

Section 2.1 summarizes LOCA frequency results provided by NUREG-1829, describing the base case results and presenting key NUREG-1829 sensitivity case results [1]. These results provide the baseline for benchmarking versus xLPR analysis results, as described in Section 4. Section 2.2 discusses the process applied in selecting the PWR piping systems identified as LOCA-sensitive in NUREG-1829 for evaluation in xLPR.

2.1 NUREG-1829 LOCA Frequencies

Section 2.1.1 describes base case LOCA frequencies as presented in NUREG-1829. Sensitivity cases from NUREG-1829 are discussed in Section 2.1.2 and Section 2.1.3, with Section 2.1.2 investigating differences between piping and non-piping contributions to the LOCA frequencies and Section 2.1.3 comparing results after 25, 40, and 60 years of plant operation. The material degradation mechanisms considered in NUREG-1829 are then discussed in Section 2.1.4.

2.1.1 Base Case LOCA Frequencies

NUREG-1829 developed LOCA frequencies using the expert elicitation approach. Results specifically relevant to the current work are shown in Figure 2-1, reflecting total PWR LOCA frequencies after adjusting for expert panel overconfidence using an error-factor scheme. They are 40-year fleet average values and take credit for typical in-service inspection (ISI) and for leak rate detection (LRD) as required by plant Technical Specifications. Additionally, these results are presented on a per-plant basis, as opposed to a per-weld basis, for each distinct LOCA category.

NUREG-1829 provides discussion of factors influencing the trends observed in these LOCA frequencies. Increased LOCA frequencies for smaller line sizes were attributed in Section 6.3.3 of NUREG-1829 to given crack sizes making up "larger percentage[s] of the pipe circumference in smaller diameter line[s]," "smaller piping [being more] often subject to fabrication flaws," and "smaller lines [including locations] fabricated from socket welded pipe." NUREG-1829 notes that "small piping is typically more difficult to inspect and ISI is not routinely performed on these lines." In contrast, NUREG-1829 notes that "larger diameter lines are inspected more rigorously and routinely and quality control/quality assurance programs are more stringent as piping size increases."

2.1.2 Piping and Non-Piping Contributions to LOCA Frequencies

NUREG-1829 LOCA frequencies considered both piping and non-piping contributions to the LOCA frequencies. Comparison between the overall LOCA frequencies and piping-only contributions is provided in Figure 2-2. For simplicity, only overall LOCA frequencies (containing both piping and non-piping contributions) are plotted in subsequent figures in this report. This approach is reasonable as the overall LOCA frequencies are the base case results from NUREG-1829, facilitating additional comparisons with other NUREG-1829 results. Furthermore, the difference between piping and non-piping contributions is small (particularly evident when viewed on a logarithmic scale). Therefore, although xLPR results do not include predicted failures due to non-piping components, the failure contribution magnitude from non-piping components is sufficiently small that it was judged appropriate to directly compare xLPR results to NUREG-1829 results.

2.1.3 LOCA Frequencies for Various Plant Operation Durations

The base case results in NUREG-1829 include LOCA frequencies at 25 years and 40 years of plant operation with overconfidence adjustment. NUREG-1829 also includes mean LOCA frequencies at 25 and 60 years without overconfidence adjustment. Considering extended license renewal for the PWR fleet, the xLPR analysis cases presented in this report consider LOCA frequencies at 80 years. For comparison, mean LOCA frequencies at 25 and 40 years (with overconfidence adjustment) and at 25 and 60 years (without overconfidence adjustment) are presented in Figure 2-3. At 25 years, mean LOCA frequency results with overconfidence adjustment are shown to be slightly greater than without overconfidence adjustment. Mean LOCA frequency results are also shown to increase as a function of time. However, as the base case 40-year LOCA frequencies from NUREG-1829 are the results for the longest plant operation duration available in NUREG-1829 with the overconfidence adjustment, subsequent figures in this report conservatively consider comparison using the base case 40-year LOCA frequencies.

2.1.4 Material Degradation Mechanisms Considered in NUREG-1829

The LOCA frequencies presented in NUREG-1829 consider a collection of material degradation mechanisms, including thermal fatigue, mechanical fatigue, PWSCC, general corrosion, local corrosion, material aging, fabrication defects and repair, flow sensitive mechanisms (including flow-accelerated corrosion and erosion/cavitation), and other unanticipated mechanisms. Results from xLPR consider only crack initiation and growth due to PWSCC and/or fatigue. However, results from xLPR still provide valuable information regarding conservatism or non-conservatism of the NUREG-1829 LOCA frequencies in the context of the mechanisms considered. A review of other potential degradation mechanisms and their influence on the comparison against NUREG-1829 is covered in Section 5. Alloy 82/182 welds susceptible to PWSCC are present in the lines most relevant to the ALS (i.e., the primary loop reactor coolant system piping). For these lines, the material degradation mechanism that is considered limiting based on industry operating experience [6] (i.e., PWSCC) is directly modeled in xLPR. Thus, for the Alloy 82/182 welds susceptible to PWSCC, the difference in material degradation mechanisms considered in NUREG-1829 and modeled in xLPR is expected to have a reduced impact on results.

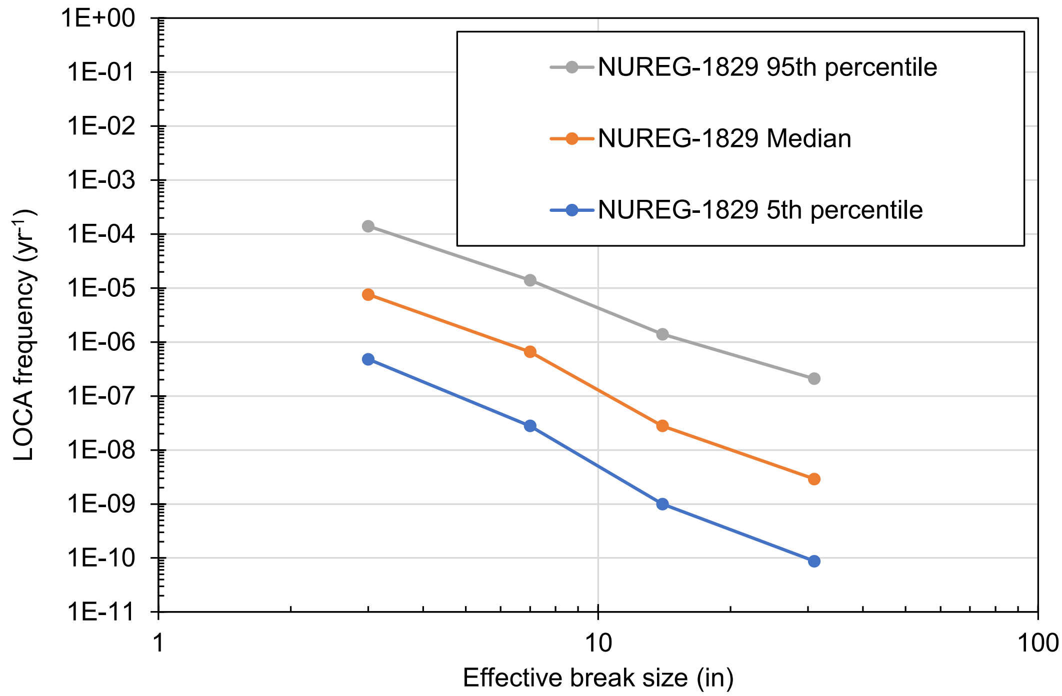

Figure 2-1
NUREG-1829 Table 1 LOCA Frequencies—PWR, End-of-Plant-License (40-years) Estimate (summary estimates after overconfidence adjustment using error-factor scheme)

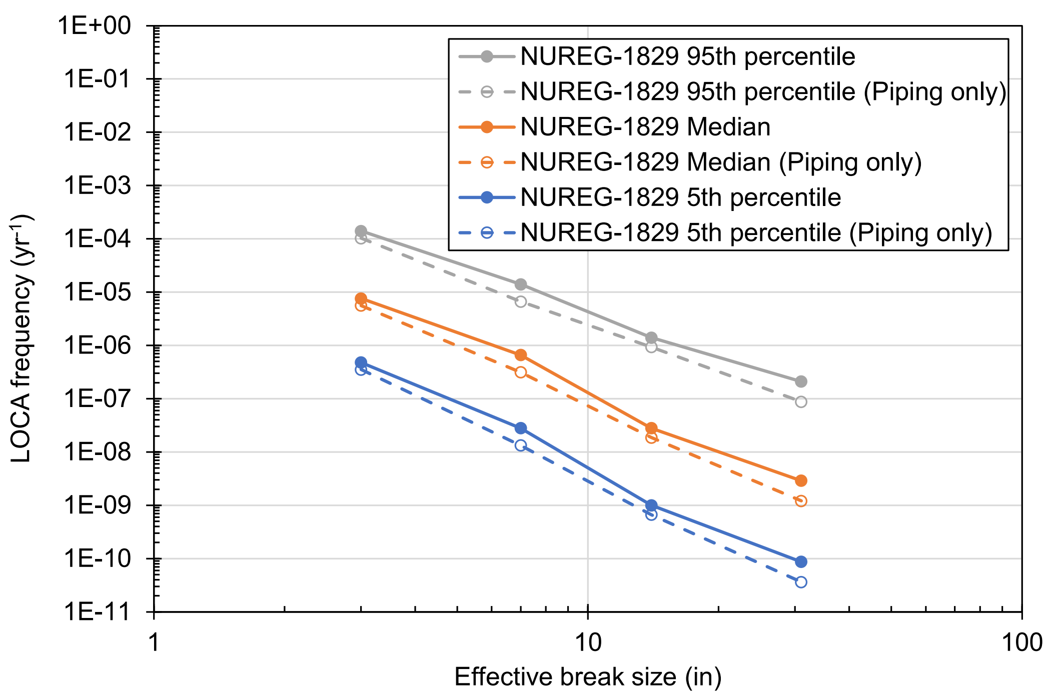

Figure 2-2
NUREG-1829 LOCA Frequencies – Comparing Overall LOCA Frequencies (NUREG-1829 Table 1) with Piping-Only LOCA Frequencies (NUREG-1829 Table 7.2)

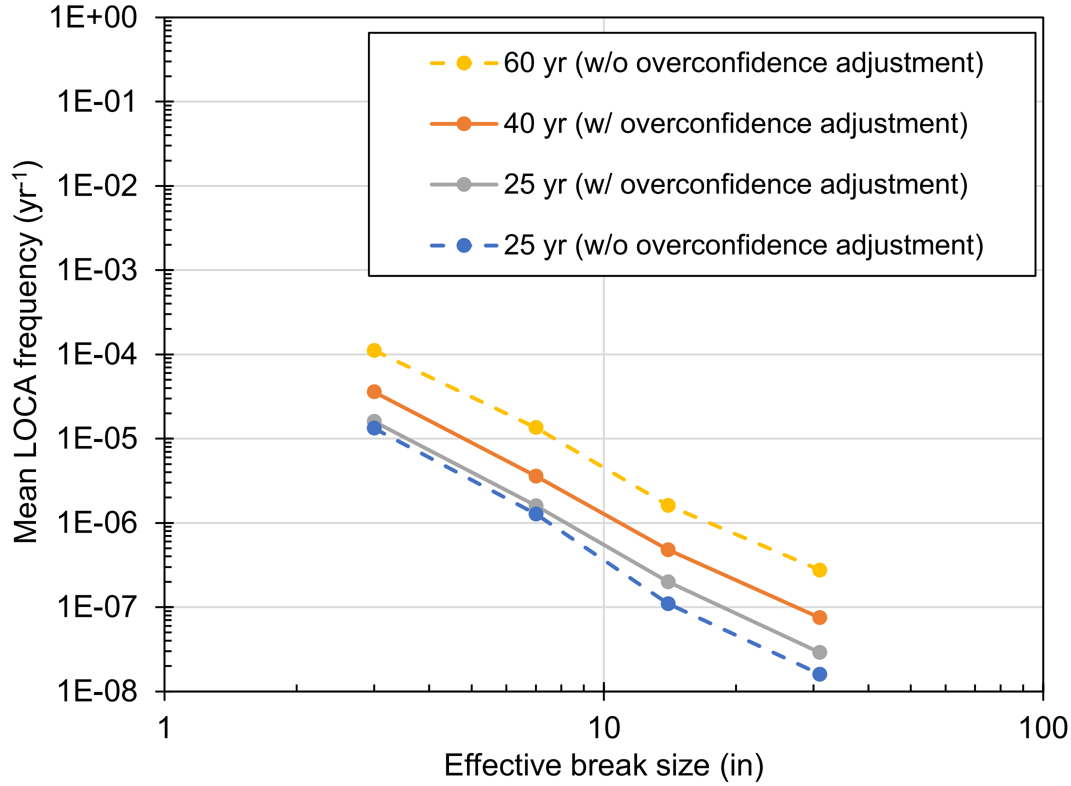

Figure 2-3
NUREG-1829 LOCA Frequencies at 25, 40, and 60 Years (NUREG-1829 Table 1 and NUREG-1829 Figure 7.8)

2.2 Line/System Selection for Evaluation Using xLPR

A range of PWR LOCA-sensitive piping systems was considered in NUREG-1829. Case selection for this benchmarking effort was performed considering xLPR computational capabilities (Section 2.2.1) and the ALS focus (Section 2.2.2). Results for systems evaluated in prior xLPR analyses (Section 2.2.3) were also considered. A summary of the PWR LOCA-sensitive piping systems considered in NUREG-1829, as well as their applicability to this effort and to the ALS is provided in Section 2.2.4.

2.2.1 xLPR Computational Capabilities

xLPR framework and module documentation was reviewed to identify whether there were computational limitations that needed to be considered. No explicit dimensional line size limitations were identified, although some xLPR modules (such as KPW, KTW, CTM, COD, and TWC_fail) include limits on nondimensional quantities such as the inner radius-to-thickness ratio (R_i/t) or mean radius-to-thickness ratio (R_m/t). The only relevant limitation to this analysis is a known instability in the leak rate calculated by Leak Analysis of Piping Oak Ridge (LEAPOR) for line sizes 4 in. (102 mm) and smaller [7]. This evaluation does not consider line sizes in the range for which this instability is applicable.

2.2.2 Alternative Licensing Strategy Considerations

The application of xLPR and results derived therefrom as detailed in this report may be applied for alternative licensing approaches for high burnup fuel (>75 GWd/MTU). High burnup fuel, when subjected to the elevated temperatures and mechanical loading likely to occur during accident conditions, can burst or rupture, resulting in FFRD. The ALS investigates the impacts of LOCAs in different PWR line sizes on LOCA-induced FFRD. For smaller break sizes, there is no cladding rupture for high burnup fuel, and thus no dispersal evaluation is required. For postulated large-break LOCAs (LBLOCAs), the unidentified leakage Limiting Condition for Operation (requiring plant shutdown prior to occurrence of a LBLOCA per plant Technical Specifications) is credited in preventing FFRD.

At the inception of this project, the lower limit line size considered in-scope for xLPR analysis was conservatively assumed as lines greater than NPS 6 (DN 150). As development of the ALS has progressed, careful evaluation of relevant LOCA-induced FFRD analyses refined the xLPR scope of analysis relevant to the ALS to be focused on the primary loop reactor coolant system piping [5]. The NPS 6 (DN 150) lower limit for line size is greater than the lower limit based on xLPR computational capabilities described in Section 2.2.1 and thus establishes the lower limit for the current study. As earlier studies documented in this report involve line sizes smaller than RCS primary loop piping, details and results for cases applicable to the latest ALS scope will be clearly identified throughout this report.

2.2.3 xLPR Piping System Analysis and Generalization Study

Reports detailing xLPR analyses in the context of probabilistic evaluations for LBB-behavior in Alloy 82/182 dissimilar metal butt welds in PWR piping systems have recently been published by the U.S. NRC. TLR-RES/DE/REB-2021-09 (ML21217A088) [8], referred to herein as the "xLPR Piping System Analysis," documented xLPR analyses of representative reactor vessel outlet and inlet nozzle welds in a Westinghouse four-loop PWR, and includes an extensive set of sensitivity studies. TLR-RES/DE/REB-2021-14 R1 (ML22088A006) [9], referred to herein as the "xLPR Generalization Study," documented xLPR analyses broadly representative of the remaining LBB-approved piping in the U.S. PWR fleet containing Alloy 82/182 dissimilar metal piping butt welds. The xLPR Generalization Study included a reduced set of sensitivity studies per analyzed component, as informed by results from the xLPR Piping System Analysis. The results of these studies are leveraged for this current effort and are supplemented with additional xLPR analysis cases as needed to cover the remaining piping systems in NUREG-1829 that are included within the scope of this study.

2.2.4 Summary of Systems Evaluated

Table 2-1 lists all PWR piping systems that are identified as LOCA-sensitive in NUREG-1829 Table 3.5 (PWR LOCA-Sensitive Piping Systems), as well as identifying if these systems are in the broader initial scope for the current study (piping at RCS normal operation conditions with size greater than NPS 6, DN 150) or are relevant to the ALS from an xLPR analysis perspective (primary loop RCS piping). Furthermore, Table 2-1 indicates if the corresponding xLPR analysis cases are detailed in the xLPR Piping System Analysis, the xLPR Generalization Study, or in this report.

Table 2-1
PWR LOCA-Sensitive Piping Systems Considered in NUREG-1829

NUREG-1829 Line	Piping Size (in)	In Scope?	Relevant to ALS?	PFM Evaluation Documented In
Reactor Coolant Piping: Hot Leg	30-44	Yes	Yes	xLPR Piping System Analysis xLPR Generalization Study
Reactor Coolant Piping: Cold Leg/Crossover Leg	22-34	Yes	Yes	xLPR Piping System Analysis xLPR Generalization Study
Surge line	10-14	Yes	No	xLPR Generalization Study
Safety Injection System (SIS): Accumulator	10-12	Yes	No	xLPR Generalization Study This report (Appendix B)
SIS: Direct Volume Injection (DVI):	2-6	No[2]	No	This report (Appendix B)
Drain line	< 2	No	No	--
Chemical Volume Control System (CVCS)	2-8[1]	No	No	--
Residual Heat Removal (RHR)	6-12	Yes	No	This report (Appendix B)
Safety Relief Valve (SRV) lines	1-6	No	No	--
Pressurizer Spray Line (PSL)	3-6	No	No	--
Control Rod Drive Mechanism (CRDM)	4-6	No	No	--
Reactor Head (RH)	< 2	No	No	--
In-Core Instrumentation (ICI)	< 2	No	No	--
Instrumentation	< 2	No	No	--

NOTES:
[1] Portions of the CVCS that are large enough to be in scope (> NPS 6 (DN150)) are not at primary coolant temperature and pressure conditions.
[2] Case documented in Appendix B modeled NPS 6 (DN150) configuration, below the limit of line sizes in scope.

3
xLPR PFM EVALUATION

A comprehensive set of cases was developed addressing all the in-scope lines/weld joint configurations for evaluation using the xLPR code [2]. This included base cases and sensitivity cases for each of the lines selected for evaluation. The base cases are defined to generally reflect expected conditions of installed components and local environmental and operating conditions, consistent with the best-estimate approach of the xLPR code. The sensitivity cases were defined to inform understanding of the base case results by investigating inputs known to have influence on xLPR results and modeling decisions made during input development, and thus were less constrained by maintaining fidelity to realistic plant conditions. Table 3-1 and Table 3-2 show summaries of the base cases and sensitivity studies for all PFM analyses leveraged in this report, including cases documented in the xLPR Piping System Analysis [8] (Section 3.1) and xLPR Generalization Study [9] (Section 3.2), as well as the additional cases documented in this report (Section 3.3 and Appendix B). Table 3-3 provides for reference the full list of cases evaluated for possible use in this study from the xLPR Piping System Analysis and xLPR Generalization Study, and the additional cases documented in this report. Appendix C provides a description of all new xLPR runs executed for this report. Full xLPR run details including inputs are stored in the EPRI electronic document repository and can be shared upon request.

Output quantities of interest from all xLPR cases are described in Section 3.4. The key outputs considered from each run were:

- Probability of rupture (applied as an analogue to probability of a LOCA occurring)
- Time between 1 gpm (3.8 lpm) detectable leakage and LBLOCA (identifying the potential for a precursor to a LBLOCA to be detected in sufficient time to allow reactor shutdown prior to the LBLOCA occurring)
- Time between 1 gpm detectable leakage and rupture (investigated for further context)

A summary of the xLPR versions used as well as a benchmark between versions is provided in Section 3.5. Section 3.6 summarizes key uncertainties and analysis assumptions.

Table 3-1
Summary of Base Cases

Study	Piping System Analysis		Generalization Study				New Analyses (This Report)		
NUREG-1829 Line/System	Reactor Coolant Piping: Hot Leg	Reactor Coolant Piping: Cold Leg	Reactor Coolant Piping: Hot Leg	Reactor Coolant Piping: Cold Leg	Surge Line	Safety Injection (Accumulator)	Safety Injection (Direct Volume Injection)	Safety Injection (Accumulator)	Residual Heat Removal
Weld Analyzed	RVON	RVIN	RVON, SGIN	SGON, RCP Nozzle DMW	PZR Surge, CE HL Branch Line DMW	CE CL Branch Line DMW	W Safety Injection	CE Safety Injection/ Accumulator DMW	Generic RHR Piping Weld
Fatigue Crack Growth	No	No	No	No	No	No	Yes	No	Yes
PWSCC Crack Growth	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Initial Flaws	No	No	No	No	No	No	Yes	Yes	Yes
Axial/Circ Flaws	Circ only	Circ only	Both	Both	Both	Both	Both	Both	Both
Seismic Effects (Earthquake Probability and SSE stresses)	No	No	No (4-loop RVON) Yes (others)	Yes	Yes	Yes	Yes	Yes	Yes
Mitigation	No	No	No (RVON); Yes (SGIN)	No	No	No	No	No	No
ISI/LRD	Optional in outputs	Optional in outputs	Optional in outputs	Optional in outputs	Optional in outputs	Optional in outputs	LRD optional in outputs	Optional in outputs	LRD optional in outputs
	Focus of ALS								

Table 3-2
Summary of Sensitivity Cases

Study	Piping System Analysis		Generalization Study				New analyses (this report)		
NUREG-1829 Line/System	Reactor Coolant Piping: Hot Leg	Reactor Coolant Piping: Cold Leg	Reactor Coolant Piping: Hot Leg	Reactor Coolant Piping: Cold Leg	Surge Line	Safety Injection (Accumulator)	Safety Injection (Direct Volume Injection)	Safety Injection (Accumulator)	Residual Heat Removal
Weld Analyzed	RVON	RVIN	RVON, SGIN	SGON, RCP Nozzle DMW	PZR Surge, CE HL Branch Line DMW	CE CL Branch Line DMW	W Safety Injection	CE Safety Injection/ Accumulator DMW	Generic RHR Piping Weld
Initiation	■		■	■	■	■	■	■	■
WRS	■		■	■	■		■	■	■
Earthquake	■						■	■	
Normal Operating Thermal Loads	■						■	■	■
LRD/ISI	■								
Mitigation	■		■	■	■			■	
Fatigue	■	■			■			■	
Initial Flaw Size	■								■
Multiple Initial Flaws							■		■
Geometry	■						■		■
Other	■ Axial cracks, hydrogen							■ WRS and Initiation (combined)	■ Transients

Focus of ALS (the four columns RVON, RVIN, RVON/SGIN and SGON/RCP Nozzle DMW)

Legend	
■	Sensitivity case included

Table 3-3
List of Cases Evaluated

Study	Case Number	Weld	Case Identifier	Objective
Piping System Analysis	1.1.0	W 4-loop RVON DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth with no ISI, mitigation, or seismic effects
Piping System Analysis	1.1.1	W 4-loop RVON DMWs	Base case – initial flaw	Assess the sensitivity of the likelihood of failure due to whether the crack initiation process is modeled in the analysis
Piping System Analysis	1.1.2	W 4-loop RVON DMWs	Severe WRS	Assess the sensitivity of the likelihood of failure due to severe, yet plausible, WRS
Piping System Analysis	1.1.3	W 4-loop RVON DMWs	DM2	Assess crack initiation model uncertainty using Direct Model 2
Piping System Analysis	1.1.4	W 4-loop RVON DMWs	Weibull	Assess crack initiation model uncertainty using the Weibull model
Piping System Analysis	1.1.5	W 4-loop RVON DMWs	SSE	Assess the sensitivity of the likelihood of failure due to SSE
Piping System Analysis	1.1.6	W 4-loop RVON DMWs	DM1 with circumferential and axial cracks	Assess the sensitivity of the likelihood of failure due to inclusion of axial cracks
Piping System Analysis	1.1.7	W 4-loop RVON DMWs	Loads	Assess the sensitivity of the likelihood of failure due to the normal operating loads
Piping System Analysis	1.1.8	W 4-loop RVON DMWs	Leak detection	Assess the impacts of leak detection on the likelihood of failure
Piping System Analysis	1.1.9	W 4-loop RVON DMWs	MSIP	Assess the impacts of MSIP on the likelihood of failure
Piping System Analysis	1.1.10	W 4-loop RVON DMWs	ISI impact	Assess the impacts of ISI on the likelihood of failure
Piping System Analysis	1.1.11	W 4-loop RVON DMWs	ISI impact – new POD curve	Assess the impacts of ISI model parameter uncertainty
Piping System Analysis	1.1.12	Case number defined but ultimately not used in Piping System Analysis TLR		
Piping System Analysis	1.1.13	Case number defined but ultimately not used in Piping System Analysis TLR		
Piping System Analysis	1.1.14	W 4-loop RVON DMWs	Hydrogen	Assess the impacts of hydrogen water chemistry on the likelihood of failure
Piping System Analysis	1.1.15	W 4-loop RVON DMWs	Fatigue impact	Assess the impacts of the combined effects of PWSCC and fatigue
Piping System Analysis	1.1.16	W 4-loop RVON DMWs	Fatigue crack initiation	Assess the likelihood of fatigue crack initiation

Table 3-3 (continued)
List of Cases Evaluated

Study	Case Number	Weld	Case Identifier	Objective
Piping System Analysis	1.1.17	W 4-loop RVON DMWs	Fatigue large initial flaw	Assess the sensitivity of the likelihood of failure due to fatigue crack growth from a large initial flaw size
Piping System Analysis	1.1.18	Case number defined but ultimately not used in Piping System Analysis TLR		
Piping System Analysis	1.1.19	W 4-loop RVON DMWs	Geometry	Assess the sensitivity of the likelihood of failure due to weld width and weld thickness
Piping System Analysis	1.1.20	W 4-loop RVON DMWs	Temperature	Assess the sensitivity of the likelihood of failure due to operating temperature
Piping System Analysis	1.1.21	W 4-loop RVON DMWs	PWSCC initial flaw size impacts	Assess the sensitivity of the likelihood of failure due to the initial flaw dimensions
Piping System Analysis	1.1.22	W 4-loop RVON DMWs	Time step	Assess the sensitivity of the likelihood of failure due to the time step
Piping System Analysis	1.1.23	W 4-loop RVON DMWs	Aleatory and epistemic uncertainties	Assess the impacts of separating aleatory and epistemic uncertainties
Piping System Analysis	1.2.0	W 4-loop RVIN DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth with no ISI, mitigation, or seismic effects
Piping System Analysis	1.2.1	W 4-loop RVIN DMWs	Fatigue impact	Assess the impacts of the combined effects of PWSCC and fatigue
Generalization Study	1.1.6a and 1.1.6c	W 4-loop RVON and RVIN DMWs	Reference case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth without mechanical mitigation
Generalization Study	1.1.6b	W 4-loop RVON and RVIN DMWs	Reference case – initial flaw	Assess the base likelihood of failure with preexisting flaws and subsequent PWSCC growth of circumferential and axial cracks without mechanical mitigation
Generalization Study	2.1.0	Westinghouse Pressurizer Surge Line Nozzle DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth without mechanical mitigation
Generalization Study	2.1.1	Westinghouse Pressurizer Surge Line Nozzle DMWs	Base case – initial flaw	Assess the base likelihood of failure with preexisting flaws and subsequent PWSCC growth of circumferential and axial cracks without mechanical mitigation
Generalization Study	2.1.2	Westinghouse Pressurizer Surge Line Nozzle DMWs	Severe WRS	Sensitivity study of Generalization Study Case 2.1.0 considering a more severe WRS profile

Table 3-3 (continued)
List of Cases Evaluated

Study	Case Number	Weld	Case Identifier	Objective
Generalization Study	2.1.3	Westinghouse Pressurizer Surge Line Nozzle DMWs	Overlay mitigation	Sensitivity study of Generalization Study Case 2.1.0 considering overlay mitigation
Generalization Study	2.1.4	Westinghouse Pressurizer Surge Line Nozzle DMWs	Fatigue	Assess the base likelihood of failure caused by fatigue initiation and growth without mechanical mitigation
Generalization Study	2.1.5	Westinghouse Pressurizer Surge Line DMWs	MSIP mitigation	Sensitivity study of Generalization Study Case 2.1.0 considering MSIP mitigation
Generalization Study	3.1.0	CE and B&W RCP Nozzle DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth without mechanical mitigation
Generalization Study	3.1.1	CE and B&W RCP Nozzle DMWs	Base case – initial flaw	Assess the base likelihood of failure with preexisting flaws and subsequent PWSCC growth of circumferential and axial cracks without mechanical mitigation
Generalization Study	3.1.2	CE and B&W RCP Nozzle DMWs	Severe WRS	Sensitivity study of Generalization Study Case 3.1.0 considering a more severe WRS profile
Generalization Study	4.1.0	Westinghouse Steam Generator Nozzle DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth with inlay mitigation
Generalization Study	4.1.1	Westinghouse Steam Generator Nozzle DMWs	Base case – initial flaw	Assess the base likelihood of failure with preexisting flaws and subsequent PWSCC growth of circumferential and axial cracks with inlay mitigation
Generalization Study	4.1.2	Westinghouse Steam Generator Nozzle DMWs	Severe WRS	Sensitivity study of Generalization Study Case 4.1.0 considering a more severe WRS profile
Generalization Study	4.1.3	Westinghouse Steam Generator Nozzle DMWs	Overlay	Sensitivity study of Generalization Study Case 4.1.0 considering overlay instead of inlay mitigation
Generalization Study	4.1.4	Westinghouse Steam Generator Nozzle DMWs	No mitigation	Sensitivity study of Generalization Study Case 4.1.0 without mechanical mitigation
Generalization Study	5.1.0	CE Hot Leg Branch Line Nozzle DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth without mechanical mitigation
Generalization Study	5.1.1	CE Hot Leg Branch Line Nozzle DMWs	Base case – initial flaw	Assess the base likelihood of failure with preexisting flaws and subsequent PWSCC growth of circumferential and axial cracks without mechanical mitigation

Table 3-3 (continued)
List of Cases Evaluated

Study	Case Number	Weld	Case Identifier	Objective
Generalization Study	5.1.2	CE Hot Leg Branch Line Nozzle DMWs	Severe WRS	Sensitivity study of Generalization Study Case 5.1.0 considering a more severe WRS profile
Generalization Study	5.2.0	CE Cold Leg Branch Line Nozzle DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth without mechanical mitigation
Generalization Study	5.2.1	CE Cold Leg Branch Line Nozzle DMWs	Base case – initial flaw	Assess the base likelihood of failure with preexisting flaws and subsequent PWSCC growth of circumferential and axial cracks without mechanical mitigation
Generalization Study	1.3.0	W 2- and 3-loop RVON and RVIN DMWs	Base case – DM1	Assess the base likelihood of failure caused by PWSCC initiation and growth without mechanical mitigation
Generalization Study	1.3.1	W 2- and 3-loop RVON and RVIN DMWs	Base case – initial flaw	Assess the base likelihood of failure with preexisting flaws and subsequent PWSCC growth of circumferential and axial cracks without mechanical mitigation
xLPR LOCA Freq	1.1.0	W Safety Injection	Base case	Establish base case results
xLPR LOCA Freq	1.1.1	W Safety Injection	Geometry	Reduced to the lower quartile of the wall thickness distribution
xLPR LOCA Freq	1.1.2	W Safety Injection	Loading	Increased mean membrane and bending stresses by 50%
xLPR LOCA Freq	1.1.3	W Safety Injection	Earthquake Probability	Increased earthquake frequency from 2.17E-4 yr^{-1} to 1E-3 yr^{-1}
xLPR LOCA Freq	1.1.4	W Safety Injection	Fatigue Initiation	Model crack initiation from fatigue
xLPR LOCA Freq	1.1.5	W Safety Injection	WRS Profile	Increase WRS by 50%
xLPR LOCA Freq	1.1.6	W Safety Injection	Two Initial Flaws	Begin with two flaws
xLPR LOCA Freq	1.1.7	W Safety Injection	Three Initial Flaws	Begin with three flaws
xLPR LOCA Freq	2.1.0	CE Safety Injection/ Accumulator DMW	Base case	Establish base case results
xLPR LOCA Freq	2.1.1	CE Safety Injection/ Accumulator DMW	SCC initiation	Modeled crack initiation due to PWSCC
xLPR LOCA Freq	2.1.2	CE Safety Injection/ Accumulator DMW	WRS profile	Considered a severe WRS profile based on xLPR Generalization Study Case 5.1.2
xLPR LOCA Freq	2.1.3	CE Safety Injection/ Accumulator DMW	Loading	Used the upper half of the distributions applied to the base case for membrane and bending stresses

Table 3-3 (continued)
List of Cases Evaluated

Study	Case Number	Weld	Case Identifier	Objective
xLPR LOCA Freq	2.1.4	CE Safety Injection/ Accumulator DMW	Earthquake loading	Increased the earthquake frequency to 1E-3 yr^{-1} (361% increase from base case)
xLPR LOCA Freq	2.1.5	CE Safety Injection/ Accumulator DMW	Fatigue	Modeled crack growth due to the combined effects of PWSCC and fatigue
xLPR LOCA Freq	2.1.6	CE Safety Injection/ Accumulator DMW	WRS profile + SCC initiation	Modeled crack initiation due to PWSCC, using the WRS profile from xLPR LOCA Freq Case 2.1.2
xLPR LOCA Freq	2.1.7	CE Safety Injection/ Accumulator DMW	Mitigation	Applied mechanical stress improvement after 30 years
xLPR LOCA Freq	1.2.0	Generic RHR Piping Weld	Base Case	Establish base case results
xLPR LOCA Freq	1.2.1	Generic RHR Piping Weld	Fatigue Initiation	Model crack initiation from fatigue
xLPR LOCA Freq	1.2.2	Generic RHR Piping Weld	WRS Profile	Used a more aggressive weld residual stress profile based on the 95th percentile of the yield stress distribution, developed in an approach that parallels the approach used for N-899 -2200
xLPR LOCA Freq	1.2.3	Generic RHR Piping Weld	Geometry	Considered the lower bound NPS (smaller line size than the base case) and lower bound schedule for RHR systems identified
xLPR LOCA Freq	1.2.4	Generic RHR Piping Weld	Initial Flaw Size	Modeled larger initial flaws, with true mean initial flaw length doubled relative to base case
xLPR LOCA Freq	1.2.5a	Generic RHR Piping Weld	Transients (Freq)	Considered transient loads with frequency doubled relative to base case
xLPR LOCA Freq	1.2.5b	Generic RHR Piping Weld	Transients (Load)	Considered transient loads with additional membrane stress increased by 50% relative to base case
xLPR LOCA Freq	1.2.5c	Generic RHR Piping Weld	Transients (xLPR-GR-IG)	Considered transient loads defined in xLPR-GR-IG
xLPR LOCA Freq	1.2.5d	Generic RHR Piping Weld	Transients (MRP-393)	Considered transient loads defined in MRP-393
xLPR LOCA Freq	1.2.6	Generic RHR Piping Weld	Loading	Used higher normal operating thermal loads, with mean loads increased by 50% relative to base case with standard deviations unchanged
xLPR LOCA Freq	1.2.7	Generic RHR Piping Weld	Multiple Flaws	Modeled two initial flaws in both axial and circumferential directions

3.1 xLPR Piping System Analysis

The xLPR Piping System Analysis [8] considered the primary loop piping in a Westinghouse four-loop PWR design. This analysis modeled Alloy 82/182 dissimilar metal welds (DMWs) located at the connections between the primary loop piping and the reactor vessel outlet nozzles (RVONs) and the reactor vessel inlet nozzles (RVINs), as the Alloy 82/182 welds are susceptible to PWSCC and thus considered limiting.

The RVON base case considered circumferential flaws only, with crack initiation and growth due to PWSCC. In-service inspection, mitigation, and seismic effects were not considered in the base case. A large number of sensitivity studies were run for these representative welds, including initial flaws, axial flaws, fatigue, in-service inspection, mitigation, combined effects of PWSCC and fatigue, initial flaw size (including shallow but substantially longer initial flaws as an analogue for multiple smaller flaws that have coalesced), safe shutdown earthquake (seismic) loading[1], and others. The benefits of mitigation techniques such as peening or zinc addition were conservatively not included in these studies. The RVIN base case considered circumferential flaws only, with crack initiation and growth due to PWSCC, and fewer sensitivity studies. For most xLPR analysis cases, all variables were sampled in just one loop of the two-loop Monte Carlo structure in xLPR, rather than sampling variables in both loops. A single loop analysis provides a more efficient way to reach statistical convergence of mean values. Approximately 100,000 realizations were executed per case explicitly modeling crack initiation and approximately 5,000 realizations were executed per case utilizing the initial flaw model, as these were the number of realizations respectively that were estimated to be necessary to guarantee that any undesirable event would not be missed in the analysis.

3.2 xLPR Generalization Study

The xLPR Generalization Study [9] included an expanded scope of components beyond that of the xLPR Piping System Analysis, including all other Alloy 82/182 DMWs in the main coolant loop and Class 1 branch line piping included in LBB-approved line segments and present in Westinghouse, CE, or B&W PWRs. These Alloy 82/182 DMWs are susceptible to PWSCC and thus considered limiting. The piping systems were sorted into six groups:

- Westinghouse four-loop RVON/RVIN DMWs (new reference cases including axial flaws)
- Westinghouse pressurizer surge line piping to pressurizer nozzle DMWs
- CE and B&W reactor coolant pump inlet and outlet nozzle DMWs
- Westinghouse steam generator inlet and outlet nozzle DMWs
- CE hot leg branch connection DMWs and high-pressure injection system DMWs
- Westinghouse two- and three-loop RVON/RVIN DMWs

---

[1] Safe shutdown earthquake (seismic) loading is modeled given a single frequency of occurrence input along with corresponding safe shutdown earthquake stress inputs which are applied at each modeled earthquake occurrence.

The base cases included axial and circumferential flaws, options for considering leak rate detection and ISI, and seismic effects[2]. Sensitivity cases considered initial flaws, more severe weld residual stress profiles, and mitigation. All variables were sampled in just one loop of the two-loop Monte Carlo structure in xLPR, rather than sampling variables in both loops. Approximately 100,000 realizations were executed per case explicitly modeling crack initiation and approximately 5,000 realizations were executed per case utilizing the initial flaw model, as these were the number of realizations respectively that were estimated to be necessary to guarantee that any undesirable event would not be missed in the analysis.

3.3 Additional xLPR Analysis Cases

xLPR analysis cases were evaluated for additional lines to complete coverage of the full scope of PWR LOCA-sensitive piping systems > NPS 6 (DN 150) considered in NUREG-1829, even though these additional cases are not relevant to the ALS scope. One case, the Westinghouse safety injection line, was analyzed as part of a scoping study, and is described in Section B.1. However, since the Westinghouse safety injection line is not > NPS 6 (DN 150), it is not discussed further in this report. To complete the coverage of the full scope of PWR LOCA-sensitive piping systems > NPS 6 (DN 150), base cases, sensitivity cases, and results for the CE safety injection/accumulator line and the Westinghouse residual heat removal (RHR) system are presented in Section B.2 and Section B.3, respectively.

The CE safety injection/accumulator cases modeled axial and circumferential flaws in an unmitigated Alloy 82/182 weld at cold leg temperature, with crack growth due to PWSCC. The Westinghouse safety injection line and RHR piping weld cases modeled axial and circumferential flaws in a genericized stainless steel weld subject to fatigue crack growth. Informed by the xLPR Piping System Analysis and xLPR Generalization Study efforts, cases for these lines considered a modest number of sensitivity cases. Investigated were key inputs known to have influence on xLPR results (as in the xLPR Generalization Study), as well as modeling decisions made during input development. Seismic loading was considered for these lines through safe shutdown earthquake loading modeled given a single frequency of occurrence input along with corresponding safe shutdown earthquake stress inputs.

3.4 Output Quantities of Interest

This section discusses the output quantities of interest, both those extracted directly from xLPR outputs and those computed in post-processing (e.g., for the analysis of LOCA frequencies, time from detectable leakage to LOCA, and time from detectable leakage to rupture).

3.4.1 Initiation, Leakage, Rupture Outputs (from xLPR)

'Occurrence of crack,' 'occurrence of leak,' and 'occurrence of rupture' are standard xLPR indicator results. 'Occurrence of crack' takes on a value of zero for realizations and time steps with no flaws, and a value of one for realizations and time steps with at least one flaw of any orientation. xLPR is also capable of reporting the total number of flaws present in a single

[2] For the xLPR Generalization Study, when calculating the time between detectable leakage and rupture, seismic effects were considered as non-probabilistically treated seismic loads applied in every time step. Occurrence of rupture results considered application of safe shutdown earthquake loading as in the xLPR Piping System Analysis (input via frequency of occurrence with corresponding safe shutdown earthquake stress inputs).

realization, although this output was not a primary Quantity of Interest (QoI) for these analyses. The 'occurrence of crack' output is used to characterize time to first crack initiation. 'Occurrence of leak' takes on a value of zero for realizations and time steps with no leakage, and a value of one for realizations and time steps with leakage from a flaw of any orientation. 'Occurrence of rupture' takes on a value of zero for realizations and time steps with no rupture, and a value of one for realizations and time steps with rupture caused by a flaw of any orientation. All these outputs are provided considering both axial and circumferential flaws, and corollary indicators are also available individually for only axial flaws or for only circumferential flaws.

3.4.2 Occurrence of Rupture Crediting ISI and LRD (from xLPR)

xLPR reports 'occurrence of rupture' with in-service inspection (ISI) and/or leak rate detection (LRD) as standard indicator results, in addition to the 'occurrence of rupture' result (described in Section 3.4.1). ISI is considered probabilistically, where a sampled probability of a scheduled in-service inspection detecting the flaw prior to rupture is evaluated. As a result, the 'occurrence of rupture with ISI' (with or without LRD) takes on values between zero and one, inclusively. LRD is evaluated deterministically, considering the leak rate in each timestep relative to the leak rate detectability input applied (for example 1 gpm, 3.8 lpm). A leak rate below the detectability input is credited as not detected, whereas a leak rate at or above the input is credited as detected. The 'occurrence of rupture with LRD' takes on a value of zero for each realization and time step without rupture. If a rupture occurs, it takes on a value of one for that time step and realization if the leak rate remains below the leak rate detectability input applied, or zero if the leak rate equals or exceeds the detectability input. xLPR results crediting both ISI and LRD are most representative of plant operations, with results crediting only ISI, only LRD, or neither providing additional conservatism.

3.4.3 LOCA Frequencies (Post-Processed)

LOCA frequencies are computed by averaging the 'occurrence of rupture' over 80 years. This method assumes that the LOCA frequency is constant over 80 years, and uses the 'occurrence of rupture' output as an analogue to a LOCA. These assumptions are investigated in Section 4.1.4 and Section 4.1.5.

LOCA frequencies with ISI and/or LRD are computed using the same method but are calculated using the xLPR occurrence of rupture with ISI and/or LRD outputs, as appropriate.

3.4.4 Time Between Detectable Leakage and Rupture (Post-Processed)

The time between detectable leakage and rupture, which is also referred to as the "lapse time," is computed in results post-processing outside of xLPR.

A detectable leak rate threshold of 1 gpm during operation represents a typical limit on unidentified leakage in plant Technical Specifications. It is noted that leakage from a degraded pressure boundary is never allowable. Further, plants typically implement lower thresholds for leak rate detection (e.g., 0.1 gpm) as action levels on unidentified leakage, e.g., as recommended in WCAP-16465-NP [10]. In xLPR, flaws which grow to become through-wall may begin leaking at leak rates less than 1 gpm.

In the majority of xLPR analyses, time steps of 1 month were modeled. These timesteps are notably longer than typical response times required in plant leakage monitoring programs. A time step of 1 month thus conservatively neglects the ability as well as the Technical Specification requirement for plant operators to detect and react to leakage on much shorter timelines. Despite this difference in temporal resolution, xLPR analysis cases with 1 month time steps provide valuable insight regarding the margin between detectable leakage and rupture.

In the NRC TLRs, the calculation methodology for the time between detectable leakage and rupture output considers the leak rate of the largest circumferential flaw and applies the circumferential flaw stability ratio output to estimate the rupture time. This approach assumes that axial leakage is negligible (based on results from Case 1.1.6 of the xLPR Piping System Analysis showing axial leak rates were less than 0.05 gpm, 0.19 lpm) and considers rupture based on the combined normal operating and non-probabilistically treated seismic loads.

For further investigation of the times from detectable leakage to rupture, an alternate methodology was applied for this current study, considering the total leak rate and the xLPR-reported ‘occurrence of rupture’ output. This methodology, discussed in more detail in Section 4.2.1, includes leakage from axial flaws, which was found to be non-negligible relative to detectable leak rate thresholds in some of the xLPR Generalization Study cases, and considers rupture caused by normal operating loads. The time between detectable leakage and rupture is computed based on the number of whole time steps between detectable leakage and rupture – that is, no interpolation is applied.

For cases where seismic loads are not considered, such as xLPR Piping System Analysis Case 1.1.6, the two approaches give nearly identical results, except that the methodology used for further investigation reports times that are 1 month shorter. This is due to the consideration of number of whole timesteps. The use of whole time steps is explained in greater detail in Section 4.2.1.

3.4.5 Occurrence of LBLOCA and Time Between Detectable Leakage and LBLOCA (Post-Processed)

In xLPR, the volumetric flow rates associated with small, medium, and large break LOCAs are user-defined thresholds with a default value for LBLOCA of 5,000 gpm (19,000 lpm). The ‘occurrence of LBLOCA’ is a standard output, which takes on a value of zero for realizations where the total leak rate is less than the user-defined threshold, and a value of one for realizations where the total leak rate is greater than or equal to the user-defined threshold.

Time between detectable leakage and LBLOCA was computed in a manner similar to the time between detectable leakage and rupture output, as described in Section 3.4.4, but considering the total leak rate and the xLPR-reported ‘occurrence of LBLOCA’ outputs instead.

3.5 xLPR Versions

As part of the xLPR code LBB application project which resulted in the xLPR Piping System Analysis [8] and xLPR Generalization Study [9] TLRs, research versions of xLPR were developed under a research version control plan [11] to correct bugs previously identified, test new features for making the code more efficient, enlarging its scope and range of applicability, or to optimize the code for specific applications. Table 3-4 summarizes the xLPR versions (including public releases and research versions) used for all xLPR analysis cases included in this report and describes the key changes made for each xLPR version.

To ensure results from research versions of xLPR are still appropriate for inclusion in this report, benchmarking was performed between xLPR v2.0d and xLPR v2.2 (the latest available xLPR version), with results presented in Section 3.5.1. Furthermore, based on a review of changes incorporated in xLPR v2.2 (and given that a portion of the corrections included in xLPR v2.2 included corrections to issues also resolved in v2.0a, v2.0b, and v2.0d), it was judged that changes incorporated in xLPR v2.2 would have a negligible impact on results generated using the prior research versions. Thus, results generated using any of xLPR v2.2, v2.0d, v2.0c, v2.0b, or v2.0a are applicable. RG 1.245 [15] notes that the NRC has approved use of the latest version of xLPR for certain applications when applied within the validated application range. The application of xLPR to PWR piping systems with line size greater than NPS 6 (DN 150) at reactor coolant system (RCS) primary operating temperature and pressure, modeling either an Alloy 82/182 dissimilar metal weld or a stainless steel similar-metal weld is within the validated application range.

Table 3-4
Summary of xLPR Versions

xLPR Version	Description	Application
xLPR v2.2 ***(public release)***	Moves to GoldSim 12, replaces Excel embedded preprocessor with new standalone executable. Corrects errors impacting circumferential COD, circumferential TWC stability, in-service inspection, TIFFANY, and Framework calculations. Includes corrections to issues resolved in v2.0a, v2.0b, and v2.0d.	New analyses (this effort)
xLPR v2.0d ***(research version)***	Corrects errors impacting in-service inspection calculations. Includes corrections to issues resolved in v2.0a and v2.0b.	xLPR Piping System Analysis xLPR Generalization Study
xLPR v2.0c ***(research version)***	Implements an optimized algorithm for Direct Model 1 for PWSCC initiation.	xLPR Piping System Analysis
xLPR v2.0b ***(research version)***	Extended the range of validity for the axial COD module. Includes corrections to issues resolved in v2.0a.	xLPR Piping System Analysis
xLPR v2.0a ***(research version)***	Corrects errors impacting circumferential COD, circumferential surface crack stability, and circumferential TWC stability calculations.	xLPR Piping System Analysis

3.5.1 Benchmark Between xLPR v2.0d and v2.2

Benchmarking between xLPR v2.0d and xLPR v2.2 was performed using two different cases, one modeling crack growth due to fatigue (Section 3.5.1.1) and one modeling crack growth due to PWSCC (Section 3.5.1.2). For each case, analyses were performed with both xLPR v2.0d and xLPR v2.2, using the same inputs and sampling options. Key outputs were then compared to verify that the results from the two versions were consistent.

3.5.1.1 Benchmarking Case Modeling Fatigue

A sensitivity study modeling crack growth due to fatigue, with large initial flaws (xLPR Piping System Analysis Case 1.1.17), was used for the fatigue benchmarking case. As no leakage or rupture had occurred in evaluating xLPR Piping System Analysis Case 1.1.17, the key output used for benchmarking was crack growth in the depth direction. The results are summarized in Figure 3-1 benchmarking xLPR v2.0d to xLPR v2.2. This case modeled initial flaws of constant size (that is, the same initial flaw size in every realization). The difference in crack sizes after 80 years of growth is negligible, thus the difference between these two xLPR versions is considered to have a negligible impact when modeling fatigue crack growth.

One notable computational difference from xLPR v2.0d to xLPR v2.2 is the preprocessor indexing error noted in xLPR-REQ-107 [12]. This benchmarking case, which examined growth of part-through-wall flaws in the depth direction, did not have sufficient flaw growth to produce any through-wall flaws. As a result, this case does not probe the impact of the REQ-107 change as only through-wall flaws were affected by the error. As none of the modeled xLPR analysis cases exhibited substantial fatigue crack growth that would result in through-wall flaws growing due to fatigue, the REQ-107 change (present in xLPR v2.2) is expected to have limited impact on analyses performed using xLPR v2.0d.

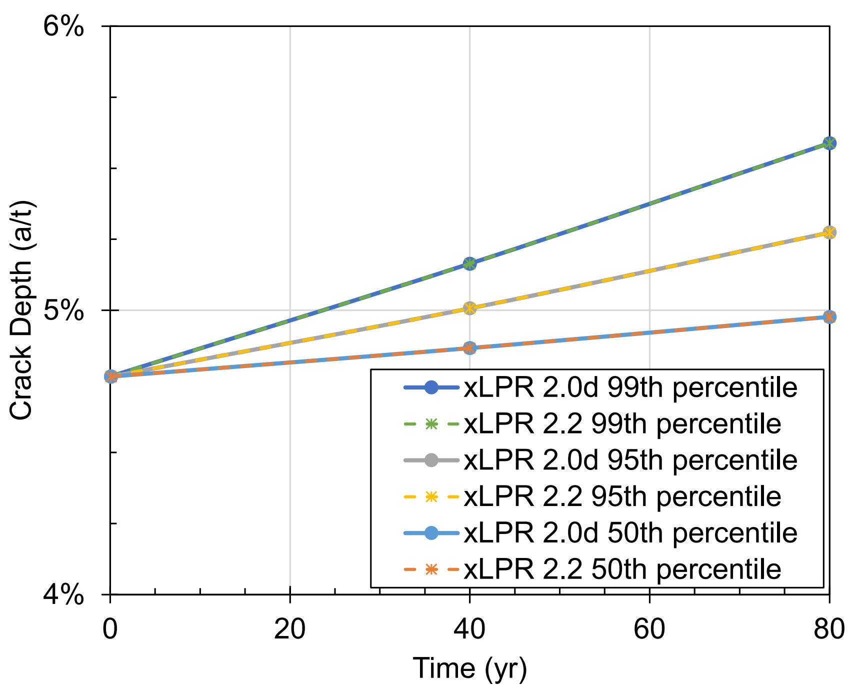

Figure 3-1
Crack Growth in the xLPR Fatigue Benchmarking Case

3.5.1.2 Benchmarking Case Modeling Stress Corrosion Cracking

Case 1.1.6 from the xLPR Piping System Analysis was used for the benchmarking case modeling PWSCC. This case models the RVON, includes PWSCC initiation, and included axial and circumferential flaws. The key outputs for this case are probability of crack initiation, leakage, and rupture. Results from xLPR-2.0d and xLPR-2.2 are compared in Figure 3-2. The differences between xLPR v2.0d and v2.2 for all three key outputs at 80 years are negligible, thus the difference between these xLPR versions is not a concern for the inputs used when modeling PWSCC crack growth in the RVON.

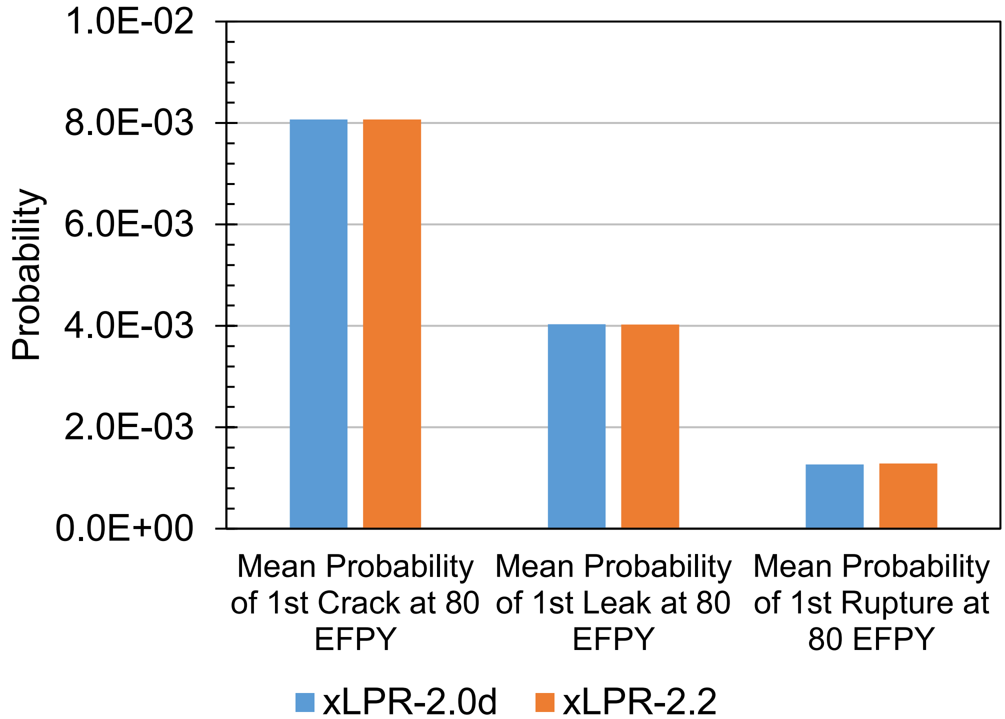

Figure 3-2
Key Outputs in the xLPR PWSCC Benchmarking Case

3.6 Uncertainties and Assumptions

The xLPR Uncertainty Report [13] documents sources of known uncertainties within xLPR for each sub-model and the computational framework. It describes how known uncertainties are accounted for to produce an output that reflects the current state of knowledge, includes consideration of assumptions and decisions made regarding how to implement this complex problem in a model rendered in computer code, and presents a qualitative assessment on the implications of these uncertainties on results from the xLPR code. The xLPR Uncertainty Report also summarizes model validation as well as any limitations for each of the xLPR modules (documented in further detail in the individual xLPR module validation reports). The key conclusions of the xLPR Uncertainty Report are:

- All xLPR results are best-estimate or slightly conservatively biased,
- Uncertainties in model development are accounted for in sampling strategy, and

- Validation (framework acceptance[3]) testing provided further benchmarking of PWSCC initiation, growth, and the other models.

The sources of uncertainty or bias in each sub-model and the computational framework directly influence xLPR results, including the results presented in this report.

Assumptions for xLPR analysis cases, including conservatisms and unknowns, are discussed in Section 5 of the xLPR Generalization Study [9]. The conservatisms included from the xLPR Generalization Study include applying highest normal operating loads, SSE loads, pressures, and temperatures, smallest pipe thickness and largest outside diameters, and lower-bound hydrogen concentrations (resulting in faster crack growth rates). A 10-year inspection frequency was used, even though many DMWs are required to be inspected more frequently. A typical value was applied for the distance between the DMW and the safe-end-to-pipe weld, which is unknown but has influence on the WRS profile. This approach results in the xLPR analysis cases producing upper bound estimates for the range of welds considered.

Welds are assumed to behave independently from each other, providing an upper bound on system-level probabilities. Consideration of only a single weld associated with the worst-case conditions as the weld that would fail first would provide a lower bound on the probability of failure (this method considers the properties and conditions to be perfectly correlated among all the welds). In practice, the true probability should lie between these two bounds. Depending on the analysis considered, one of the bounds may be more representative than the other.

[3] xLPR Framework acceptance testing included validation test cases which compared xLPR analysis results to operating experience from V.C. Summer, North Anna, Ringhals, and Tsuruga nuclear power plants, where PWSCC was observed in primary system piping components.

4
ANALYSIS OF PFM RESULTS

The focus of this study was to use xLPR to develop analytically derived LOCA frequency estimates to both complement and compare against similar estimates presented in NUREG-1829, and to evaluate the time between detectable leakage and LOCA. This chapter compares xLPR-estimated LOCA frequencies with NUREG-1829 estimates (Section 4.1), investigates the time from detectable leakage to rupture (Section 4.2), investigates time from detectable leakage to LBLOCA (Section 4.3), and discusses these analyses in the context of Regulatory Guide 1.245 [15] (Section 4.4).

4.1 xLPR Estimation of LOCA Frequencies

This section discusses the approach taken to estimate LOCA frequencies, provides a comparison between xLPR LOCA frequency estimates and those presented in NUREG-1829, and includes discussion of the assumptions made.

4.1.1 Approach Taken to Estimate xLPR LOCA Frequencies

LOCA frequencies were computed using xLPR based on the probability of rupture output at 80 years. For cases applying the xLPR crack initiation models to determine the time to initiation for flaws prior to crack growth and rupture, the LOCA frequency over the 80-year period was calculated using the following equation:

$$LOCA\ freq = P(rupture)/80$$

This computation assumes that the LOCA frequency is constant over the 80-year time period. Furthermore, this computation assumes that LOCA and rupture are analogous events. These assumptions are further evaluated in Section 4.1.4 and Section 4.1.5.

For cases modeling initial flaws at the start of the simulation, the mean rupture probability for initial flaws was multiplied by the mean probability of crack initiation based on results of associated sensitivity cases - that is, the probability of rupture is estimated by the following equation:

$$P(rupture) \sim P(rupture \mid initiation) \times P(initiation)$$

where $P(rupture \mid initiation)$ is evaluated in the case modeling initial flaws, and $P(initiation)$ is evaluated in associated sensitivity studies modeling initiation. Use of this approximation, decoupling crack initiation and rupture, is advantageous as it allows for evaluation of results with lower probabilities without the need to run excessively large numbers of realizations in xLPR. Some of the cases evaluated in the xLPR Piping System Analysis and Generalization Study evaluated enough realizations in base cases modeling initiation, as well as cases modeling initial flaws, to investigate the impact of decoupling crack initiation and rupture in this manner. Comparison between these methods of evaluating LOCA frequencies is summarized in

Table 4-1. Note that other cases evaluated enough realizations to be considered in this comparison, but had no occurrences of circumferential crack initiation or occurrences of rupture in the base case and are therefore not included in this table. Overall, this comparison shows that the approximation decoupling crack initiation and rupture is reasonable, with results differing from the direct calculation by less than a factor of 2.5.

For cases where the 'occurrence of rupture' was greater than zero, but the 'occurrence of rupture with LRD' was zero, a 95% upper bound one-sided confidence interval was considered when calculating LOCA frequencies with LRD. This confidence interval was estimated using a binominal distribution, as defined in Table 4-2. This approach is described in NUREG/CR-7278, Section 4.3.6.4 [16] as a method for developing a one-sided confidence interval if no failures (e.g., no ruptures with LRD) are observed. This estimation considers the number of realizations executed and accounts for the probability of initiation. These values convey a level of confidence in the "zero" results, even though they are not based on direct modeling of physical phenomena.

Table 4-1
Comparison Between LOCA Frequencies Evaluated Using Initiation and Using Initial Flaws

Direct Calculation of LOCA Freq. for Cases Modeling Initiation			Calculation of LOCA Freq. by Decoupling Crack Initiation and Rupture				Ratio between LOCA Freq
Case Modeling Initiation	Mean Prob. of Rupture @80 yr	LOCA Freq.	Case Modeling Initial Flaws	Mean Prob. of Circ Flaw Initiation @80 yr (from Case Modeling Initiation)	Prob. of Rupture, Given Initiation @80 yr	LOCA Freq.	
Piping System Analysis 1.1.0	1.20E-3	1.50E-5	Piping System Analysis 1.1.1	3.32E-3	7.68E-1	3.12E-5	2.13
Piping System Analysis 1.3.0	8.36E-4	1.05E-5	Piping System Analysis 1.3.1	1.6E-3	7.50E-1	1.50E-5	1.44
Generalization Study 2.1.0	1.09E-4	1.36E-6	Generalization Study 2.1.1	1.2E-4	8.69E-1	1.30E-6	0.96

Table 4-2
Estimation of 95% Confidence Interval

<table>
<tr><th>Is There Rupture Without LRD?</th><th>Is There Rupture with LRD?</th><th>If the Case Models…</th><th>Then the 95% Upper Bound, Given n Realizations Run, Is Equal to</th></tr>
<tr><td rowspan="3">Yes</td><td rowspan="2">No</td><td>Crack Initiation</td><td>$(1 - 0.05^{1/n})/80$</td></tr>
<tr><td>Initial Flaws</td><td>$P(crack) \times \left(1 - 0.05^{1/n}\right)/80$
where $P(crack)$ is based on an associated case modeling initiation</td></tr>
<tr><td>Yes</td><td colspan="2">Not applicable</td></tr>
<tr><td>No</td><td colspan="3">Not applicable</td></tr>
</table>

4.1.2 Comparison of xLPR LOCA Frequency Estimates with NUREG-1829

As noted in Section 3.4.1 and Section 3.4.2, xLPR provides several versions of the rupture output, including the ‘occurrence of rupture’ (conservatively not crediting ISI or LRD, essentially modeling 80 years of plant operation with no operator intervention), ‘occurrence of rupture with LRD’ (considering leak rate detection but not in-service inspection), ‘occurrence of rupture with ISI’ (considering in-service inspection but not leak rate detection), and ‘occurrence of rupture with ISI and LRD’ (considering both leak rate detection and in-service inspection, and thus most representative of actual plant operation for Alloy 82/182 dissimilar metal welds).

Figure 4-1 shows xLPR LOCA frequencies at 80 years (for all xLPR cases evaluated and listed in Table 3-3) calculated using the ‘occurrence of rupture’ output (i.e., without crediting ISI and LRD), compared with LOCA frequencies from NUREG-1829 at 40 years (further discussion of LOCA frequencies for various plant operating durations is provided in Section 2.1.3). All xLPR cases evaluated and listed in Table 3-3 with a nonzero ‘occurrence of rupture’ output are plotted in Figure 4-1. Without crediting ISI or LRD in the xLPR results, the predicted LOCA frequencies are significantly higher than the NUREG-1829 estimates, which do take credit for typical ISI and for LRD as required by plant Technical Specifications. It is noted that in addition to not considering ISI or LRD, many of the components modeled in the xLPR Piping System Analysis and xLPR Generalization Study conservatively considered unmitigated components at high temperatures. Although some unmitigated components do exist, a notable fraction of components at hot leg temperature and all components at pressurizer temperature are now mitigated, as shown in Figure 4-2. Thus, modeling unmitigated components at pressurizer or hot leg temperature is conservative relative to the situation for currently operating PWRs. However, the results in NUREG-1829 also do not consider mitigation in the PWR LOCA frequency estimates (as a larger fraction of components was unmitigated at the time NUREG-1829 was developed). Considering these factors, these xLPR LOCA frequency estimates without crediting ISI or LRD are very conservative and thus considered not realistic, but do provide important context for comparison when later crediting ISI or LRD. All cases represented in Figure 4-1 are cases modeling crack growth due to PWSCC – cases with crack growth due to only fatigue showed no leaks or ruptures.

Figure 4-3 shows a comparison between the xLPR LOCA frequencies (for all xLPR cases evaluated and listed in Table 3-3) crediting LRD (but not crediting ISI) and LOCA frequencies from NUREG-1829. For most of the xLPR cases, the ‘occurrence of rupture with LRD’ is zero and these data are plotted per the one-sided confidence interval method (described in Section 4.1.1). The green arrows in Figure 4-3 indicate that the plotted values are the upper bound confidence intervals, which would be lower if additional realizations were evaluated and the ‘occurrence of rupture with LRD’ remained to be zero. The three cases with nonzero ‘occurrence of rupture with LRD’ values are shown explicitly. Overall, when LRD is credited and the 95% upper bound estimation is considered, the LOCA frequency estimates are on a similar order of magnitude as, or slightly higher than, NUREG-1829 LOCA frequency estimates.

When ISI is also considered for the three cases with nonzero ‘occurrence of rupture with LRD,’ as shown in Figure 4-4, the xLPR-estimated LOCA frequencies decrease by about two orders of magnitude, and are then on a similar order of magnitude as the LOCA frequencies from

NUREG-1829. It is noted that the few cases with ruptures with ISI and LRD are cases that model scenarios that are not representative of plant conditions and operations, as further discussed in Section 4.2.1.2. Furthermore, all cases with ruptures with ISI and LRD are sensitivity cases.

Cases which already had a zero 'occurrence of rupture with LRD' similarly have a zero 'occurrence of rupture with ISI and LRD.' The 95% upper bound estimation is based on the number of realizations run, and thus the same between the 'occurrence of rupture with LRD' and 'occurrence of rupture with ISI and LRD' results. Thus, as these cases with a zero 'occurrence of rupture with LRD' are already plotted in Figure 4-3, they are not repeated in Figure 4-4.

As xLPR analysis results are provided on a per-weld basis, the xLPR Generalization Study [9] also included an assessment of system-level failure frequencies. However, as all base case probabilities of rupture with 1 gpm LRD were zero through 80 years, it was concluded that the plant level probabilities of rupture with 1 gpm LRD could also be taken as zero.

Overall, the benchmarking shows that the LOCA frequency estimates from the xLPR analyses and NUREG-1829 are of a similar order of magnitude, which increases confidence in both the xLPR and NUREG-1829 results.

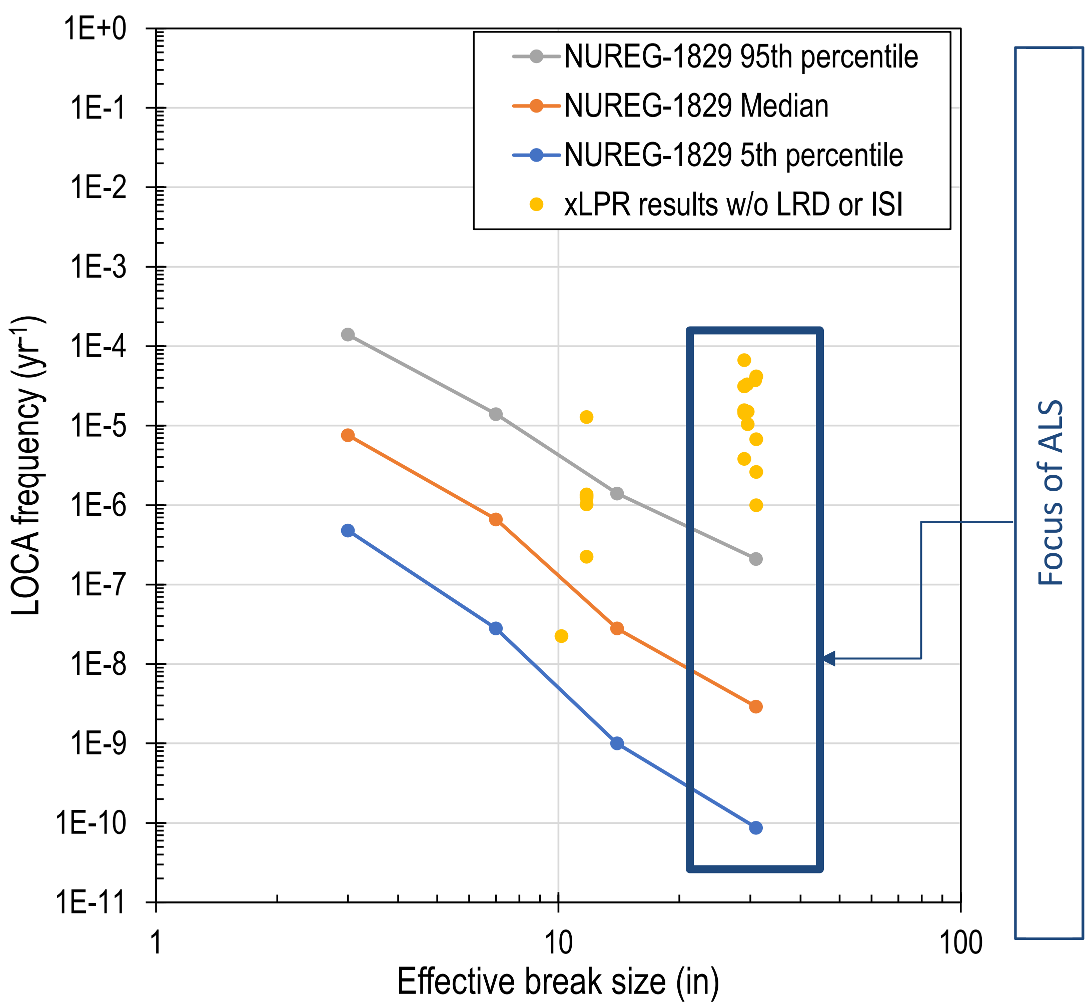

Figure 4-1
xLPR LOCA Frequency Without ISI or LRD Compared to NUREG-1829 Table 1

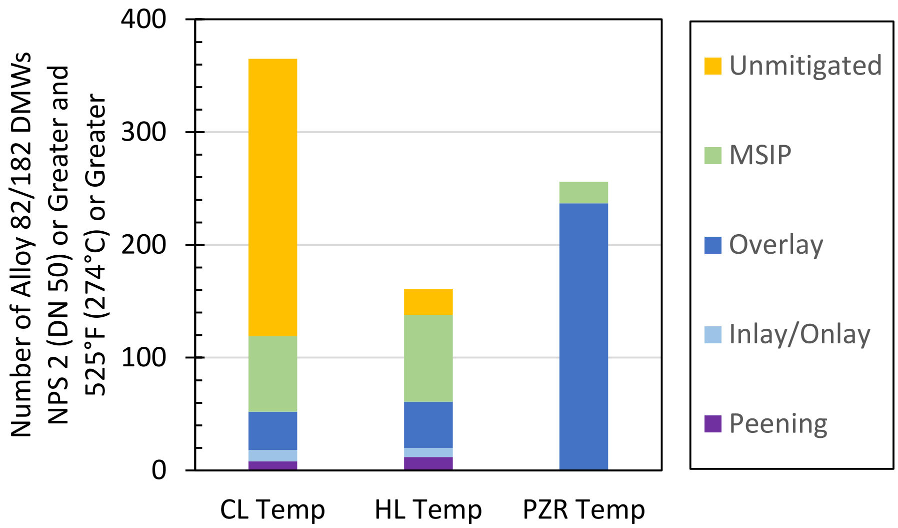

Figure 4-2
Summary of Mitigation Status for Alloy 82/182 DMWs

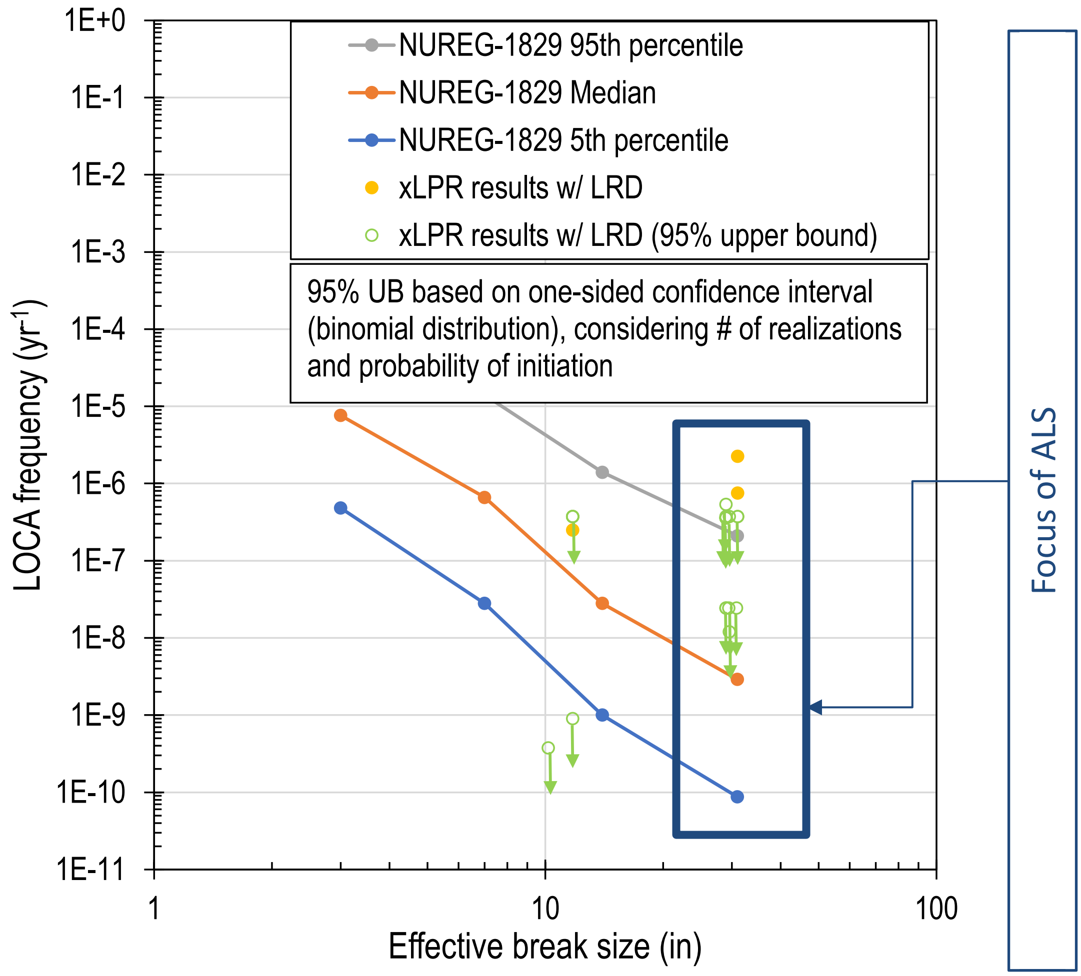

Figure 4-3
xLPR LOCA Frequency Considering LRD (but not ISI) Compared to NUREG-1829 Table 1

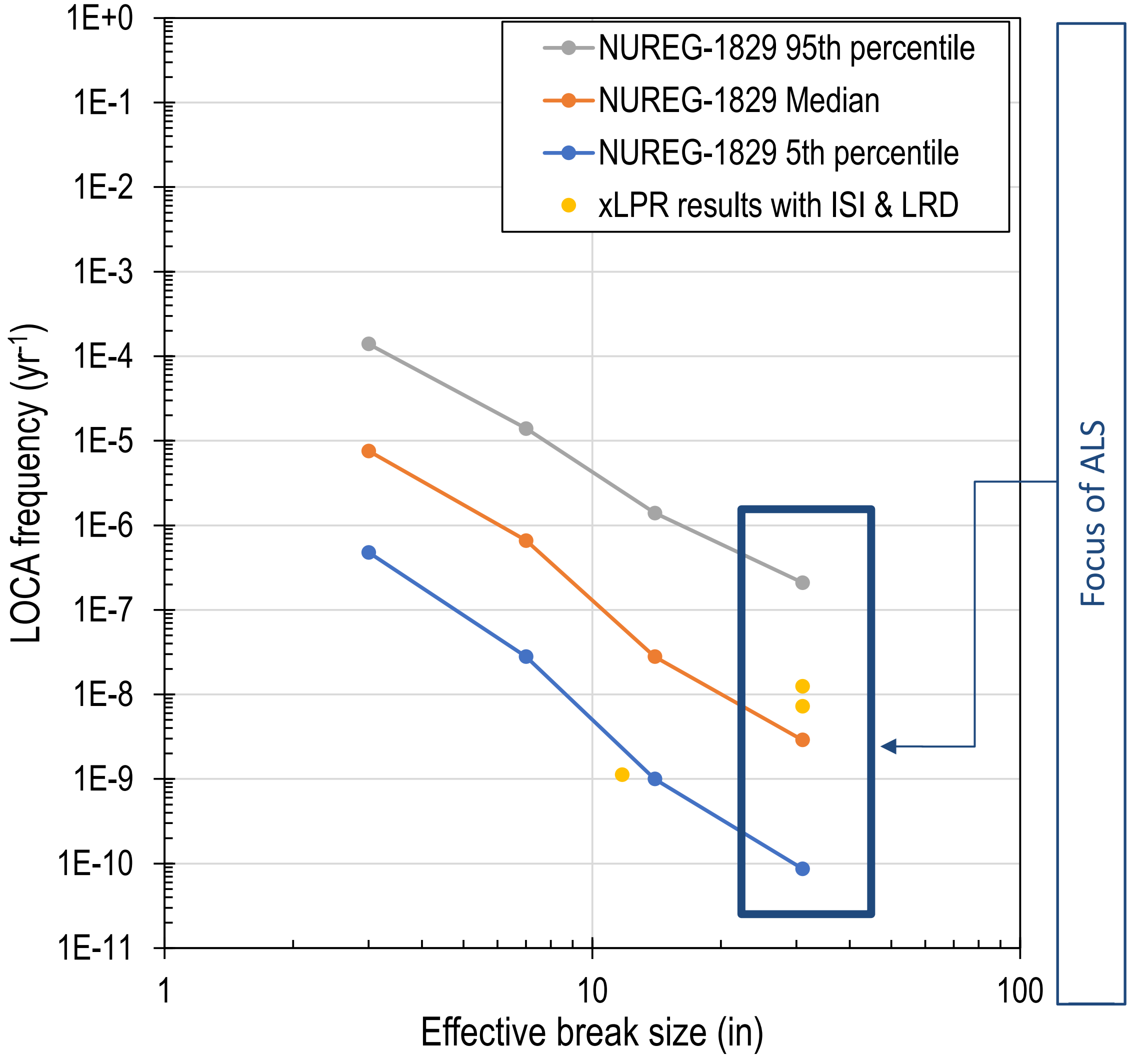

Figure 4-4
xLPR LOCA Frequency Considering LRD and ISI Compared to NUREG-1829 Table 1

4.1.3 Investigation of 95% Upper Bound Confidence Intervals

As stated in Section 4.1.1, 95% upper bound confidence intervals are calculated for cases where xLPR calculates an 'occurrence of rupture' (i.e., without crediting ISI and/or LRD) greater than zero, but an 'occurrence of rupture with LRD' of zero. It is noted that the 95% upper bound confidence intervals for the probability of rupture with LRD are greater than the median values for many cases from NUREG-1829. This is because the 95% upper bound confidence interval values are primarily based on the number of realizations executed in xLPR. If more realizations were executed and still no cases showed rupture with LRD, then these 95% upper bound estimates would be lower. The number of realizations required such that the 95% upper bound confidence interval would be equal to the median and 95th percentile LOCA frequencies in NUREG-1829 is shown in Table 4-3, and further detailed in Figure 4-5. Executing the number of realizations required to equal the median LOCA frequency for each case in xLPR is impractical, particularly for the larger line sizes.

To assess the impact of increasing the realization count on potentially identifying ruptures with LRD, one case was re-run in xLPR with one million (1E6) realizations. The selected case was xLPR Piping System Analysis Case 1.1.6, modeling the RVON with axial and circumferential flaws. The results, as well as the corresponding 95% upper bound confidence interval are summarized in Table 4-4. There are no significant changes to the results between 70,000 realizations and one million realizations, demonstrating convergence in those results. Furthermore, no ruptures with LRD were observed even for one million realizations.

Table 4-3
Realizations Required for 95% Confidence Interval Upper Bound to Equal NUREG-1829 Median

Effective Pipe Break Size (in)	NUREG-1829 Median LOCA Frequency (yr^{-1})	Number of Realizations for Median LOCA Frequency	NUREG-1829 95th Percentile LOCA Frequency (yr^{-1})	Number of Realizations for 95% Percentile LOCA Frequency	Notes
7	6.6E-7	~56,000	1.4E-5	~3,000	-
14	2.8E-8	~1,340,000	1.4E-6	~27,000	-
31	2.9E-9	~12,900,000	2.1E-7	~180,000	Focus of ALS

Table 4-4
Comparison of Results with 1E6 Realizations

Realization Count	Mean 'Occurrence of Crack' @80 yr	Mean 'Occurrence of Leak' @80 yr	Mean 'Occurrence of Rupture' @80 yr	Mean 'Occurrence of Rupture with LRD' @80yr	LOCA Frequency Based on 95% Upper Bound One-Sided Confidence Interval
70,000 (xLPR Piping System Analysis Case 1.1.6)	8.07E-3	4.03E-3	1.27E-3	0	5.3E-7 yr^{-1}
1,000,000 (Further investigation)	8.17E-3	4.11E-3	1.34E-3	0	3.7E-8 yr^{-1}

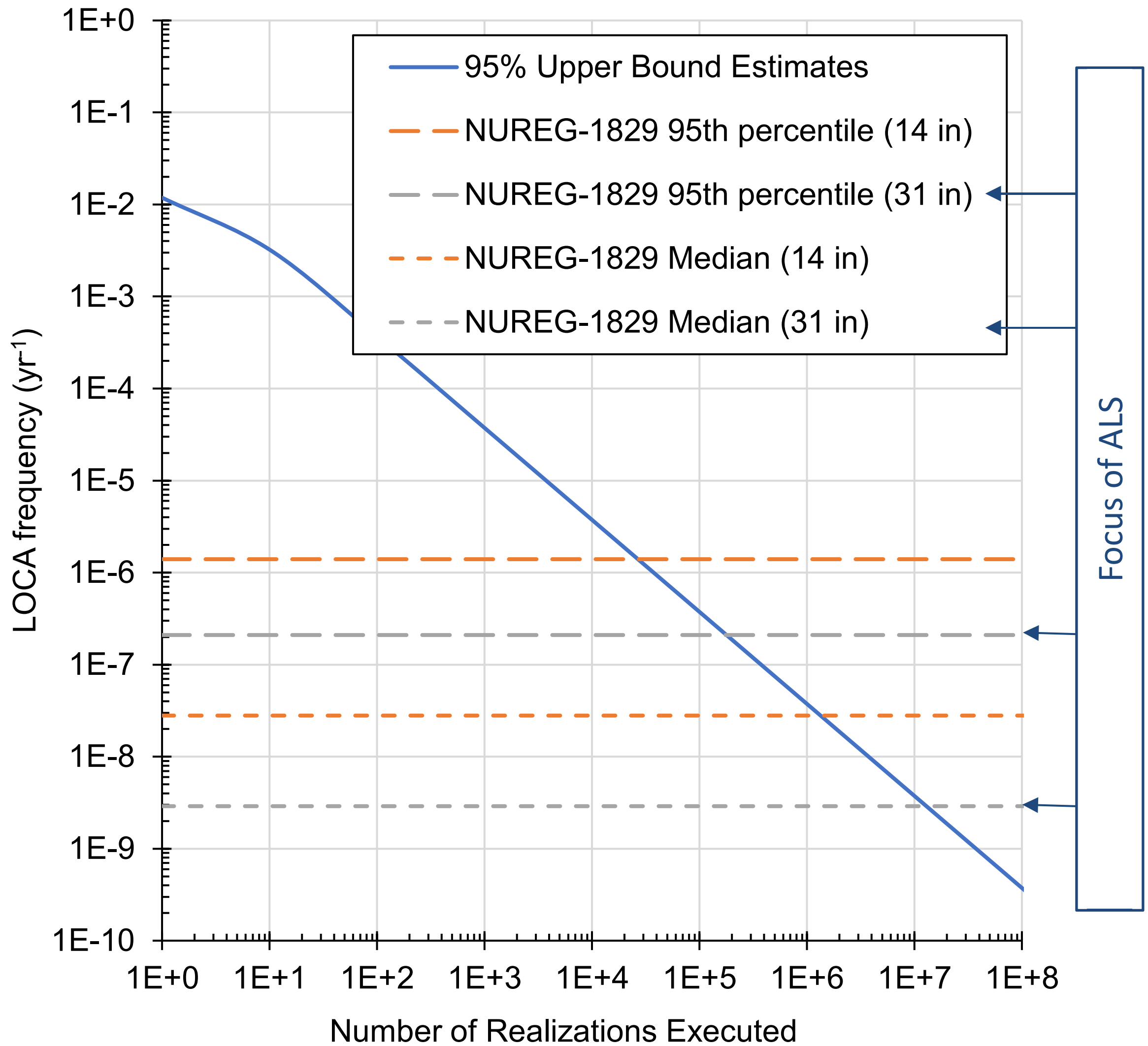

Figure 4-5
Number of Realizations Required to Obtain 95% Upper Bound Equal to NUREG-1829 LOCA Frequency Estimates

4.1.4 Approximation of LOCA Frequency as Constant

As noted in Section 4.1.1, the 80-year LOCA frequency is approximated from the 80-year ‘occurrence of rupture’ output (taken as analogue to occurrence of LOCA – see Section 4.1.5) assuming the frequency to be constant over that time horizon. This section investigates the assumption of a constant LOCA frequency over the 80-year period relative to more granular reporting of LOCA frequencies (i.e., reported per decade).

For this investigation, LOCA frequencies were calculated per decade (that is, looking at results in 10-year blocks) for a subset of xLPR analysis cases performed, as shown in Table 4-5. This subset of fifteen cases includes all cases that had ruptures with LRD, base cases that had ruptures, as well as sensitivity studies that had ruptures when modeling initial flaws. The cases in

Table 4-5 represent approximately 20% of all cases in this study, covering a breadth of lines and modeling scenarios, providing insights which are considered generally applicable. Table 4-5 lists the highest per-decade LOCA frequency for each of the cases considered in this assumption investigation (computed based on ruptures with LRD for the three cases with nonzero occurrence of rupture with LRD and computed based on ruptures without LRD for the remaining cases listed in Table 4-5) and displays the ratio of the highest per-decade LOCA frequency for each case to the uniform 80-year LOCA frequency.

Two cases with mitigation had a difference in 80-year and highest 10-year LOCA frequency that was a factor of 7 or greater. In Generalization Study Case 2.1.3, only two ruptures with LRD occurred, both of which occurred after overlay mitigation and in the same 10-year period. The flaws that led to these ruptures would both be highly likely to have been detected with in-service inspection. In Generalization Study Case 4.1.3, all ruptures occurred prior to overlay mitigation at 20 years. There are no remaining unmitigated steam generator inlet nozzles in the U.S. PWR fleet. Although the differences between 80-year and highest 10-year LOCA frequencies are greater for these two cases, these cases model situations not representative of current plant operating conditions. As a result, the differences between 80-year and highest 10-year LOCA frequencies for Generalization Study Case 2.1.3 and Generalization Study Case 4.1.3 are not considered to be significant.

Two cases modeling initial flaws had a difference in 80-year and highest 10-year LOCA frequency that was between a factor of 3 and a factor of 4 – Generalization Study Cases 3.1.1 and 5.2.1. These cases exhibit exceptionally low crack growth rates, which leads to ruptures being concentrated close to the end of the simulation, as Generalization Study Cases 3.1.1 and 5.2.1 model welds at cold leg temperature. Furthermore, Generalization Study Cases 3.1.1 and 5.2.1 model scenarios in which the probability of crack initiation was found to be zero in the associated base cases. Therefore, the differences in 80-year and highest 10-year LOCA frequencies identified in Generalization Study Cases 3.1.1 and 5.2.1 are not considered to be significant.

The remaining cases in Table 4-5 have ruptures distributed relatively evenly over time, with 80-year LOCA frequency and highest 10-year LOCA frequency within a factor of 3. Thus, the approximation of LOCA frequency as constant over the 80-year plant operating period is not considered to be significant.

Table 4-5
Maximum LOCA Frequency Decades

Case	Decade with Highest LOCA Frequency	Ratio of Highest 10-Year Average to 80-year Average	xLPR Output Used for Comparison	Note
Re-run of Piping System Analysis 1.1.6 (1E6 realizations)	70-80 yrs	1.82	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3)
Piping System Analysis 1.1.1	30-40 yrs	1.50	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3)
Piping System Analysis 1.1.2	60-70 yrs	2.00	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3)
Generalization Study 2.1.0	20-30 yrs	2.67	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3, and only 12 ruptures occurred)
Generalization Study 2.1.1	10-20 yrs	2.21	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3), and modeled initial flaws with high crack growth rates (unmitigated weld at pressurizer temperature)
Generalization Study 2.1.2	10-20 yrs	1.41	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3)
Generalization Study 2.1.3	70-80 yrs	8.00	'Occurrence of rupture with LRD'	Only two ruptures with LRD occurred, both in the final 10 years
Generalization Study 2.1.4	60-70 yrs	2.18	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3, and only 11 ruptures occurred)
Generalization Study 3.1.1	70-80 yrs	3.31	'Occurrence of rupture'	Modeled initial flaws at cold leg temperature, and no crack initiation occurred in base case
Generalization Study 4.1.1	10-20 yrs	1.87	'Occurrence of rupture with LRD'	Difference not considered to be significant (less than factor of 3), and no ruptures occurred when smaller initial flaws were considered (Section 4.2.1.2)
Generalization Study 4.1.2	70-80 yrs	2.91	'Occurrence of rupture with LRD'	Difference not considered to be significant (less than factor of 3, and only 11 ruptures occurred), and no ruptures occurred when smaller initial flaws were considered (Section 4.2.1.2)
Generalization Study 4.1.3	10-20 yrs	7.03	'Occurrence of rupture'	Mitigation modeled at 20 yrs, with no ruptures occurring after mitigation

Table 4-5 (continued)
Maximum LOCA Frequency Decades

Case	Decade with Highest LOCA Frequency	Ratio of Highest 10-Year Average to 80-year Average	xLPR Output Used for Comparison	Note
Generalization Study 4.1.4	60-70 yrs	2.81	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3)
Generalization Study 5.1.1	70-80 yrs	2.00	'Occurrence of rupture'	Difference not considered to be significant (less than factor of 3)
Generalization Study 5.2.1	70-80 yrs	3.78	'Occurrence of rupture'	Modeled initial flaws at cold leg temperature, and no crack initiation occurred in base case.

4.1.5 Use of Rupture as Analogue for LOCA

Although xLPR does include an 'occurrence of LBLOCA' output and considers any through-wall crack leakage greater than a certain user-defined value (5,000 gpm, 19,000 lpm by default) to be a LBLOCA, this output was not retained in the xLPR Piping System Analysis and xLPR Generalization Study run results to optimize the use of memory. Thus, in development of xLPR-based LOCA frequencies within this current study, 'occurrence of rupture' was used as an analogue for 'occurrence of LBLOCA.' This simplifying assumption allowed leveraging the prior work from the xLPR Piping System Analysis and the xLPR Generalization Study. To investigate the impact of applying rupture as an analogue for a LBLOCA, xLPR Piping System Analysis Case 1.1.6 was re-run with 20,000 realizations (that is, 29% of the number of realizations evaluated for this case within the xLPR Piping System Analysis), resulting in 30 realizations with rupture occurring, enough for comparing LBLOCA and rupture results. The results showed that every realization which had an 'occurrence of LBLOCA' also had an 'occurrence of rupture.' As such, it was judged appropriate to consider the 'occurrence of LBLOCA' and 'occurrence of rupture' outputs at 80 years as equivalent for purposes of computing LOCA frequencies for main loop piping welds such as the RVON. However, the 'occurrence of rupture' and 'occurrence of LBLOCA' do not necessarily occur in the same time step. This is because LBLOCA is calculated based on leak rate (5,000 gpm,19,000 lpm), which may occur prior to rupture which is determined based on crack stability calculations. Thus, rupture and LBLOCA cannot be treated as equivalent in lapse times. The time from detectable leakage to rupture is investigated in detail in Section 4.2, with time from detectable leakage to LBLOCA investigated in detail in Section 4.3.

For line sizes too small to result in a LBLOCA, application of rupture as an analogue for a LOCA is done for convenience. This assumption was investigated using xLPR Generalization Study Case 2.1.1, which modeled an NPS 14 (DN 350) line, re-run with 1,000 realizations. Through use of the initial flaw model, this provided over 200 realizations with rupture occurring, considered more than sufficient for comparing LOCA and rupture results. The comparison showed that every realization with 'occurrence of rupture' also had 'occurrence of small-break LOCA' (100 gpm, 380 lpm by default), but only about 60% of realizations with 'occurrence of rupture' had 'occurrence of medium-break LOCA' (1,500 gpm, 5,700 lpm by default). Even though rupture of an NPS 14 (DN 350) pipe should lead to a medium-break LOCA, the final leak rate is calculated in the time step prior to rupture, so it is possible for xLPR to report no medium-break LOCA. In a larger line size, this similarly could lead to a LBLOCA occurring without being reported. The findings from this investigation further support use of ‘occurrence of rupture’ instead of xLPR-calculated LOCA outputs in evaluating the LOCA frequency.

4.2 Time from Detectable Leakage to Rupture

The time between detectable leakage and rupture was calculated, considering a 1 gpm detectable leak rate threshold, for all realizations ending in rupture within each base or sensitivity case. These results were reviewed for further context and to identify xLPR analysis cases and individual realizations warranting further investigation, which are discussed in Section 4.2.1. Results for the time from detectable leakage to LOCA are discussed in Section 4.3. It is also worth noting that the time steps applied in most of the xLPR analyses (1 month) are substantially longer than typical response times required in plant Technical Specification leakage monitoring programs.

Figure 4-6 shows the minimum times (i.e., for the most limiting realization within a given case analyzed) and Figure 4-7 shows the mean (with error bars equal to standard error) times from detectable leakage to rupture for all xLPR realizations by case (base and sensitivity) analyzed that had ruptures. For all base and most sensitivity cases considered, the minimum observed times from 1 gpm detectable leakage to rupture exceeded three months. Cases with minimum times from detectable leakage to rupture under three months considered unmitigated welds subject to PWSCC growth at hot leg or pressurizer temperatures or included modeling not representative of plant conditions and operations. All cases with minimum times from 1 gpm detectable leakage to rupture below three months are documented in the xLPR Generalization Study TLR and xLPR Piping System Analysis TLR and are further investigated and dispositioned in Section 4.2.1. All these cases are sensitivity cases, with inputs selected to investigate factors known to influence xLPR results and were not otherwise constrained to be a good representation of realistic plant conditions. For the base cases that are most relevant to the ALS (i.e., the primary loop reactor coolant system piping), the minimum time (i.e., for the most limiting realization) from detectable leakage to rupture was 14 months.

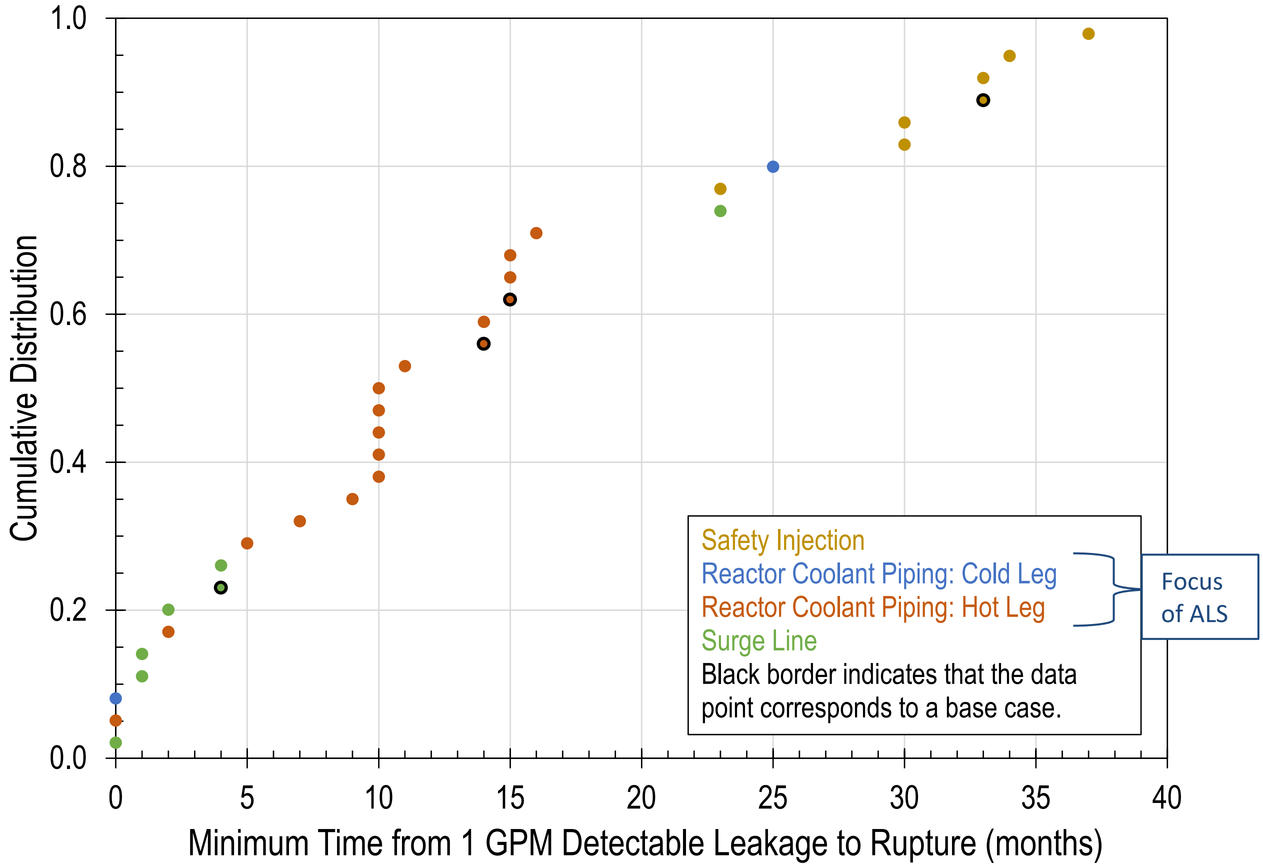

Figure 4-6
Minimum Times from Detectable Leakage to Rupture

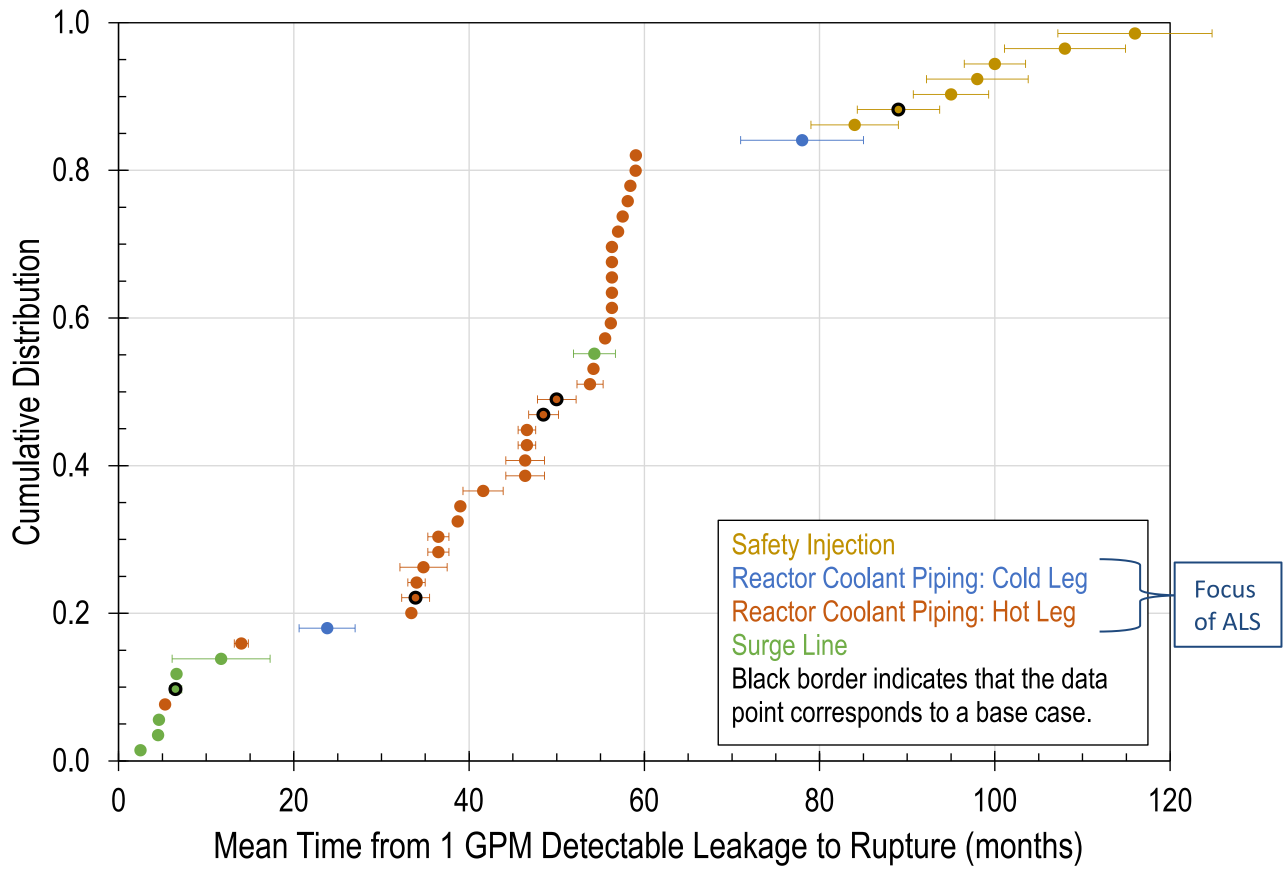

Figure 4-7
Mean Times from Detectable Leakage to Rupture

4.2.1 xLPR Cases Warranting Further Investigation

Several sensitivity cases from the xLPR Piping System Analysis and xLPR Generalization Study, listed in Table 4-6, warrant further investigation. There are three general situations that represent these cases:

- Cases where the minimum time from detectable leakage to rupture is greater than or equal to one month but less than three months, where the precision of the minimum time may be influenced by the length of the time steps applied in the analysis.
- Cases where modeling is sufficiently unrealistic that updated input selection or alternative outputs may need to be considered to better assess short lapse-time significance.
- Cases where the minimum time from detectable leakage to rupture is less than one month, but the probability of rupture with leak rate detection is zero.

This section discusses more specific details of these cases. It is noted that these cases all consider more severe conditions than the associated base cases. This further effort revisits input or modeling assumptions made in the xLPR Piping System Analysis and xLPR Generalization study, and more closely investigates intermediate variables and outputs within those individual realizations to provide additional insight.

Table 4-6
Limiting Times from Detectable Leakage to Rupture

Case	Description	Mean Rupture Freq. (yr^{-1})	Mean Rupture Freq. w/ LRD (yr^{-1})	Min Time from 1 gpm Leakage to Rupture (months)	Comments
xLPR Piping System Analysis 1.1.2 *Focus of ALS*	RVON severe WRS	1.54E-5	0	1	Short minimum time from detectable leakage to rupture warrants further investigation with shorter xLPR time steps.
xLPR Generalization Study 2.1.1	PZR surge initial flaw	1.30E-6	0	2	
xLPR Generalization Study 2.1.2	PZR surge severe WRS	1.29E-5	0	1	
xLPR Generalization Study 2.1.3	PZR surge w/ overlay	1.03E-6	2.5E-7	0	Unrealistic modeling: xLPR Generalization Study states that application of the overlay is the cause of these ruptures.
xLPR Generalization Study 2.1.4	PZR surge w/ fatigue	1.25E-6	0	1	Short minimum time from detectable leakage to rupture warrants further investigation with shorter xLPR time steps.
xLPR Generalization Study 4.1.1 *Focus of ALS*	SGIN initial flaw	1.00E-6	7.5E-7	N/A	Unrealistic modeling: ruptures associated w/ flaws initiating deeper than Alloy 52 inlay material. xLPR Generalization Study states that the nature of these ruptures makes the distribution of times from detectable leakage to rupture irrelevant.
xLPR Generalization Study 4.1.2 *Focus of ALS*	SGIN severe WRS	2.63E-6	2.25E-6	N/A	
xLPR Generalization Study 4.1.3 *Focus of ALS*	SGIN overlay mitigation	4.16E-5	0	0	Cases show 0-month time from detectable leakage to rupture but 0 rupture frequency w/ LRD. As noted in the NRC TLRs, the minimum times are greater than zero when considering only normal operating loads (that is, non-probabilistically treated seismic loads are not included).
xLPR Generalization Study 4.1.4 *Focus of ALS*	SGON no mitigation	6.75E-6	0	0	

4.2.1.1 Cases With Short Times from Detectable Leakage to Rupture

The four cases with time from detectable leakage to rupture of at least one month but less than three months were xLPR Piping System Analysis Case 1.1.2 as well as xLPR Generalization Study Cases 2.1.1, 2.1.2, and 2.1.4. These cases all model unmitigated welds at pressurizer or hot leg temperature. In these cases, the minimum time (i.e., for the most limiting realization) from 1 gpm leakage to rupture is short, and the precision of these results may be influenced by the xLPR time step.

Figure 4-8 shows the leak rate history for the realization with the limiting time from 1 gpm leakage to rupture for xLPR Piping System Analysis Case 1.1.2. In this realization, the first time step with leakage in excess of 1 gpm is at 885 months, and the rupture occurs at 887 months. The last month with a meaningful reported leak rate is 886 months. If the leak rate history was plotted continuously, 1 gpm leak rate would occur sometime between 884 and 885 months, and rupture would occur somewhere between 886 and 887 months. By computing the lapse time based only on the number of whole time steps between 1 gpm leakage and rupture, the reported lapse time is a lower bound, so this approach conservatively interprets the data. However, since the time step modeled in xLPR is one month, it is necessary to investigate the effect of using a shorter time step on these results.

The limiting realization from Piping System Analysis Case 1.1.2 (a sensitivity case modeling an unmitigated reactor vessel outlet nozzle with a severe weld residual stress profile) was re-run with time steps of 0.2 and 0.05 month (~6 and 1.5 days respectively). Even though the time from 1 gpm leakage to rupture was calculated as at least one month based on the results with one month time steps, the minimum lapse time was slightly lower than one month for shorter timesteps – 0.8 month with a 0.2-month time step, and 0.85 month with a 0.05-month time step. As shown in Figure 4-9, reducing the time step duration has minimal impact on results until within 12 months of rupture, when crack growth rates are highest. The crack growth results with the time steps of 0.2 and 0.05 month shown in Figure 4-9 are in close agreement during the period of greater acceleration of crack growth immediately prior to rupture, but the results for the 1-month time step are not in close agreement. Thus, a time step of 0.2 month is judged appropriate to provide a reasonable estimate of the minimum time from detectable leakage to rupture for cases with low minimum times from detectable leakage to rupture. These realizations with short times from detectable leakage to rupture are the only scenarios identified where reduced time steps provide further insight. The differences identified with the reduced timesteps would have negligible or no impact on probabilities of crack initiation, leakage, or rupture, or on realizations with longer time from detectable leakage to rupture.

Based on these findings, the limiting realizations (all realizations with time from detectable leakage to rupture of less than 3 months) in xLPR Generalization Study Cases 2.1.1, 2.1.2, and 2.1.4 were also re-run with a time step of 0.2 month to improve accuracy and precision of the reported time from detectable leakage to rupture. As a result of findings discussed in Section 4.2.1.3, Generalization Study Case 4.1.4 was also re-run with a time step of 0.2 month.

The results with reduced time step durations are summarized in Table 4-7. The shortest reported times from detectable leakage to rupture are 0.8 month (~24 days) in Piping System Analysis Case 1.1.2 and 0.6 month (~18 days) in Generalization Study Case 2.1.2. Both cases modeled more severe weld residual stresses in an unmitigated weld at hot leg (Piping System Analysis Case 1.1.2) and pressurizer (Generalization Study Case 2.1.2) temperatures. While a minority of

PWSCC-susceptible components at hot leg temperature are unmitigated, all such components at pressurizer temperature are mitigated, as shown in Figure 4-2. So, while Piping System Analysis Case 1.1.2 models a scenario that is extreme but still plausible, Generalization Study Case 2.1.2 models a scenario that is not representative of components present in the currently operating U.S. PWR fleet.

Table 4-7
Summary of Short Times from Detectable Leakage to Rupture with Reduced Timestep (see Section 4.2.1.1)

Case	# of Realizations with Time from Detectable Leakage to Rupture <3 months	Minimum Time from Detectable Leakage to Rupture with 1-month Timestep (months)	Minimum Time from Detectable Leakage to Rupture with 0.2-month Timestep (months)
xLPR Piping System Analysis 1.1.2 *Focus of ALS*	8	1	0.8
xLPR Generalization Study 2.1.1	17	2	2.4
xLPR Generalization Study 2.1.2	16	1	0.6
xLPR Generalization Study 2.1.4	6	1	1.2
xLPR Generalization Study 4.1.4 *Focus of ALS*	1	2	2.8

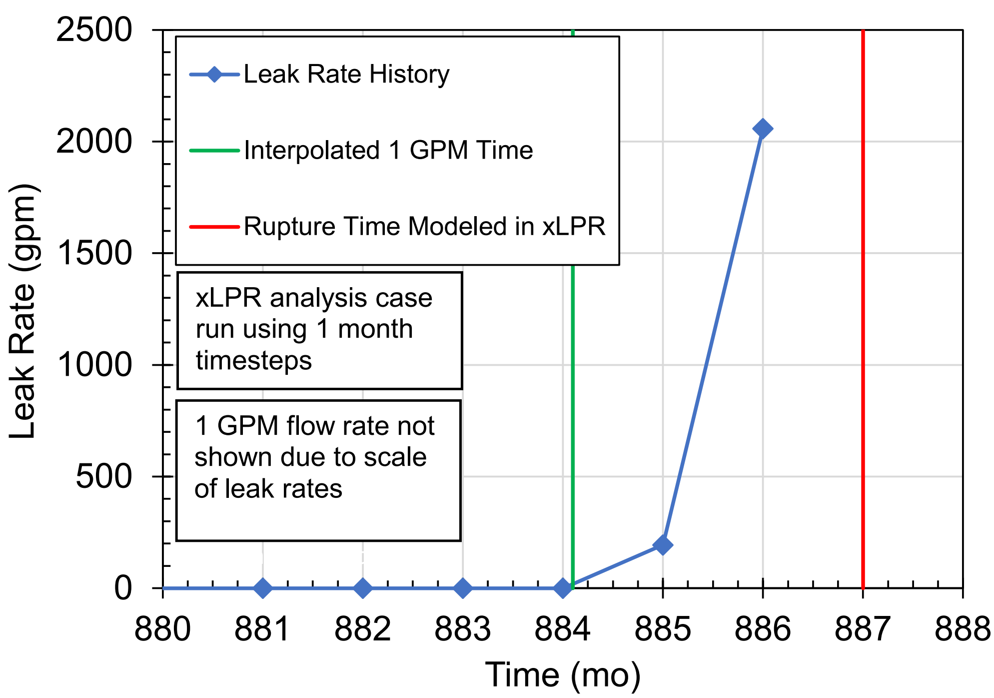

Figure 4-8
Leak Rate History for xLPR Piping System Analysis Case 1.1.2 Limiting Realization

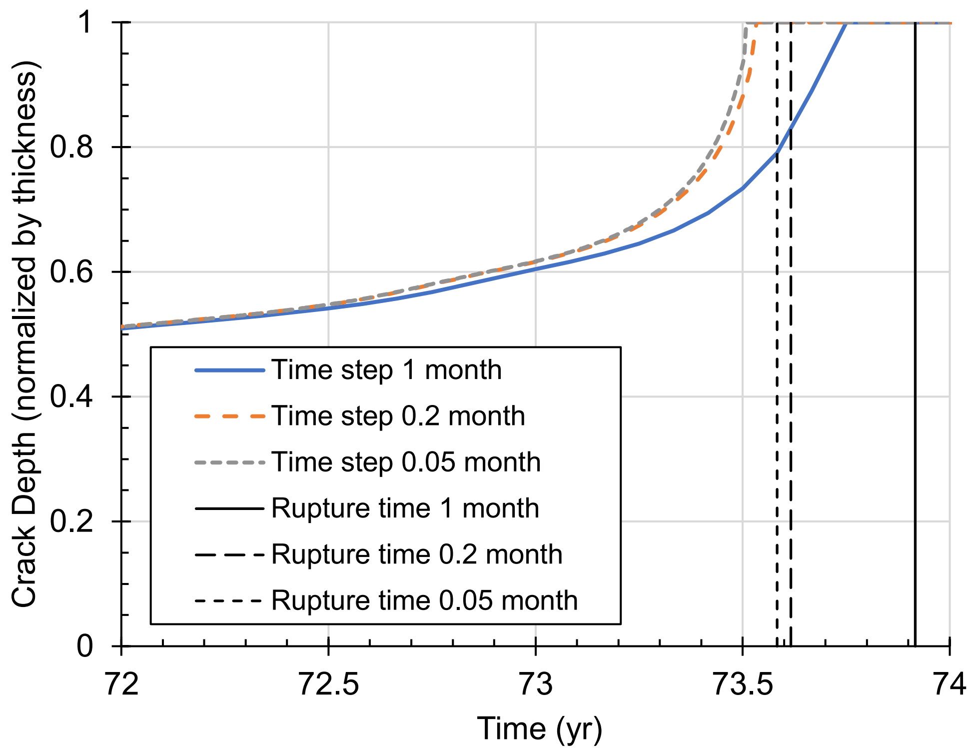

Figure 4-9
Effect of Time Step Refinement on Crack Depth (xLPR Piping System Analysis Case 1.1.2)

4.2.1.2 Cases With Unrealistic Modeling

xLPR Generalization Study Case 2.1.3 modeled a pressurizer surge nozzle with a weld overlay and included two realizations that had ruptures with leak rate detection. One realization included a surface crack rupture, and in the other realization rupture occurred as soon as the crack grew through-wall. The treatment of the weld overlay in xLPR causes crack growth to slow in the depth direction due to the overlay, but crack growth in the length direction may continue at an unchanged rate. As a result of the sampled input sets for these two realizations, these flaws become very long and cause rupture quickly before or immediately after growing through-wall. However, it takes a long time for such cracks to substantially grow into or through-wall through the Alloy 52 weld overlay material. In both cases, the flaw length at the inner diameter exceeded 50% of the inner diameter 10 years prior to rupture, so in-service inspections would be highly likely to detect the flaw, further reducing the probability of rupture when crediting ISI.

xLPR Generalization Study Cases 4.1.1 and 4.1.2 both had a significant frequency of rupture with leak rate detection, caused by similar phenomena for both cases. The xLPR Generalization Study noted that these cases were influenced by the distribution used for the initial flaw depth (for Generalization Study Case 4.1.1, which modeled initial flaws) and PWSCC initiation flaw depth (for Generalization Study Case 4.1.2, which modeled PWSCC flaw initiation), and that about 1.6% of these flaws would be deeper than or within 0.1 mm of the depth of the inlay. While crack growth rates in the Alloy 52 inlay are reduced, crack growth in the Alloy 82/182 weld material is more rapid. Transitioning through-wall flaws are modeled using a trapezoidal shape in xLPR with different inner and outer flaw lengths. As a result, flaws that initially grow through the inlay depth and subsequently grow to become transitioning through-wall flaws exhibit a small opening on the inside diameter and a large opening on the outside diameter, as illustrated in Figure 4-10. These flaws are modeled to have low leak rates because of their small inside diameter crack opening areas, but the outside diameter crack length can grow to the full circumference, leading to rupture at low leak rates. Flaw shapes built in to xLPR include semi-elliptical surface flaw, trapezoidal transitioning through wall flaw, and idealized through wall flaw geometries defined based on inner half-length and depth, as well as outer half-length for through-wall flaws. However, finite element analyses ([17], [18]) show that this scenario, with a flaw growing through an Alloy 52 inlay into an Alloy 82/182 base metal, would lead to balloon-shaped flaws rather than trapezoidal flaws as modeled in xLPR. Thus, xLPR Generalization Study Case 4.1.1 and 4.1.2 model situations that cannot be modeled representatively with the current flaw shape assumptions built in to xLPR.

The xLPR Generalization Study suggested that "it's possible that a more realistic initial crack depth would lead to the disappearance of, or strong reduction in, the rupture events" [9]. NRC has approved alternate inspection intervals for steam generator inlet nozzles based on a deterministic approach that used an initial inside surface flaw of 50% of the inlay depth [19], so an initial flaw depth with flaw sizes distributed uniformly between 40% and 60% of inlay depth (1.32 mm, 1.1% through-wall to 1.98 mm, 1.6% through-wall) was used for a re-run of Generalization Study Cases 4.1.1 and 4.1.2. In the re-run of Generalization Study Case 4.1.1, no ruptures were observed, leakage only occurred through axial flaws, and the deepest circumferential flaw at 80 years was 42% through-wall. In the re-run of Generalization Study Case 4.1.2, no leaks or ruptures were observed, and the deepest circumferential flaw at 80 years was 40% through-wall. Thus, after analysis with revisited initial crack depth inputs, no ruptures occurred for the re-run Generalization Study Cases 4.1.1 and 4.1.2.

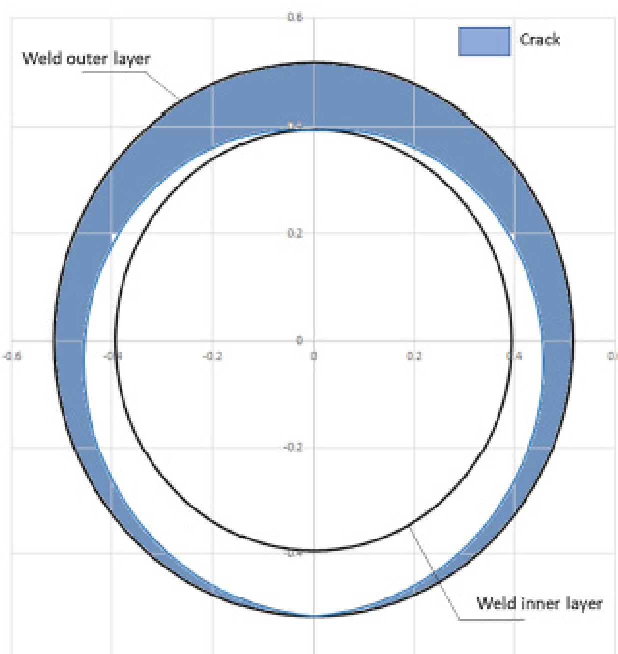

Figure 4-10
xLPR Generalization Study Case 4.1.1 Through-wall Crack Representation (Figure 3-63 from xLPR Generalization Study [9])

4.2.1.3 Cases With Zero Rupture with Leak Rate Detection and Zero Time from Detectable Leakage to Rupture

For Generalization Study Cases 4.1.3 and 4.1.4, the xLPR Generalization Study TLR reported that the ‘occurrence of rupture with LRD’ was zero, but the minimum time from detectable leakage to rupture was zero. For both cases, the times from detectable leakage to rupture were re-computed using the total leak rate and ‘occurrence of rupture’ outputs (as discussed in Section 3.4.4) so that the specific realizations in question could be identified. The distributions of time from detectable leakage to rupture are shown in Figure 4-11 (Generalization Study Case 4.1.3) and Figure 4-12 (Generalization Study Case 4.1.4).

For Generalization Study Case 4.1.3, the number of realizations with lapse times of zero decreased, although there were two realizations which still showed lapse times of zero. All ruptures (not just those with short lapse times) occurred prior to weld overlay mitigation. There are no remaining unmitigated steam generator inlet nozzles in the U.S. PWR fleet, so while these findings are of interest, they are not representative of current operating conditions.

For Generalization Study Case 4.1.4, the revised analytical approach as described above shows that the minimum time from detectable leakage to rupture was 2 months – that is, there were no realizations with time from detectable leakage to rupture of zero. Consistent with the approach taken in Section 4.2.1.1 for cases with limiting times from detectable leakage to rupture less than 3 months, the limiting realization was re-run with a time step of 0.2 month, and the minimum time was found to be 2.8 months.

For Generalization Study Case 4.1.4, the validity of the assumption in the Generalization Study TLR [9] that axial leakage was negligible was specifically investigated. This assumption was based on results from the xLPR Piping System Analysis. In xLPR Generalization Study Case 4.1.4, the frequency of axial flaw leakage is significantly higher (6% of realizations in Generalization Study Case 4.1.4) than the frequency of circumferential flaw leakage (0.07% of realizations in Generalization Study Case 4.1.4), so the implications of this assumption are meaningful. As shown in Figure 4-13, axial flaw leakage occurred prior to circumferential flaw leakage in 55.6% of the realizations with ruptures, and axial flaw leakage alone exceeded the 1 gpm leak rate detection threshold in 20.4% of realizations with ruptures.

Further investigation of xLPR Generalization Study Case 4.1.4 results also revealed one realization where it appears that the methodology applied in the xLPR Generalization Study [9] to compute time from detectable leakage to rupture would have incorrectly identified the time from detectable leakage to rupture as zero. The xLPR version used for this case saved individual leak rates only for the first three circumferential flaws modeled. However, this realization had four circumferential cracks, three of which coalesced into a single flaw, and no axial cracks. In xLPR, when two flaws coalesce, the numbering of the final flaw depends on the coalescence direction input selected. In this specific instance, it happened that resulting flaw was the fourth flaw, so the first three circumferential flaws showed no detectable leakage prior to rupture. This is illustrated in Figure 4-14. However, since flaws one through three do not grow through-wall and thus do not leak, the leak rate of the fourth flaw can only be determined from total leak rate history. For this realization, the detectable leakage threshold would have been reached 22 months prior to rupture. This was the only identified case where the methodology applied in the xLPR Generalization Study would have incorrectly computed the time from detectable leakage to rupture as zero. It is possible that in other cases, results for individual realizations could have been impacted by situations where leakage from a fourth flaw was not credited. However, since all cases with minimum lapse times of less than 3 months were investigated, any further impact of this finding would be on mean/minimum lapse times for cases with lapse times greater than 3 months reported in the xLPR Generalization Study TLR.

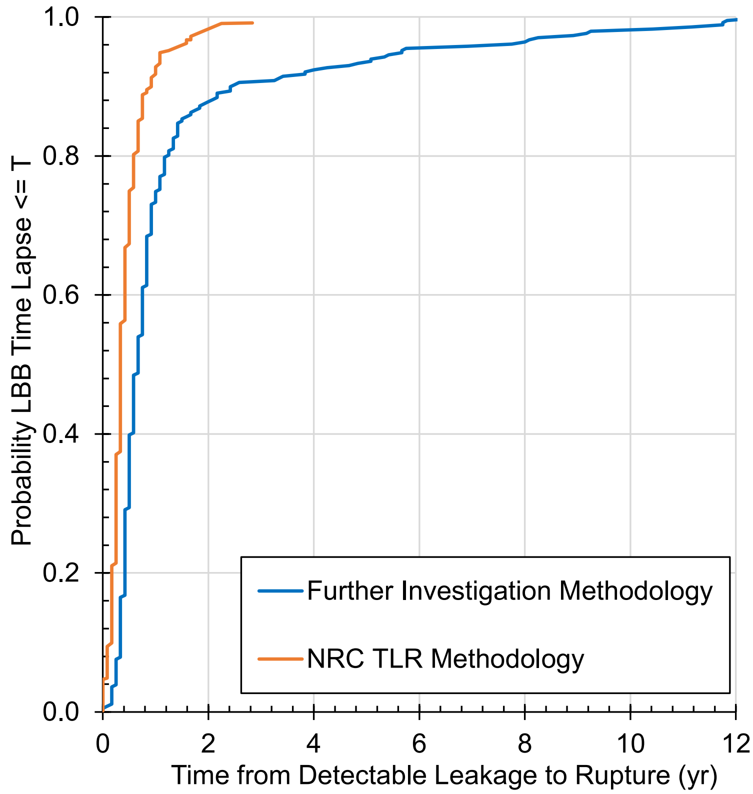

Figure 4-11
Comparison of Times from Detectable Leakage to Rupture for xLPR Generalization Study Case 4.1.3

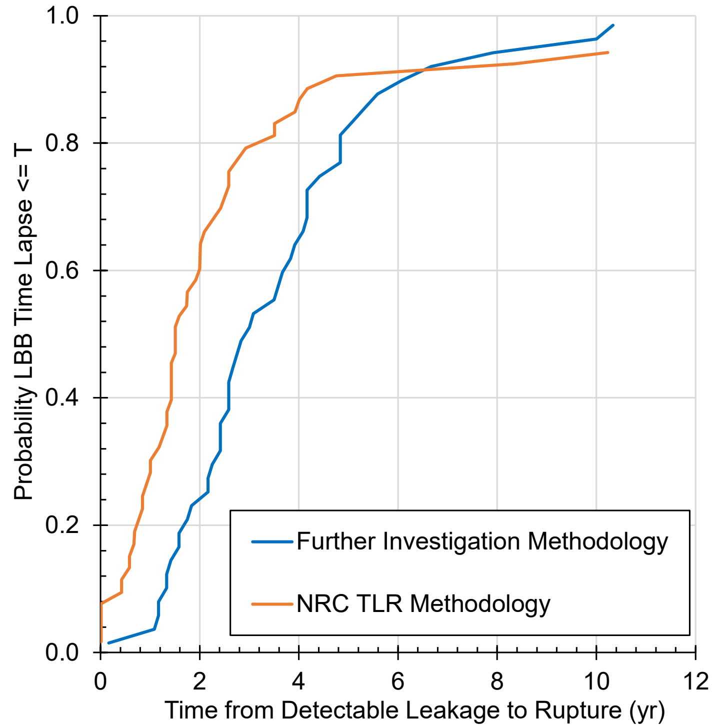

Figure 4-12
Comparison of Times from Detectable Leakage to Rupture for xLPR Generalization Study Case 4.1.4

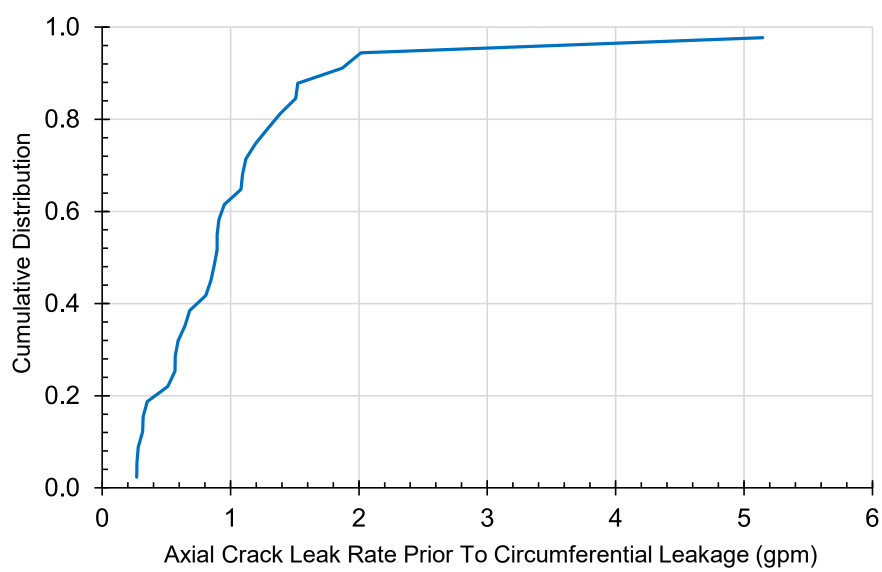

Figure 4-13
Axial Crack Leak Rates in xLPR Generalization Study Case 4.1.4

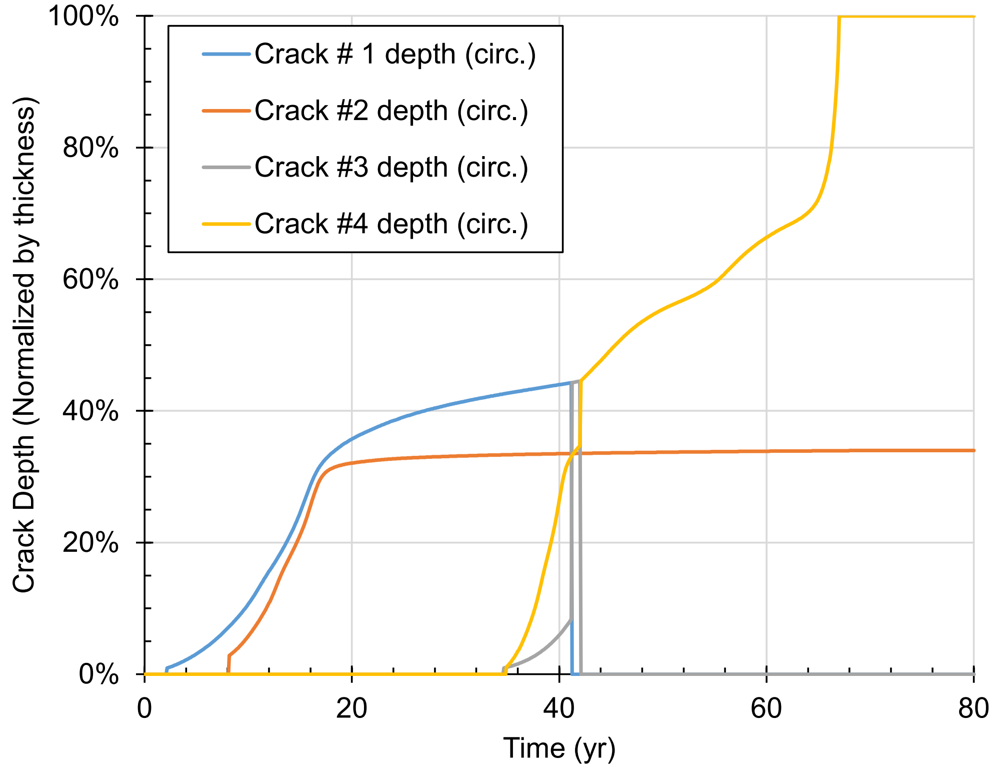

Figure 4-14
Crack Growth and Coalescence for xLPR Generalization Study Case 4.1.4 Run #1 Realization #567

4.2.1.4 Summary of Investigation of Limiting Sensitivity Cases

Table 4-8 summarizes findings from the investigation into the limiting cases. Overall, this investigation shows that there are no cases which indicate any significant probability of rupture without a detectable leak in normal operating conditions.

Table 4-8
Limiting Times from Detectable Leakage to Rupture

Case	Description	Minimum Time (i.e., Most Limiting Realization) from 1 gpm Leakage to Rupture After Investigation	Comments (Relative to Table 4-6)
xLPR Piping System Analysis 1.1.2 *Focus of ALS*	RVON severe WRS	0.8 month [~24 days]	Models unmitigated weld at hot leg temperature with severe WRS. Use of a shorter time step improved precision.
xLPR Generalization Study 2.1.1	PZR surge initial flaw	2.4 months	Models unmitigated weld at pressurizer temperature (not representative of U.S. PWR fleet). Use of a shorter time step improved precision.
xLPR Generalization Study 2.1.2	PZR surge severe WRS	0.6 month [~18 days]	Models unmitigated weld at pressurizer temperature (not representative of U.S. PWR fleet) with severe WRS. Use of a shorter time step improved precision.
xLPR Generalization Study 2.1.3	PZR surge w/ overlay	N/A –highly likely to be detected with ISI prior to rupture	Flaw lengths exceed 50% of inner circumference 10 years prior to rupture.
xLPR Generalization Study 2.1.4	PZR surge w/ fatigue	1.2 months	Models unmitigated weld at pressurizer temperature (not representative of U.S. PWR fleet). Use of a shorter time step improved precision.
xLPR Generalization Study 4.1.1 *Focus of ALS*	SGIN initial flaw	N/A – No ruptures occur	No ruptures occurred when case was re-run with reduced initial flaw sizes shallower than the inlay depth.
xLPR Generalization Study 4.1.2 *Focus of ALS*	SGIN severe WRS	N/A – No ruptures occur	No ruptures occurred when case was re-run with reduced initial flaw sizes shallower than the inlay depth.
xLPR Generalization Study 4.1.3 *Focus of ALS*	SGIN overlay mitigation	N/A – No ruptures occur	No ruptures occurred after mitigation (no unmitigated SGINs remain in the fleet).
xLPR Generalization Study 4.1.4 *Focus of ALS*	SGON no mitigation	2.8 months	When crediting axial flaw leakage and normal operating loads, and using a shorter time step for improved precision, the minimum time from detectable leakage to rupture is greater.

4.3 Time from Detectable Leakage to LBLOCA

As discussed in Section 4.1.5, the use of rupture as an analogue for LBLOCA does not impact the xLPR-estimated LOCA frequency results. However, as LBLOCA may occur prior to rupture in an xLPR analysis, the time from 1 gpm detectable leakage to LBLOCA may be less than the time from detectable leakage to rupture. Thus, in this section, the time from detectable leakage to LBLOCA is characterized for each evaluated xLPR analysis case for components within the ALS scope.

4.3.1 Investigation into Time from Detectable Leakage to LBLOCA for Components within ALS Scope

4.3.1.1 Reactor Vessel Outlet Nozzle (RVON)

The xLPR Piping System Analysis evaluated a wide variety of cases modeling the RVON. When ISI and LRD are not credited, LBLOCAs were found to occur in numerous realizations. However, no LBLOCAs were observed to occur if ISI and LRD are credited. For the approximately 27,000 realizations in which LBLOCA was observed to occur (not crediting ISI or LRD), the distribution of times from detectable leakage to LBLOCA is shown in Figure 4-15.[4]

A lower bound 95/95 one-sided tolerance interval is defined such that there is a 95% probability that the constructed limit is less than 95% of the population of interest for the surveillance interval selected. For the distribution of times shown in Figure 4-15, the 95/95 one-sided tolerance interval is 19 months, calculated considering the distribution-free assurance-to-quality (A/Q) criterion described in Chapter 24 of NUREG-1475 [14]. Figure 4-16 shows the lower tail of the distribution of times from detectable leakage to LBLOCA, showing the data that would fall below the lower bound 95/95 tolerance interval. Of note, only 4 realizations of the approximately 27,000 realizations in which LBLOCA was modeled to occur had a time from detectable leakage to LBLOCA of less than 6 months.

[4] The only cases excluded were cases which modeled scenarios identical to other cases in terms of time from detectable leakage to rupture (such as cases modeling different ISI parameters or using a two-loop Monte Carlo structure instead of single-loop), and one case modeling different time steps. The case numbers are: xLPR Piping System Analysis Cases 1.1.0.003 (a second run of case 1.1.0 with a two-loop structure), 1.1.10, 1.1.11, 1.1.22, and 1.1.23.

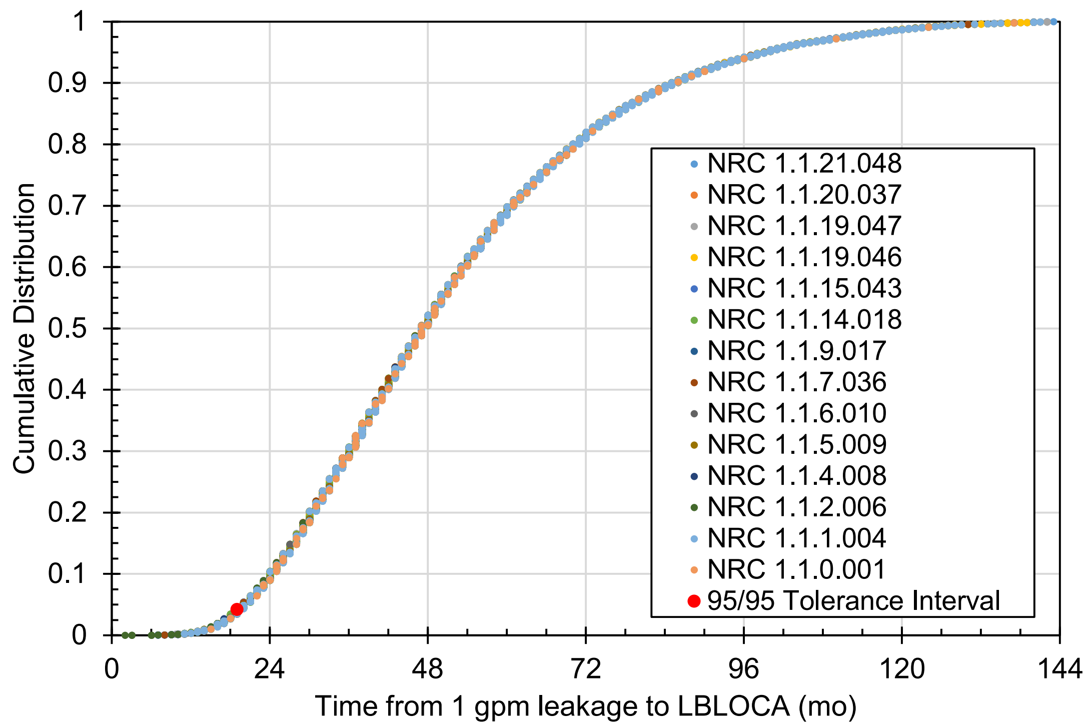

Figure 4-15
Distribution of Times from Detectable Leakage to LBLOCA

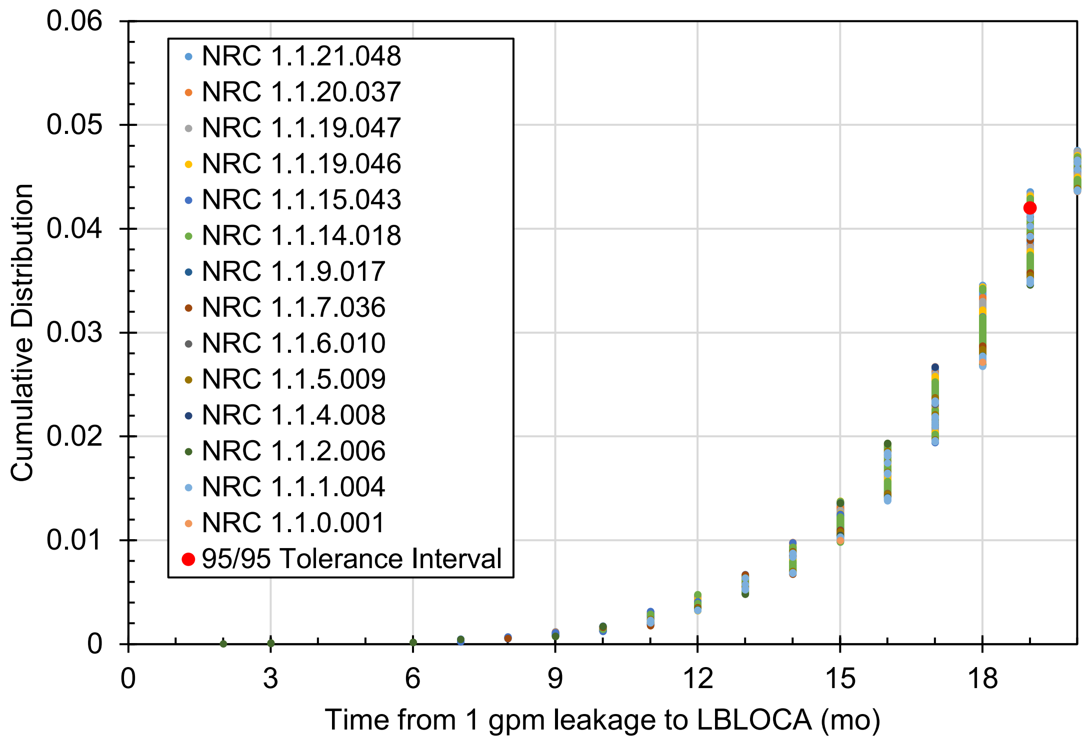

Figure 4-16
Lower Tail of Distribution of Times from Detectable Leakage to LBLOCA

4.3.1.2 Reactor Vessel Inlet Nozzle (RVIN)

The results of xLPR Piping System Analysis Cases 1.2.0 and 1.2.1 showed no occurrences of crack, leak, LBLOCA, or rupture. The observed lack of crack initiation further supports the low likelihood of a LBLOCA occurring for the RVIN.

4.3.1.3 Reactor Coolant Pump Nozzle (RCP)

The results of xLPR Generalization Study Cases 3.1.0 and 3.1.2, which modeled flaw initiation due to PWSCC, showed that no leaks, LBLOCAs, or ruptures occurred. The observed lack of leakage, a typical precursor event to LBLOCA, supports the low likelihood of a LBLOCA occurring for the RCP nozzle. Case 3.1.1, which modeled initial flaws, did show that there was a small probability of rupture. For this case, the minimum time from detectable leakage to LBLOCA corresponding to the most limiting realization was 25 months, showing substantial time to shut down the reactor prior to a LBLOCA occurring.

4.3.1.4 Steam Generator Inlet Nozzle (SGIN)

The results of xLPR Generalization Study cases 4.1.0 and 4.1.3 showed that no leaks, LBLOCAs, or ruptures occurred after mitigation in any of the cases considered. Cases 4.1.1 and 4.1.2 in the NRC TLRs showed a significant probability of rupture with LRD. Following the further investigation (see Section 4.2.1.2 for more details) and re-running cases 4.1.1 and 4.1.2 with more realistic initial flaw size inputs as suggested in the NRC TLRs, no ruptures or LBLOCAs were observed post-mitigation and leakage only occurred for axial flaws. Based on these xLPR analysis results, as all SGINs in the U.S. PWR fleet have now been mitigated, no potential LBLOCAs are expected to occur in SGINs.

4.3.1.5 Steam Generator Outlet Nozzle (SGON)

The steam generator outlet nozzle is modeled in xLPR Generalization Study Case 4.1.4. For this case, there are two realizations where the time from detectable leakage to LBLOCA is zero. In these realizations, the leak rate increases from less than 1 gpm to over 5,000 gpm (19,000 lpm) in a single time step, even when the timestep is reduced to 0.2 month. Crack depth as a function of time for each of these two realizations is shown in Figure 4-17. In both realizations, multiple flaws coalescing lead to extremely long flaws prior to growing through-wall, resulting in extremely high initial leak rates. In one realization, there were two flaws that were in excess of 20% through-wall depth for 40 years prior to rupture, and in the other, there were three. As a result, these flaws would have likely been detected by periodic ISI prior to LBLOCA occurring – the xLPR-reported probability that these ruptures would occur when considering 10-year ISI (“occurrence of rupture with ISI” output at 80 years) is considered is on the order of 1E-5. Considering that this occurs in 2 realizations out of 100,000, this is an annual frequency on the order of 1E-12 yr^{-1}, a highly unlikely scenario. As a final note, while xLPR Generalization Study Case 4.1.4 is representative of the current U.S. PWR fleet, only one plant has unmitigated Alloy 82/182 steam generator outlet nozzle welds, so this modeling scenario is not one that would occur frequently.

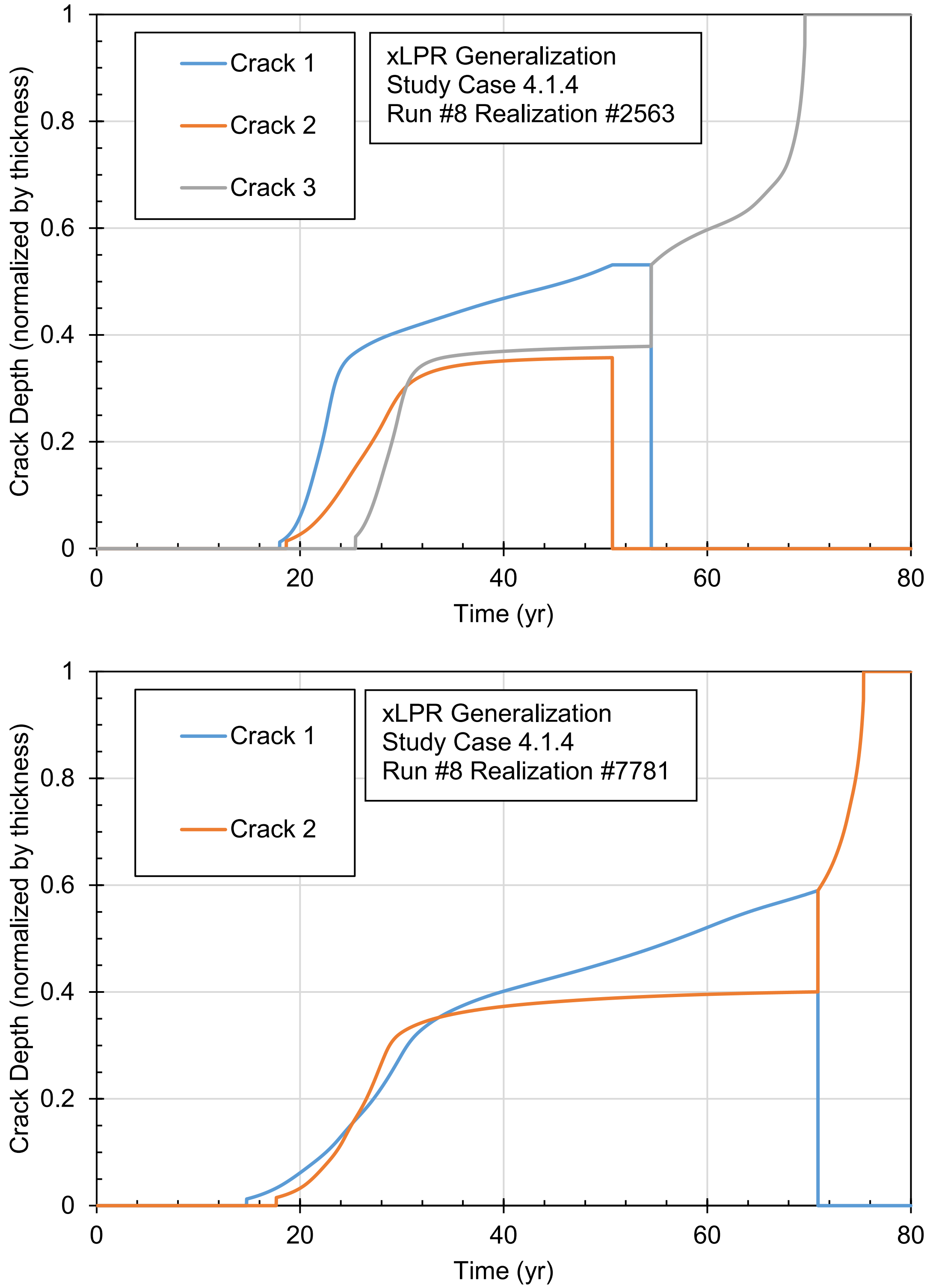

Figure 4-17
Crack Growth in Limiting Realizations of xLPR Generalization Study Case 4.1.4

4.3.2 Summary of Investigation

Table 4-9 summarizes findings from the investigation in time from detectable leakage to LBLOCA. Overall, these results demonstrate that there is sufficient time between detectable leakage and LBLOCA to shut down the reactor and prevent LBLOCA.

Table 4-9
Summary of Time from Detectable Leakage to LBLOCA for Components within ALS Scope

Component	Summary of Time from Detectable Leakage to LBLOCA
Reactor Vessel Outlet Nozzle (RVON)	Data for all realizations resulting in LBLOCA (~27,000 realizations) were evaluated further, showing a lower bound 95/95 one-sided tolerance interval of 19 months.
Reactor Vessel Inlet Nozzle (RVIN)	This component is at cold leg temperature. xLPR results showed no occurrence of crack, leak, LBLOCA, or rupture.
Reactor Coolant Pump Nozzle (RCP)	This component is at cold leg temperature. xLPR results in cases modeling flaw initiation showed no occurrence of leakage (and therefore no significant probability of LBLOCA). Cases modeling initial flaws did have ruptures, but the minimum time from detectable leakage to LBLOCA corresponding to the most limiting realization was 25 months.
Steam Generator Inlet Nozzle (SGIN)	All SGINs in the U.S. PWR fleet have been mitigated, and xLPR results showed no leaks or ruptures in mitigated components. (Includes results from re-runs of two cases with a more realistic initial flaw size, based on suggestions in the xLPR Generalization Study)
Steam Generator Outlet Nozzle (SGON)	There are two realizations where the time from detectable leakage to LBLOCA is zero. When ISI is credited, these scenarios are highly unlikely.

4.4 Regulatory Guide 1.245

In Regulatory Guide 1.245 [15], the U.S. Nuclear Regulatory Commission (NRC) presents a framework to develop contents of a licensing submittal when performing PFM analyses. The companion document, NUREG/CR-7278 [16], provides a technical basis for the framework of Regulatory Guide 1.245. These two NRC documents provide guidance and best practices for PFM analyses and documentation that are incorporated into this EPRI report directly or by reference, including supporting analyses, sensitivity analyses, and V&V. Table 4-10 provides an overview of the classification of the xLPR analyses documented herein in the context of Regulatory Guide 1.245, along with an overview of the report sections which include content related to each of the tables in Regulatory Guide 1.245.

Table 4-10
Regulatory Guide 1.245 Categories

Regulatory Guide 1.245 Table	Category	Description	Report Section/ Reference
C-2: SQA and V&V Code Categories	QV-1A	Code used in NRC-approved application, exercised within previously validated range	Section 3.5
C-3: Submittal Guidelines for Models	M-1	Model from a code in category QV-1A within the same validated range	NUREG-2247 [21]
C-5: Submittal Guidelines for Inputs	Range of categories for various xLPR inputs		Appendix C, TLR-RES/DE/REB-2021-09 [8], and TLR-RES/DE/REB-2021-14 R1 [9]
C-6: Submittal Guidelines for Uncertainty Propagation	UP-1	Analysis does not employ a surrogate model	NUREG-2247 [21]
C-7: Submittal Guidelines for Statistical Convergence	*Note: xLPR results are being used to complement and compare against those in NUREG-1829 and to characterize time between detectable leakage and LOCA – no direct acceptance criteria*		
C-8: Submittal Guidelines for Sensitivity Analysis	SA-1	Previously applied code with same QoI characteristic and same input parameters	TLR-RES/DE/CIB-2021-11 [22]
C-9: Submittal Guidelines for Output Uncertainty Characterization	*Note: xLPR results are being used to complement and compare against those in NUREG-1829 and to characterize time between detectable leakage and LOCA – no direct acceptance criteria*		
C-10: Submittal Guidelines for Sensitivity Studies	SS-1	Category QV-1A code with same QoI characteristic	Sections 3.1, 3.2, B.1.2, B.2.2, and B.3.2, and TLR-RES/DE/CIB-2021-11 [22]

5 INVESTIGATION INTO APPLICABLE DEGRADATION MECHANISMS

The only methods of crack growth evaluated in these xLPR analyses are PWSCC and fatigue, whereas NUREG-1829 considered other degradation modes such as thermal fatigue, erosion/cavitation, other unanticipated mechanisms, and aggravating conditions including fabrication defects and repairs. The Materials Degradation Matrix (MDM) [6] covers material degradation modes that are applicable to PWR primary pressure boundary components for all relevant materials. The MDM presents a broad perspective on materials degradation issues and the state of industry knowledge related to specific reactor technologies and prioritizes important knowledge gaps for resolution. This section provides a summary of degradation mechanisms for the relevant pressure boundary materials, stainless steel, and nickel-based alloys, considered in the xLPR analyses documented in this report.

5.1 Assessment of Degradation Mechanisms for Stainless Steel

A summary of the discussion in the MDM [6] for 300 series stainless steels in PWR primary pressure boundary components (for base metal, heat-affected zone [HAZ], and welds), is presented and expanded upon in the following subsections. Additional commentary is also provided relative to the xLPR analyses documented in this report.

5.1.1 Pitting Corrosion

Generally, pitting initiates at a critical pitting potential, E_{pit}. The actual mechanism of pit initiation at or above E_{pit} is not fully understood, but a proposed theory for austenitic stainless steels based on empirical evidence describes a process involving the increase of chloride concentration at the passive film of the stainless steel as the corrosion potential increases. “Salt islands” can then form and cause a high-chloride, low pH microenvironment to form beneath the island leading to a hydrolysis reaction [23]. Once initiated, the anodic production of positive iron cations will attract negatively charged chloride anions to the initiation site, creating an autocatalytic mechanism of pit growth.

A qualitative measure of pitting resistance can be found by determining the pitting resistance equivalent number (PREN) using the chromium (Cr), molybdenum (Mo), and nitrogen (N) content of the steel of interest. The compositional values are used to calculate the PREN by applying the following equation:

$$PREN = wt\%Cr + 3.3 \times wt\%Mo + 16 \times wt\%N$$

The PREN indicates the ability of the steel to resist pitting corrosion, with higher PREN values generally denoting a higher resistance to pitting. The PREN alone will not signify whether the steel will undergo pitting or not; rather, it is a tool for comparison purposes. For example, carbon steel has PREN values of 0.14 to 0.93 while austenitic stainless steels such as Type 304 or 316 have PREN values ranging from 18.0 to 30.5. The large difference in PREN values between two steels illustrates Type 300 series steels' high resistances to pitting compared to low-alloy steel alternatives [24].

Lastly, although the stochastic nature of pit initiation and growth makes predicting its behavior difficult, the applicability of pitting to stainless steel piping is low due to the minimum chemical requirements of pitting not being met. Because the stainless steel piping considered in this analysis contains primary water that meets EPRI PWR water chemistry guidelines, the probability of pit initiation will be negligible due to the insufficient amount of chlorides present [25].

This assumption is further supported by operating experience which indicates that only RCS components exposed to elevated dissolved oxygen and impurities representative of occluded conditions exhibit pitting [26]. Therefore, the issue of pitting corrosion in primary water is generally considered insignificant given the environmental conditions experienced by stainless steel piping considered in this analysis.

5.1.2 Stress Corrosion Cracking (SCC)

Instances of SCC in wrought stainless steels in the PWR RCS have occurred in two primary regimes:

- Occluded/stagnant/off-chemistry environments (more common).
- Free flowing, non-contaminated primary water when coupled with severe cold work (less common).

Both situations generally require off-normal conditions, and tools exist to manage these degradation risks. The stainless steel piping considered in this analysis is exposed to RCS primary water; therefore, for SCC susceptibility to be considered high, the piping would need to be severely cold worked and/or subject to off-chemistry environments.

Cases of SCC of austenitic stainless steel components in free-flowing PWR primary water have all been associated with elevated hardness values of 300 HV or greater [26]. These hardness values are generally found in heat exchanger tubing and pressurizer heaters that have undergone bending and swaging without proper stress relief through heat treatment. Similarly, SCC of stainless steel welds in PWR primary system piping has been relatively rare and usually associated with exposure to dissolved oxygen in combination with anionic impurities and improper welding techniques. Procedural controls have resolved this issue.

One example of cracking occurring in free-flowing conditions includes the recent circumferential SCC flaws identified in safety injection lines and residual heat removal lines in several French reactors. Based on destructive analysis, factors identified and likely contributing to the cracking included weld repairs, deviations from normal welding procedures, and stratification in stagnant lines. No SCC has been found in analogous welds in U.S. PWRs, and operating experience has shown that SCC cracking in Type 300 series stainless steel is unlikely without significant off-normal conditions such as severe cold work, contamination, or off-normal welding [27].

A 75th percentile CGR disposition equation for SCC in austenitic stainless steels was recently developed in MRP-458 [28]:

$$CGR = 3.19 \times 10^{-18} K^{2.5} Hv^{6.0} \exp\left(-\frac{85{,}000}{RT}\right)$$

Where CGR is in mm/sec, K in MPa√m, Hv in Vickers Hardness, T in Kelvin, and R = 8.314 J/(mole-K). The equation was determined by compiling a database of 924 SCC growth rate datapoints, scoring and sorting the data based on quality, and finally evaluating a subset of high quality data (scores equal to or lower than 3 out of 5) that was obtained at low oxygen, chloride, and sulfate levels. Relevant dependencies included a power law dependency for stress intensity factor, an Arrhenius dependency for temperature, and a power law dependency for Vickers Hardness. For a hardness of 220 Hv and temperature of 290°C (554°F), the 75th percentile CGR defined by this disposition equation for a K of 25 MPa√m and 50 MPa√m is 1.5E-11 m/s and 8.3E-11 m/s, respectively. With hardness as an input to the MRP-458 CGR equation, SCC growth in austenitic stainless steels is of greatest concern in off-normal conditions with elevated hardness (e.g., due to severe cold work).

An initiation model primarily based on cold work mechanisms was developed in EPRI report 1019032 [29]. However, the applicability of this initiation model to a PWR environment is limited to susceptible components exposed to significantly off-normal water chemistry resulting from oxygen and other contaminant accumulation. This further emphasizes that SCC in stainless steels in the PWR RCS is generally limited to off-normal chemistry environments or severe cold work, contamination, or off-normal welding. These conditions are not expected for the set of cases modeled in this effort, so no SCC is modeled in stainless steels.

5.1.3 Fatigue (High-Cycle Fatigue Due to Thermal Cycling)

High-cycle fatigue resulting from thermal cycling is a design/location-dependent phenomenon and is well characterized. Specific MRP guidance has been developed for the management of thermal fatigue in normally stagnant non-isolable RCS branch lines, documented as NEI 03-08 [30] "needed" guidance in MRP-146 R2 [31]. The MRP-146 R2 screening approach is based on the physical pipe configuration, presence of check valve in-leakage, and temperature monitoring data or heat transfer analysis, as well as supplemental inspections. Actions identified in MRP-146 R2 that may be taken to mitigate against thermal fatigue include plant modifications, changes in plant operations, or isolation valve preventative maintenance. MRP has also developed guidance for thermal fatigue in RHR mixing tees, documented as NEI 03-08 "good practice" guidance in MRP-192 R4 [32]. The MRP-192 R4 approach is to perform evaluations and inspections when the temperature differential across the RHR heat exchanger exceeds a given threshold for a given duration. This specific MRP guidance has been used to effectively manage thermal fatigue in normally stagnant non-isolable RCS branch lines as well as RHR mixing tees, reducing the concern for high-cycle fatigue due to thermal cycling in stainless steel primary piping system components.

5.1.4 Fatigue (Environmentally Assisted Fatigue)

Crack initiation and growth from environmentally assisted fatigue caused by plant transient loading are included in the xLPR analyses that were performed and are documented in this report.

5.1.5 Reduction in Fracture Properties (Thermal Aging)

High levels of delta-ferrite can eventually lead to reduction in fracture properties primarily caused by delta-ferrite's spinodal decomposition into brittle deleterious phases. However, delta-ferrite formation is necessary for welding and casting processes to prevent hot-cracking. Reduction in fracture properties due to thermal aging only applies to 300 series stainless steel welds in the presence of elevated delta-ferrite.

Screening criteria for potentially significant thermal aging effects are based on measured or calculated delta ferrite content, with 14 and 20% delta-ferrite being the threshold values for high Mo content in statically and centrifugally cast austenitic stainless steels respectively [33]. Therefore, it is unlikely that the low levels of delta ferrite present in well-controlled austenitic stainless steel welds (3 - 10%) will lead to a significant reduction in fracture properties of the stainless steel piping considered in this analysis.

5.1.6 Reduction in Fracture Properties (Environmental)

Aqueous environmental effects on fracture properties typically involve unstable crack growth occurring due to the combination of hydrogen embrittlement and reduced temperatures representative of shutdown and startup conditions. This phenomenon is known as low temperature crack propagation (LTCP). However, as there has been no plant experience or evidence of such an environmental reduction of fracture properties in stainless steel, this is not a degradation mode of concern [6].

5.1.7 Irradiation Embrittlement

Exposure to high levels of neutron irradiation for extended periods of time can lead to significant reductions in the fracture toughness of austenitic stainless steels. Drops in fracture toughness occur rapidly between fluence levels of 1 to 5 dpa, with little to no change in toughness occurring below 0.5 dpa [34]. Therefore, irradiation embrittlement concerns are associated with components in the beltline region of the reactor vessel, where fluence values are greater than 0.5 dpa. Because the stainless steel piping considered in this analysis is outside the beltline region, irradiation embrittlement is not a degradation mode of concern.

5.1.8 Conclusions of Stainless Steel Degradation Mechanism Assessment

All the material degradation mechanisms relevant to 300 series stainless steels in PWR primary pressure boundary components listed in the MDM are either evaluated herein, addressed and well-managed by other industry guidance, or not considered to be degradation modes of concern. This is commensurate with the results of the performed xLPR analyses for stainless steel welds, which resulted in no leaks or ruptures due to fatigue. Therefore, the xLPR analyses presented herein with the supporting MDM-based evaluation of all degradation mechanisms relevant to stainless steels, are considered consistent with the NUREG-1829 LOCA frequency estimates.

5.2 Assessment of Degradation Mechanisms for Nickel-Based Alloys

For Alloy 82/182 primary pressure boundary welds, the applicable material degradation modes identified in the MDM are summarized as follows along with additional commentary relative to the xLPR analyses documented in this report:

- SCC – Stress corrosion crack initiation and growth are included in the xLPR analyses that were performed and are documented in this report.
- Fatigue (environmentally assisted fatigue) – Fatigue crack growth is included in an xLPR analysis sensitivity case that was performed and is documented in this report.
- Reduction in fracture properties (environmental) – Research indicates that nickel-based weld metals exhibit some reduction in fracture properties at low temperatures (typical of startup or shutdown) in simulated PWR primary water chemistry environments. As noted in MRP-293 [35], reductions in fracture toughness have been observed in laboratory tests involving temperature and hydrogen concentration combinations representative of plant startup and shutdown conditions. However, the low temperature crack propagation rates observed for Alloy 600/82/182 are not of definitive engineering significance for a plant life of 80 years and are of little safety concern given the current inspection protocols. As stated in MRP-293, this conclusion relies significantly on the understanding that no plant transients result in rapidly rising loads.

Although NUREG-1829 considers additional material degradation mechanisms that are not included in xLPR, the material degradation mechanisms relevant to Alloy 82/182 welds in PWR primary system piping are rigorously identified in the Materials Degradation Matrix [6]. The MDM presents a broad perspective on materials degradation issues and the state of industry knowledge related to resolving knowledge gaps and mitigating degradation concerns. The listed mechanisms are either evaluated herein or are not anticipated to be degradation modes of concern.

6 CONCLUSIONS

Overall conclusions of this work are described in Section 6.1, with conclusions specific to the ALS provided in Section 6.2. Plant applicability criteria are provided in Section 6.3.

6.1 Overall Conclusions

xLPR [2] was used to evaluate PWR piping systems identified as LOCA-sensitive in NUREG-1829 [1]. Key outputs from these cases included rupture frequency outputs (which were compared against LOCA frequency estimates given in NUREG-1829), outputs for the time between detectable leakage and LOCA, as well as outputs for the time between detectable leakage and rupture. For each piping system evaluated, a base case and several sensitivity cases were developed. The base cases were defined to generally reflect expected conditions of installed components and local environmental and operating conditions, consistent with the best-estimate approach of the xLPR code. The sensitivity cases were defined to inform understanding of the base case results by investigating inputs known to have influence on xLPR results and modeling decisions made during input development. Consequently, the sensitivity cases were less constrained by maintaining fidelity to realistic plant conditions.

When crediting ISI and LRD, the ‘occurrence of rupture’ results are zero for most of the xLPR cases considered. For the xLPR cases with nonzero ‘occurrence of rupture with ISI and LRD,’ those results are on a similar order of magnitude as the NUREG-1829 LOCA frequency estimates. It is also noted that the cases with ruptures crediting ISI and LRD are all sensitivity cases that model scenarios that are not representative of current plant conditions and operations. Overall, this benchmarking increased confidence in both the xLPR and NUREG-1829 results.

The time between detectable leakage and rupture was thoroughly investigated for each base and sensitivity analysis case. The resulting probability distributions provided important insights into the time available from identification of an RCS leak to then place the plant in a safe condition in accordance with plant Technical Specification Limiting Conditions for Operation. Furthermore, xLPR analysis cases with individual realizations exhibiting times between detectable leakage and rupture less than three months were subjected to further investigation. Ultimately, this investigation showed that there are no cases which indicate any significant probability of rupture for the operating fleet without a detectable leak in normal operating conditions. The time between detectable leakage and LOCA results were investigated for components within the ALS scope. Conclusions of this assessment are provided in Section 6.2.

Although other degradation mechanisms are also considered in NUREG-1829, results from xLPR considering PWSCC and fatigue provide valuable information regarding conservatism or nonconservatism of the NUREG-1829 LOCA frequencies in the context of the material degradation mechanisms considered in xLPR. A review of other potential degradation mechanisms covered in the Materials Degradation Matrix [6] was performed. This review did not identify other mechanisms of significant concern that were not modeled herein or are not addressed by other industry guidance (e.g., MRP-146 R2 for the case of thermal fatigue in normally stagnant non-isolable RCS branch lines).

The xLPR analyses performed herein, when considering ISI and LRD, produced 80-year LOCA frequency estimates on a similar order of magnitude to those in NUREG-1829. Supported by additional consideration of time between detectable leakage and LOCA results, time between detectable leakage and rupture results, as well as investigation of applicable degradation mechanisms, this collection of work further improves confidence in the NUREG-1829 LOCA frequency estimates for future applications. Furthermore, the favorable benchmarking outcome between xLPR analysis results and NUREG-1829 LOCA frequency estimates increases confidence in the estimates produced by xLPR.

6.2 Conclusions Specific to the ALS

Fuel cladding rupture simulations are expected to demonstrate that LOCAs in lines smaller than RCS main loop piping do not lead to cladding rupture for high burnup fuel and therefore do not result in FFRD. Furthermore, dissimilar metal welds (DMW) within the primary system piping are known to be the most susceptible to active degradation and thus most limiting. Consequently, the main loop piping DMW cases for the reactor vessel inlet/outlet nozzles, steam generator inlet/outlet nozzles, and reactor coolant pump inlet/outlet nozzles are the focus of cases relevant to the ALS.

When crediting ISI and LRD, the ‘occurrence of rupture’ results are zero for most of the xLPR cases considered in this study. For the cases with nonzero ‘occurrence of rupture with ISI and LRD,’ the 80-year results are on a similar or lower order of magnitude than NUREG-1829 results at 40 years. Notably, the cases exhibiting ruptures while crediting ISI and LRD are sensitivity cases modeling scenarios not representative of current plant conditions and operations. The xLPR Generalization Study [9] concluded that since all base case probabilities of rupture with 1 gpm LRD (evaluated on a per-weld basis) were zero through 80 years, the plant level probabilities of rupture with 1 gpm LRD could also be taken as zero.

The time between detectable leakage and LOCA was characterized for the components relevant to the ALS. For the reactor vessel inlet nozzle, the reactor coolant pump nozzle, and steam generator inlet nozzles (which have all been mitigated), LBLOCA was not observed to occur. For the reactor vessel outlet nozzle, the xLPR results showed that LBLOCA does not occur when crediting ISI and LRD, and the distribution of times between detectable leakage and LBLOCA can be characterized by a lower bound 95/95 one-sided tolerance interval of 19 months. For unmitigated steam generator outlet nozzles (which only exist in one plant in the current U.S. PWR fleet), when crediting ISI, LBLOCA scenarios are highly unlikely with an annual frequency of occurrence on the order of 1E-12 yr^{-1}. These results provide important insights on the potential for leakage to be detected in sufficient time to shut down the reactor prior to a LBLOCA or pipe rupture occurring.

The subset of cases relevant to the ALS are cases modeling the largest line size analyzed in NUREG-1829. For these lines, the extensive analysis documented herein, including comparisons of LOCA frequencies evaluated using xLPR, consideration of time between detectable leakage and LOCA results, and investigation of applicable degradation mechanisms, further improves confidence in the NUREG-1829 LOCA frequency estimates. Collectively, these results provide a robust technical basis that sufficient margin is available for timely identification of an RCS leak and subsequently placing the plant in a safe condition in accordance with plant Technical Specification Limiting Conditions for Operation to prevent pipe rupture.

6.3 Plant Applicability Criteria

As noted in the xLPR Piping System Analysis [8] and Generalization Study [9] TLRs, the xLPR analyses considered in this assessment were prepared generically to bound the welds and operating stresses in U.S. PWR primary loop piping. Eighty effective full-power years (EFPY) were modeled to bound plant operation, assuming a 100% capacity factor throughout the entire period of operation. Other inputs were selected to bound all inservice welds represented by a given analysis case. Bounding normal operating loads, SSE loads, pressures, temperatures, and dissolved hydrogen concentrations were selected, along with the largest outside diameters and thinnest pipe wall thicknesses. Sensitivity studies were also used to investigate more conservative input values, such as more severe WRS profiles producing upper bound estimates for the range of welds considered. Thus, the range of xLPR analyses considered within this assessment are expected to bound the U.S. PWR fleet.

7
REFERENCES

1. U.S. Nuclear Regulatory Commission, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process; Main Report." NUREG-1829, Vol. 1, April 2008 [NRC ADAMS Accession No.: ML082250436].
2. *Probabilistic Fracture Mechanics Code: xLPR, Version 2.2*. EPRI, Palo Alto, CA: 2023. 3002023872.
3. U.S. NRC SECY-15-0148, Evaluation of Fuel Fragmentation, Relocation and Dispersal Under Loss-of-Coolant Accident (LOCA) Conditions Relative to the Draft Final Rule on Emergency Core Cooling System Performance During a LOCA (50.46c), November 2015 [NRC ADAMS Accession No.: ML15230A200].
4. *Alternative Licensing Approaches for Higher Burnup Fuel: A Scoping Study on Deterministic and Risk-Informed Alternatives Supporting Fuel Discharge Burnup Extension.* EPRI, Palo Alto, CA: 2020. 3002018457.
5. Letter from E. Hussler (Westinghouse) to F. Smith (EPRI), "Transmittal of Piping Diameters Considered in LOCA Cladding Rupture Simulations Supporting the EPRI Alternate Licensing Strategy," dated March 16, 2023. NSD-EPRI-23-4.
6. *EPRI Materials Degradation Matrix, Revision 4*. EPRI, Palo Alto, CA: 2018. 3002013781.
7. xLPR Code Maintenance Traveler in Response to xLPR-REQ- 120, "LEAPOR Instability at Smaller Line Sizes," August 31, 2021.
8. Technical Letter Report, TLR-RES/DE/REB-2021-09, *Probabilistic Leak-Before-Break Evaluation of Westinghouse Four-Loop Pressurized-Water Reactor Primary Coolant Loop Piping using the Extremely Low Probability of Rupture Code*, August 13, 2021 [NRC ADAMS Accession No.: ML21217A088].
9. Technical Letter Report, TLR-RES/DE/REB-2021-14 R1, *Probabilistic Leak-Before-Break Evaluations of Pressurized-Water Reactor Piping Systems using the Extremely Low Probability of Rupture Code*, April 2022 [NRC ADAMS Accession No.: ML22088A006].
10. "Pressurized Water Reactor Owners Group Standard RCS Leakage Action Levels and Responses Guidelines for Pressurized Water Reactors," WCAP-16465-NP Revision 0, September 2006. [NRC ADAMS Accession No. ML070310082].
11. *xLPR Code Application Project-Research Code Version Control Plan (Revision 0)*. EPRI, Palo Alto, CA: 2019.
12. xLPR Code Maintenance Traveler in Response to xLPR-REQ-107, "TIFFANY TW K Array Initialization Error," November 8, 2021.
13. xLPR Version 2.0 Technical Basis Document, "Sources and Treatment of Uncertainty," xLPR-TR-UNCERT, November 2018 [NRC ADAMS Accession No.: ML19337C165].

14. U.S. Nuclear Regulatory Commission, “Applying Statistics.” NUREG-1475, Rev. 1, March 2011 [NRC ADAMS Accession No.: ML11102A076].
15. U.S. NRC Regulatory Guide 1.245, Revision 0, “Preparing Probabilistic Fracture Mechanics Submittals,” January 2022. [NRC ADAMS Accession No.: ML21334A158].
16. U.S. Nuclear Regulatory Commission, “Technical Basis for the use of Probabilistic Fracture Mechanics in Regulatory Applications.” NUREG/CR-7278, January 2022 [NRC ADAMS Accession No.: ML22014A406].
17. D. Rudland, et al., “Evaluation of the Inlay Process as a Mitigation Strategy for Primary Water Stress Corrosion Cracking in Pressurized Water Reactors,” April 2010 [NRC ADAMS Accession No.: ML101260554].
18. D. Rudland, et al., “PWSCC Crack Growth Mitigation With Inlay,” *Proceedings of the ASME 2011 Pressure Vessels & Piping Division Conference,* July 17-21, 2011, Baltimore, MD. PVP2011-57954.
19. “Virgil C. Summer Nuclear Station, Unit No. 1 – Re: Extension of Steam Generator Primary Inlet Nozzle Dissimilar Metal Weld Inspection Interval,” December 15, 2022 [NRC ADAMS Accession No.: ML22341A197]
20. “NRC Staff Interpretation of 95/95 Tolerance Limits in Safety System Setpoint Analysis,” September 2010. [NRC ADAMS Accession No.: ML102980536].
21. U.S. Nuclear Regulatory Commission, “Extremely Low Probability of Rupture Version 2 Probabilistic Fracture Mechanics Code.” NUREG-2247, August 2021 [NRC ADAMS Accession No.: ML21225A736].
22. Technical Letter Report, TLR-RES/DE/CIB-2021-11, *Sensitivity Studies and Analyses Involving the Extremely Low Probability of Rupture Code*, May 14, 2021 [NRC ADAMS Accession No.: ML21133A485].
23. D. Jones, *Principles and Prevention of Corrosion*. Macmillan Pub. Co.; Maxwell Macmillan Canada; Maxwell Macmillan International Pub. Group 1992.
24. Strategic Highway Research Program, “Appendix C Chloride Threshold for Various Reinforcement Steel Types.”
25. *Pressurized Water Reactor Primary Water Chemistry Guidelines, Volume 1, Revision 7*. EPRI, Palo Alto, CA: 2014. 3002000505.
26. *Materials Reliability Program: Stress Corrosion Cracking of Stainless Steel Components in Primary Water Circuit Environments of Pressurized Water Reactors (MRP-236, Rev. 1).* EPRI, Palo Alto, CA: 2017. 3002009967.
27. Meeting Transcript, Slides and Viewgraphs, *Transcript of the Advisory Committee on Reactor Safeguards Fuels, Materials, and Structures Subcommittee Meeting*, November 2022, [NRC ADAMS Accession No.: ML22335A495].
28. *Materials Reliability Program: Stress Corrosion Crack Growth Rates in Stainless Steels in PWR Environments (MRP-458).* EPRI, Palo Alto, CA: 2022. 3002020451.
29. *Stress Corrosion Cracking Initiation Model for Stainless Steel and Nickel Alloys: Effects of Cold Work.* EPRI, Palo Alto, CA: 2009. 1019032.

30. NEI 03-08, Rev. 4, Guideline for the Management of Materials Issues, Nuclear Energy Institute, Washington D.C.: October 2020. [NRC ADAMS Accession No.: ML20315A536]

31. *Materials Reliability Program: Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines (MRP-146, Revision 2).* EPRI, Palo Alto, CA: 2016. 3002007853.

32. *Materials Reliability Program: Assessment of Residual Heat Removal Mixing Tee Thermal Fatigue in PWR Plants (MRP-192, Revision 4)*. EPRI, Palo Alto, CA: 2022. 3002023891.

33. *Evaluation of Thermal Aging Embrittlement for Cast Austenitic Stainless Steel Components.* EPRI, Palo Alto, CA: 2000. 1000976.

34. NUREG/CR-6960, *Crack Growth Rates and Fracture Toughness of Irradiated Austenitic Stainless Steels in BWR Environments,* March 2008, [NRC ADAMs Accession No.: ML081130709].

35. *Materials Reliability Program: Low-Temperature Crack Propagation in Pressurized Water Reactor Materials (MRP-293)*. EPRI, Palo Alto, CA: 2011. 1021018.

APPENDIX A
TEMPLATE FOR RUN DESCRIPTION FORM

Run ID #	
Plant	
Component	
Case Identifier	

Record of Revisions

Revision	**Signatures**		**Issue Date**
	Preparer	**Reviewer**	

Description

xLPR Version

Run Date

Run Platform

RAM	
Processor	
OS	
Hard Disk	
Goldsim License Type	
Goldsim Version	

Benchmarking Information

Multiprocessing Used?	
Number of Slave Processes	
Run Time	

Sampling Settings

# Aleatory Realizations	
# Epistemic Realizations	
Aleatory Random Seed	
Epistemic Random Seed	

Input Summary

Input ID	**Name**	**Value / Distribution Parameters**	**Units**	**Basis**

Output Summary

- (List saved outputs in bullet form)

Realization Count Basis

General Observations

APPENDIX B
ADDITIONAL XLPR ANALYSES PERFORMED

This Appendix describes the additional xLPR analysis cases performed for this effort. Section B.1 describes the analysis cases for the Westinghouse safety injection line, Section B.2 describes the analysis cases for the CE safety injection/accumulator line, and Section B.3 describes the analysis cases for the Westinghouse residual heat removal system. References used throughout this appendix are identified in Section B.4.

B.1 Westinghouse Safety Injection Line

The Westinghouse safety injection line is a nominal pipe size (NPS) 6 (diametre nominal [DN] 150) line and is attached directly to the hot legs and cold legs of the reactor coolant loop piping or to the accumulator line, which is then connected to the reactor coolant loop piping. The line is typically fabricated from Type 316 stainless steel and is, therefore, considered susceptible only to fatigue and not to PWSCC. One genericized representative weld within the portion of the line exposed to RCS normal operating conditions was selected for evaluation using xLPR.

For this study, initial flaws were modeled in most cases, and flaw initiation was modeled separately in a sensitivity case. For the base case, 20,000 realizations were executed. For each sensitivity case, 10,000 realizations were executed. The lack of flaw growth in any case modeled for the Westinghouse safety injection line indicates that this modest number of realizations is acceptable. All variables were sampled in just one loop of the two-loop Monte Carlo structure in xLPR, rather than sampling variables in both loops.

B.1.1 Base Case

Key xLPR inputs for the base case were the following:

- Plant operation time: 80 years (capacity factor of 100%, a conservative assumption consistent with xLPR Piping System Analysis and xLPR Generalization Study).
- Axial and circumferential cracks modeled with one initial flaw in each direction.
- Pipe outer diameter 168.28 mm (6.625 in.); pipe wall thickness uniformly distributed between 13 mm (0.512 in.) and 18.3 mm (0.720 in.). ([1],[2],[3],[4])
- Circumferential and axial initial flaw length: lognormal distribution with true mean of 8.608 mm (0.339 in.) and true standard deviation of 4.849 mm (0.191 in.). [5]
- Circumferential and axial initial flaw depth: lognormal distribution with true mean of 3 mm (0.118 in.) and true standard deviation of 0.05 mm (0.002 in.). [5]
- Flow rate in Westinghouse safety injection line: uniform distribution between 11.045 and 16.753 m/s (36.2 and 55.0 ft/s). ([6], [7], [8], [9], [10], [11], [12], [13])
- Operating pressure: 15.41 MPa (2.235 ksi). [5]

- Operating temperature: uniform distribution between 319.7 and 325.6°C (607.5 and 618.1°F). ([1],[2],[3],[4])
- Earthquake probability of 2.17E-4 yr-1. [5]
- Earthquake Δ stress: membrane stress normal distribution with mean 0.9767 MPa (0.142 ksi) and standard deviation 0.757 MPa (0.110 ksi) and bending stress normal distribution 3.537 MPa (0.513 ksi) and standard deviation 68.21 MPa (9.893 ksi). ([1],[2],[3],[4])
- Membrane stress: normal distribution, mean 0.3467 MPa (0.050 ksi) and standard deviation 0.7514 MPa (0.109 ksi). ([1],[2],[3],[4])
- Bending stress: normal distribution, mean 2.02 MPa (3.19 ksi) and standard deviation 14.11 MPa (2.05 ksi). ([1],[2],[3],[4])
- Material properties for Type 316 stainless steel defined in xLPR-GR-IG v1 [5] applied to the "left pipe," "right pipe," and "weld" inputs in xLPR. The same material property inputs were applied to the base metals and the weld metal as a modeling simplification.
- Weld residual stress (WRS) profiles developed in an approach that parallels the approach used for N-899 paragraph -2200, with the xLPR Framework adjusting as needed to result in an axial WRS profile that is equilibrated through the thickness of the weld [14].
- Transients for plant heat-up, cooldown, loading, unloading, step load increase, step load decrease, large step load decrease, loss of load, partial loss of flow, and reactor trip as defined in xLPR-GR-IG v1 [5] (It is noted that safety injection transients were not modeled in this study.)

Stress distributions, geometry parameters, and operating conditions were fit to values obtained from various industry submittals for deterministic LBB applications for welds within the portion of the safety injection line exposed to RCS normal operating conditions to develop inputs for a genericized representative weld.

B.1.2 Sensitivity Cases

Table B-1 lists the cases run (base case and sensitivity cases) for the Westinghouse Safety Injection Line, and describes the changes made to the base case model.

Table B-1
Summary of Sensitivity Cases for the Westinghouse Safety Injection/Direct Volume Injection Line

Case Number	Case Identifier	Description	Number of Realizations
xLPR LOCA Freq 1.1.0	Base case	Establish base case results	20,000
xLPR LOCA Freq 1.1.1	Geometry	Reduced to the lower quartile of the wall thickness distribution	10,000
xLPR LOCA Freq 1.1.2	Loading	Increased mean membrane and bending stresses by 50%	10,000
xLPR LOCA Freq 1.1.3	Earthquake probability	Increased earthquake frequency from 2.17E-4 yr^{-1} to 1E-3 yr^{-1}	10,000
xLPR LOCA Freq 1.1.4	Fatigue initiation	Model crack initiation from fatigue	10,000
xLPR LOCA Freq 1.1.5	WRS profile	Increase WRS by 50%	10,000
xLPR LOCA Freq 1.1.6	Two initial flaws	Begin with two flaws	10,000
xLPR LOCA Freq 1.1.7	Three initial flaws	Begin with three flaws	10,000

B.1.3 Results

None of the cases resulted in any leaks or ruptures. The crack growth results from the xLPR analyses show that the amount of crack growth was limited. In all cases analyzed, no realization saw the 95th percentile of crack depths exceed 25% of the wall thickness. The only case in which the 95th percentile of crack depths grew by more than 0.1% of the wall thickness was the loading sensitivity case, and even in that case the maximum crack growth was less than 2% of the wall thickness. The observed crack growth behavior was found to be very similar for axial and circumferential flaws. Furthermore, results from a sensitivity case investigating fatigue crack initiation showed no axial or circumferential cracks initiating as a result of fatigue in 10,000 realizations.

B.2 CE Safety Injection/Accumulator Line

The accumulators contain large volumes of cool pressurized borated water, which is released into the primary system if system pressure drops sufficiently following a LOCA. The CE safety injection/accumulator line is an NPS 12 (DN 300) Sch 140 or 160 line, which has an inner diameter (ID) of approximately 10 in. (254 mm). This line is attached to the cold leg of the RCS and is thereby exposed to reactor cold leg temperature. The piping in this line is fabricated from Type 316 stainless steel. In at least one plant, the cold leg nozzle is an A-182, Grade F1 nozzle with a CF8M safe end and Alloy 82/182 dissimilar metal weld [5]. This Alloy 82/182 weld was selected for evaluation using xLPR as appropriately bounding for this line. At most such plants, the Alloy 82/182 weld in the CE safety injection/accumulator line has not been mitigated to reduce its susceptibility to PWSCC. For purposes of this study, the focus of the xLPR analysis was on PWSCC of the Alloy 82/182 weld, and, therefore, thermal embrittlement of the cast austenitic stainless steel (CASS) safe end material was not in the scope of this assessment. An assessment of other potential degradation mechanisms can be found in Section 5.

For this study, initial flaws were modeled in most cases, and flaw initiation was modeled separately in a sensitivity case. For each case modeling initial flaws, 10,000 realizations were executed. When modeling initiation, 20,000 realizations were executed. The approach of decoupling crack initiation and rupture is advantageous as it allows for evaluation of results with lower probabilities without the need to run excessively large numbers of realizations in xLPR. This approach is discussed in further detail in Section 4.1.1. All variables were sampled in just one loop of the two-loop Monte Carlo structure in xLPR, rather than sampling variables in both loops.

B.2.1 Base Case

Key xLPR inputs for the base case were the following:

- Plant operation time of 80 years (capacity factor of 100%, a conservative assumption consistent with xLPR Piping System Analysis and xLPR Generalization Study).
- Axial and circumferential cracks modeled with one initial flaw in each orientation.
- Pipe outer diameter of 323.85 mm (12.75 in.); pipe wall thickness of 32.5 mm (1.28 in.). [15]
- Circumferential and axial initial flaw length (PWSCC, initial flaw) sampled from a lognormal distribution with geometric mean of 0.0048 m (1.89 in.) and geometric standard deviation of 2.226 m (87.63 in.). [5]
- Circumferential and axial initial flaw depth (PWSCC, initial flaw) sampled from a lognormal distribution with geometric mean of 0.0015 m, geometric standard deviation of 1.419 m, minimum of 0.0005 m (0.0197 in.), and maximum of 0.0325 m (1.28 in.). [5]
- Flow rate in CE safety injection/accumulator line sampled from a uniform distribution between 3.081 and 3.956 m/s (10.11 and 12.98 ft/s). ([16], [17], [18], [19], [20])
- Operating pressure of 15.41 MPa (2.235 ksi). [5]
- Operating temperature of 289.4°C (552.9°F). [5]
- Earthquake probability of 2.17E-4 yr^{-1}. [5]
- Earthquake Δ stress with membrane stress sample from a uniform distribution between 0.3103 and 2.8571 MPa (0.045 and 0.414 ksi) and bending stress sampled from a uniform distribution between 8.1634 and 73.0362 MPa (1.184 and 10.59 ksi). [15]
- Membrane stress sampled from a uniform distribution between 0.1517 and 4.0128 MPa (0.022 and 0.582 ksi). [15]
- Bending stress sampled from a uniform distribution between 17.0025 and 95.4924 MPa (2.466 and 13.85 ksi). [15]

- Material properties for A-182 Grade F1, A351 CF8M, and Alloy 82/182 applied to the "left pipe," "right pipe," and "weld" inputs in xLPR, respectively (material property inputs applied were defined in xLPR-GR-IG v1 [5] and prior xLPR input sets developed for the xLPR Generalization Study work [9]).
- A DM weld mixture ratio input value of 0.5 was applied. [5]
- WRS profiles based on those developed for the xLPR Generalization Study work. [9]
- Transients for plant heatup, cooldown, loading, unloading, step load decrease, and reactor trip/loss of flow are given by Materials Reliability Program (MRP) -393 [21] (it is noted that safety injection transients were not modeled).
- Stress distributions, geometry parameters, and operating conditions were fit to values provided in WCAP-16925-NP [15] to develop inputs for a genericized representative Alloy 82/182 weld in the CE safety injection/accumulator line.

B.2.2 Sensitivity Cases

Table B-2 lists the cases run (base case and sensitivity cases) for the CE Safety Injection/ Accumulator, and describes the changes made to the base case model.

Table B-2
Summary of Sensitivity Cases for the CE Safety Injection/Accumulator Line

Case #	Case Identifier	Description
xLPR LOCA Freq 2.1.0	Base case	Establish base case results
xLPR LOCA Freq 2.1.1	SCC initiation	Modeled crack initiation due to PWSCC
xLPR LOCA Freq 2.1.2	WRS profile	Considered a severe WRS profile based on xLPR Generalization Study Case 5.1.2
xLPR LOCA Freq 2.1.3	Loading	Used the upper half of the distributions applied to the base case for membrane and bending stresses
xLPR LOCA Freq 2.1.4	Earthquake loading	Increased the earthquake frequency to 1E-3 yr^{-1} (361% increase from base case)
xLPR LOCA Freq 2.1.5	Fatigue	Modeled crack growth due to the combined effects of PWSCC and fatigue
xLPR LOCA Freq 2.1.6	WRS profile + SCC initiation	Modeled crack initiation due to PWSCC, using the WRS profile from xLPR LOCA Freq Case 2.1.2
xLPR LOCA Freq 2.1.7	Mitigation	Applied mechanical stress improvement after 30 years

B.2.3 Results

Results for this set of cases are summarized in Table B-3 and Table B-4. The outputs of interest are 'occurrence of rupture' and 'occurrence of leakage' (for all cases), and 'occurrence of crack' initiation (for cases modeling initiation). For these cases modeling the CE safety injection/accumulator line, there were no ruptures when crediting LRD, as well as no ruptures when crediting ISI and LRD.

Most cases modeled initial flaws. The probability of rupture (at 80 yr) in the base case was 0.63%, and the greatest probability of rupture in the sensitivity cases was 1.79%. The WRS profile and pipe loading sensitivity cases led to the greatest probability of leakage and rupture. Including fatigue and increasing earthquake probability did not lead to significant changes in the probability of leakage and rupture. As expected, mitigation by mechanical stress improvement was the only sensitivity case that saw a decrease in the probability of circumferential crack leakage.

For the cases looking at crack initiation, the base case with initiation showed that the probability of an axial crack initiating is 3% in 80 years and in the sensitivity case with the more aggressive WRS profile, that probability increases to 5.2% in 80 years. However, circumferential cracks are of greater interest because those cracks can lead to rupture. Applying the base case WRS profile, no circumferential cracks initiated. Substituting the more severe WRS profile (with less compressive stresses at the ID), the results show that the probability of a circumferential crack initiating is 0.01%. No leaks or ruptures occurred.

Table B-3
Summary of Results for the CE Safety Injection/Accumulator Line – Leakage and Rupture

Case Number	Case Identifier	Mean Probability of leakage at 40 yr (axial)	Mean Probability of leakage at 40 yr (circ)	Mean Probability of rupture at 40 yr (circ)	Mean Probability of leakage at 80 yr (axial)	Mean Probability of leakage at 80 yr (circ)	Mean Probability of rupture at 80 yr (circ)
xLPR LOCA Freq 2.1.0	Base case	19.62%	0.21%	0.14%	36.24%	0.80%	0.63%
xLPR LOCA Freq *2.1.1*	*SCC initiation*	*0.30%*	*0.00%*	*0.00%*	*0.92%*	*0.00%*	*0.00%*
xLPR LOCA Freq 2.1.2	WRS profile	22.30%	0.84%	0.49%	40.44%	2.45%	1.79%
xLPR LOCA Freq 2.1.3	Loading	18.64%	0.39%	0.20%	35.84%	1.31%	0.91%
xLPR LOCA Freq 2.1.4	Earthquake Probability	19.02%	0.23%	0.08%	36.28%	0.74%	0.51%
xLPR LOCA Freq 2.1.5	Fatigue	19.25%	0.21%	0.11%	36.80%	0.85%	0.65%
xLPR LOCA Freq *2.1.6*	*WRS profile +SCC initiation*	*0.85%*	*0.00%*	*0.00%*	*1.99%*	*0.00%*	*0.00%*
xLPR LOCA Freq 2.1.7	Mitigation	13.84%	0.45%	0.09%	14.11%	0.64%	0.53%

Note: italicized cases modeled SCC initiation rather than initial flaws.

Table B-4
Crack Initiation Sensitivity Case Results for the CE Safety Injection/Accumulator Line

Case Number	Case Identifier	Mean Probability of initiation at 40 yr (axial)	Mean Probability of initiation at 40 yr (circ)	Mean Probability of initiation at 80 yr (axial)	Mean Probability of initiation at 80 yr (circ)
xLPR LOCA Freq 2.1.1	SCC initiation	2.00%	0.00%	2.99%	0.00%
xLPR LOCA Freq 2.1.6	WRS profile + SCC initiation	3.81%	0.00%	5.19%	0.01%

B.3 Westinghouse Residual Heat Removal System

The Westinghouse Residual Heat Removal (RHR) system is used to cool the reactor coolant system during and after plant shutdown. There are three sections of the RHR system; the suction line which takes water from the RCS hot leg, the heat exchanger, which cools the water, and the return line, which pumps water back to the cold leg. Only the suction line, which is exposed to RCS normal operating conditions, is considered in this analysis. The RHR system piping is typically fabricated from Type 316 stainless steel and is, therefore, considered susceptible only to fatigue and not to PWSCC. Applicable degradation mechanisms are discussed in more detail in Section 5. One genericized weld in the suction line was selected for evaluation using xLPR.

For all cases, 5,000 realizations were run, except for the fatigue initiation case, for which 10,000 realizations were run. The lack of flaw growth in any case modeled for the RHR system (including cases modeling initial flaws) indicates that this modest number of realizations is acceptable. All variables were sampled in just one loop of the two-loop Monte Carlo structure in xLPR, rather than sampling variables in both loops.

B.3.1 Base Case

Key xLPR inputs for the base case were the following:

- Plant operation time of 80 years (capacity factor of 100%, a conservative assumption consistent with xLPR Piping System Analysis and xLPR Generalization Study).
- Axial and circumferential cracks modeled with one initial flaw in each direction.
- Pipe outer diameter of 355.6 mm (14.00 in) and pipe wall thickness of 31.75 mm (1.250 in), corresponding to NPS 14 Sch 140 (the upper bound NPS and lower bound schedule for RHR systems identified). ([22], [23], [24], [25])
- Circumferential and axial flaw length sampled from a lognormal distribution with true mean of 8.608 mm (0.339 in.) and true standard deviation of 4.849 mm (0.191 in.). [5]
- Circumferential and axial flaw depth sampled from a lognormal distribution with true mean of 3 mm (0.118 in.) and true standard deviation of 0.05 mm (0.002 in.). [5]
- Flow rate input is N/A (transients are input in xLPR as Type III [directly input change in mechanical membrane and bending stresses] and thus require no flow rate input).
- Operating pressure of 15.41 MPa (2.235 ksi). [5]
- Operating temperature sampled from a truncated normal distribution with mean of 320.5°C (608.9°F), standard deviation of 5.705°C (10.27°F), max of 326.7°C (620.1°F), and min of 306.1°C (583.0°F). [5]
- Earthquake probability of 2.17E-4 yr^{-1}. [5]
- Earthquake Δ stress with membrane stress sampled from a normal distribution with true mean of 1.608 MPa (0.2332 ksi) and true standard deviation 3.829 MPa (0.5553 ksi), and bending stress sampled from a lognormal distribution with true mean of 14.31 MPa (2.075 ksi) and true standard deviation of 9.494 MPa (1.377 ksi). ([22], [23], [24], [25])

- Membrane stress sampled from a normal distribution with mean of 0.036 MPa (0.0052 ksi) and standard deviation of 0.7905 MPa (0.115 ksi). ([22], [23], [24], [25])
- Bending stress sampled from a normal distribution with mean of 23.605 MPa (3.424 ksi) and standard deviation of 16.205 MPa (2.350 ksi). ([22], [23], [24], [25])
- Material properties for Type 316 stainless steel defined in xLPR-GR-IG v1 [5] applied to the “left pipe,” “right pipe,” and “weld” inputs in xLPR.[5]
- Weld residual stress (WRS) profiles developed from NP-4690-SR [26].
- Transients applied as Type III transients (change in membrane/bending stress) based on ML18299A119 [27].
- Stress distributions, geometry parameters, and operating conditions were fit to values obtained from various industry submittals for deterministic LBB applications ([22], [23], [24], [25]) for welds within the portion of the RHR suction exposed to RCS normal operating conditions to develop inputs for a genericized representative weld.

B.3.2 Sensitivity Cases

Table B-5 lists the cases run (base case and sensitivity cases) for the Westinghouse RHR system, and describes the changes made to the base case model as part of each sensitivity case.

---

[5] The same material property inputs were applied to the base metals and weld metal as a modeling simplification for this case. This simplification is considered reasonable given the limited crack growth observed in the Type 316 stainless steel for these xLPR analysis cases.

Table B-5
Summary of Sensitivity Cases for the Westinghouse RHR System

Case #	Case Identifier	Description
xLPR LOCA Freq 1.2.0	Base Case	Establish base case results
xLPR LOCA Freq 1.2.1	Fatigue Initiation	Model crack initiation from fatigue
xLPR LOCA Freq 1.2.2	WRS Profile	Used a more aggressive weld residual stress profile based on the 95th percentile of the yield stress distribution, developed in an approach that parallels the approach used for N-899 -2200
xLPR LOCA Freq 1.2.3	Geometry	Considered the lower bound NPS (smaller line size than the base case) and lower bound schedule for RHR systems identified
xLPR LOCA Freq 1.2.4	Initial Flaw Size	Modeled larger initial flaws, with true mean initial flaw length doubled relative to base case
xLPR LOCA Freq 1.2.5a	Transients (Freq)	Considered transient loads with frequency doubled relative to base case
xLPR LOCA Freq 1.2.5b	Transients (Load)	Considered transient loads with additional membrane stress increased by 50% relative to base case
xLPR LOCA Freq 1.2.5c	Transients (xLPR-GR-IG)	Considered transient loads defined in xLPR-GR-IG
xLPR LOCA Freq 1.2.5d	Transients (MRP-393)	Considered transient loads defined in MRP-393
xLPR LOCA Freq 1.2.6	Loading	Used higher normal operating thermal loads, with mean loads increased by 50% relative to base case with standard deviations unchanged
xLPR LOCA Freq 1.2.7	Multiple Flaws	Modeled two initial flaws in both axial and circumferential directions

B.3.3 Results

None of the cases modeled for the RHR system resulted in any leaks or ruptures. The crack growth results from the xLPR analyses, summarized in Table B-6, show that the amount of crack growth was limited. In all cases analyzed, no realization saw the maximum crack depth in excess of 27% of the wall thickness. For the deepest flaw in each case, the greatest increase in flaw depth over 80 years was from 16.8% TW to 22.5% TW (0.071 in. (1.8 mm) of growth). The observed crack growth behavior was found to be very similar for axial and circumferential flaws. Furthermore, results from a sensitivity case investigating fatigue crack initiation showed no axial or circumferential cracks initiating as a result of fatigue in 10,000 realizations.

Table B-6
Summary of Percent Through-Wall Crack Depth Growth (a/t) for the Westinghouse RHR System

Case #	Case Identifier	50th %ile Crack Depth (1 mo)	50th %ile Crack Depth (40 yr)	50th %ile Crack Depth (80 yr)	99th %ile Crack Depth (1 mo)	99th %ile Crack Depth (40 yr)	99th %ile Crack Depth (80 yr)
xLPR LOCA Freq 1.2.0	Base Case	9.33%	9.42%	9.51%	13.72%	13.93%	14.13%
xLPR LOCA Freq 1.2.1	Fatigue Initiation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
xLPR LOCA Freq 1.2.2	WRS Profile	9.34%	9.56%	9.75%	13.70%	14.11%	15.02%
xLPR LOCA Freq 1.2.3	Geometry	14.38%	14.50%	14.62%	21.28%	21.50%	21.70%
xLPR LOCA Freq 1.2.4	Initial Flaw Size	9.33%	9.55%	9.75%	13.42%	13.89%	14.58%
xLPR LOCA Freq 1.2.5a	Transients (Freq)	9.35%	9.53%	9.69%	13.78%	14.23%	15.32%
xLPR LOCA Freq 1.2.5b	Transients (Load)	9.34%	9.63%	9.89%	13.61%	14.11%	14.93%
xLPR LOCA Freq 1.2.5c	Transients (xLPR-GR-IG)	9.28%	9.28%	9.29%	13.73%	13.74%	13.75%
xLPR LOCA Freq 1.2.5d	Transients (MRP-393)	9.31%	9.31%	9.32%	13.61%	13.62%	13.62%
xLPR LOCA Freq 1.2.6	Loading	9.33%	9.44%	9.55%	13.68%	13.82%	14.20%
xLPR LOCA Freq 1.2.7	Multiple Flaws	9.35%	9.44%	9.54%	13.90%	14.00%	14.21%

B.4 References

1. M. D. Sartain (Virginia Electric and Power Company), letter to U.S. NRC, “Surry Power Station Units 1 and 2, Request for NRC Approval to Apply Leak-Before-Break Methodology to Reactor Coolant System Branch Piping,” October 22, 2020 [NRC ADAMS Accession No.: ML20296A623].
2. C. V. McFeaters (PSEG Nuclear), letter to U.S. NRC, “License Amendment Request to Exclude the Dynamic Effects of Specific Postulated Pipe Ruptures from the Design and Licensing Basis Based on Leak-Before-Break Methodology,” April 24, 2020 [NRC ADAMS Accession No.: ML20115E374].

3. Structural Integrity Associates, SIA Report No. 0900634.401, "Updated Leak-Before-Break Evaluation for Several RCS Piping at Prairie Island Nuclear Generating Plant Units 1 and 2," December 21, 2009 [NRC ADAMS Accession No.: ML100200131].
4. Westinghouse Electric Company, WCAP-18309-NP, Revision 0, "Technical Justification for Eliminating Safety Injection Line Rupture as the Structural Design Basis for D.C. Cook Units 1 and 2, Using Leak-Before-Break Methodology," January 2018 [NRC ADAMS Accession No.: ML18072A015].
5. xLPR Version 2.0 Technical Basis Document, "Inputs Group Report," xLPR-GR-IG, Version 1.0, December 2017 [NRC ADAMS Accession No.: ML19337B876].
6. "Beaver Valley Power Station, Unit 2, Revision 25 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features." November 23, 2020. [NRC ADAMS Accession No.: ML20335A139].
7. "R.E. Ginna Nuclear Power Plant, Revision 29 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features, Sections 6.1 through 6.6." November 20, 2020. [NRC ADAMS Accession No.: ML20339A065].
8. "North Anna Power Station, Units 1 & 2, Revision 56 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features." September 30, 2020. [NRC ADAMS Accession No.: ML20309A608].
9. "Shearon Harris Nuclear Plant, Unit 1, Amendment 63 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features." May 15, 2020. [NRC ADAMS Accession No.: ML20147A023].
10. "Salem Generating Station, Units 1 & 2, Revision 31 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features." December 5, 2019 [NRC ADAMS Accession No.: ML19360A113].
11. "Callaway Plant, Unit 1, Rev. OL-24 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features." November 13, 2019. [NRC ADAMS Accession No.: ML20209A042].
12. "Donald C. Cook Nuclear Plant Units 1 & 2, Revision 29 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features." October 24, 2019 [NRC ADAMS Accession No.: ML19317D004].
13. "Vogtle Electric Generating Plant, Units 1 & 2, Revision 22 to Updated Final Safety Analysis Report, Chapter 6, (Part 3) & Chapter 7, (Part 1)" October 21, 2019. [NRC ADAMS Accession No.: ML19296C749].
14. ASME Boiler and Pressure Vessel Code, 2019 Edition. The American Society of Mechanical Engineers. New York, NY. 2019.
15. Westinghouse Electric Company, WCAP-16925-NP, Revision 1, "Flaw Evaluation of CE Design RCP Suction and Discharge, and Safety Injection Nozzle Dissimilar-Metal Welds," July 2009 [NRC ADAMS Accession No.: ML092740086].
16. "Millstone Power Station Unit 2, Revision 38 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features Systems." June 22, 2020 [NRC ADAMS Accession No.: ML20209A355].

17. “Palisades Nuclear Plant, Revision 34 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safeguards Systems, Tables.” May 23, 2019. [NRC ADAMS Accession No.: ML19154A287].
18. “Redacted St. Lucie, Unit 1, Amendment 29 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features.” October 4, 2018. [NRC ADAMS Accession No.: ML18320A265].
19. “St. Lucie Unit 2 Amendment 25 to Updated Final Safety Analysis Report, Chapter 6, Engineered Safety Features, Sections 6.3 through 6.6.” March 25, 2019. [NRC ADAMS Accession No.: ML19101A072].
20. “Waterford, Unit 3, Revision 310 to Final Safety Analysis Report, Chapter 6, Engineered Safety Features (EPID L-2020-LLA-0164) – Redacted” July 25, 2018. [NRC ADAMS Accession No.: ML20255A242].
21. *Materials Reliability Program: Characterization of U.S. Pressurized Water Reactor (PWR) Fleet Operational Transients (MRP-393)*. EPRI, Palo Alto, CA: 2014. 3002003085.
22. Sargent & Lundy Report SL-4518, “Leak-Before-Break Evaluation for Stainless Steel Piping Byron and Braidwood Nuclear Power Stations Units 1 and 2,” May 12, 1989 [NRC ADAMS Accession No.: ML20247L184].
23. WCAP-18302-NP, Revision 0 "Technical Justification for Eliminating Residual Heat Removal, Line Rupture as the Structural Design Basis for D.C. Cook Units 1 and 2, Using Leak-Before-Break Methodology,” January 2018 [NRC ADAMS Accession No.: ML18072A014].
24. LR-N20-0010 LAR S19-08, “License Amendment Request to Exclude the Dynamic Effects of Specific Postulated Pipe Ruptures from the Design and Licensing Basis Based on Leak-Before-Break Methodology,” April 24, 2020 [NRC ADAMS Accession No.: ML20115E374].
25. “Virginia Electric and Power Company, Surry Power Station Units 1 and 2, Request for NRC Approval to Apply Leak-Before-Break Methodology to Reactor Coolant System Branch Piping,” October 22, 2020 [NRC ADAMS Accession No.: ML20296A623].
26. Special Report, EPRI NP-4690-SR, *Evaluation of Flaws in Austenitic Steel Piping*, July 1986.
27. Structural Integrity Associates Engineering Report No. 0901350.401, Revision 4, "Leak-Before-Break Evaluation - Accumulator, Pressurizer Surge, and Residual Heat Removal Lines, Turkey Point Units 3 and 4," October 12, 2018 [NRC ADAMS Accession No.: ML18299A119].

APPENDIX C
DESCRIPTION OF xLPR RUNS FOR ADDITIONAL CASES

Case	Description	# of Realizations	Input Description
Runs for Benchmarking Between xLPR-2.0 and xLPR-2.2			
xLPR Piping System Analysis Case 1.1.6	Re-run of case 1.1.6 using xLPR-2.2 to benchmark against results with xLPR-2.0.	70,000	No changes to inputs relative to NRC case.
xLPR Piping System Analysis Case 1.1.17	Re-run of case 1.1.17 using xLPR-2.2 and xLPR-2.0 for benchmarking purposes.	5,000	No changes to inputs relative to NRC case.
Run with 1,000,000 Realizations			
xLPR Piping System Analysis Case 1.1.6	Re-run of NRC case 1.1.6 using xLPR 2.2 and executing 1,000,000 realizations.	1,000,000	No changes to inputs relative to NRC case.
Runs Comparing Occurrence of Rupture and LOCA			
xLPR Piping System Analysis Case 1.1.6	Re-run of case 1.1.6, with LOCAs enabled as an xLPR output for comparison between the occurrence of rupture and LOCA.	20,000	No changes to inputs relative to NRC case.
xLPR Generalization Study Case 2.1.1	Re-run of case 2.1.1, with LOCAs enabled as an xLPR output for comparison between the occurrence of rupture and LOCA.	1,000	No changes to inputs relative to NRC case.
Runs with Reduced Time Steps			
xLPR Piping System Analysis Case 1.1.2	Re-run of the realization from Case 1.1.2 with the shortest time from detectable leakage to rupture with reduced time steps, investigating the effect of different time steps on the time from detectable leakage to rupture.	1	Reduced timestep to 0.2 and 0.05 month. No other changes to inputs relative to NRC case.
xLPR Piping System Analysis Case 1.1.2	Re-run of the realizations from Case 1.1.2 with the shortest time from detectable leakage to rupture with time step of 0.2 month to improve precision of reported time.	8	Reduced timestep to 0.2 month. No other changes to inputs relative to NRC case.

Case	Description	# of Realizations	Input Description
Runs with Reduced Time Steps (continued)			
xLPR Generalization Study Case 2.1.1	Re-run of the realizations from Case 2.1.1 with the shortest time from detectable leakage to rupture with time step of 0.2 month to improve precision of reported time.	17	Reduced timestep to 0.2 month. No other changes to inputs relative to NRC case.
xLPR Generalization Study Case 2.1.2	Re-run of the realizations from Case 2.1.2 with the shortest time from detectable leakage to rupture with time step of 0.2 month to improve precision of reported time.	16	Reduced timestep to 0.2 month. No other changes to inputs relative to NRC case.
xLPR Generalization Study Case 2.1.4	Re-run of the realizations from Case 2.1.4 with the shortest time from detectable leakage to rupture with time step of 0.2 month to improve precision of reported time.	6	Reduced timestep to 0.2 month. No other changes to inputs relative to NRC case.
xLPR Generalization Study Case 4.1.4	Re-run of the realization from Case 4.1.4 with the shortest time from detectable leakage to rupture with time step of 0.2 month to improve precision of reported time.	1	Reduced timestep to 0.2 month. No other changes to inputs relative to NRC case.
Runs with Modified Inputs			
xLPR Generalization Study Case 4.1.1	DEI revision of NRC case 4.1.1, limiting initial flaw depth to be less than inlay depth.	5,000	Initial flaws distributed from 40% to 60% of inlay depth.
xLPR Generalization Study Case 4.1.2	DEI revision of NRC case 4.1.2, limiting initial flaw depth to be less than inlay depth.	10,000	Initial flaws distributed from 40% to 60% of inlay depth.
Runs for Westinghouse Safety Injection (Direct Volume Injection)			
xLPR LOCA Frequencies Case 1.1.0	Base Case for a Westinghouse Safety Injection (Direct Volume Injection) line, considering axial and circumferential cracks, initial flaws, and fatigue crack growth.	20,000	Models a stainless steel weld.
xLPR LOCA Frequencies Case 1.1.1	Sensitivity case for a Westinghouse Safety Injection (Direct Volume Injection) line, addressing the sensitivity of the results to the line geometry, in particular the wall thickness.	10,000	Sets the wall thickness to the bottom quartile of the base case distribution.

Case	Description	# of Realizations	Input Description
Runs for Westinghouse Safety Injection (Direct Volume Injection) (continued)			
xLPR LOCA Frequencies Case 1.1.2	Sensitivity case for a Westinghouse Safety Injection (Direct Volume Injection) line, addressing the sensitivity of the results to the piping loads.	10,000	Mean loads increased by 50% from the base case, standard deviations remain unchanged.
xLPR LOCA Frequencies Case 1.1.3	Sensitivity case for a Westinghouse Safety Injection (Direct Volume Injection) line, addressing the sensitivity of the results to the earthquake probability of occurrence.	10,000	Uses the maximum earthquake probability listed in MRP-216.
xLPR LOCA Frequencies Case 1.1.4	Sensitivity case for a Westinghouse Safety Injection (Direct Volume Injection) line, assuming no initial flaw and only fatigue crack initiation.	10,000	Models crack initiation due to fatigue only.
xLPR LOCA Frequencies Case 1.1.5	Sensitivity case for a Westinghouse Safety Injection (Direct Volume Injection) line, exploring the sensitivity of the results to a more severe weld residual stress profile.	10,000	WRS values set to be 50% higher than in the base case.
xLPR LOCA Frequencies Case 1.1.6	Sensitivity case for a Westinghouse Safety Injection (Direct Volume Injection) line, increasing the number of initial flaws to two to determine if the higher number of flaws leads to leakage and/or rupture.	10,000	Models two initial axial and two initial circumferential flaws.
xLPR LOCA Frequencies Case 1.1.7	Sensitivity case for a Westinghouse Safety Injection (Direct Volume Injection) line, increasing the number of initial flaws to three to determine if the higher number of flaws leads to leakage and/or rupture.	10,000	Models three initial axial and three initial circumferential flaws.

Case	Description	# of Realizations	Input Description
Runs for CE Safety Injection (Accumulator)			
xLPR LOCA Frequencies Case 2.1.0	Base Case for a CE Safety Injection (Accumulator) line, considering axial and circumferential cracks, initial flaws, in-service inspection, and PWSCC crack growth.	10,000	Models an Alloy 82/182 dissimilar metal weld.
xLPR LOCA Frequencies Case 2.1.1	Sensitivity Case for a CE Safety Injection (Accumulator) line, exploring the probability of crack initiation due to PWSCC instead of assuming an initial flaw.	20,000	Models crack initiation due to PWSCC only.
xLPR LOCA Frequencies Case 2.1.2	Sensitivity Case for a CE Safety Injection (Accumulator) line, exploring the sensitivity of the results to the weld residual stress profile.	10,000	Applied "severe" WRS profile from Case 5.1.2 of xLPR Generalization Study.
xLPR LOCA Frequencies Case 2.1.3	Sensitivity Case for a CE Safety Injection (Accumulator) line, exploring the sensitivity of the results to the applied loads.	10,000	Applied loads from the upper half of the base case distribution.
xLPR LOCA Frequencies Case 2.1.4	Sensitivity Case for a CE Safety Injection (Accumulator) line exploring the sensitivity of the results to the earthquake frequency in the simulation.	10,000	Uses the maximum earthquake probability listed in MRP-216.
xLPR LOCA Frequencies Case 2.1.5	Sensitivity Case for a CE Safety Injection (Accumulator) line, exploring the sensitivity of the results to the inclusion of fatigue crack growth.	10,000	Crack growth due to PWSCC and fatigue (as per case description).
xLPR LOCA Frequencies Case 2.1.6	Sensitivity Case for a CE Safety Injection (Accumulator) line, investigating the probability of crack initiation considering the more "severe" WRS.	20,000	Uses the same inputs as xLPR LOCA Frequencies case 2.1.2, but with crack initiation due to PWSCC.
xLPR LOCA Frequencies Case 2.1.7	Sensitivity Case for a CE Safety Injection (Accumulator) line, investigating the sensitivity of the results to performing MSIP mitigation.	10,000	Mitigation by MSIP after 30 years. Post-MSIP WRS from rule-based model from xLPR-MSGR-WRS.

Case	Description	# of Realizations	Input Description
Runs for Westinghouse Residual Heat Removal			
xLPR LOCA Frequencies Case 1.2.0	Base Case for a Residual Heat Removal (RHR) line, considering axial and circumferential cracks, initial flaws, and fatigue crack growth.	5,000	Models a stainless steel weld
xLPR LOCA Frequencies Case 1.2.1	Sensitivity case for a Residual Heat Removal (RHR) line considering fatigue crack initiation.	10,000	Crack initiation due to fatigue only (as per case description)
xLPR LOCA Frequencies Case 1.2.2	Sensitivity case for a Residual Heat Removal (RHR) line considering a more aggressive weld residual stress profile.	5,000	Set based on yield stress, developed in an approach that parallels the approach used for N-899 -2200.
xLPR LOCA Frequencies Case 1.2.3	Sensitivity case for a Residual Heat Removal (RHR) line considering a smaller line size, corresponding to the lower bound for the RHR systems identified.	5,000	Models Schedule 140 pipe size.
xLPR LOCA Frequencies Case 1.2.4	Sensitivity case for a Residual Heat Removal (RHR) line considering a greater initial flaw length.	5,000	True mean initial flaw length doubled relative to base case.
xLPR LOCA Frequencies Case 1.2.5a	Sensitivity case for a Residual Heat Removal (RHR) line, considering more frequent transient loads.	5,000	Transient frequency doubled relative to base case.
xLPR LOCA Frequencies Case 1.2.5b	Sensitivity case for a Residual Heat Removal (RHR) line, considering more aggressive transient loads.	5,000	± Membrane Stress increased by 50% relative to base case.
xLPR LOCA Frequencies Case 1.2.5c	Sensitivity case for a Residual Heat Removal (RHR) line, considering the transients defined in xLPR-GR-IG.	5,000	Model transients as temperature-pressure time histories with no stratification, using values from xLPR-GR-IG.
xLPR LOCA Frequencies Case 1.2.5d	Sensitivity case for a Residual Heat Removal (RHR) line, considering the transients defined in MRP-393	5,000	Model transients as temperature-pressure time histories with no stratification, using values from MRP-393.
xLPR LOCA Frequencies Case 1.2.6	Sensitivity case for a Residual Heat Removal (RHR) line, considering more aggressive normal operating loads.	5,000	Mean loads multiplied by a factor of 1.5 relative to the base case. Standard deviations remain unchanged.
xLPR LOCA Frequencies Case 1.2.7	Sensitivity case for a Residual Heat Removal (RHR) line, considering multiple initial flaws.	5,000	Models two initial axial and two initial circumferential flaws.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

THE TECHNICAL CONTENTS OF THIS PRODUCT WERE PREPARED AS AUGMENTED QUALITY IN ACCORDANCE WITH THE EPRI QUALITY PROGRAM MANUAL WORK CLASSIFIED AS AUGMENTED QUALITY IS NOT SUBJECTTO THE REQUIREMENTS OF 10CFR PART21.

PROGRAM

Pressurized Water Reactor Materials Reliability Program (MRP), P41.01.04

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

3002023895 **February 2024**

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • **www.epri.com**