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Safety Evaluation for a Topical Report

Summary Information

Topical Report No.: Electric Power Research Institute Technical Report No. 3002023895

Topical Report Title: Materials Reliability Program: xLPR [Extremely Low Probability of Rupture] Estimation of PWR [Pressurized Water Reactor] Loss-of-Coolant Accident Frequencies (MRP-480)

Sponsor: Electric Power Research Institute (EPRI)

Summary of Request: EPRI requests that the U.S. Nuclear Regulatory Commission (NRC) review TR 3002023895 as part of the NRC's review of the Alternative Licensing Strategy (ALS) analysis as it demonstrates that analytically determined loss-of-coolant accident frequencies in PWRs using the xLPR probabilistic fracture mechanics code are similar to those presented in NUREG-1829.

Applicability: Westinghouse, Combustion Engineering, Babcock & Wilcox PWRs

Submittal: April 26, 2024, ADAMS Accession No. ML24121A203

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1. INTRODUCTION

By application dated April 26, 2024 (Agencywide Documents Access and Management System Accession No. ML24121A204), EPRI, Inc. (EPRI), submitted topical report (TR) EPRI Technical Report No. 3002023895, "Materials Reliability Program: xLPR [Extremely Low Probability of Rupture] Estimation of PWR [Pressurized Water Reactor] Loss-of-Coolant Accident [(LOCA)] Frequencies (MRP-480)," February 2024 (ML24123A223, hereinafter MRP-480) for U.S. NRC review and approval. MRP-480 was supplemented by letters dated August 29 and October 31, 2025 (ML25241A333 and ML25304A106), which included EPRI's responses to requests for additional information (RAIs).

EPRI stated that the objectives of MRP-480 are to use Extremely Low Probability of Rupture (xLPR) to (a) develop analytically derived LOCA frequency estimates to complement and compare against similar estimates presented in NUREG-1829 (Ref. 1); and (b) rigorously investigate the time between detectable leakage and a LOCA.

EPRI submitted MRP-480 as part of the EPRI ALS. As stated in TR, EPRI Report No. 3002028673, "Loss-of-Coolant-Accident-Induced Fuel Fragmentation, Relocation, and Dispersal with Leak-Before-Break Credit," April 2024 (ML24121A207), currently undergoing a separate review by the NRC staff, the ALS approach provides a pathway for an individual plant licensee to request license amendments to address LOCA-induced Fuel Fragmentation, Relocation, and Dispersal (FFRD) in high burnup (HBU) fuel. Also, as stated in EPRI Report No. 3002028673, the ALS objective is to determine if LOCA-induced FFRD of fuel may be addressed based on demonstrating that (a) the likelihood of LOCAs in the reactor coolant system (RCS) main loop piping (a LOCA in the RCS main loop piping is called a large-break LOCA (LBLOCA)) is extremely unlikely as documented in NUREG-1829, thus making FFRD of HBU fuel not credible; and (b) the break of the largest branch lines of the RCS main loop shows acceptable fuel relocation and no fuel cladding rupture of HBU fuel. MRP-480 is the technical basis for the first ALS objective.

2. EVALUATION CRITERIA

2.1 Regulations

Title 10 of the *Code of Federal Regulations* Part 50 (10 CFR 50), "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," Criterion 4, "Environmental and dynamic effects design bases," specifies, in part, that when analyses approved by the NRC demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping, dynamic effects associated with postulated pipe ruptures may be excluded from the design basis.

The ALS under which MRP-480 is implemented leverages the plant-specific approved leak-before-break (LBB) analyses for the RCS main loop piping of PWRs that were performed to meet the criterion of "the probability of fluid system piping rupture is extremely low" in 10 CFR Part 50, Appendix A, Criterion 4. The probabilistic fracture mechanics (PFM) analyses in MRP-480 are used to supplement the approved LBB analyses to further demonstrate that the likelihood of rupture under a LOCA is extremely low. The PFM analyses in MRP-480 are performed in the context of LBB behavior in Alloy 82/182 dissimilar metal welds (DMWs), in which an active degradation mechanism of primary water stress corrosion cracking (PWSCC) is

present. Currently, there are no other active degradation mechanisms in the RCS main loop piping.

2.2 Mandated Licensing Basis Document Information

Not applicable

2.3 NRC-Approved Topical Reports Dependencies

Not applicable

2.4 Applicable Guidelines

NUREG-1829, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process," Volume 1 (Ref. 1)

Regulatory Guide (RG) 1.245, "Preparing Probabilistic Fracture Mechanics Submittals," Revision 0 (Ref. 2)

RG 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Revision 3 (Ref. 3)

3. TECHNICAL EVALUATION

3.1 Overview of MRP-480

Section 1, "Introduction," summarizes the background of MRP-480 as it relates to NUREG-1829, ALS, and FFRD; the objectives and scope of the MRP-480; and the analysis approach used in MRP-480.

Section 2, "NUREG-1829 LOCA Frequencies and xLPR Case Selection for Evaluation," describes the LOCA frequencies determined in NUREG-1829 and the LOCA-sensitive PWR piping systems selected for xLPR analyses. This section states that MRP-480 leverages the results of the studies in the xLPR Piping System Analysis Report (Ref. 4) and xLPR Generalization Study Report (Ref. 5).

Section 3, "xLPR PFM Evaluation," provides details of the xLPR analyses performed in MRP-480, including the base and sensitivity cases, key output quantities of interest (Qols), xLPR versions used, and a summary of the uncertainties and assumptions in the analyses.

Section 4, "Analysis of PFM Results," provides details of the xLPR analysis results that support these objectives of MRP-480: estimation of LOCA frequencies, determination of time from detectable leakage to rupture, and determination of time from detectable leakage to LBLOCA.

Section 5, "Investigation Into Applicable Degradation Mechanisms," summarizes the degradation mechanisms for the relevant pressure boundary materials considered in the xLPR analyses in MRP-480.

Section 6, "Conclusions," discusses overall conclusions of MRP-480, conclusions specific to ALS, and the plant applicability criteria for the use of MRP-480.

Appendix A, "Template for Run Description Form," provides a form template for an xLPR run description.

Appendix B, "Additional xLPR Analyses Performed," describes new xLPR cases (i.e., analyses) performed in MRP-480 that supplement the cases in the xLPR Piping System Analysis Report and xLPR Generalization Study Report.

Appendix C, "Description of xLPR Runs for Additional Cases," tabulates additional xLPR runs performed in MRP-480 with summary descriptions for both the new cases described in Appendix B of MRP-480 and reruns of existing cases.

3.2 NRC Staff Evaluation

The NRC staff evaluated the PFM analyses in MRP-480 to determine whether the analyses adequately support the objectives stated in Section 1.2 of the report. EPRI stated that the objectives of MRP-480 are to use xLPR, a PFM code, to (a) develop analytically derived LOCA frequency estimates to complement and compare against similar estimates presented in NUREG-1829; and (b) rigorously investigate the time between detectable leakage and a LOCA. The NRC staff noted that MRP-480 contains PFM analyses of piping smaller than the RCS main loop piping, such as the surge line, safety injection line, and residual heat removal line, as indicated in Tables 2-1 and 3-1 of MRP-480. However, since MRP-480 is the technical basis for demonstrating the ALS objective that the likelihood of LOCAs in the RCS main loop piping is extremely low, the NRC staff evaluated the PFM analyses of the RCS main loop piping only.

Section 1.1 of MRP-480 states: "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." In response to RAI 2, EPRI clarified this statement, citing its letter dated April 26, 2024 (ML24121A204) that the requested review scope for MRP-480 is for supporting ALS, and that other applications of MRP-480 outside the scope of ALS would require separate NRC review and approval specific to those applications.

In Section 3 of MRP-480, EPRI stated that the key xLPR Qols (i.e., output, for demonstrating the above objectives) are (a) probability of rupture (applied as an analogue to probability of a LOCA); (b) time between 1 gallon per minute (gpm) (3.8 liters per minute (lpm)) detectable leakage and LBLOCA; and (c) time between 1 gpm detectable leakage and rupture. Given the objectives of MRP-480 and these xLPR Qols, the NRC staff evaluated EPRI's determination of LOCA frequency estimates (Section 3.2.1 of this SE) and the time between detectable leakage and LOCA (Section 3.2.2 of this SE). In Section 4.4 of MRP-480, EPRI discussed the PFM analyses in MRP-480 in the context of the PFM submittal guidance in RG 1.245. Therefore, the NRC staff evaluated the classification of the PFM analyses in MRP-480 per the guidance in RG 1.245 (Section 3.2.3 of this SE).

The NRC staff conducted a regulatory audit, from April 22 to April 25, 2025, to clarify its understanding of the technical aspects of the PFM analyses in MRP-480 (Refs. 6 and 7).

3.2.1. Evaluation of LOCA Frequency Estimates

EPRI calculated LOCA frequency estimates using xLPR and compared the results with those determined from NUREG-1829, as shown in Figures 4-1, 4-3, and 4-4 of MRP-480. In

Section 4.1.2 of MRP-480, EPRI stated that the xLPR analyses and the NUREG-1829 results are of a similar order of magnitude. The NRC staff confirmed that the NUREG-1829 results shown in these figures are consistent with those in NUREG-1829.

Figure 4-1 presents the xLPR results without credit for inservice inspections (ISI) or leak rate detection (LRD), Figure 4-3 presents the xLPR results with credit for LRD (no credit for ISI), and Figure 4-4 presents the xLPR results with credit for LRD and ISI. The xLPR results are from the cases analyzed and described in the xLPR Piping System Analysis Report and xLPR Generalization Study Report and listed in Table 3-3 of MRP-480. The NRC staff noted that these two reports document extensive xLPR analyses of RCS main loop and non-main loop piping systems, including investigating the likelihood of rupture under a LOCA for these piping systems and the time from detectable leakage to LOCA. The NRC staff noted that, therefore, the xLPR analyses in these two reports are directly aligned with the two objectives of MRP-480.

In the summary of base and sensitivity cases in Tables 3-1 and 3-2 of MRP-480, EPRI highlighted that the focus of ALS is the RCS main loop piping. Based on this, the NRC staff noted that the cases in Table 3-3 of MRP-480 relevant to and specific to ALS (collectively called "ALS Cases" in this SE) are Cases 1.1.0 through 1.1.23, 1.2.0 and 1.2.1, 1.3.0 and 1.3.1, 3.1.0 through 3.1.2, and 4.1.0 through 4.1.4. Detailed descriptions of these cases are in the xLPR Piping System Analysis Report and xLPR Generalization Study Report.

Probability of rupture as an analogue for probability of LOCA

In Section 4.1.1 of MRP-480, EPRI stated that LOCA frequencies were computed using the xLPR code based on the probability of rupture [$P(\text{rupture})$] output at 80 years. In Section 4.1.5 of MRP-480, EPRI stated that "occurrence of rupture" (i.e., $P(\text{rupture})$), was used as an analogue for the "occurrence of LBLOCA" (i.e., probability of LBLOCA) in the development of xLPR-based LOCA frequencies in the report. EPRI selected Case 1.1.6 in Table 3-3 of MRP-480 to illustrate that every realization (one deterministic calculation out of the total specified number of realizations for a particular case) where an LBLOCA occurred, a rupture also occurred. Based on this, the NRC staff noted that the xLPR LOCA frequency results in Figures 4-1, 4-3, and 4-4 of MRP-480 runs are based on $P(\text{rupture})$.

In response to RAI 6, EPRI further explained that while in theory not every realization with LBLOCA would necessarily lead to a rupture, in practice the $P(\text{rupture})$ output in xLPR is more robust than LBLOCA probability output for calculating LOCA frequencies due to limitations in the code. EPRI noted that xLPR does not recompute the leak rate during the timestep when rupture occurs, and thus, LBLOCA is not reported by xLPR when rupture occurs; therefore, in a model of the RCS main loop piping, a rupture would necessarily imply a LBLOCA because of the piping size. EPRI stated that Case 1.1.2 in Table 3-3 of MRP-480 was further analyzed to illustrate this limitation in xLPR in that the LBLOCA output would result in a LBLOCA frequency that is 17 percent lower than if the $P(\text{rupture})$ output was used. EPRI further explained that in the 30 realizations resulting in LBLOCA and rupture in Case 1.1.6 in Table 3-3 of MRP-480, the final leak rates were greater than the 5000 gpm threshold above which LBLOCA occurs. EPRI reasoned that by the time leak rates approach 5000 gpm, the modeled flaws are very large and growing very quickly, and as such, rupture is expected to occur shortly thereafter. Based on the above explanation, the NRC staff concludes that use of $P(\text{rupture})$ is an adequate analogue to probability of LBLOCA (i.e., occurrence of LBLOCA or LBLOCA frequency) because EPRI provided sufficient information to demonstrate that a LBLOCA is very likely to lead to rupture for the RCS main loop piping.

In Section 4.1.1 of MRP-480, EPRI stated that for cases applying the xLPR crack initiation models, the LOCA frequency over the 80-year period was determined by taking the $P(\text{rupture})$ value at 80 years and dividing by 80 years: $\text{LOCA frequency} = P(\text{rupture})/80$. The NRC staff noted that this assumption is conservative based on the plots of $P(\text{rupture})$ histories in the xLPR Piping System Analysis Report and xLPR Generalization Study Report. These plots show that the $P(\text{rupture})$ value at 80 years divided by 80 years is greater than the tangential slope of the plot at 80 years. For cases applying the xLPR initial flaw models, the value of $P(\text{rupture})$ at 80 years in the above equation is estimated by multiplying $P(\text{rupture})$ at 80 years by the probability of crack initiation at 80 years.

The NRC staff verified that the xLPR LOCA frequency results in Figures 4-1, 4-3, and 4-4 of MRP-480 are consistent with the $P(\text{rupture})$ and probability of crack initiation results provided in Appendix A of the xLPR Piping System Analysis Report and xLPR Generalization Study Report for the cases relevant to ALS. The NRC staff noted that, as stated in the beginning of the appendix of both reports, all the cases in the xLPR Piping System Analysis Report and the base cases in the xLPR Generalization Study Report resulted in a $P(\text{rupture})$ value of zero with 1 gpm LRD.

Based on the discussion above, the NRC staff determined that the use of probability of rupture as an approximate analogue to probability of LBLOCA is acceptable for the analyses in MRP-480 relevant to ALS because EPRI provided adequate explanation that a realization in the PFM analysis that results in a LBLOCA is very likely to lead to a rupture.

Impact of PWSCC initiation model

The NRC staff noted in the “Summary of Analysis Cases” in Table 3-1 of the xLPR Piping System Analysis Report and xLPR Generalization Study Report that the majority of the ALS Cases use the xLPR crack initiation model, Direct Model 1 (DM1). The NRC staff noted that in general, the use of the crack initiation model in xLPR leads to lower LOCA frequencies compared to those resulting from the use of the initial flaw model, because in the former, the time it takes to initiate a crack is factored into the calculation of the LOCA frequencies. In Section 3.6 of MRP-480, EPRI stated that the xLPR Uncertainty Report (Ref. 8) summarizes model validation as well as any limitations for each of the xLPR modules. In response to RAI 4, EPRI provided further details of DM1 regarding conservatisms in the model, calibration of the model, and sensitivity studies performed on the model. EPRI stated that DM1 calculates initiation time directly as a function of temperature and surface stress and that a stress threshold of zero was recommended for DM1 in the xLPR Calibration Report (Ref. 9) and applied in MRP-480. The stress threshold is the stress value below which PWSCC initiation does not occur. EPRI stated that the stress threshold used to develop the base case model parameters led to the assumption that PWSCC occurred at near-surface stresses below 80 percent of the operating temperature yield strength for some components in the field data set, even though PWSCC initiation is not expected at stress levels less than 80 percent of the operating temperature yield strength. EPRI stated that this assumption has a net conservative effect on the PWSCC initiation model parameters recommended in the xLPR Calibration Report (Ref. 9).

EPRI also explained that during model parameter development, “indications” (i.e., discontinuities identified in ultrasonic examinations that may be indicative of a defect) were conservatively interpreted as instances of PWSCC. EPRI further explained that when considering field data with multiple smaller flaws, such smaller flaws were assumed to be planar

and congruent such that they are conservatively represented by one continuous flaw that is idealized by the maximum depth and length of the flaw.

In addition, EPRI explained that, during model parameter development, inspections that did not detect any indications were treated conservatively by being excluded from the data analysis. EPRI explained that including these inspections would bias the fitted distribution of the data toward longer predicted initiation times.

During the audit, the NRC staff verified that the PWSCC initiation recommended model parameters for DM1 (stress threshold, stress exponent, inverse proportionality constants) from the xLPR Calibration Report were entered in the xLPR input deck for the particular case (e.g., ALS Case 1.1.0 for the reactor vessel outlet nozzle (RVON)).

Regarding calibration of the model, EPRI referred to Section 8.3 of the xLPR Uncertainty Report, which cites the PWSCC initiation calibration in the xLPR Calibration Report (Ref. 9). That report states that both laboratory and field datasets were considered during model calibration. Section 8.3 of the xLPR Uncertainty Report notes that the aggregate prediction of initiation time based solely on laboratory results is expected to underpredict the time to PWSCC initiation observed in the field. Therefore, the report notes that estimation of the probabilistic failure time model was done using field data. The report further states that this approach has the advantage of implicit treatment of the effects of surface condition and material susceptibility during model calibration. Section 8.3 of the xLPR Uncertainty Report also states that the general statistical framework used in the calibration effort applies laboratory data for refinement of underlying model dependencies and field data for calibration of the initiation-time prediction.

Regarding sensitivity studies performed on the model, EPRI referred to Section 3.2.2.2 of the xLPR Piping System Analysis Report for a sensitivity study using the Weibull PWSCC initiation model; Appendix C of the xLPR Piping System Analysis Report for a sensitivity study using laboratory data only; and Sections 7 and 8 of the xLPR Calibration Report for numerous sensitivity studies performed during the model calibration process. The NRC staff reviewed these documents that EPRI cited for sensitivity studies performed on crack initiation and concluded that the sensitivity studies the applicant performed are sufficient to ensure uncertainties on the DM1 crack initiation model were adequately addressed based on the extensive analyses performed, including comparisons with laboratory data and data statistics.

The NRC staff concludes the impact of the PWSCC initiation model, DM1, acceptable for the xLPR analyses of the RCS main loop piping in MRP-480 because (a) adequate conservatism were included during development of the model parameters, especially in the stress threshold parameter being set to zero since it has been observed that a significant tensile stress (80 to 100 percent of the yield strength of the PWSCC-susceptible material) is needed to initiate PWSCC (Ref. 9); (b) DM1 was calibrated with field data, which reflects operating and material conditions in the field; and (c) sufficient sensitivity studies were performed on DM1 to ensure uncertainties of the model were adequately addressed.

Weld-level versus system-level PFM results

In Sections 3.1 and 3.2 of MRP-480, EPRI stated that the analyses in the xLPR Piping System Analysis Report and xLPR Generalization Study Report modeled Alloy 82/182 DMWs, and in Section 6.2 of MRP-480 EPRI stated that DMWs within the RCS main loop piping are known to be the most susceptible to active degradation and thus most limiting. Section 1.3 of MRP-480

states that xLPR considers only one weld at a time by design. Because of this, the NRC staff noted that individual weld-level failure frequencies may be different than the system-level failure frequencies. Section 4.1.2 of MRP-480 discusses the assessment of weld-level versus system-level failure frequencies and refers to the discussion of this topic in the xLPR Generalization Study Report. Additionally, the NRC noted the following recommendation from Section 4.3.2 of the xLPR Piping System Analysis Report:

Ignore the data in the final statistics if the failure probability of a given weld type multiplied by the number of welds of the type in the system is less than an order of magnitude below the probability of the same event for the worst-case weld type.

The NRC staff used the above recommendation to compare system-level failure probabilities between DMWs and similar metal welds (SMWs) in the RCS main loop piping since xLPR considers only one weld at a time and the PFM results of the ALS Cases in MRP-480 are for DMWs that are known to be the most susceptible to active degradation (i.e., considered the "worst-case" weld type). For Case 1.1.0 for the RVON, for instance, the $P(\text{rupture})$ value at 80 years without credit for LRD and ISI is approximately $1\text{E-}03$, per Appendix A of the xLPR Piping System Analysis report. Table 4-1 of the xLPR Generalization Study report indicates that a Westinghouse 4-Loop plant has five DMWs for the RVON. The total $P(\text{rupture})$ value at 80 years for five DMWs is therefore $5\text{E-}03$. While the exact number of SMWs in an RCS main loop piping is generally not known, for this comparison calculation the NRC staff assumed, based on general knowledge of PWR RCS main loop piping systems, that 100 SMWs are a reasonable estimate for a 4-loop plant. $P(\text{rupture})$ values for SMWs are also generally not known, but since stress corrosion cracking is not a known active degradation mechanism for SMWs of PWR RCS main loop piping exposed to primary coolant, the $P(\text{rupture})$ value at 80 years is expected to be much less than $1\text{E-}06$. Supporting this expectation, the NRC staff noted the fatigue crack growth study of a SMW performed in Section B3 of MRP-480. Even though $P(\text{rupture})$ values were not reported in the study, the NRC staff inferred that they would be very low, because the study showed that the amount of crack growth was minimal. Therefore, for 100 SMWs, each with a $P(\text{rupture})$ value at 80 years of $1\text{E-}06$, the NRC staff calculated a total $P(\text{rupture})$ value at 80 years of $1\text{E-}04$, which is an order of magnitude less than the total $P(\text{rupture})$ value at 80 years of $5\text{E-}03$ for five DMWs. Therefore, the NRC staff concludes that it was acceptable for the applicant to only consider individual welds. The NRC staff noted that the $P(\text{rupture})$ value at 80 years for this example, when credit is taken for LRD and ISI, is zero, because the example is based on Case 1.1.0 of MRP-480.

Regarding stainless steel materials, the NRC staff noted that some RCS main loop piping is made of cast austenitic stainless steel (CASS) which is subject to thermal aging that could lead to a reduction in fracture toughness of the steel. In Section 5.1.5 of MRP-480, EPRI stated that reduction in fracture properties due to thermal aging can occur in 300 series stainless steel welds with high delta-ferrite levels. EPRI also stated that the screening criteria for potentially significant thermal aging effects are based on measured or calculated delta-ferrite content, with 14 percent and 20 percent delta-ferrite being the threshold values for high molybdenum content in statically and centrifugally CASS, respectively. EPRI stated that low levels of delta-ferrite (3 percent to 10 percent) present in well-controlled austenitic stainless steel welds are unlikely to lead to a significant reduction in fracture properties of the stainless steel piping considered in the MRP-480 analyses. During the audit, the NRC staff noted that the reduction in fracture properties of CASS impacts LOCA frequencies of RCS main loop piping that is made of CASS.

The NRC staff also noted during the audit that the recent PFM work performed by EPRI on CASS RCS main loop piping in non-proprietary report MRP-479 (Ref. 10) showed failure frequencies that are on the same order of magnitude of LOCA frequencies (less than 1E-07 per year) as those in NUREG-1829. The NRC staff confirmed that MRP-479 included a case with delta-ferrite content of 40 percent representing a bounding reduction in fracture toughness properties of CASS. Therefore, the NRC staff finds that this recent PFM work on CASS in MRP-479 adequately shows that CASS piping with a bounding reduction in fracture toughness properties results in failure frequencies that are on the same order of magnitude of LOCA frequencies (less than 1E-07 per year) as those in NUREG-1829 and, therefore, LOCA of CASS material in RCS main loop piping is extremely unlikely.

The NRC staff also noted that Table 3-3 of MRP-480 includes three cases for Combustion Engineering (CE) and Babcock & Wilcox (B&W) designs, which have ferritic steel piping (base and weld metal) in the RCS main loop piping. Section 5 of MRP-480 assesses degradation mechanisms in stainless steels and nickel-based alloys but does not include an assessment of degradation mechanisms in ferritic steels. In response to RAI 3, EPRI stated that in CE and B&W designs, RCS piping is made of carbon steel with internal stainless-steel cladding. EPRI summarized the degradation mechanisms that could impact ferritic steel piping, including pitting corrosion (of the stainless cladding), stress corrosion cracking, cracking due to high cycle fatigue, cracking due to environmentally assisted fatigue, and embrittlement. Of these, EPRI further evaluated cracking due to environmentally assisted fatigue, which is generally known to be the degradation mechanism of note in RCS piping. EPRI stated that the xLPR analyses of the stainless-steel welds in MRP-480 apply to the cladding material of the ferritic piping. As discussed above, the NRC staff noted that the amount of crack growth in the similar metal (i.e., stainless steel) weld analyzed in Section B3 of MRP-480 was minimal. EPRI performed sensitivity cases based on Case 3.1.1 of MRP-480 for the CE and B&W reactor coolant pump (RCP) nozzle to analyze fatigue crack growth in genericized [sic] welds in ferritic steel piping, with initial flaw depths up to approximately 20 percent of the wall thickness. The results of the sensitivity cases showed zero probability of leakage or rupture and minimal amount of crack growth for 80 years. The NRC staff concludes the sensitivity cases for ferritic steel piping acceptable because there was minimal crack growth for 80 years and, therefore, they are bounded by the xLPR analyses of the DMWs in MRP-480.

Seismic impacts and inspections

Table 3-1 of MRP-480 indicates that seismic effects were included in the analyses for the RVON, steam generator (SG) inlet nozzle, SG outlet nozzle (SGON), and RCP nozzle, which are all in the ALS scope. Details of the seismic effects are in the xLPR Piping System Analysis Report (Ref. 4) and xLPR Generalization Study Report (Ref. 5). Appendix B of these two reports shows the values of seismic stresses used in the analyses of the piping in the ALS scope. The NRC staff noted the high degree of uncertainty regarding the impact of seismic loads on piping systems and that ISI of the RCS main loop piping could address some of this uncertainty. Additionally, the NRC staff noted that in the context of risk-informed decision making (RIDM) and consistent with RG 1.245, Revision 0 (Ref. 2) for PFM submittals specifically and RG 1.174, Revision 3 (Ref. 3) generically, PFM is only one aspect when used as the basis in regulatory and safety decisions. PFM analyses work in tandem with other RIDM principles, particularly the performance monitoring principle. For the RCS main loop piping, ISI is one of the primary means of performance monitoring.

In response to RAI 1, EPRI discussed considerations regarding seismic risk and performance monitoring for the RCS main loop piping by citing a Nuclear Energy Institute (NEI) white paper (Ref. 11) issued in October 2025 and publicly available for download from the NEI website. Section 8 of the NEI white paper assesses the seismic risk pertaining to the RCS main loop piping (also known as the primary loop piping (PLP) in the white paper) by addressing the risk due to a seismically-induced LBLOCA and by summarizing the multiple technical bases and programs that justify the minimal impact of PLP degradation on seismic fragility. Section 3 of the NEI white paper assesses existing inspection programs for the RCS main loop piping that focus on locations with the highest safety and risk significance. The NRC staff determined that the information in the white paper would be generally applicable to plants in scope of this topical report because it does not depend on site specific features.

Seismic impacts

Section 8 of the NEI white paper cites the seismic probabilistic risk assessments (SPRAs) performed for fifteen plants, eleven of which were PWRs, and submitted to the NRC as part of the post-Fukushima effort to assess seismic risk. The fifteen plants in these SPRAs represent plants with the highest seismic demands (i.e., seismic hazard exceeded the seismic design basis) and a broad range of diversity in reactor type, reactor manufacturer, reactor model, and soil conditions. These SPRAs identified dominant risk contributors for seismic core damage frequency and seismic large early release frequency that were associated with LBLOCA. The NRC staff noted that from the dominant risk contributors that were identified, the highest probability of failure (i.e., $P(rupture)$), per year values were $1.2E-05$ for indirect PLP failures and $8.9E-06$ for direct PLP failures. The probability of failure result for direct PLP failures is less than the PLP break probability limit value of $1E-05$ per year due to seismic events established in NUREG-1903 (Ref. 12). Although the probability of failure value for indirect PLP failures is slightly greater than $1E-05$ per year, the NEI white paper states that indirect failures result from failures of primary loop supports, which are assumed to lead to PLP failure even though the primary loop supports are not susceptible to degradation mechanisms (unlike those of the PLP exposed to the RCS environment). Moreover, the NEI white paper states the primary loop supports are managed by inspection and maintenance programs. The NRC staff noted that the $P(rupture)$ value of $1.2E-05$ per year for indirect PLP failures assumes that the component support failure leads to a 100 percent piping rupture and that this is a conservative assumption. The NRC staff also noted that primary loop supports are inspected under the Structures Monitoring aging management program (AMP) for PWRs and the requirements of the American Society of Mechanical Engineers (ASME) Code, Section XI, Subsection IWF. Therefore, based on this discussion, the NRC staff determined that the risk due to a seismically-induced LBLOCA is low.

The NEI white paper also summarizes several technical evaluations and programs that support the conclusion that PLP degradation has a minimal impact on seismic fragility. The paper discusses that (a) LBB evaluations account for the impact of thermal embrittlement of CASS materials and safe shutdown earthquake with a margin of at least 2 between the leakage flaw size and the critical flaw size (i.e., the critical flaw size is at least twice the size of the leakage flaw); (b) the xLPR Piping System Analysis Report (Ref. 4) and xLPR Generalization Study Report (Ref. 5) include seismic loads and conclude that seismic effects do not compromise LBB behavior of DMWs in PLP; (c) Case 1.1.5 of MRP-480 for the RVON includes design basis safe shutdown earthquake stresses scaled to a factor of five, corresponding to a peak ground acceleration with an annual frequency of occurrence of $1E-06$ per year; (d) seismic loading is considered as part of the design basis for non-piping RCS components; (e) recent PFM work on

CASS in the MRP-479 report (Ref. 10) shows that the failure frequency of CASS materials in the PLP is less than 1E-06 per year (this is discussed further in this SE in the section titled "Weld-level versus system-level PFM results"); and (f) AMPs relevant to the PLP, such as the Alloy 600 AMP, ISI AMP, Fatigue Monitoring AMP, and Thermal Aging Embrittlement of CASS AMP, are designed to monitor and mitigate degradation mechanisms in the PLP. The NRC staff noted that these evaluations and programs assure that the impact of PLP degradation on piping/component is minimal because they include seismic effects with adequate margin (e.g., in LBB evaluations procedures, leakage flow sizes are based on 10 gpm leak rate compared to 1 gpm LRD capability, and a margin of 2 between the leakage flow size and critical flow size must be demonstrated), and the AMPs are well-established programs that have been effective in age management of PLP degradation. NUREG-1903 (Ref. 12) defines seismic fragility as the relationship between the seismic response and probability of failure. The NRC staff noted that PLP degradation is related to seismic response, e.g., a highly degraded PLP could lead to a significant change in the seismic response of the PLP because PLP degradation could change the overall stiffness of the PLP system. Given the definition of seismic fragility above, the NRC staff noted that a minimal impact on piping/component integrity indirectly means a minimal impact on seismic fragility.

Based on the discussion above, the NRC staff determined that EPRI adequately addressed seismic risk of the RCS main loop piping because the risk due to a seismically-induced LBLOCA was determined to be low and the impact of piping degradation on piping/component integrity (and therefore on seismic fragility) was shown to be minimal.

Inspections

In response to RAI 1, EPRI stated that the existing inspection programs for the RCS main loop piping, along with industry's current materials management programs, are sufficient to support ongoing performance monitoring for the welds within the scope of the MRP-480 analyses and ALS. These existing inspection programs are the risk-informed ISI (RI-ISI) programs (traditional and streamlined) and augmented inspection program. The RI-ISI programs are both NRC-approved programs and the augmented inspection program (i.e., ASME Code, Section XI, Code Case N-770-7, "Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated with UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities Section XI, Division 1") for the RCS main loop piping DMWs is incorporated by reference in 10 CFR 50.55a. The NRC staff noted that the basic approach in these RI-ISI programs is to bin piping welds into risk categories based on operating experience and susceptibility to degradation mechanisms (two main considerations among other aspects) and specify a certain percentage of those welds be inspected. The NRC staff noted that, generally, for piping welds designated in the medium to high risk (or high safety significant) category in the RI-ISI programs, a minimum inspection of 10 percent of the welds for a particular bin is required. The NEI white paper describes a survey of U.S. PWRs implementing the RI-ISI program (specifically, the streamlined method). This survey revealed that some NUREG-1829 welds, including SMWs, are currently being inspected in accordance with the RI-ISI program. Table 3.1 of the NEI white paper indicates that from the survey of 25 PWRs and 12 BWRs, a total of 287 SMWs in the PLP are being inspected, with an average of about 10 percent of the welds for each of the three PWR design types. The table also indicates that for the RCS main loop piping of PWRs, the welds being inspected are in the hot leg, cold leg, and crossover legs of the piping. The NRC staff noted that some of the Westinghouse plants are not inspecting PLP SMWs in the RI-ISI program inspection population, as shown in the table. However, Table 3.1 of

the NEI white paper indicates a 25 percent sample of the pressurizer surge line of a high-risk location (Category 2 under the traditional RI-ISI method) is being inspected under the RI-ISI program. The NRC staff noted that this 25 percent sample of pressurizer surge line high-risk location welds is a sufficient leading indicator of degradation for those Westinghouse plants that are not inspecting PLP SMWs because of the adverse conditions in the pressurizer surge line, including high temperature, thermal stratification, and fatigue cracking due to insurge/outsurge events.

Section 3 of the NEI white paper also discusses the augmented inspection program relevant to the RCS main loop piping, specifically the augmented inspection program for managing and mitigating PWSCC in DMWs. This augmented inspection program, defined in ASME Code, Section XI, Code Case N-770-7, is incorporated by reference into 10 CFR 50.55a(a)(1)(iii)(D) and specifies requirements for managing and mitigating PWSCC in DMWs in the RCS main loop piping to provide adequate assurance of structural integrity of those welds.

Based on the discussion above, the NRC staff determined that EPRI adequately justified that the existing inspection programs for the RCS main loop piping are sufficient for assuring safety (i.e., assurance against break-before-leak) of the piping systems in the scope of ALS without the need for additional or expanded inspections because the existing inspection programs focus on high safety significant locations and include sufficient sample of SMWs.

Based on the combined discussion above on seismic impacts and inspections, the NRC staff finds that seismic uncertainty is adequately addressed for the ALS Cases in MRP-480 because the risk due to a seismically-induced LBLOCA is low, the impact of piping degradation on seismic fragility is minimal, and existing inspection programs focus on high safety significant locations and include a sufficient sample of SMWs.

Conclusion on LOCA Frequency Estimates

Based on the discussions above, the NRC staff concludes that the xLPR LOCA frequency estimates in Figures 4-1, 4-3, and 4-4 of MRP-480, are acceptable because EPRI adequately addressed the technical aspects of the PFM analyses relevant to the xLPR results, particularly the impact of the PWSCC initiation model, the difference between weld-level and piping system-level results, and the assessment of seismic risk and inspection programs for the RCS main loop piping to address seismic uncertainty. Therefore, the NRC staff determined that the results of the xLPR analyses in MRP-480 relevant to ALS are of a similar order of magnitude to those determined in NUREG-1829. The NRC staff noted that the range of PFM results in NUREG-1829 is large because of the large uncertainty inherent in the underlying PFM analyses in NUREG-1829, and because the PFM analyses in NUREG-1829 were performed by several organizations. Therefore, the NRC staff noted that demonstration of the MRP-480 xLPR analyses relevant to ALS being within the range of PFM results in (i.e., similar order of magnitude to) NUREG-1829 is sufficient confirmation of the NUREG-1829 results. Since one of the overall objectives of ALS is to demonstrate that the likelihood of LBLOCAs in the RCS main loop piping is extremely unlikely as documented in NUREG-1829, the NRC staff determined that the xLPR analyses in MRP-480 relevant to ALS adequately show that LBLOCAs in the RCS main loop piping of PWRs are extremely unlikely.

3.2.2. Evaluation of Time Between Detectable Leakage and LOCA

In Section 4.3 of MRP-480, EPRI discussed the second objective of MRP-480, which is to rigorously investigate the time between detectable leakage and LOCA (i.e., LBLOCA) to demonstrate that sufficient time exists to allow for reactor shutdown and the reduction of decay heat generation, thereby preventing the progression to the occurrence of a LBLOCA. EPRI stated that when ISI and LRD are not credited, LBLOCAs were observed to occur in 27,000 realizations for the RVON. No LBLOCAs were observed when crediting ISI and LRD. From these 27,000 realizations in which LBLOCA was observed to occur, EPRI determined a time between detectable leakage and LBLOCA of 19 months based on a lower bound 95/95 one-sided tolerance confidence interval for piping relevant to ALS. EPRI calculated this lower bound 95/95 one-sided tolerance confidence interval per the statistical recommendations in NUREG-1475 (Ref. 13). Since rupture was used as an analogue for LBLOCA (i.e., probability of rupture as an analogue for probability of LBLOCA as discussed in Section 3.2.1 of this SE), EPRI also reported a minimum time from detectable leakage to rupture of 14 months for the base cases analyzed for piping relevant to ALS. The NRC staff noted that while this minimum time from detectable leakage to rupture of 14 months is below the 95/95 lower bound detectable leakage to LBLOCA of 19 months, 14 months is sufficient time for safe shutdown of the plant in the event of a leakage from the RCS main loop piping.

EPRI also stated that Case 4.1.4 in Table 3-3 of MRP-480 for an unmitigated (i.e., not protected by a PWSCC resistant inlay) SGON resulted in two realizations with time between detectable leakage and LBLOCA of zero. EPRI explained that the two realizations for this particular case represent large cracks that would be detectable by ISI, and that there is only one plant in the U.S. PWR fleet with an Alloy 82/182 SGON weld that has not been mitigated, but continues to be periodically inspected as required by ASME Code, Section XI, Code Case N-770-7 (see discussion in Section 3.2.1 of this SE). As discussed in the previous section of this SE, EPRI used the occurrence of rupture as an analogue to the occurrence of LOCA. Therefore, for further context of the time between detectable leakage and LBLOCA, EPRI discussed the time between detectable leakage and rupture in Section 4.2 of MRP-480. EPRI explained that the cases in which the time between detectable leakage and rupture was under three months were sensitivity cases that are not representative of plant conditions and operations (unlike the cases for which the 19 months 95/95 lower bound period were determined), such as modeling of unmitigated welds in the nozzle (e.g., Case 4.1.4 discussed in the previous paragraph), modeling of severe weld residual stress, and modeling flaws that initiate deeper than the Alloy 52 inlay material.

The NRC staff noted that EPRI's determination of the time between detectable leakage and LBLOCA and time between detectable leakage and rupture is based on a 1 gpm leak rate threshold. The NRC staff verified that a 1 gpm RCS operating leakage is a specified limiting condition for operation (LCO) in the Standard Technical Specifications (STS) for the three nuclear steam supply system designs—NUREG-1430, 1431, and 1432 (Refs. 14, 15, and 16) for B&W, Westinghouse, and CE, respectively. Since not all PWRs have adopted STS, the NRC staff also verified that all PWR units in the U.S. has a 1 gpm RCS operating leakage as an LCO. The NRC staff reviewed Sections 4.2 and 4.3 of MRP-480 and determined that, for the reasons discussed above, the discussions in these two sections provide adequate information that demonstrate that the cases with small times between detectable leakage and LBLOCA (or rupture) are unlikely to occur or are not representative of plant conditions and operations. Of note is Case 4.1.4 in Table 3-3 of MRP-480 for an unmitigated SGON, in which the time between detectable leakage and LBLOCA (or rupture) is zero. The NRC staff noted that this

case produced realizations with deep flaws that would be detected by the periodic ISI volumetric examinations, since the flaw depths in the flaw acceptance standards used with these volumetric examinations are based on detectable flaw depth and are smaller than the flaw depths observed in the realizations. Additionally, the NRC staff verified that there is only one plant in the U.S. PWR fleet with an Alloy 82/182 SGON weld that has not been mitigated (but continues to be periodically inspected as required by the ASME code).

Conclusion on Time Between Detectable Leakage and LOCA

Based on the discussion above, the NRC staff concludes that 19 months is an acceptable estimate for the time between detectable leakage and LBLOCA for piping relevant to ALS because it is based on a statistical lower bound 95/95 one-sided tolerance confidence interval, thereby providing high confidence that there is sufficient time for safe shutdown of the plant in the event of a leakage from the RCS main loop piping.

3.2.3. Evaluation of RG 1.245 PFM Submittal Categorization

In Section 4.4 of MRP-480, EPRI discussed the PFM submittal categorization of MRP-480 per the guidance in RG 1.245, Revision 0 (Ref. 2). In Table 4-10 of MRP-480, EPRI showed the classification of the PFM submittal for the various categories in RG 1.245. The NRC staff reviewed EPRI's categorization of MRP-480 in Table 4-10 of MRP-480 per the submittal content guidance in RG 1.245 and noted that MRP-480 met the guidelines in Tables C-2, C-3, C-6, C-8, and C-10. Therefore, the NRC staff determined that EPRI appropriately categorized the various submittal aspects of the xLPR analyses in MRP-480 and provided an adequate explanation when the RG 1.245 category was not directly applicable. For instance, while EPRI did not specifically include a category for knowledge and importance of inputs (Table C-4 of RG 1.245), it referred to the xLPR Piping System Analysis report (Ref. 4) and xLPR Generalization Study report (Ref. 5) for details of the inputs used in the PFM analyses for the submittal input category (Table C-5 of RG 1.245). As the NRC staff noted in Section 3.2.1 of this SE, these two reports document extensive xLPR analyses of RCS main loop and non-main loop piping systems and are directly aligned with the two objectives of MRP-480. For output uncertainty characterization (Table C-9 of RG 1.245), EPRI stated that "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." The NRC staff noted that meeting the two objectives of MRP-480 addresses output uncertainty characterization because the PFM results in MRP-480 are compared against a broad range of known PFM results in NUREG-1829 (Section 3.2.1 of this SE) and detectable leakage and LOCA results are based on a statistical lower bound 95/95 one-sided tolerance confidence interval (Section 3.2.2 of this SE).

The NRC staff evaluated further statistical convergence (Table C-7 of RG 1.245) and sensitivity studies (Table C-10 of RG 1.245) because these are crucial aspects in determining whether the results of the PFM analyses are reasonable.

Table C-7 Submittal Guidelines for Statistical Convergence

In Table 4-10 of MRP-480, EPRI stated that the xLPR results are used to complement and compare against the results in NUREG-1829 and that there was "no direct acceptance criteria" for convergence. Additionally, Section 3.1 of MRP-480 states:

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.

In response to RAI 5, EPRI explained that adequate convergence is based on the discussion in Section 2.3 of the xLPR Piping System Analysis Report (Ref. 4) and xLPR Generalization Study Report (Ref. 5). Section 2.3 of these two reports states that for cases modeling crack initiation, a sample size of approximately 100,000 realizations was selected because it is expected that with this sample size, the annual frequency of an event being in the range of $1E-06$ (which is often used as the failure frequency criterion in PFM analyses of RCS systems) would be detected. For cases modeling initial flaws, a sample size of 5,000 was considered large enough to provide accurate results because the probability of having a circumferential crack from a PWSCC initiation model is approximately $3E-03$ or at most 0.05. To analyze convergence, EPRI used methods described in Section 4.3.5 of NUREG/CR-7278 (Ref. 17), including calculating sampling uncertainty metrics, assessing stability of a QoI estimate, and comparing QoI estimates over replicate simulations. Additionally, EPRI used the Latin Hypercube Sampling (LHS) technique discussed in Section 4.3.2 of NUREG/CR-7278. EPRI stated that LHS is a method to obtain a sample that is more spread out across the input space than a simple random sampling method, thereby producing QoI estimates with more statistical precision on average.

The NRC staff determined that adequate convergence was achieved in xLPR results of the analyses of the RCS main loop piping in MRP-480 because techniques for assessing and reaching convergence were based on the guidance in NUREG/CR-7278. Of note is the use of the LHS sampling method, which allows convergence to be reached with a lower number of realizations compared to the simple random sampling method. The NRC staff noted that additional demonstration of adequate convergence is described in Section 3.2.1 of the xLPR Piping System Analysis Report, which shows $P(rupture)$ among two other standard QoIs, with 95 percent confidence intervals for the RVON case for a sample size of approximately 100,000 realizations (Figures 3-7 and 3-8 of the xLPR Piping System Analysis Report) and a sample size of 5,000 realizations (Figure 3-28 of the xLPR Piping System Analysis Report). Finally, the NRC staff noted that Case 1.1.23 in Table 3-3 of MRP-480 assessed the impact of sampling over two loops (the aleatory and epistemic loops) versus sampling over a single loop. The sampling over two loops resulted in negligible difference in $P(rupture)$ value compared to single loop sampling. Therefore, the NRC staff concludes that EPRI adequately addressed convergence of the results of the xLPR analyses of the RCS main loop piping in MRP-480.

Table C-10 Submittal Guidelines for Sensitivity Studies

In Table 4-10 of MRP-480, EPRI referred to Sections 3.1, 3.2, B.1.2, B.2.2, and B.3.2 of the MRP-480 and generic sensitivity studies report for xLPR (Ref. 18) regarding the sensitivity studies performed in MRP-480. Table 3-2 of MRP-480 summarizes the sensitivity studies, including the piping system cases relevant to ALS, and Table 3-3 of MRP-480 lists the base cases with the associated sensitivity study cases. The sensitivity studies discussed here are distinct from the DM1 crack initiation model sensitivity studies. The RVON case in Table 3-2, for instance, has one base case (Case 1.1.0 in Table 3-3) and 23 sensitivity cases (Cases 1.1.1 to 1.1.23 in Table 3-3). Detailed descriptions of the sensitivity cases are in Section 3 of the xLPR Piping System Analysis Report (Ref. 4) and xLPR Generalization Study Report (Ref. 5).

Based on this, the NRC staff determined that adequate descriptions of the sensitivity cases performed for the ALS Cases (see Section 3.2.1 of this SE) have been provided. Of note is the sensitivity case on the impact of initial flaws as compared to the use of a crack initiation model (e.g., Case 1.1.0 as compared to Case 1.1.1 for the RVON); this case is noteworthy because the initial flaws led to a nearly 3 orders of magnitude increase in the $P(\text{rupture})$ result without crediting LRD and ISI. The impact of crack initiation (i.e., PWSCC initiation) is discussed in detail in Section 3.2.1 of this SE. Another sensitivity case of note is Case 4.1.4 in Table 3-3 of MRP-480 for an unmitigated SGON; this case is noteworthy because the time between detectable leakage and LBLOCA (or rupture) is zero, as the NRC staff discussed in Section 3.2.2 of this SE. The NRC staff noted that these cases exemplify that the sensitivity studies that were performed included extreme cases that provided useful insights to the base cases.

Conclusion on RG 1.245 PFM Submittal Categorization

Based on the discussion above, the NRC staff concludes that EPRI appropriately categorized the various aspects of the xLPR analyses in MRP-480 and provided an adequate explanation when the RG 1.245 category was not directly applicable. Additionally, the NRC concludes that EPRI adequately addressed convergence of the PFM results and performed adequate sensitivity studies that demonstrate the PFM results are reasonable.

4. REFERENCING AND USE OF MRP-480

The NRC staff concludes that MRP-480, as modified by the supplements in letters dated August 29 and October 31, 2025 (ML25241A333 and ML25304A106) and evaluated in this SE, may be referenced in license amendment applications that implement ALS for an 80-year operating period for the RCS main loop piping of the U.S. PWRs. As discussed in Section 3.2 of this SE, applications of MRP-480 outside the scope of ALS would require separate NRC review and approval specific to those applications.

5. CONCLUSION

Based on its evaluation, the NRC staff concludes that the xLPR analyses in MRP-480 adequately demonstrate that the LOCA frequencies in the RCS main loop piping are on a similar order of magnitude to those in NUREG-1829. The NRC staff also concludes that the xLPR analyses in MRP-480 adequately demonstrate that there is sufficient time for placing the plant in a safe condition in accordance with the plant technical specification (TS) after detection of an RCS leak. Accordingly, MRP-480, as modified by the supplements in letters dated August 29 and October 31, 2025 (ML25241A333 and ML25304A106) and evaluated in this SE, is acceptable for referencing in ALS applications to demonstrate that the likelihood of a LOCA in the RCS main loop piping of PWRs for an 80-year operating period is extremely low.

6. REFERENCES

- 1) NUREG-1829, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process," Vol. 1 (ML080630013).
- 2) Regulatory Guide 1.245, Revision 0, "Preparing Probabilistic Fracture Mechanics Submittals," January 2022 (ML21334A158).

- 3) Regulatory Guide 1.174, Revision 3, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," January 2018 (ML17317A256).
- 4) 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 (ML21217A088).
- 5) 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 (ML22088A006).
- 6) Regulatory Audit Plan by the Office of Nuclear Reactor Regulation in Support of the Review of Technical Report 3002023895, "Materials Reliability Program: xLPR Estimation of PWR Loss-of-Coolant Accident Frequencies (MRP-480)" (ML25073A190).
- 7) Regulatory Audit Report by the Office of Nuclear Reactor Regulation in Support of the Review of Technical Report 3002023895, "Materials Reliability Program: xLPR Estimation of PWR Loss-of-Coolant Accident Frequencies (MRP-480)" (ML25156A331).
- 8) xLPR Technical Report, "Sources and Treatment of Uncertainties," November 16, 2020 (ML19337C165).
- 9) xLPR Technical Report, "Primary Water Stress-Corrosion Cracking Initiation Model Parameter Development, Confirmatory Analyses, and Validation," August 1, 2017 (ML19337C202).
- 10) EPRI Report No. 3002023893, Materials Reliability Program: Probabilistic Fracture Mechanics Evaluation of PWR Cast Austenitic Stainless Steel Piping Components (MRP-479), June 2024 (Package No. ML26030A176).
- 11) Nuclear Energy Institute White Paper, Revision 0, "Materials Degradation Research and NEI 03-08 Materials Initiative – Demonstration of the Proven Effectiveness of Existing Materials Management and Inspection Programs," September 19, 2025 (ML25262A163)
- 12) NUREG-1903, "Seismic Considerations For the Transition Break Size," February 2008 (ML080880140).
- 13) NUREG-1475, Revision 1, "Applying Statistics," March 31, 2011 (ML11102A076).
- 14) NUREG-1430, Volume 1, Revision 5.0, "Standard Technical Specifications – Babcock and Wilcox Plants," September 2021 (ML21272A363).
- 15) NUREG-1431, Volume 1, Revision 5.0, "Standard Technical Specifications – Westinghouse Plants," September 2021 (ML21259A155).
- 16) NUREG-1432, Volume 1, Revision 5.0, "Standard Technical Specifications – Combustion Engineering Plants," September 2021 (ML21258A421).

- 17) NUREG/CR-7278, "Technical Basis for the use of Probabilistic Fracture Mechanics in Regulatory Applications," January 2022 (ML22014A406).
- 18) Technical Letter Report, TLR-RES/DE/CIB-2021-11, "Sensitivity Studies and Analyses Involving the Extremely Low Probability of Rupture Code," May 14, 2021 (ML21133A485).