Development of Feedwater Line & Main Steam Line Break Initiating Event Frequencies for Ringhals Pressurized Water Reactors

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Abstract: During the last years the LOCA initiating event frequencies in the PSA's for the three Ringhals PWR units has been updated using the piping reliability data provided in the R-Book. Since the data currently presented in the R-Book only covers ASME Code Class 1 and 2 it cannot be used for initiating event frequency update for ASME Code Class 3 and 4 (the intention is though that the R-Book shall also cover Code Class 3 and 4 in the future). In order to proceed with initiating pipe break frequency update for the Ringhals PWR units a project has been started with the purpose to develop updated initiating event frequencies for certain Feed Water Line Break and Main Steam Line Break scenarios. The updated initiating event frequencies shall account for the known piping damage and degradation mechanisms, applicable industry-wide and plant-specific service experience data, the plant specific piping layout and material specifications, as well as the plant-specific risk-informed in-service inspection (RI-ISI) program currently implemented for the Main Steam Line and Main Feed Water systems. The updated frequencies shall reflect state-of-the-art piping reliability models that explicitly address aleatory and epistemic uncertainties. Also, the data analysis that underlies this frequency calculation shall be consistent with the requirements of the ASME/ANS PRA Standard Capability Category II. The causes of pipe failure (e.g., loss of structural integrity) are attributed to damage or degradation mechanisms. Oftentimes a failure occurs to synergistic effects involving operating environment and loading conditions. In piping reliability analysis, two classes of failure are considered. The first class is so called "Event-Driven Failures". These failures are pipe stress driven and attributed to conditions involving combinations of equipment failures (other than piping itself; e.g., loose/failed pipe support, leaking valve) and unanticipated loading (e.g., hydraulic transient or operator error). Examples of event-based failures include various fatigue failures (high-cycle vibration fatigue, thermal fatigue). The second class is defined as "Failures Attributed to Environmental Degradation". Environmental degradation is defined by unique sets of conjoint requirements that include operating environment, material and loading conditions. These conjoint requirements differ extensively across different piping designs (material, diameter, wall thickness, method of construction/fabrications). Similarly, pipe flaw incubation time growth rates differ extensively across the different combinations of degradation susceptibility and operating environments. For the piping systems included in the scope (i.e. Main Steam and Main Feed Water systems), flow accelerated corrosion constitutes a potentially key degradation mechanism. The initiating event frequency calculation will be based on a methodology similar to the one used in previous applications of R-book. This means that service experience data together with a Bayesian analysis framework will be utilized to derive piping reliability parameters for input to PSA models and PSA model applications. The piping service experience data input to the pipe failure rate and rupture frequency calculations will be taken from the Lloyd's Register Consulting proprietary PIPExp database which includes detailed information on piping damage and degradation mechanisms in Code Class 1, 2 and 3 and non-Code piping systems. The paper will present the work that has been performed together with conclusions and insights achieved during the project.

Keywords: LOCA, Feedwater, Steam, Degradation, Bayesian

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1. INTRODUCTION

In the current version of the Ringhals-3 PSA model the FWLB and MSLB initiating event frequencies are adapted from SKI Report 94:12 [1]; Initiating Events at the Nordic Nuclear Power Plants (the "I-Book"). Appendix III of Reactor Safety Study (WASH-1400) [2] provided the technical basis for "pipe break initiating event frequencies" in the I-Book. Therefore, the current Ringhals-3 FWLB and MSLB initiating event frequencies reflect the state-of-knowledge of the WASH-1400 era (early 1970s).

Major progress has been made in the advancement of piping reliability analysis methodology. This progress is, in part, due to R&D in probabilistic fracture mechanics as well as in statistical models of piping reliability. Significant work has addressed pipe failure data collection and evaluation. Finally, the application of risk-informed in-service inspection (RI-ISI) methodologies has enabled highly realistic characterization of the consequences of pipe failures as a function of degradation mechanism (DM), break location and inspection strategy. During the past ten years, RI-ISI has been implemented at Ringhals Units 2, 3 and 4. The RI-ISI implementation project at Ringhals is referred to as RIVAL.

The technical challenge that is to be addressed here is to enhance and update the characterization of the five initiating event frequencies. Specifically, the project will address the following technical aspects:

- Apply state-of-the-art piping reliability models. This includes application of DM-centric conditional rupture probability (CRP) models. Also, DM-centric and location-specific failure rate distributions will be developed through a DM analysis coupled with exposure term definitions that account for plant-to-plant variability in component populations.
- Derivation of piping reliability parameters based on the applicable, current body of industry-wide and plant-specific service experience data.
- Completeness and modeling uncertainty will be addressed according to existing industry guidelines.
- Consideration of the Ringhals piping integrity management practices and procedures.

1.1. Task breakdown and work flow

The scope of work in this proposed project includes six (6) tasks. Included are technical tasks to calculate the initiating event frequencies, as well as additional tasks to facilitate the management of the project and to address specific items unique to the Ringhals PWR Units 2, 3 and 4:

- Task 1. Project Mobilization; this task includes the kick-off meeting, work scope definition and information collection.
- Task 2. Definition of Calculation Cases
- Task 3. Parameter Estimation
- Task 4. Documentation
- Task 5. Review & Comment Resolution
- Task 6. Technology Transfer

The scope of the proposed work includes calculating new IE frequencies associated with a feedwater line break inside and outside containment (T_{Fx}), and steam line break (T_{Sx}).

2. TECHNICAL APPROACH

The technical approach to estimate FWLB and MSLB initiating event (IE) frequencies is based on the model expressed by Equations (1) and (2) for estimating the frequency of an IE of a given magnitude. Oftentimes, the magnitude is expressed by an equivalent break size (EBS) and corresponding through-wall flow rate. The parameter x is treated as a discrete variable representing different equivalent break-size ranges.

$$F(IE_x) = \sum_i m_i \rho_{ix} \tag{1}$$

$$\rho_{ix} = \sum_k \lambda_{ik} P(R_x | F_{ik}) I_{ik} \tag{2}$$

Where:

$F(IE_x) =$ Frequency of pipe break of size *x*, per reactor calendar-year, subject to epistemic uncertainty calculated via Monte Carlo simulation

$m_i =$ Number of pipe welds (or fittings or inspection locations of type *i*; each type determined by pipe size, weld type, applicable damage or degradation mechanisms, and inspection status (leak test and NDE); no significant uncertainty

$\rho_{ix} =$ Frequency of rupture of component type *i* with break size *x*, subject to epistemic uncertainty calculated via Monte Carlo simulation or lognormal formulas

$\lambda_{ik} =$ Failure rate per "location-year" for pipe component type *i* due to failure mechanism *k*, subject to epistemic uncertainty determined by RI-ISI Bayes method and Eq. (3) below

$P(R_x | F_{ik}) =$ Conditional probability of rupture of size *x* given failure of pipe component type *i* due to damage or degradation mechanism *k*, subject to epistemic uncertainty. This parameter may be determined on the basis of expert elicitation or service experience insights.

$I_{ik} =$ Integrity management factor for weld type *i* and failure mechanism *k*, subject to epistemic uncertainty determined by Monte Carlo simulation and Markov model

Point estimates of the failure rate for type *i* and failure mechanism *k* is calculated according to formula (3):

$$\lambda_{ik} = \frac{n_{ik}}{\tau_{ik}} = \frac{n_{ik}}{f_{ik} N_i T_i} \tag{3}$$

Where:

$n_{ik} =$ Number of failures in pipe component (i.e., weld) type *i* due to failure mechanism *k*; very little epistemic uncertainty. The component boundary used in defining exposure terms is a function of DM.

$\tau_{ik} =$ Component exposure population for welds of type *i* susceptible to failure mechanism *k*, subject to epistemic uncertainty determined by expert opinion

$f_{ik} =$ Estimate of the fraction of the component exposure population for weld type *i* that is susceptible to failure mechanism *k*, subject to epistemic uncertainty, estimated from results of RI-ISI for population of plants and expert opinion

$N_i =$ Estimate of the average number of pipe welds of type *i* per reactor in the reactor years exposure for the data query used to determine n_{ik} , subject to epistemic uncertainty, estimated from results of RI-ISI for population of plants and expert knowledge of damage mechanisms

$T_i =$ Total exposure in reactor-years for the data collection for component type *i*; little or no uncertainty

For a Bayes' estimate, a prior distribution for the failure rate is updated using n_{ik} and τ_{ik} with a Poisson likelihood function. The formulation of Equation (3) enables the quantification of conditional failure rates, given the known susceptibility to the given damage or degradation mechanism. When the parameter f_{ik} is applied, the units of the failure rate are failures per welds susceptible to the damage or degradation mechanism. This formulation of the failure rate estimate is done because the susceptible damage or degradation mechanisms typically are known from the results of a previously performed degradation mechanism analyses that are part of RI-ISI evaluations. If the parameter f_{ik} is set to 1.0, the failure rates become unconditional failure rates, i.e., independent of any knowledge about the susceptibility of damage or degradation mechanism, or alternatively that 100% of the components in the population exposure estimate are known to be susceptible to a certain degradation mechanism (e.g., flow-accelerated corrosion, FAC).

2.1. Analysis Convention & Nomenclature

The causes of pipe failure (e.g., loss of structural integrity) are attributed to damage or degradation mechanisms. Oftentimes a failure occurs to synergistic effects involving operating environment and loading conditions. In piping reliability analysis, two classes of failure are considered:

- Event-Driven Failures. These failures are pipe stress driven and attributed to conditions involving combinations of equipment failures (other than piping itself; e.g., loose/failed pipe support, leaking valve) and unanticipated loading (e.g., hydraulic transient or operator error). Examples of event-based failures include various fatigue failures (high-cycle vibration fatigue, thermal fatigue).
- Failures Attributed to Environmental Degradation. Environmental degradation is defined by unique sets of conjoint requirements that include operating environment, material and loading conditions. These conjoint requirements differ extensively across different piping designs (material, diameter, wall thickness, method of construction/fabrications). Similarly, pipe flaw incubation times flaw growth rates differ extensively across the different combinations of degradation susceptibility and operating environments. For the piping systems that are in the scope of work (i.e., System 411, Main Steam, and System 415, Main Feedwater), flow accelerated corrosion constitutes a potentially key degradation mechanism.

Synthesized in Figure 1 is the existing worldwide service experience with metallic piping in commercial nuclear power plants; in excess of 8,820 failure records. Included in this figure are the unique failure manifestations of concern. In piping reliability, a "failure" is any degraded condition that necessitates repair or replacement. The "magnitude" of a failure manifestation can be measured through non-destructive or destructive examination. Through-wall defects are characterized by the size of a flaw and resulting leak or flow rate (from perceptible leakage to gross leakage). As depicted in Figure 1, certain combinations of material, operating environments have produced "major structural failures." The high-level database summary in Figure 1 is used to formulate specifications for a quantitative analysis of pipe failure parameters.

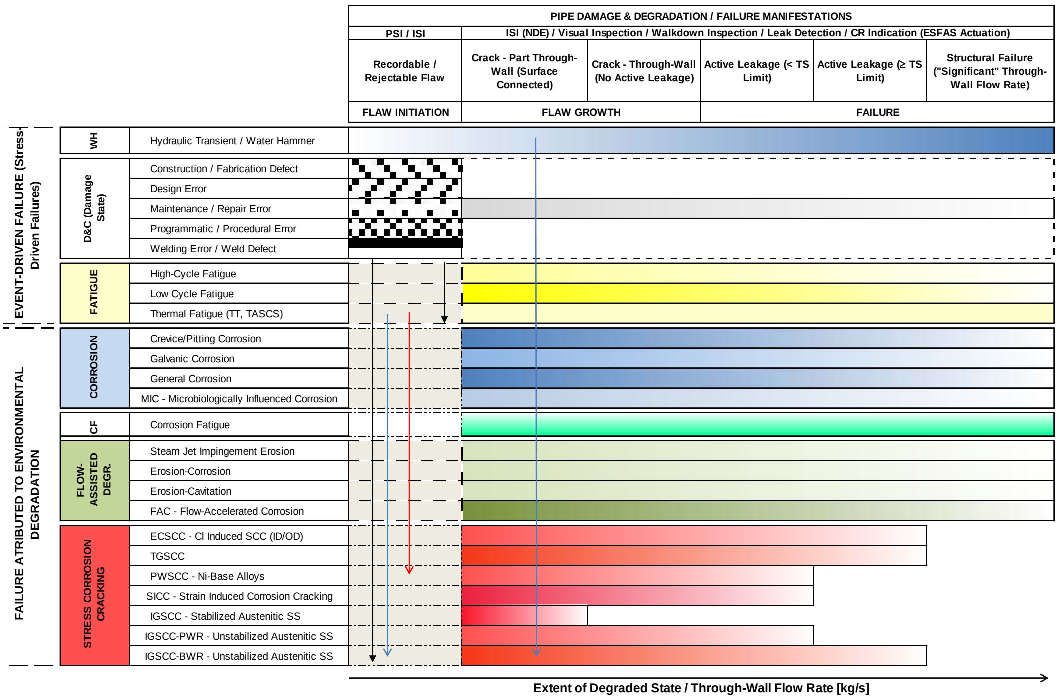

Figure 1 – Pipe Failure Manifestations.

2.2. Definition of Calculation Cases

Task 2 is concerned with the desired degree of IE frequency model refinement. For example, an underlying assumption is that a single set of "representative IE frequencies" for the three PWR units is to be developed. It should also be defined if the IE frequency models should address the positive effect on IE frequency by different ISI strategies or degradation mitigation strategies. For illustrative purposes, the chart in Figure 2 shows results from a sensitivity study performed within the scope of the Kewaunee HELB IE Frequency Study. This sensitivity study addressed three cases:

1) no or inadequate implementation of a FAC program,
2) effect on Extraction Steam piping reliability through implementation of an effective FAC program consistent with NSAC-202L [3] guidelines, and
3) effect on Extraction Steam piping reliability by replacement of original carbon steel piping with a FAC-resistant material (e.g., stainless steel).

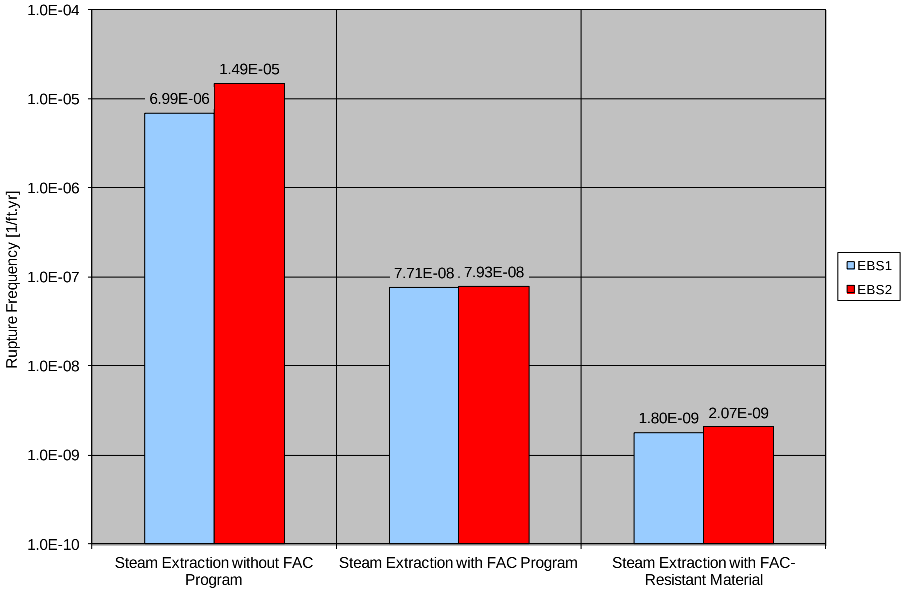

Figure 2 – Example of HELB IE Frequency Sensitivity Analysis.

Another technical consideration is the correlation of IE frequencies with equivalent break sizes as required by a PSA model. Potentially, the IE frequency models require the consideration of a spectrum of pipe break sizes; e.g., ESFAS (Engineered Safety Features Actuation System) set points. The piping reliability analysis methodology includes the application of a conditional rupture probability (CRP) model for a range of pipe break sizes. The break sizes to be considered range from the minimum break sizes triggering ESFAS actuation at the upper end and a double-ended guillotine break (DEGB) at the lower end of the "actuation distribution".

2.3. Parameter estimation

The parameter estimation task encompasses the estimation of the pipe failure parameters that are necessary to quantify the IE frequency models. The IE frequency is calculated by multiplying the number of components in a given system by a rupture frequency per unique component category. The parameter estimation task consists of the following subtasks:

- Finalization of Calculation Workbooks. All calculations will be performed in MS-Excel with Oracle Crystal Ball^{TM} (for uncertainty propagation) and R-DAT Plus^{TM} (for data specialization). The workbook format originally developed for the Kewaunee HELB IE Frequency Analysis will be modified to include a new CRP model and to fit the requirements specific to this study.

- Preparation of Calculation Input Parameters. This subtask establishes event populations and corresponding exposure terms.
- Parameter Estimation. This subtask consists of parameter estimation using the aforementioned MS-Excel workbook and quantification of the IE frequency models.

2.4. Information requirements

The detailed information requirements are itemized in Table 1. Three types of technical information are needed: 1) drawings (i.e., isometric drawings and P&IDs) that clearly define the system boundaries for the IE frequency calculation, 2) in-service inspection (ISI) information, and 3) plant-specific service experience data for the data specialization subtask.

Table 1: List of Information Requirements

Information Item	Comment / Question
System Design Information / Drawings	
Full set of isometric drawings for Systems 411 & 415	The drawings shall correspond with system boundaries that are defined for the IE Frequency calculation. Also, the drawings serve as input to the exposure term definitions in the piping reliability parameter estimation task. What System 415 piping routing changes inside containment were implemented in connection with steam generator replacements?
Full set of P&IDs for Systems 411 & 415	The P&ID information supports the interpretation of the isometric drawing information
Piping material & pipe size data	For the pipe segments selected for this scope of work, need line ID with material specification, nominal pipe size, and wall thickness
ISI Reference Material	
Itemized list of inspection locations	This information is used in identifying the potentially DM-susceptible locations. It is used as input to the reliability parameter estimation tasks to support the calculation of location-specific data for the IE frequency model
RIVAL DM Evaluation Report	This document identifies the DM-susceptible locations in Systems 411 & 415
ISI Reference Material	
List of flaw indications (R2, R3, R4)	This list itemizes the observed flaws (i.e., wall thinning in excess of minimum allowable wall thickness, and through-wall flaws), location, date. Included in the list are events that have required power reduction (to affect repairs) and forced outages.
List of piping replacements	This list itemizes the replacements made as a result of degraded conditions. For System 415 and sections inside containment, what is the service experience pre- and post-S/G replacement?
Applicable Reportable Occurrence (RO) reports submitted to SKI/SSM	

3. DAMAGE MECHANISM EVALUATION

In developing the FWLB and MSLB initiating event frequency models, piping reliability parameters are estimated that are conditional on the presence of certain active degradation mechanisms. The process of estimating these reliability parameters begins by performing a systematic degradation mechanism (DM) evaluation of all pipe segments within the evaluation boundary. The DM evaluation addresses the conjoint requirements for degradation; the material, operating environment and pipe stress conditions necessary for material degradation (cracking, wall thinning, leakage or rupture) to occur.

3.1. Scope of DM evaluation

The following five initiating events involve plant transients caused by a pipe break inside or outside the containment:

TFI: A break of the feed water line between one of the check valves 415-1243, 415-1244 and 415-1245 and the respective steam generator.

TFY: Transient TFY models a break of the feed water line inside/outside the containment up to the check valves 415-1243, 415-1244, and 415-1245.

TSI: Steam line break inside the containment is defined as a break of a main steam line between the steam generator steam line outlet and the main steam isolation valves 411-1131, 411-1132, and 411-1133.

TSY: A steam line break outside the containment is a break downstream of the steam isolation valves 411-1131, 411-1132, 411-1133 up to the turbine stop valves and the steam dump valves to the condenser 411V113, -114, -115, -116.

TSH: Transient TSH models a break, which occurs on the steam piping to the steam-driven auxiliary feed water pump.

The subject DM evaluation addresses piping material damage and degradation mechanisms potentially affecting the Feedwater (System 415) and Main Steam (System 411) pressure boundary integrity. The evaluation utilizes industry wide and plant specific service experience insights applicable to the five initiating events.

3.2. High-Level Service Experience Overview

The service experience related to the main feedwater piping includes cracking and wall thinning of feedwater nozzles and piping. The cause of the cracking was determined to be thermal fatigue, possibly corrosion assisted, and the root cause was generally attributed to thermal stratification of the coolant in the nozzle. Although fatigue cracking from thermal stratification (TASCS) has been found only in the feedwater nozzle area, the presence of thermal stratification has been verified from temperature measurements of the piping wall far upstream of the nozzle but inside the containment. The high loads from thermal stratification have bowed pipes and damaged feedwater piping. Insights from DM evaluations performed in support of RI-ISI program development confirm that the piping may experience thermal gradients between the top and bottom of the main feedwater piping at hot standby conditions and startup due to flow low enough to cause the Richardson number[†] (*Ri*) to be greater than 4. This is considered cyclic in the horizontal piping near the SG. Fatigue is not the only degradation mechanism that has caused damage to the PWR feedwater systems. Flow-accelerated corrosion has caused wall thinning in feedwater lines. Also, the feedwater nozzle thermal sleeves have experienced thinning at the leading edge, possibly because of flow-accelerated corrosion.

Water hammer can fracture piping at areas degraded by fatigue or flow-accelerated corrosion, and have caused through-wall cracks and ruptures of nozzles and piping. Water hammer events have also damaged piping supports.

[†] A dimensionless parameter used to determine whether stratification will occur. If $Ri < 4$ stratification will not occur. This occurs if the temperature difference between two fluids is low or flow velocity is high, causing mixing. Additional details can be found in EPRI TR-103581, "Thermal Stratification, Cycling and Striping" (1994).

Illustrated in Figure 3 is the MS-specific, worldwide piping service experience involving all damage and degradation mechanisms. The steam exiting the steam generators is dry, superheated steam. Assuming long-term base load operation of the reactor, the MS piping is less likely to be exposed to FAC than the FW-specific piping.

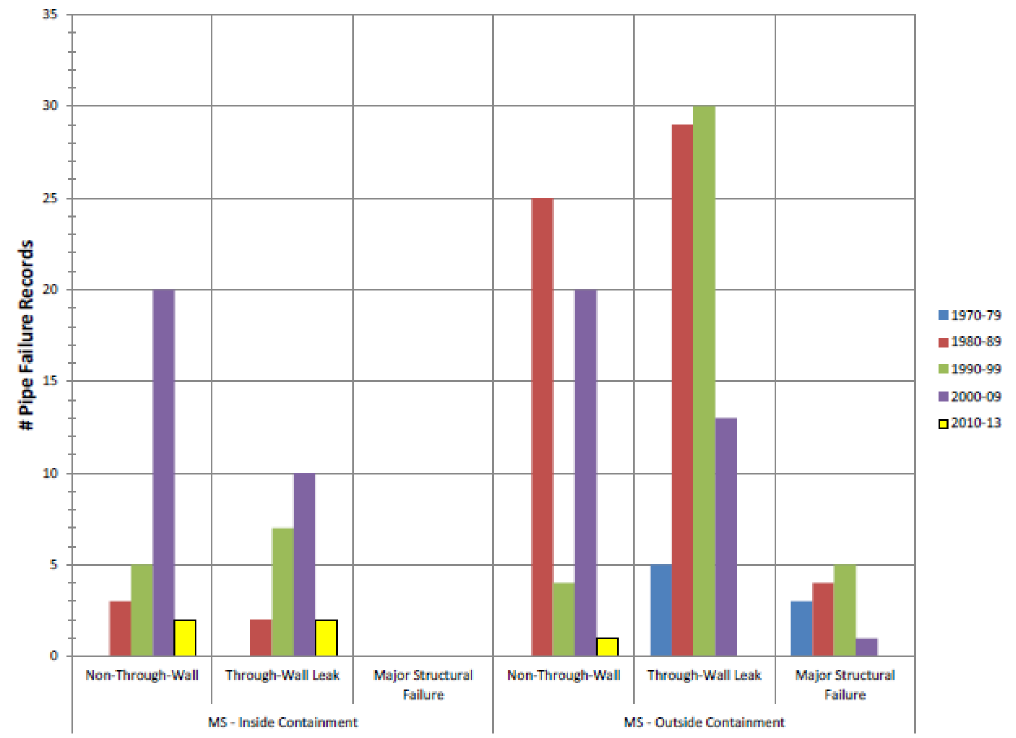

Figure 3 – Service experience with MS piping.

3.3. DM evaluation guidance

According to the EPRI RI-ISI methodology, all inspection locations in the assessed systems must be classified by failure potential. This classification is accomplished by determining those damage and degradation mechanisms that might apply to each assessed piping system location. The damage and degradation mechanisms to be assessed are given below:

- TASCS Thermal Stratification, Cycling, Striping
- TT Thermal Transient
- IGSCC Intergranular Stress Corrosion Cracking
- TGSCC Transgranular Stress Corrosion Cracking
- ECSCC External Chloride Stress Corrosion Cracking
- PWSCC Primary Water Stress Corrosion Cracking
- MIC Microbiologically-Influenced Corrosion
- PIT Pitting
- CC Crevice Corrosion
- E/C Erosion-Corrosion
- E-C Erosion-Cavitation
- FAC Flow-Accelerated Corrosion
- SH Steam Hammer
- WH Water Hammer

3.4. Evaluation of FW and MS systems DM susceptibility

The following conclusions were made for the two systems on their susceptibility for different DMs:

- The piping between the steam generator and first elbow is therefore considered susceptible to TASCS.
- Thermal transient (TT) can occur in the piping between the steam generator and first elbow during hot standby conditions due to the large temperature differences between mixing fluids.
- The FW piping inside and outside containment is susceptible to flow-sensitive (FS) wall thinning. Erosion cavitation (E-C) is a concern for areas immediately downstream flow control valves. All FW piping falls under the scope of the managed FAC program.
- With reference to Ringhals-3, it is noted that certain sections of the FW piping consists of low-alloy steel (LAS) of type 15Mo3 with a chromium content of 0.3% (weight %), which is resistant to FAC. Therefore these pipe sections are assigned low-to-very-low failure potential.
- According to the available service experience data, water hammer events have been found to occur in six areas in the FW system: 1) Upstream of the steam generator, 2) downstream of the FW flow control valves, 3) adjacent to the FW recirculation valves, 4) at the FW pump turbine steam supply line, 5) piping adjacent to the FW pump suction and discharge piping, and 6) preheater bypass line.
- According to the available service experience data, water/steam hammer events have been found to occur in three areas: 1) Adjacent to the main steam isolation valves, 2) piping downstream of the turbine bypass valve, and 3) in the main steam relief valve piping.

The overall conclusion from the DM evaluation was that credible degradation mechanisms potentially affecting the structural integrity of the R3 FW and MS piping include FAC of carbon steel piping, and LDIE of low-alloy steel piping. FAC “entrance effects” may impact localized areas at or near the interface between carbon steel and low-alloy steel pipe sections.

4. INPUT PARAMETERS

This section summarizes the Service Experience Data and Exposure Term Data, the results of these two tasks provide the input to the subsequent piping reliability parameter estimation.

4.1. Pipe failure data source

The source of all piping service experience data supporting this study is the proprietary PIPExp Database. Established in 1993, it is a continuously maintained and updated database on the service experience with piping in commercial nuclear power plants worldwide. It covers the period 1970 to date. An early (1998) version of this database serves as the ‘parent database’ of the OECD Nuclear Energy Agency (NEA) international database projects OPDE (2002-2011) and CODAP (2011-2014)[‡].

The PIPExp Database is a relational database developed to support a broad range of piping reliability analysis tasks. The database structure is documented in a Coding Guideline and the basic database functionalities are documented in an Applications Handbook. An integral element of all database applications involves defining data screening rules and data query functions. There are two types of queries. A ‘topical query’ is performed to identify those data records of direct relevance to an application. Application-specific queries are performed to invoke data screening rules to address unique combinations of piping reliability attributes and influence factors.

[‡] Additional information is available on the Internet at www.oecd-nea.org.

4.1. Calculation case summary

The definition of calculation cases that are needed for the five initiating event frequency models address unique combinations of piping reliability attributes and influence factors. Pipe failure rates are to be generated for each calculation case. All FW and MS piping system components in the respective IE model are assigned a Calculation Case. A derived failure rate is common to all piping component IDs within the calculation case. Key inputs that are needed to define calculation cases include:

- Results of the degradation mechanism (DM) evaluation;
- Assignment of a DM to each of the piping components in respective IE model;
- Pipe materials, pipe size and component type.

Tables 2 and 3 identify the proposed calculation cases.

Table 2: FW System Calculation Cases

Calculation Case ID	DM	CRP Model Basis	Comment
1.a	TASC	NUREG-1829 - PWR Thermal Fatigue - CRP technical basis is presented in STP GSI-191 Technical Report	This calculation case applies to the FW pipe-to-SG-nozzle welds; one location per FW loop
1.b	TASC	Same as 1.a	This case applies to first straight section between SG nozzle and check valve - one pipe section per loop
2	LC-FAT	Specific CRP model is developed	Case 2 applies to welds in pipe sections for which no active DM is identified.
3.a	FAC	Specific CRP model is developed. The model applies to single-phase flow conditions.	Case 3.a applies to bends and elbows in carbon steel pipe sections
3.b	FAC	See Case 3.a	Case 3.b applies to locations immediately downstream of welds between low alloy steel and carbon steel (interface between FAC-resistant and FAC-susceptible piping. This calculation case addresses potential FAC-entrance effects.
4	LDIE	Specific CRP model is developed	Case 4 applies to bends and elbows in low alloy steel pipe sections. This calculation case addresses potential localized erosion attributed to cavitation[§].
5	VF	Service experience data	Case 5 applies to small-bore branch connection weld locations.

Table 3: MS System Calculation Cases

Calculation Case ID	DM	CRP Model Basis	Comment
1	SH/WH	Specific CRP model is developed	This calculation case applies to welds at MS relief valves and MSIVs
	LC-FAT	Specific CRP model is developed	Case 2 applies to welds in pipe sections for which no active DM is identified.
3	LDIE	Specific CRP model is developed	Case 3 applies to bends and elbows – the MS piping is considerably less susceptible to FAC than the FW piping

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[§] Low alloy steels, such as 15Mo3, have less FAC wear rate than carbon steels. 15Mo3 has a carbon content of 0.3%. For chromium contents greater than 0.04% the wear rate decreases linearly on a log-log-scale. According to experimental data, with a 0.1% of chromium, the wear rate is approximately 2.5 times lower than standard carbon steel.

4.1. Data reduction principles

The FW service experience data is applicable to the FWLB evaluation boundary as well as Westinghouse type PWR plants. Because differences in piping design/layout and material selections, service experience from Babcock & Wilcox (B&W), Combustion Engineering (CE) and KWU/Siemens plants was not considered. The MS service experience data only considers pipe sections subjected to single-flow conditions (super-heated steam). Excluded from the service experience evaluation are Main Steam Cross-under, Extraction Steam, and Moisture Separator Reheater piping.

5. CONDITIONAL RUPTURE PROBABILITY MODELS

This section documents the development of the conditional rupture probabilities (CRPs; $P(R_x \mid F_x)$) given presence of a degraded condition for different pipe break sizes for each of the component types defined. A degraded condition can be an embedded flaw (not connected to the inside diameter of a piping component), a non-through-wall crack, a thinned pipe wall, or a through-wall flaw.

The likelihood of a pipe flaw propagating to a significant structural failure is expressed by the conditional failure probability $P(R_x / F_{ik})$). With no service data available to support a direct statistical estimation of the conditional probability the assessment can be based on probabilistic fracture mechanics (PFM), expert judgment, or a combination of service data insights, expert judgment and PFM. Different PFM algorithms have been developed, but with a focus on fatigue growth through vibration fatigue, thermal fatigue) and stress corrosion cracking in Reactor Coolant Pressure Boundary piping. There remain issues of dispute with respect to reconciliation of results obtained through statistical estimation and extrapolation versus the physical models of PFM, however.

The approach taken in this study is to utilize service experience insights and results from the expert elicitation documented in NUREG-1829 [4]. For certain combinations of material, loading conditions and degradation susceptibility, sufficient service experience exists to support direct CRP estimation. As an example, extensive data exists on FAC-induced pipe rupture. Correlating, the statistical evidence on equivalent break size (EBS), material and flow conditions (e.g., single-phase vs. two-phase flow) provides an empirical CRP-EBS correlation.

For other types of degradation mechanisms (DMs), only “precursor data” is available. That is, the service experience data is limited to observations of rejectable non-through-wall flaws and minor through-wall flaws. The technical approach to CRP development for DMs other than FAC is structured to capture the current state of knowledge of LOCA frequencies as documented in NUREG-1829. The expert elicitation as documented in NUREG-1829 synthesizes inputs from experts representing two schools of thought on how to best quantify pipe break frequencies: one based on statistical analysis of service data and simple models, and another based on probabilistic fracture mechanics approaches. The 12 experts that participated in this expert elicitation provided a balanced perspective on these two approaches and produced estimates of the LOCA frequencies vs. break size for use in risk-informed evaluations. NUREG-1829 included some “base case” analyses that were performed on selected components to inform the expert elicitation. The technical approach to CRP model development used herein is designed to make use of both sets of information developed in NUREG-1829, namely, the base case analyses and the inputs provided by the nine experts and documented in NUREG-1829.

Details on the technical approach are documented in ASME-PVP-2007-26281 [5] and References [6][**] and [7].

[**] Available on the Internet at http://nrc.gov/wba/ (accession No. ML112770237).

5.1. CRP models for FWLB & MSLB initiating event Frequency analysis

Based on the results of preceding tasks, the FWLB and MSLB initiating event frequency analysis require the following CRP models:

- FAC-centric CRP model that reflects single-phase flow conditions in carbon steel piping. The proposed CRP model is based on empirical data;
- LC-FAT-centric CRP model that reflects the through-wall growth of a pre-existing weld flaw under the influence of low-cycle fatigue loading such as normal cooldown and heatup cycles. This CRP model is derived from NUREG-1829 and the South Texas Project and Vogtle Electric Power Station GSI-191 LOCA frequency evaluations.
- LDIE-centric CRP model that reflects localized erosion in low alloy steel (LAS) piping. The proposed CRP model is derived from NUREG-1829 using the technical approach documented in Section 5 above.
- TASCS-centric CRP that reflects thermal fatigue acting on the Code Class 2 FW nozzles. This CRP model is derived from NUREG-1829 using the technical approach documented in Section 5 above.
- SH/WH-centric CRP, which is based on empirical data.

6. CONCLUSIONS

Given the analysis framework, the knowledge about possible damage mechanisms with respective conditional rupture probabilities, the mapping of piping components (welds, bends etc), and the service experience gained from more than 4000 reactor years of operation updated initiating event frequencies have been derived during the project. At this stage the calculations are ongoing but we hope that the results will be possible to present during the PSAM12 conference.

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