Development of LOCA Initiating Event Frequencies for South Texas Project GSI-191

Final Report for 2011 Work Scope

Developed for
South Texas Project Electric Generating Station

by
Karl N. Fleming
KNF Consulting Services LLC

Bengt O. Y. Lydell
Danielle Chrun
SCANDPOWER
Risk Management Inc

September 2011

Table of Contents

Figures

Tables

Acronyms

ASME	American Society of Mechanical Engineers
B-J	ASME Section XI Similar Metal Weld
B-F	ASME Section XI Bimetallic Weld
BC	Branch Connection Weld
CRP	Conditional Rupture Probability
CVCS	Chemical Volume and Control System
D&C	Design and Construction Defects
DEGB	Double Ended Guillotine Break
DM	Damage (Degradation)Mechanism
ECCS	Emergency Core Cooling System
EPRI	Electric Power Research Institute
GM	Geometric Mean
GSI	Generic Safety Issue
HPI	High Pressure Injection
IGSCC	Intergranular Stress Corrosion Cracking
LOCA	Loss of Coolant Accident
NPS	Nominal Pipe Size
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
PZR	Pressurizer
RCS	Reactor Coolant System
RI-ISI	Risk Informed Inservice Inspection
SB	Small Bore
SIR	Safety Injection and Recirculation Systems
TASC	Thermal Stratification
TF	Thermal Fatigue
TT	Thermal Transients
SC	Stress Corrosion Cracking
TGSCC	Transgranular Stress Corrosion Cracking
VF	Vibration fatigue

1. Introduction

1.1 Background

This report documents the analysis of loss of coolant accident (LOCA) frequencies in support of a risk-informed evaluation of Generic Safety Issue (GSI) 191 for the South Texas Project Electric Generating Station (STPEGS) Units 1 and 2. The scope of work covered in this report is to develop the location- and break size-dependent initiating event frequencies and associated uncertainties, and to provide technical support to interfacing tasks that are necessary to determine the risk significance of debris-induced failures of core recirculation heat removal during LOCAs.

Historically, probabilistic risk assessments (PRAs) have included a small set of initiating events characterized by the physical sizes and through-wall flow rates associated with breaches in the primary reactor coolant system (RCS) pressure boundary, commonly known as LOCAs. Consideration of the location of the breach has largely been limited to that associated with so-called “excessive LOCAs”, i.e. breaches in the reactor pressure vessel that exceed the capabilities of the emergency core cooling systems (ECCSs) to prevent core damage, and “interfacing system LOCAs (ISLs). ISLs refer to events where the integrity of the RCS pressure boundary is breached through failure of isolation valves which separate the RCS from safety systems of lower design pressure. The resulting over-pressurization could lead to a LOCA with leak flow path bypassing the containment and thereby defeating the recirculation cooling functions of the ECCS. In typical PRAs, the remaining LOCAs inside the containment are differentiated only with respect to size, based on there being different success criteria for preventing core damage for different-sized LOCAs. The differences in success criteria for the different LOCA sizes relate to differences in requirements for secondary side heat removal, high pressure and low pressure safety injection, and for implementing reactor shutdown.

The current STPEGS PRA model has different initiating events for breaches with equivalent break size of 0.5" to 2.0", referred to as Small LOCAs, those with break sizes between 2" and 6", referred to as Medium LOCAs, and those with break sizes from 6" up to and including a double-ended break from the largest pipe in the RCS, known as Large LOCAs. The Very Small LOCAs, with break sizes less than 0.5", are excluded because they would be small enough to be within the makeup of the chemical volume and control system (CVCS), whose operation would be expected to preclude a safety system actuation to mitigate a LOCA.

The STP Risk-Informed GSI-191 Closure study investigates the size and location of LOCAs more finely in order to assess the risk of debris formation during the LOCAs that could interfere with the operation of the ECCSs during the recirculation phase after an RCS breach. The size and location of the break could influence the amount of debris formation and the timing and need for actions to initiate or terminate containment sprays and recirculation cooling. The purpose of this study is to revise the LOCA initiating event frequency as needed to determine the most risk-significant break sizes and locations for this generic safety issue.

1.2 Objectives

The objectives of this study are to:

- Define of a sufficient set of RCS piping system failure categories to support each location to be evaluated for debris formation – to be worked out with the integrated team.
- Provide failure rates vs. break size for all LOCA locations within the scope of the evaluation. This includes a full quantification of aleatory and epistemic uncertainties that addresses both parameter and modeling uncertainties. The locations shall include pipe welds, non-weld locations within the piping, and non-pipe contributions, e.g., Reactor Coolant Pump (RCP) seals.
- Provide revised estimates of the initiating event frequencies for Small, Medium, and Large LOCAs for use as inputs to the PRA model for this GSI-191 evaluation.
- Include the results of the RI-ISI (risk-informed in-service inspection) evaluation, including damage mechanism (DM) assessment results and which weld locations are selected for inclusion for non-destructive examinations (NDE).
- Support the calculation flow sheet interfaces among the LOCA frequency, debris formation, thermal hydraulics analysis, and risk analysis to ensure proper integration.
- Support project meetings and NRC meetings and associated reviews.
- Incorporate input from independent reviews that are being done to support the project.

The current report considers LOCAs initiated at or near the location of pipe and nozzle welds. A revision planned for 2012 will address pipe failures at other locations and non-pipe-related failures in the RCS pressure boundary.

1.3 Report Guide

The technical approach to determining LOCA frequencies is summarized in Section 2. This approach makes use of a model that expresses LOCA initiating event frequencies as a function of piping system failure rates and conditional probabilities of pipe rupture over a range of break sizes. The models and data used to develop the piping system failure rates are documented in Section 3. Section 4 presents the approach that was selected to derive the conditional rupture probability (CRP) vs. break size, given pipe failure, together with a technical description of the resulting CRP models. The LOCA frequency results are presented in Section 5. These results include those to be used at specific locations within the RCS pressure boundary, as well as the Small, Medium, and Large LOCA frequencies for use in the PRA model. Comparisons with generic industry estimates of LOCA frequencies are included with these results.

2. Technical Approach to LOCA Frequency Quantification

2.1 Basic LOCA Frequency Model

The technical approach to estimating LOCA initiating event frequencies is based on the model expressed by Equations (2.1) and (2.2) for estimating the frequency of a LOCA of a given size. The parameter *x* is treated as a discrete variable representing different break-size ranges. Here, *x* takes on values {1,2,3,4,5,6} to correspond with the LOCA categories defined in NUREG-1829 [1]. We shall use the NUREG-1829 categories with the understanding that these may be re-defined later if necessary.

$$F(LOCA_x) = \sum_i m_i \rho_{ix} \tag{2.1}$$

$$\rho_{ix} = \sum_k \lambda_{ik} P(R_x | F_{ik}) I_{ik} \tag{2.2}$$

where:

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

$m_i =$ Number of pipe welds of type *i*; each type determined by pipe size, weld type, applicable damage 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 or lognormal formulas

$\lambda_{ik} =$ Failure rate per weld-year for pipe component type *i* due to failure mechanism *k*, subject to epistemic uncertainty determined by RI-ISI Bayes method and Eq. (2.3) below

$P(R_x | F_{ik}) =$ Conditional probability of rupture of size *x* given failure of pipe component type *i* due to damage mechanism *k*, subject to epistemic uncertainty determined via expert elicitation using NUREG-1829 data

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

For a point estimate of the failure rate for type *i* and failure mechanism *k*:

$$\lambda_{ik} = \frac{n_{ik}}{\tau_{ik}} = \frac{n_{ik}}{f_{ik} N_i T_i} \tag{2.3}$$

where:

$n_{ik} =$ Number of failures in pipe component (i.e., weld) type *i* due to failure mechanism *k*; very little epistemic uncertainty

τ_{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 (2.3) enables the quantification of conditional failure rates, given the known susceptibility to the given damage mechanism. When the parameter f_{ik} is applied, the units of the failure rate are failures per welds susceptible to the damage mechanism. This formulation of the failure rate estimate is done because the susceptible damage mechanisms are known from the results of a previously performed risk-informed in-service inspection evaluation for STPEGS. 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 mechanism, or alternatively that 100% of the components in the population exposure estimate are known to be susceptible.

The key inputs that are needed to provide the pipe failure rate information include:

- Identification of which locations will be investigated for debris formation, the groupings of locations that will be performed to support the risk evaluation, and a definition of component categories that are representative of all pipe failure locations within the STPEGS Class 1 pressure boundary.
- Counts of pipe failures in applicable nuclear industry piping systems – essentially all the failure data in ASME Class 1 and 2 piping systems in PWRs in U.S. service experience and applicable international plants with similar designs and integrity management programs – from the PIPExp database.[2]
- Pipe exposure estimates – quantity of pipe and pipe welds and the reactor years of service experience that produced the failure counts identified above. These estimates are based on information contained in the PIPExp database as well as the information available in risk-informed in-service inspection submittals to the NRC, which include an enumeration of weld counts in different categories and the results of damage mechanism evaluations.
- Estimates of the fractions of piping system components in the service data that are susceptible to different damage mechanisms. These estimates are based on NUREG-1829 and supporting

computer files that provide information on epistemic uncertainty about pipe rupture frequencies vs. break size for different pressure boundary components.

- STP RI-ISI evaluation report and supporting calculations providing information on applicable damage mechanisms for each weld and an identification of which welds are selected for NDE.
- Results of inspection reports and other evidence of any pipe failure or degradation at STP that may influence the plant-specific failure rates, as well as the information needed to estimate exposure data.

The integrity management factor I_{ik} of Equation (2.2) is quantified using the Markov model for Piping Reliability that was developed to support the EPRI RI-ISI projects.

The methodology outlined above and the methods and databases that have been developed to implement this approach were originally developed to support the EPRI RI-ISI methodology that has been implemented for many of the existing NRC-licensed plants and several foreign plants. The part of this methodology that is relevant to estimating LOCA frequencies is described in detail in Reference [3] and has been recently applied in EPRI-sponsored projects to develop piping system failure rates for use in internal flooding and high energy line break PRAs, as documented in References [4] and [5]. The original EPRI study that was responsible for developing the Markov model and Bayes' method for estimating pipe failure rates and rupture frequencies was documented in EPRI TR-110161 [6], and an early version of the pipe failure rate database for both conditional and unconditional pipe failure rates was published in EPRI TR-111880 [7]. An independent review of these reports was carried out by the University of Maryland, which validated the methodology that was developed in these reports. These methods and data were then used as part of the EPRI RI-ISI technical approach as described in the EPRI RI-ISI Topical Report [9]. The NRC approved these methods and data for use in applied RI-ISI evaluations as documented in the Safety Evaluation Report (SER) [10]. The SER was supported by an independent review of the Bayes' failure rate method and the Markov model by Los Alamos National Laboratory [11], which provides a second independent review of the methodology, including a validation of the Markov model solutions.

The application of the Markov model requires the development of rather complex closed-form solutions to the differential equations supporting the Markov model, which were originally developed in TR-110161 and are also published in Reference [12]. Using these closed-form solutions, it is straightforward to quantify the uncertainties in the resulting inspection factors using Monte Carlo simulation methods via Microsoft Excel™ and Oracle Crystal Ball™, which is the approach being used in this STP GSI-191 evaluation. Bayes' update steps in the analysis of LOCA frequency were performed using the R-DAT Plus™ Version 1.5.8 Program.

2.2 Step-by-Step Procedure for LOCA Frequency Evaluation

A step-by-step procedure for evaluating the LOCA frequencies for each location as a function of break size and collectively for the determination of Small, Medium, and Large LOCA frequencies for the PRA model is comprised of the steps in Table 2-1 and depicted in Figures 2-1 and 2-2.

Table 2-1 Step-by-Step Approach to LOCA Frequency Development

1. Failure Rate Development	
1.1	Determine component and weld types - i
1.2	Perform data query for failure counts - n
1.3	Estimate component exposure - T
1.4	Develop component failure rate prior distributions for each damage mechanism (DM)
1.5	Perform Bayes' update for each exposure case (combination of weld count case and DM susceptibility [DMS] case)
1.6	Develop mixture distribution to combine results for different exposure hypotheses to yield conditional failure rate distributions λ_{ik} given STP-specific applicable DMs
1.7	Calculate total failure rate over all applicable damage mechanisms - $\Sigma\lambda_{ik}$
2. Conditional Rupture Probability (CRP) Development $P(R_x \mid F_{ik})$	
2.1	Select components to define conditional rupture probability (CRP) model categories
2.2	Obtain expert reference LOCA distributions from NUREG-1829
2.3	Obtain expert multiplier distributions for 40-yr LOCA frequencies from NUREG-1829
2.4	Determine 40-yr LOCA distributions (product of Steps 2.2 and 2.3) for each expert, fit to lognormal
2.5	Determine geometric mean of expert distributions from Step 2.4 (lognormal)
2.6a	Benchmark Lydell Base Case Analysis for selected components
2.6b	Determine failure rate distribution for Lydell Base Case Analysis in NUREG-1829; fit to lognormal
2.6c	Apply Lydell CRP model from Base Case Analysis
2.6d	Determine LOCA frequency distribution from Lydell Base Case Analysis
2.7	Determine mixture distribution of NUREG-1829 GM (from Step 2.5) and Lydell LOCA frequency (from Step 2.6d to obtain Target LOCA frequency distribution for each CRP category component
2.8	Apply formulas to calculate CRP distributions to be used as prior distributions for each valid combination of CRP category and component
2.9	For each component in a given CRP category, perform Bayes' update with evidence of failure and rupture counts from service data
3. STP-Specific LOCA Frequency Development	
3.1	Determine weld counts and pipe sizes for each component - m_i
3.2	Identify which locations are in and out of the NDE program
3.3	Combine the results of Step 1 and Step 2 for component LOCA frequencies
3.4	Apply Markov model to specialize rupture frequencies for NDE or no NDE - I_{ik}
3.5	Provide location-by-location LOCA frequencies vs. break size to CASAGRANDE - ρ_{jx}
3.6	Provide Small, Medium, and Large LOCA frequencies to RISKMAN - $F(LOCA_x)$

The application of Steps 1, 2, and 3 is documented in Sections 3, 4, and 5, respectively.

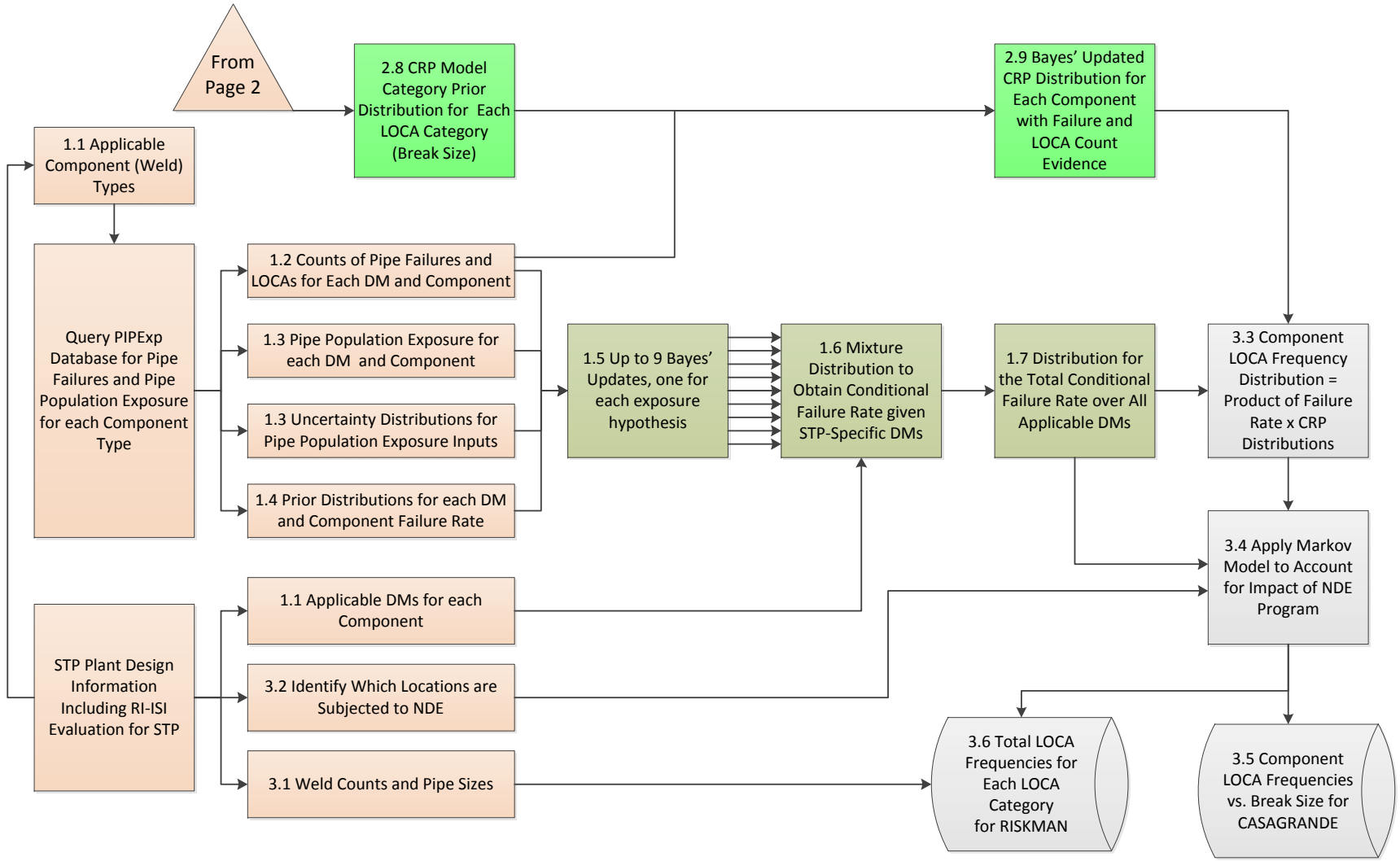

Figure 2-1 Step-by-Step Procedure for LOCA Frequency Quantification – Page 1 of 2

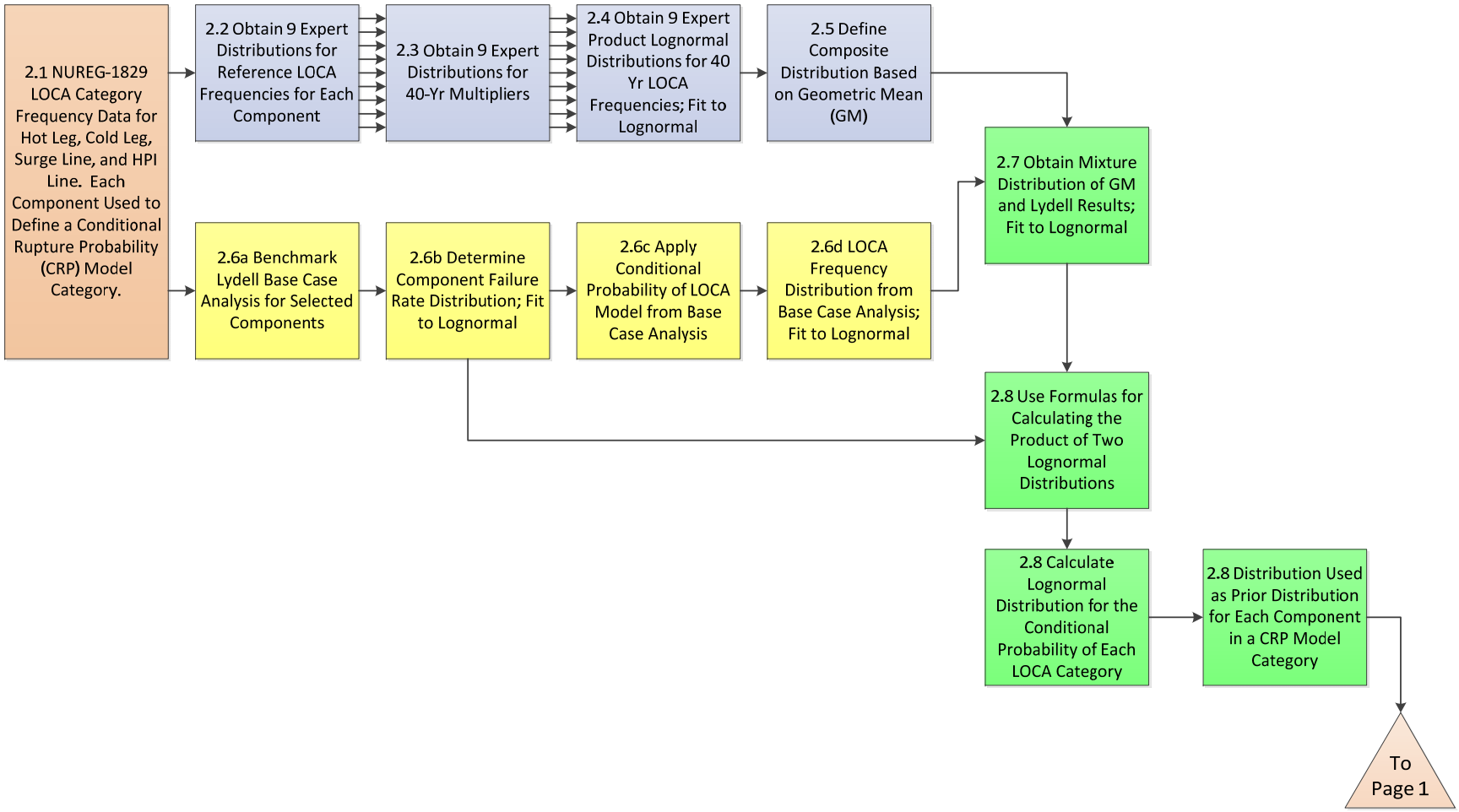

Figure 2-2 Step-by-Step Procedure for LOCA Frequency Quantification – Page 2 of 2

3. Failure Rate Development (Step 1)

This section documents the failure rate development for STPEGS piping systems, which comprises Step 1 in the procedure outlined in Section 2. As described in the previous section, this step is composed of the following key tasks:

1.1 Determine component and weld types

1.2 Perform data query for failure counts

1.3 Estimate component exposure

1.4 Develop component failure rate prior distributions for each damage mechanism (DM)

1.5 Perform Bayes' update for each exposure case (combination of weld count case and DM susceptibility case)

1.6 Develop mixture distribution to combine results for different exposure hypotheses to yield conditional failure rate distributions given STP-specific applicable DMs

1.7 Calculate total failure rate over all applicable DMs

3.1 Definition of Component Types (Step 1.1)

The first three tasks of failure rate development (determine component types, perform data query for failure counts, and estimation of component exposure) are performed as an iterative process. Insights from reviewing failure data are used to formulate criteria for defining homogeneous populations for estimating failure rates. The available data from which to estimate component exposures also influences the characterization of component types in the sense that some groups of components may exhibit unusually high or low incidence of failures compared to other similar components. The following criteria were used to determine homogeneous piping component types:

- Pipe materials
- Pipe size
- Applicable damage or degradation mechanisms[1] (DMs)
- Unusual distribution of component failures
- In-service inspection program status (within or outside the scope of non-destructive examinations [NDEs])

The first step in defining component categories was to define the eight major piping system cases, described in Table 3-1 based on the criteria listed above. These cases were then further subdivided to account for specific combinations of damage mechanisms and pipe sizes, as shown in Table 3-2. This more refined subdivision formed the homogeneous component categories that have distinct failure pipe failure rates and rupture frequency distributions. The 8 system cases give rise to 45 component

[1] The terms damage mechanism and degradation mechanism are used interchangeably in this report.

calculation cases. In general, it is assumed that the maximum break size is the equivalent break size of a double-ended guillotine break (DEGB) of the pipe. If D is the inside diameter of the pipe, the DEGB size is $\sqrt{2}D$.

Table 3-1 Definition of Major Piping System Component Cases

Case	Description	Weld Type	Damage Mechanism (DM)	Comment
1	RCS Hot Leg Excl. SG Inlet	B-F	PWSCC, D&C	Design basis LOCA location; B-F weld has higher failure rate but located inside Rx cavity
		B-J	TF, D&C	
2	RCS Cold Leg	B-F	PWSCC, D&C	Lower temperatures and different pipe sizes relative to hot leg
		B-J	D&C	
3	RCS Hot Leg SG Inlet	B-F	PWSCC, D&C	This case defined to address S/G Inlet nozzle-to-safe-end weld that has unusual failure count distribution[1]
4	PZR Surge Line	B-F	PWSCC, TF, D&C	Includes surge line from branch connections and nozzles to pressurizer safe end; entire surge line subjected to thermal transients during startup and shutdown
		B-J, BC	TF, D&C	
5	PZR Medium Bore Piping	B-F	PWSCC, TF, D&C	This includes pressurizer spray, and relief valve piping excluding the pressurizer surge line; B-F welds at STP in this category have weld overlays[2]
		B-J, BC	TF, D&C	
6	Class 1 Small Bore Piping	B-J	TF, D&C, TGSCC, VF	This is all the Class 1 piping of size 2" and less and inside isolation valves
7	Class 1 Medium Bore SIR Piping	B-J	TF, D&C, IGSCC	Safety injection and residual heat removal (RHR) systems in standby during normal operation; Class 1 is inside the isolation valves
8	Class 1 Medium Bore CVCS Piping	B-J, BC	TF, D&C, TGSCC, VF	CVCS piping with injection and letdown flow during normal operation

B-F	ASME XI Category B-F welds (bimetallic)
B-J	ASME XI Category B-J welds (single metal)
BC	Branch connection welds, B-J welds used at branch connections
CVCS	Chemical, Volume, and Control System
D&C	Design and Construction Defects
IGSCC	Intergranular Stress Corrosion Cracking
PWSCC	Primary Water Stress Corrosion Cracking
PZR	Pressurizer
RCS	Reactor Coolant System
SIR	Safety Injection and Recirculation Systems
TF	Thermal Fatigue, including that due to thermal transients (TT) and thermal stratification (TASC)
TGSCC	Transgranular Stress Corrosion Cracking
VF	Vibration Fatigue

Notes :
[1] An unusually high incidence of failures of this component was observed at Japanese plants following Steam Generator replacements. Until it can be ruled out for STP it is included in this study.
[2] NOC-AE-06002099 (January 30, 2007): Inspection and Mitigation of Alloy 82/182 Pressurizer Butt Welds, South Texas Nuclear Operating Company.

Table 3-2 Definition of Specific Component Categories

System Case	System	Component Case	Weld Type	Applicable DM	STP Total No. of Welds	Pipe Size (in.)	DEGB Size (in.)
1	RC Hot Leg	1A	B-F	SC, D&C	4	29	41.0
		1B	B-J	D&C	11	29	41.0
		1C	B-J	TF, D&C	1	29	41.0
2	RC SG Inlet	2	B-F	SC, D&C	4	29	41.0
3	RC Cold Leg	3A	B-F	SC, D&C	4	27.5	38.9
		3B	B-J		4	31	43.8
		3C	B-J	D&C	12	27.5	38.9
		3D	B-J		24	31	43.8
4	RC Surge	4A	B-F	SC, TF, D&C	1	16	22.6
		4B	B-J	TF, D&C	7	16	22.6
		4C	BC		2	16	22.6
		4D	B-J		6	2.5	3.5
5	PZR	5A	B-J	TF, D&C	29	6	8.5
		5B	B-J		14	3	4.2
		5C	B-J	D&C	53	4	5.7
		5D	B-J		4	3	4.2
		5E	B-J		29	6	8.5
		5F	B-F	SC, TF, D&C	0	6	8.5
		5G	B-F	SC, D&C	0	6	8.5
		5H	B-F	D&C (Weld Overlay)	4	6	8.5
		5I	BC	D&C	2	4	5.7
		5J	B-J	TF, D&C	2	2	2.8
6	Small Bore	6A	B-J	VF, SC, D&C	16	2	2.8
		6B	B-J		193	1	1.4
7	SIR Lines Excl. Accumulator	7A	B-J	TF, D&C	21	12	17.0
		7B	B-J		9	8	11.3
		7C	B-J	SC, TF, D&C	3	8	11.31
		7D	B-J	SC, D&C	3	12	17.0
		7E	B-J, BC	D&C	57	12	17.0
		7F	B-J		30	10	14.1
		7G	B-J, BC		42	8	11.3
		7H	B-J		23	6	8.49
		7I	BC		5	4	5.7
		7J	BC		9	3	4.24
		7K	BC		10	2	2.8
		7L	B-J		0	1.5	2.1

System Case	System	Component Case	Weld Type	Applicable DM	STP Total No. of Welds	Pipe Size (in.)	DEGB Size (in.)
	SIR Accumulator Lines	7M	B-J	SC, D&C	0	12	17.0
		7N	B-J	TF, D&C	35	12	17.0
		7O	B-J, BC	D&C	15	12	17.0
8	CVCS	8A	B-J	TF, VF, D&C	10	2	2.8
		8B	B-J		19	4	5.7
		8C	B-J	VF, D&C	47	2	2.8
		8D	B-J		6	4	5.7
		8E	BC	TF, D&C	4	4	5.7
		8F	BC	D&C	1	4	5.7
				Total	775		

3.2 Evaluation Scope for 2011

The evaluation that is documented in this report is limited to the ASME III Class 1 piping system pressure boundary failures; i.e., non-isolable LOCAs. The Class 1 boundary consists of all hot leg, cold leg and crossover leg piping, pressurizer surge, spray, auxiliary spray, relief valve, safety valve and vent lines, and one unit 1 drain line. It also includes branch piping to the Safety Injection System (SIS), Chemical & Volume Control System (CVCS), and Residual Heat Removal System (RHRS). All piping attached to the RCS loops or pressurizer vessel is considered Class 1 out to the second valve. Class 1 SIS, CVCS and RHRS piping between the first and second valve off the RCS is discussed in later sections.

Isolable LOCAs, seismically induced LOCAs, and LOCAs due to failures of components other than pipes will be considered for the 2012 work scope, as necessary to characterize debris-induced core damage risks. Also excluded in the current scope are steam line and feedwater line breaks inside the containment that could lead to a need to implement recirculation cooling and/or containment spray actuation as well non-piping passive component failures. If those break locations are regarded as significant to GSI-191, they will also be addressed in 2012.

3.3 Failure Data Query (Step 1.2)

This study uses the term "pipe failure" to include any condition that leads to repair or replacement of the affected piping component. This includes flaws that exceed ASME criteria for repair or replacement, cracks, leaks, and, if they were observed to occur, pipe ruptures. The failure data query found the most severe type of pipe failure to be leak with leak flow rate less than 10 gpm. Non-pipe failures that can produce a LOCA are to be addressed in 2012. Insights from review of service experience clearly show that for failures in ASME Class 1 piping systems, with the exception of leaks from valves and seals, piping system failures occur almost exclusively at or near welds. In fact, the results of our data query show that 100% of the experienced pipe failures occur at or near a weld. Since the welds in a Class 1 pressure boundary are relatively evenly distributed around the piping systems, identifying the failure locations at or near welds also provides for a representative set of pipe failure locations. Hence, all pipe failures that

significantly contribute to LOCA frequencies may be assumed to occur at or near welds. This assumption will be replaced by an explicit accounting for non-pipe-induced LOCAs in 2012.

At STP, there are approximately 775 weld locations within the Class 1 RCS pressure boundary including approximately 200 weld locations in small bore pipe (≤ 2”). Hence, modeling pipe failures at these weld locations using the 45 component categories in Table 3-2 will facilitate the analysis of LOCAs at large number pipe failure locations.

The source of the analyzed pipe failure data is the PIPExp database[2] which is depicted in Figure 3-1. The failure data query was performed on Westinghouse, Mitsubishi Heavy Industries (MHI), and Framatome PWR plant operating experience from 1970 through 2010 and included ASME Class 1 piping systems. This generally includes RCS piping and systems that interface with the RCS inside the isolation valves that normally separate the RCS from interfacing ASME Class 2 piping. Interfacing systems include the emergency core cooling, residual heat removal, chemical volume and control system, and various other systems including Reactor Pressure Vessel (RPV) head vents and instrumentation lines. Class 1 piping service experience with Babcox and Wilcox, Combustion Engineering, and KWU/Seimens PWR plants was not considered on the basis of different materials and degradation susceptibilities relative to Westinghouse PWRs and those derived from the Westinghouse design. A contributing factor to this decision is that there is sufficient data from Westinghouse type plants to meet the needs of this study.

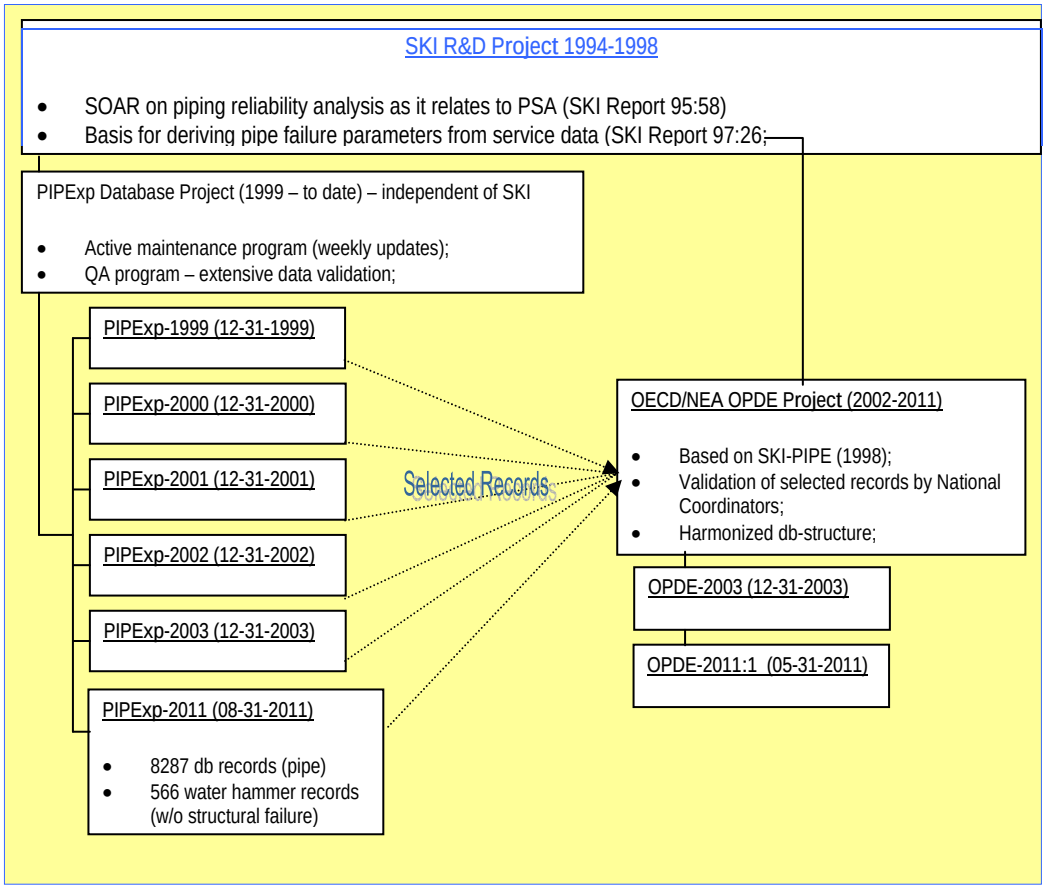

Figure 3-1 PIPExp Database and Relationship to Other Databases [20]

The results of the failure data query are shown in Table 3-3. Because roughly half of the current fleet of operating plants were designed and built prior to the development of ASME nuclear piping codes, much of this pipe was originally designed to B31.1 design codes, and then inspection and ISI requirements for Class 1 piping were retrofitted into these plants. So from a design and materials perspective, the LOCA-sensitive piping actually reflects a mixture of B31.1 and Class 1 pipe.

Table 3-3 Results of Class 1 Failure Data Query by System and Component

System Case	System	Event Type	Nominal Pipe Size	Failure Count by DM - Weld Locations					
				Totals	D&C	SC	PWSCC	TF	V-F
1	RCS Hot Leg	Crack	32"	5			5		
	RCS Hot Leg	Leak	32"	1			1		
2	RCS Cold Leg	Crack	32"	3			3		
3	S/G Inlet	Crack	32"	19	1		18		
4	PZR-Surge	Crack	16"	3			3		
5	PZR-PORV	Crack	4" ≤ ø ≤ 10"	2			2		
	PZR-SPRAY	Crack	4" ≤ ø ≤ 10"	2			2		
	PZR-SPRAY	Leak	4" ≤ ø ≤ 10"	1					1
	PZR-SRV	Crack	4" ≤ ø ≤ 10"	6	1		5		
	PZR-SRV	Leak	4" ≤ ø ≤ 10"	1			1		
6	CVCS	Crack	≤ 1"	1					1
	CVCS	Leak	≤ 1"	6	1				5
	Safety Injection	Leak	≤ 1"	2					2
	PZR-Sample/Instr.	Crack	≤ 2"	5	1	2	2		
	PZR-SPRAY	Crack	≤ 1"	1		1			
	PZR-SPRAY	Leak	≤ 1"	3	1	1			1
	RCS	Crack	≤ 2"	14	1	3	2	1	7
	RCS	Leak	≤ 2"	62	12	10	2	2	36
	RHR	Leak	≤ 1"	6	1				5
	S/G System	Crack	≤ 1"	2		1			1
	S/G System	Leak	≤ 1"	4	2	2			
7	Safety Injection	Crack	4" ≤ ø ≤ 12"	3		1		2	
	Safety Injection	Leak	4" ≤ ø ≤ 12"	3				3	
	RHR	Crack	4" ≤ ø ≤ 12"	1	1				
8	CVCS	Crack	2" ≤ ø ≤ 4"	1				1	
	CVCS	Leak	2" ≤ ø ≤ 4"	6	1				5
Total				163	23	21	46	9	64

3.4 Component Population Exposure (Step 1.3)

3.4.1 Reactor-Years of Service Experience

Pipe component exposure is evaluated in the current analysis in terms of pipe welds in the data query. This is estimated from a combination of reactor-years of service experience and an estimate of the total number of welds per plant. In principle, the number of welds per plant is known but is seldom found in public domain references. In addition, there is usually significant plant-to-plant variability in the number of welds for different components. To address this, the component exposure, i.e., total weld-years of

experience responsible for the identified failures, is treated as an uncertain parameter in failure rate development. In addition, to support the estimation of failure rates from different damage mechanisms, it is necessary to estimate the fraction of the exposure that is susceptible to a given damage mechanism, which is also uncertain. Results of published reports on RI-ISI evaluations provided the basis for both weld count and fraction-susceptible estimates.

The reactor-years of service experience by reactor type responsible for the failures in Table 2-3 are listed in Table 3-4.

Table 3-4 Service Experience by Westinghouse-Type PWRs

WE Type Rx	Reactor-Calendar Years	
	Initial Grid Connection	Initial Criticality
2-Loop	570.1	581.4
3-Loop	2052.6	2096.1
4-Loop	1193.9	1236.5
Total	3816.6	3914.0

For the purposes of failure rate estimation, reactor-calendar years was based on the initial grid connection.

3.4.2 Component Exposure Estimates for Hot Leg Welds

To illustrate the detailed approach to failure rate development, the piping components for the hot leg are examined. As shown in Table 3-2, the hot leg has two types of welds: B-F (bimetallic) welds and B-J (single metal welds). To estimate failure rates requires estimating the number of welds in the reactor population that corresponds to the reactor-years in the data query. For this purpose, the authors of this report from Scandpower reviewed isometric drawings for a selected sample of PWR plants and determined from this sample a best estimate, upper bound, and lower bound of weld counts per reactor in the database. These three estimates were used to define a three-point discrete distribution to characterize the uncertainty in the total reactor year population that was queried for failure counts. This approach was developed to support pipe failure rate development for the EPRI RI-ISI program [7] as part of the overall Bayes' method for pipe failure rate estimation. This was reviewed by LANL (Los Alamos National Laboratory) for the NRC [11] and approved for use in RI-ISI evaluations by the NRC [10].

As shown in Table 3-4, the reactor-year population is distributed among 2-loop, 3-loop, and 4-loop PWR plants. For components like the hot-leg and cold-leg welds, the number of welds per plant may be reasonably assumed to be proportional to the number of coolant loops. The review of isometric drawings at 10 PWR reactors produced the hot leg weld estimates that are presented in Table 3-5. This sample was used to determine the average number of welds per loop, the minimum, and the maximum. This information is used to characterize the uncertainty in the exposure terms as described in the sections below.

Table 3-5 Estimation of Hot Leg Welds per Reactor

Plant	PWR Type	NPS29 Weld Population			
		B-F Welds	B-J Welds	B-F Welds/loop	B-J Welds/loop
Braidwood-1	4-Loop	8	12	2	3
Braidwood-2	4-Loop	8	12	2	3
Byron-1	4-Loop	8	12	2	3
Byron-2	4-Loop	8	11	2	2.75
Kewaunee	2-Loop	4	6	2	3
Koeberg-1	3-Loop	3	9	1	3
Koeberg-2	3-Loop	3	9	1	3
STP-1	4-Loop	8	8	2	2
STP-2	4-Loop	8	8	2	2
V.C. Summer	3-Loop	6	6	2	2
			Average	1.8	2.68
			Min	1	2
			Max	2	3

3.4.3 Degradation Mechanism Assessment

As was determined in the development of failure rates for the EPRI RI-ISI evaluations, it is assumed that all welds are subject to design and construction defects. Insights from service experience indicate that certain weld types are always susceptible to a specific DM, whereas in some cases a DM can be ruled out generically for a given weld type. In other cases, there is uncertainty on how many welds in the reactor-year population that was queried for the failure counts are susceptible to a given DM. The evaluation of DM susceptibility for the hot leg welds is shown in Table 3-6.

Table 3-6 Damage Mechanism Assessment for Hot Leg Welds

Calc. Case	System	Location	Confidence Level	Weld Susceptibility Fractions								
				C-F	D&C	ECSCC	Fretting	IGSCC	PWSCC	TF	TGSCC	VF
1A	RC Hot Leg	B-F (Un-mitigated)	Low	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
			Medium	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
			High	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
1B, 1C		B-J	Low	N/A	1	N/A	N/A	N/A	N/A	0.01	N/A	N/A
			Medium	N/A	1	N/A	N/A	N/A	N/A	0.02	N/A	N/A
			High	N/A	1	N/A	N/A	N/A	N/A	0.08	N/A	N/A

The damage mechanism assessment is based on insights from service experience, results of completed RI-ISI evaluations for Westinghouse-type PWRs, and understanding of the DM criteria that were developed for the EPRI RI-ISI evaluation [9]. Other sources of information that were available to assess damage mechanisms include the Expert Panel Report on Proactive Materials Degradation Assessment (NUREG/CR-6923) [16], SCAP-SCC Working Group [17][18], OECD Nuclear Energy Agency topical report on thermal fatigue [19]. Dissimilar metal welds (Category B-F welds) are known to be susceptible to primary water stress corrosion cracking (PWSCC). Only a small, albeit uncertain fraction of the B-J welds

are susceptible to thermal fatigue and both are susceptible to design and construction defects. For the Phase I scope weld population and because of the unique conjoint conditions for degradation that are associated with the PWR primary system operating environment, all other identified damage mechanisms identified in Figure 3-2 can be ruled out. Service-induced degradation of reactor components results from synergies among material characteristics, stress and environment conditions. Illustrated in Figure 3-2 are four categories of degradation mechanisms and their failure potential. The four categories are:

1) stress corrosion cracking (SCC) mechanisms,
2) flow-assisted mechanisms,
3) corrosion mechanisms, and
4) fatigue mechanisms.

In order for SSC or fatigue mechanisms to develop into structural degradation or failure a crack initiation must occur and then grow into a surface connected crack and beyond. Design and construction (D&C) defects oftentimes provide for crack/flaw initiation, but not for crack/flaw growth.

In addition to the above generic industry inputs to assessment of degradation mechanisms, the study also benefitted from a plant specific risk-informed inservice inspection (RI-ISI) evaluation of Class 1 piping that was performed for STP in 2001 [21]. This evaluation included a deterministic engineering evaluation of all the Class 1 pipe welds against screening criteria that were developed by EPRI for use in RI-ISI evaluations. These screening criteria and their technical bases are documented in the EPRI RI-ISI Topical Report [9] which was approved by the NRC for use in applied RI-ISI evaluations [10]. The RI-ISI application at STP was also approved by the NRC.

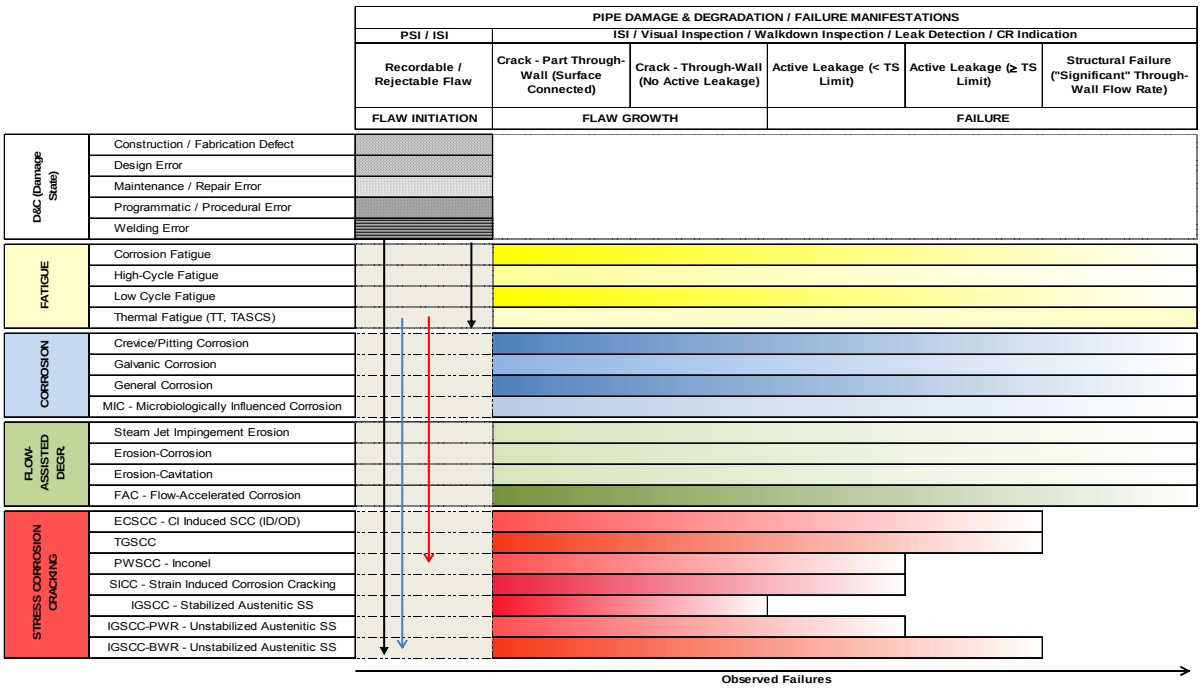

Figure 3-2 Damage and Degradation Mechanisms in Commercial Light Water Reactor Plants

3.4.4 Component Exposure for Hot Leg Welds

The uncertainty in component exposure is determined by the uncertainty in the component's welds per reactor and by the fraction of those welds that are susceptible to the various DMs. Table 3-5 showed that for the hot leg welds, there is uncertainty in the components per reactor for both B-F and B-J welds. In addition there is uncertainty in B-J weld susceptibility for thermal fatigue. Based on the methodology developed in the EPRI RI-ISI program, each of these sources of uncertainty are characterized by three-point discrete distributions. For the B-J welds prone to thermal fatigue, there are nine combinations of exposure derived from the two three-point distributions, as shown in Figure 3-3.

3.5 Prior Distributions for Hot Leg Weld Failure Rates (Step 1.4)

Prior distributions for each DM were developed for the failure rate development in the EPRI RI-ISI program in Reference [7], based on early estimates of pipe failure rates, engineering judgment, and insights from review of service data. This is part of the methodology that was reviewed by LANL [11] and approved by the NRC [10] for RI-ISI evaluations using the EPRI RI-ISI methodology [9]. The applicable prior distributions for the hot leg welds and other Class 1 welds subject to these same DMs are presented in Table 3-7. These are very broad distributions, all lognormal with range factors of 100. As such, they only weakly influence the posterior distributions during the Bayes' updating process.

Table 3-7 Prior Distributions for Weld Failure Rates by Damage Mechanism

Damage Mechanism	Prior Distribution			
	Distribution Type	Failure Rate per Weld-Yr		Range Factor
		Mean	Median	
Stress Corrosion Cracking	Lognormal	4.27E-05	8.48E-07	100
Design and Construction Errors	Lognormal	2.75E-06	5.46E-08	100
Thermal Fatigue	Lognormal	1.34E-05	2.66E-07	100

3.6 Failure Rate Bayes' Updates (Step 1.5)

The next step in the LOCA frequency quantification procedure is to perform Bayes' updates for each component/DM/population-exposure estimate that supports the calculation. The prior distributions used in this assessment are based on those that were developed in Reference [7] for use in the EPRI RI-ISI evaluations that followed the methodology in the EPRI RI-ISI Topical Report [9], which was reviewed by the NRC and LANL as documented in References [10] and [11]. The evidence for the updates is based on three failures of B-F surge line welds due to PWSCC, and zero failures for both the branch connection and B-J welds for the surge line. The parameters of the prior and updated distributions for all the cases that were needed to support the surge line welds are listed in Table 2-7. The failure data query yielded a total of six pipe failures for hot leg welds, all of which failures were at B-F welds and caused by primary water stress corrosion cracking.

Welds/Loop	Number	Number/Average
Average	2.675	1
Minimum	2	0.75
Maximum	3	1.12

Welds/Loop	Loops	Rx-yrs	Weld-yrs
2.675	2	570	3,050
2.675	3	2,053	16,472
2.675	4	1,194	12,775
Base Exposure			32,297

Weld Count Uncertainty	Fraction of B-J Welds Susceptible to Thermal Fatigue	Exposure Case Probability	Exposure Multiplier	Exposure
	p=.25	0.0625	0.08972	2,898 weld-yrs
	High (.08 x Base)			
p=.25	p=.50	0.125	0.02243	724 weld-yrs
High (1.12 x Base)	Medium (.02 x Base)			
	p=.25	0.0625	0.011215	362 weld-yrs
	Low (.01 x Base)			
	p=.25	0.125	0.08	2,584 weld-yrs
	High (.08 x Base)			
p=.50	p=.50	0.25	0.02	646 weld-yrs
Medium (1.0 x Base)	Medium (.02 x Base)			
	p=.25	0.125	0.01	323 weld-yrs
	Low (.01 x Base)			
	p=.25	0.0625	0.059813	1,932 weld-yrs
	High (.08 x Base)			
p=.25	p=.50	0.125	0.014953	483 weld-yrs
Low (0.75 x Base)	Medium (.02 x Base)			
	p=.25	0.0625	0.007477	241 weld-yrs
	Low (.01 x Base)			

Figure 3-3 Event Tree Model to Represent Uncertainty in Hot Leg Weld Exposure for Thermal Fatigue

Table 3-8 Parameters of Bayes' Updates for Hot Leg Weld Failure Rate Cases

Weld Type and DM[3]	Weld Count Case	DM Susceptibility Case	Prior Distribution[1]			Evidence[2]		Bayes' Posterior Distribution[1]				
			Type	Median	RF	Failures	Exposure	Mean	5%tile	50%tile	95%tile	RF[4]
Hot Leg B-F SC	Low	Base	Lognormal	8.48E-07	100	6	12,074	4.32E-04	1.78E-04	4.05E-04	7.78E-04	2.1
	Medium	Base	Lognormal	8.48E-07	100	6	21,732	2.43E-04	1.01E-04	2.29E-04	4.37E-04	2.1
	High	Base	Lognormal	8.48E-07	100	6	24,147	2.20E-04	9.10E-05	2.06E-04	3.94E-04	2.1
Hot Leg B-F DC	Low	Base	Lognormal	5.46E-08	100	0	12,074	1.02E-06	5.34E-10	5.16E-08	4.05E-06	87.1
	Medium	Base	Lognormal	5.46E-08	100	0	21,732	8.31E-07	5.28E-10	5.01E-08	3.54E-06	81.9
	High	Base	Lognormal	5.46E-08	100	0	24,147	8.31E-07	5.28E-10	5.01E-08	3.54E-06	81.9
Hot Leg B-J TF	Low	Low	Lognormal	2.66E-07	100	0	241	8.88E-06	2.65E-09	2.64E-07	2.53E-05	97.6
	Medium	Low	Lognormal	2.66E-07	100	0	323	8.41E-06	2.65E-09	2.63E-07	2.49E-05	97.0
	High	Low	Lognormal	2.66E-07	100	0	362	8.22E-06	2.65E-09	2.63E-07	2.47E-05	96.7
	Low	Medium	Lognormal	2.66E-07	100	0	483	7.74E-06	2.64E-09	2.62E-07	2.43E-05	95.8
	Medium	Medium	Lognormal	2.66E-07	100	0	646	7.25E-06	2.64E-09	2.61E-07	2.37E-05	94.8
	High	Medium	Lognormal	2.66E-07	100	0	724	7.05E-06	2.64E-09	2.60E-07	2.35E-05	94.3
	Low	High	Lognormal	2.66E-07	100	0	1,932	5.38E-06	2.61E-09	2.54E-07	2.06E-05	88.9
	Medium	High	Lognormal	2.66E-07	100	0	2,584	4.90E-06	2.60E-09	2.51E-07	1.96E-05	86.7
	High	High	Lognormal	2.66E-07	100	0	2,898	4.72E-06	2.59E-09	2.50E-07	1.91E-05	85.8
Hot Leg B-J DC	Low	Base	Lognormal	5.46E-08	100	0	24,147	7.99E-07	5.26E-10	4.98E-08	3.45E-06	80.9
	Medium	Base	Lognormal	5.46E-08	100	0	32,297	7.14E-07	5.22E-10	4.87E-08	3.17E-06	77.9
	High	Base	Lognormal	5.46E-08	100	0	36,221	6.82E-07	5.20E-10	4.83E-08	3.06E-06	76.7

Notes:
(1) Failure rates expressed in failures per weld-year.
(2) Exposure expressed in weld-years.
(3) DM = Damage Mechanism; SC = stress corrosion cracking; TF = thermal fatigue; DC = design and construction defects.
(4) RF = Range Factor = SQRT (95%tile/5%tile).

3.7 Failure Rate Distribution Synthesis (Steps 1.6 and 1.7)

The total weld failure rates are calculated using a Monte Carlo posterior weighting technique to combine the distributions from the different weld-count and DM susceptibility hypotheses and then summing the contributions from applicable DMs. The result is often referred to as a mixture distribution. For B-J welds, the failure rate for thermal fatigue was developed by Monte Carlo sampling from a discrete distribution defined by probabilities and exposure cases in Figure 3-3 to determine which of the lognormal distributions for B-J TF from Table 3-8 to sample for that trial. Repeating this process over many trials (100,000 trials used for all Monte Carlo calculations in this report) yields a single distribution for the B-J weld failure rate due to thermal fatigue. This single failure rate incorporates a probabilistically weighted contribution from each supporting weld-count and DM susceptibility hypothesis. For the B-J weld failure rate due to design and construction (D&C) defects, only three cases are required to model uncertainty in the weld counts because all welds are assumed to be susceptible to D&C. Then the total failure rate for B-J welds due to thermal fatigue (Case 1C) is calculated by summing the contributions from TF and D&C. For B-J welds that are not susceptible to thermal fatigue (as determined at STP in the RI-ISI evaluation), only the D&C contribution applies. For the B-F welds, there is no significant uncertainty for DM susceptibility. Hence only the three cases for weld count uncertainty need to be combined for the SC contribution to the B-F failure rate, as well as three cases for the D&C failure rate, and then the SC and D&C contributions are summed to obtain the total B-F weld failure rate for Case 1A. It is significant that the mean failure rates for the three calculation cases span more than two orders of magnitude, from B-J welds that are not subject to thermal fatigue on the low side, to the B-F welds on the high side. The uncertainty in the B-F weld failure rate (Case 1A) as measured by the range factor is relatively small due to the significant number of pipe failures in these welds. The range factors are much higher for the B-J weld cases (1B and 1C) because there were zero failures. In these situations, the large range factor used in the prior distribution has a much larger influence on the posterior distribution parameters. These results are expected due to the properties of Bayes' updating.

Table 3-9 Total Failure Rates for Hot Leg Weld Calculation Cases

Calculation Case	Weld Type	DM	Failure Rate Distribution (failures per weld-year)				
			Mean	5%tile	50%tile	95%tile	RF
1A	B-F	SC + D&C	2.73E-04	1.04E-04	2.33E-04	5.78E-04	2.4
1B	B-J	D&C	1.44E-06	5.27E-10	4.12E-08	3.19E-06	77.8
1C		TF + D&C	1.07E-05	1.79E-08	5.79E-07	2.83E-05	39.8

3.8 Failure Rates for Other Calculation Cases (Step 1.7)

This section presents information that can be used to derive the results for the failure rate distributions for the remaining Calculation Cases in Table 3-2. The process outlined in the previous section was repeated for all the cases in Table 3-2. Actual weld counts from the 10 PWR units in Table 3-5 were used to characterize the uncertainty in the weld population per plant using the average value from the sample as the best estimate, the minimum in the sample as the lower bound, and the maximum in the sample as the upper bound. Table 3-10 provides a summary of the best estimate, upper bound, and lower bound weld-years estimated for each component type. As seen in this table, the population exposure accounted for in this failure rate development is several million component-years of experience.

Table 3-10 Component Population Exposure Estimates for Pipe Failure Rates

System Case	System	Component Case	Weld Type	Best Estimate	Upper Bound	Lower Bound
1	RCS Hot Leg	1A	B-F	21,732	24,147	12,074
		1B, 1C	B-J	32,297	36,221	24,147
2	RCS SG Inlet	2	B-F	12,074	12,074	12,074
3	RCS Cold Leg	3A	B-F	22,315	24,794	12,397
		3B	B-J	123,764	177,279	99,177
4	RCS Surge	4A	B-F	3,914	3,914	3,914
		4B	B-J	27,007	54,013	13,503
		4C	BC	7,828	7,828	7,828
5	PZR	5A–5D	B-J	351,127	496,158	286,245
		5E–5G	B-F	19,083	19,083	19,083
6	SB	6A–6B	B-J	744,237	1,144,980	366,394
7	SIR Lines Excl. Accumulator	7A–7L	B-J	590,797	637,190	507,518
	SIR Accumulator Lines	7M–7O	B-J	175,067	277,693	132,810
8	CVCS	8A–8D	B-J	562,348	627,324	403,018
		8E, 8F	BC	81,393	90,797	58,332
Total Estimated Weld-Yrs				2,774,983	3,633,494	1,958,513

Table 3-11 presents the DM susceptibility matrix for the development of fraction of the component population susceptible to each DM. This is based on the results of the failure data query, EPRI criteria for screening for DM susceptibility, and insights from review of pipe failure data in this and previous pipe failure rate studies performed by the authors.

Table 3-12 and Figure 3-4 present the results of the failure rate uncertainty analysis that supports all the calculation cases. These exhibits show that the mean failure rates span more than three orders of magnitude. They also indicate that bimetallic welds (B-F) tend to have much higher failure rates than B-J or Branch Connection (BC) welds. This is due to the susceptibility of B-F welds to PWSCC, a higher incidence of failures for this DM in the service data, and a smaller component exposure population than

that of the B-J and BC welds. At STP, there has been some cracking observed in the Pressurizer B-F welds, which has been mitigated through application of weld overlays. The failure rates for these welds (Case 5G) is estimated by using the failure rate for D&C defects that is assumed to apply to these weld overlays. This is viewed as a conservative assumption because no credit is taken for the capability of the underlying cracked material to inhibit a rupture if the overlay weld would fail. There are fewer distinct failure rates than calculation cases because the additional calculation cases are differentiated only by pipe size. For example, this applies to Cases 3A and 3B. When we develop the LOCA frequencies vs. break size in the following sections, each of these cases will have a different maximum break size, but they otherwise will exhibit an identical frequency vs. break size curve.

Table 3-11 Damage Mechanism Susceptibility Matrix for Failure Rate Development

System	Location	Confidence Level	Weld Susceptibility Fractions								
			C-F	D&C	ECSCC	Fretting	IGSCC	PWSCC	TF	TGSCC	VF
RC Hot Leg	B-F (Un-mitigated)	Low	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
	B-J	Low	N/A	1	N/A	N/A	N/A	N/A	0.01	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	N/A	0.02	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	N/A	0.08	N/A	N/A
RC Cold Leg	B-F	Low	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	B-J	Low	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
RC Hot Leg / SG Inlet	B-F	Low	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
Pressurizer Surge Line	B-F	Low	N/A	1	N/A	N/A	N/A	1	1	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	1	1	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	1	1	N/A	N/A
	B-J	Low	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
	RC-HL Branch Connection	Low	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
Pressurizer PRV/SRV & Spray Lines	B-F (Unmitigated)	Low	N/A	1	N/A	N/A	N/A	1	0.01	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	1	0.04	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	1	0.20	N/A	N/A
	B-J	Low	N/A	1	N/A	N/A	0.01	N/A	0.01	N/A	N/A
		Medium	N/A	1	N/A	N/A	0.02	N/A	0.04	N/A	N/A
		High	N/A	1	N/A	N/A	0.08	N/A	0.20	N/A	N/A

System	Location	Confidence Level	Weld Susceptibility Fractions								
			C-F	D&C	ECSCC	Fretting	IGSCC	PWSCC	TF	TGSCC	VF
Small Bore	B-J	Low	N/A	1	N/A	N/A	1	N/A	N/A	N/A	1
		Medium	N/A	1	N/A	N/A	1	N/A	N/A	N/A	1
		High	N/A	1	N/A	N/A	1	N/A	N/A	N/A	1
SIR – Medium Bore	B-J	Low	N/A	1	N/A	N/A	0.01	N/A	0.01	N/A	N/A
		Medium	N/A	1	N/A	N/A	0.05	N/A	0.04	N/A	N/A
		High	N/A	1	N/A	N/A	0.25	N/A	0.20	N/A	N/A
	C-F-1	Low	N/A	1	N/A	N/A	0.01	N/A	0.01	N/A	N/A
		Medium	N/A	1	N/A	N/A	0.05	N/A	0.04	N/A	N/A
		High	N/A	1	N/A	N/A	0.25	N/A	0.20	N/A	N/A
SIR – Large Bore (Accumulator lines)	B-J	Low	N/A	1	N/A	N/A	N/A	N/A	0.01	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	N/A	0.04	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	N/A	0.20	N/A	N/A
CV	B-J	Low	N/A	1	N/A	N/A	N/A	N/A	0.01	N/A	1
		Medium	N/A	1	N/A	N/A	N/A	N/A	0.04	N/A	1
		High	N/A	1	N/A	N/A	N/A	N/A	0.20	N/A	1
	C-F-1	Low	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
		Medium	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A
		High	N/A	1	N/A	N/A	N/A	N/A	1	N/A	N/A

C-F Corrosion-Fatigue
D&C Design & Construction Flaws
ECSCC External Chloride-induced SCC
IGSCC Inter-granular SCC
PWSCC Primary Water SCC
SCC Stress Corrosion Cracking
TF Thermal Fatigue
TGSCC Trans-granular SCC
VF Vibration Fatigue

Table 3-12 Uncertainty Distributions for Calculation Case Failure Rates

System Case	System	Calculation Case	Weld Type	Applicable Damage Mechanisms	Failure Rate Distribution (Failures per Weld-Year)				RF
					Mean	5%tile	50%tile	95%tile	
1	RC Hot Leg	1A	B-F	SC, D&C	2.73E-04	1.04E-04	2.33E-04	5.78E-04	2.4
		1B	B-J	D&C	1.44E-06	5.27E-10	4.12E-08	3.19E-06	77.8
		1C	B-J	TF, D&C	1.07E-05	1.79E-08	5.79E-07	2.83E-05	39.8
2	RC SG Inlet	2	B-F	SC, D&C	1.42E-03	9.22E-04	1.37E-03	2.06E-03	1.5
3	RC Cold Leg	3A, 3B	B-F	SC, D&C	1.25E-04	2.99E-05	9.34E-05	3.17E-04	3.3
		3C, 3D	B-J	D&C	2.39E-06	2.14E-08	4.35E-07	8.84E-06	20.3
4	RC Surge	4A	B-F	SC, TF, D&C	5.19E-04	1.26E-04	4.04E-04	1.28E-03	3.2
		4B	BC	TF, D&C	8.06E-06	1.80E-08	5.39E-07	2.24E-05	35.3
		4C	B-J	TF, D&C	4.52E-06	1.51E-08	4.04E-07	1.40E-05	30.4
5	Pressurizer	5A, 5B	B-J	TF, D&C	6.29E-06	1.63E-07	1.32E-06	1.61E-05	10.0
		5C, 5D	B-J	D&C	1.61E-06	7.31E-08	6.59E-07	5.93E-06	9.0
		5E	B-F	SC, TF, D&C	4.80E-04	2.59E-04	4.49E-04	7.83E-04	1.7
		5F	B-F	SC, D&C	4.69E-04	2.56E-04	4.43E-04	7.68E-04	1.7
		5G	B-F	D&C (Weld Overlay)	8.72E-07	5.29E-10	5.05E-08	3.66E-06	83.2
6	Small Bore	6A, 6B	B-J	VF, SC, D&C	1.23E-04	7.03E-05	1.11E-04	2.02E-04	1.7
7	SIR Excl. Accumulator	7A, 7B	B-J	TF, D&C	2.59E-04	2.17E-05	1.50E-04	8.81E-04	6.4
		7C	B-J	SC, TF, D&C	2.91E-04	3.06E-05	1.78E-04	9.37E-04	5.5
		7D	B-J	SC, D&C	3.32E-05	1.24E-06	9.38E-06	1.25E-04	10.1
		7E–7L	B-J, BC	D&C	1.07E-06	5.61E-08	4.64E-07	3.89E-06	8.3
	SIR Accumulator Lines	7M	B-J	SC, D&C	3.32E-05	1.24E-06	9.38E-06	1.25E-04	10.1
		7N	B-J	TF, D&C	6.72E-06	1.42E-08	3.90E-07	1.66E-05	34.2
		7O	B-J, BC	D&C	5.45E-07	4.61E-10	2.72E-08	1.60E-06	59.0
8	CVCS	8A, 8B	B-J	TF, VF, D&C	5.33E-06	2.43E-07	1.49E-06	1.43E-05	7.7
		8C, 8D	B-J	VF, D&C	1.76E-06	1.37E-07	8.61E-07	6.01E-06	6.6
		8E	BC	TF, D&C	7.75E-06	3.03E-07	2.76E-06	2.80E-05	9.6
		8F	BC	D&C	1.07E-06	5.61E-08	4.64E-07	3.89E-06	8.3

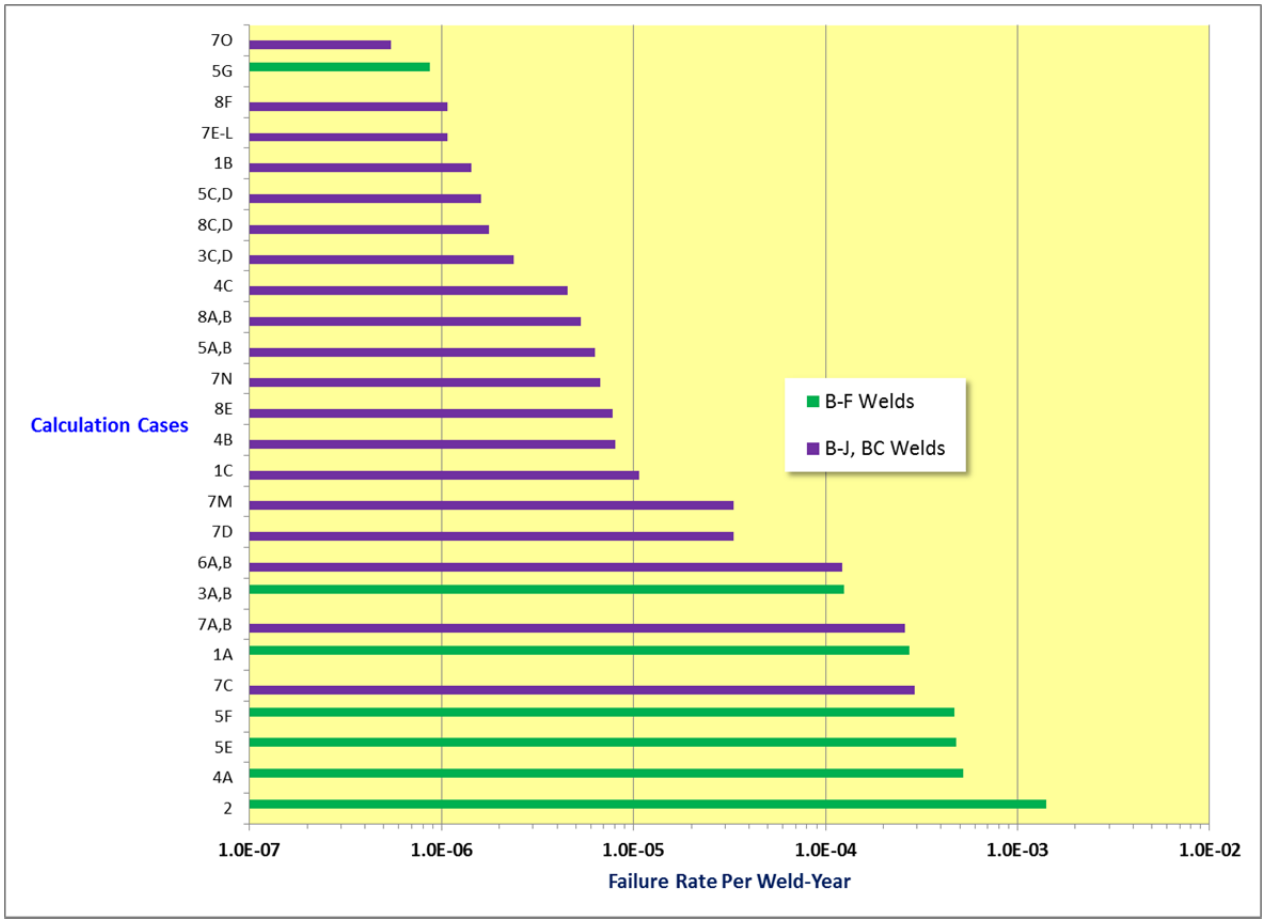

Figure 3-4 Comparison of Mean Failure Rates for Calculation Cases

4. Conditional Rupture Mode Probability Model (Step 2)

4.1 Overview of CRP Model Approach

This section documents the development of the conditional rupture probabilities (CRPs) given pipe failure for an appropriate range of pipe break sizes for each component. The components to be covered by this analysis are determined by the Component Categories in Table 2-3. In accordance with the step-by-step approach to LOCA frequency determination presented in Section 2, this section covers the following key tasks of Step 2, Conditional Rupture Probability (CRP) Development [$P(R_x | F_{ik})$ in Equation (2.2)]:

- 2.1 Select components to define conditional rupture probability (CRP) model categories
- 2.2 Obtain expert reference LOCA distributions from NUREG-1829
- 2.3 Obtain expert multiplier distributions for 40-yr LOCA frequencies from NUREG-1829
- 2.4 Determine 40-yr LOCA distributions (product of Steps 2.2 and 2.3) for each expert, fit to lognormal
- 2.5 Determine geometric mean of expert distributions from Step 2.4 (lognormal)
- 2.6a Benchmark Lydell Base Case Analysis for selected components
- 2.6b Determine failure rate distribution for Lydell Base Case Analysis in NUREG-1829; fit to lognormal
- 2.6c Apply Lydell CRP model from Base Case Analysis
- 2.6d Determine LOCA frequency distribution from Lydell Base Case Analysis
- 2.7 Determine mixture distribution of NUREG-1829 GM (from Step 2.5) and Lydell LOCA frequency (from Step 2.8) to obtain Target LOCA Frequency Distribution for each CRP category component
- 2.8 Apply formulas to calculate CRP distributions to be used as prior distributions for each component assigned to each CRP category
- 2.9 For each component in a given CRP category, perform Bayes' update with evidence of failure and rupture counts from service data.

The goal of this section is to establish a set of CRPs vs. break size for each Component Category in Table 3-2. For each Component Category, the break sizes to be considered range from an equivalent break size of 0.5" to the break size corresponding to a double-ended guillotine break (DEGB) of the pipe. The lower bound is based on the lower bound of the Small LOCA initiating event in the STP PRA model, which covers breaks in the range of 0.5" to 2.0". The break size for a DEGB is assumed to be $\sqrt{2}D$, where D is the inside diameter of the pipe. (This comes from the fact that an offset rupture effectively doubles the flow area, which would be equivalent to increasing the break size diameter of a single break by the factor $\sqrt{2}$.) This model of maximum break size, as is that for a DEGB for all Class 1 pipes, is conservative for pipe locations with a closed end on one side of the break, which would be the case for most branch connection welds in the safety injection and recirculation system piping.

Results for LOCA frequencies at each location can generally be depicted as a curve of CRP vs. break size. However, this study generates a family of curves due to the epistemic uncertainty in estimating the CRP for each component. This yields both a mean curve and various curves representing different percentiles

of the LOCA frequency uncertainty distributions. In this report, results are presented in terms of means, 5%tiles, 50%tiles (medians), and 95%tiles.

The technical approach to CRP development used here has been structured to capture the current state of knowledge of LOCA frequencies. The steps to deriving CRPs for each component are based on the following strategy for LOCA frequency estimation. It was a study objective to make use of information on LOCA frequencies in NUREG-1829 [1], which reasonably captures the current state of knowledge among piping system reliability experts on LOCA frequencies. The expert elicitation that is documented in this report captured 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. One set of these base case analyses was performed by Bengt Lydell, who is a co-author of this report. Lydell performed his base case analysis using a methodology that is very similar to that used in this study and produced a set of LOCA results with a quantification of epistemic results for a set of PWR cases, namely the hot leg, the surge line, and a high pressure injection system line. In addition to these base case analyses, nine of the participating experts provided individual distributions for LOCA frequencies for a range of components, including the components covered in the base case analyses. The technical approach to CRP model development was 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 Reference [14].

Our approach to developing CRPs is to establish a set of target LOCA frequencies that captures the epistemic uncertainties developed for NUREG-1829. Inputs from the nine experts who provided inputs at the component level are collected in Steps 2.2 and 2.3 and used to recreate their respective LOCA frequency distributions in Step 2.4. A composite distribution of these nine expert distributions is developed using a geometric mean method similar to that used in NUREG-1829 in Step 2.5. In parallel with these steps, the Lydell Base Case Analysis for these same components is benchmarked and deconstructed in Step 2.6 and is used to provide an alternative model to the target LOCA frequencies for these components. In Step 2.7, the LOCA frequency distributions provided by Lydell and the geometric mean composite distributions from Step 2.5 are combined to produce the target LOCA frequency distribution. In Step 2.8, formulas are used to derive the equivalent CRP distributions. These CRP distributions serve as prior distributions for the final step in the CRP model development, Step 2.9, in which Bayes' updates of the CRP distributions are performed for each component category.

To appropriately apply to this study the information from NUREG-1829 and the supporting inputs and analyses, the following differences between that study and this study need to be understood.

- NUREG-1829 was meant to develop estimates of PWR and BWR total LOCA frequencies for generic application to U.S. nuclear power plants. In contrast, this study is intended to develop plant-specific estimates of LOCA frequencies not only for a plant as a whole but for numerous locations within a

plant. This is made possible by the modeling assumption that LOCA frequencies can be estimated as the product of a pipe failure rate and a CRP.

- The PWR LOCA frequencies address plant-to-plant variability in design characteristics such as number of coolant loops, piping system designs, and configurations, whereas this study focuses on a specific 4-loop PWR with three trains of emergency core cooling system interface piping that is unique to STP.
- This study has benefitted from several hundred reactor-years of service data on PWR piping systems that were not available when the technical inputs to NUREG-1829 were created.

4.2 Use of NUREG-1829 Data

The expert elicitation that was performed and documented in NUREG-1829 [1] provided estimates of the frequencies for LOCAs based on a set of LOCA categories selected to span the break sizes and leak rates that are normally modeled in PWR and BWR PRAs. The estimates provided in NUREG-1829 included both pipe failures and non-pipe failures. However, only pipe failures are within the scope of this study. LOCAs caused by non-pipe failures will be addressed in 2012. The LOCA categories for PWRs used in NUREG-1829 are summarized in Table 4-1. Since the largest pipes in a PWR reactor coolant system, which correspond to the cold leg piping, are on the order of 31” nominal pipe size (NPS), the NUREG-1829 LOCA categories do not differentiate a DEGB from a single break of the largest pipe in the system. The effective DEGB size of a cold leg pipe of 31” NPS would be about 44”.

Table 4-1 NUREG-1829 and STP PRA LOCA Categories

LOCA Category	STP PRA Category	Effective Break Size (in.)	Flow Rate (gpm)
1	Small LOCA(1)	≥0.5	≥100
2	Medium LOCA(1)	≥1.5	≥1,500
3	Large LOCA	≥3	≥5,000
4		≥6.75	≥25,000
5		≥14	≥100,000
6		≥31.5	≥500,000

Note:
(1) In the STP PRA, the breakpoint between Small and Medium LOCAs is actually 2”, and the breakpoint between Medium and Large LOCAs is 6”.

The approach to using information in NUREG-1829 to develop estimates of the conditional probability of pipe ruptures is based on the following observations and information presented in that document.

- Base case results are presented in the report for three well-defined piping components for PWRs, namely, hot leg piping, pressurizer surge line piping, and high pressure injection piping, which comprise part of the ASME Class 1 pressure boundary. For each component, four independent estimates were provided for each applicable LOCA category: two estimates based on a statistical analysis of service data and simple models similar to those that will be used in the STP GSI-191 evaluation, and two estimates based on probabilistic fracture mechanics

analyses. These base case results were provided as input to the experts, and some experts chose to use them as anchors for their respective inputs. The base case results are summarized in Section 4 of NUREG-1829 as well as in the supporting appendices of that document.

- As part of the elicitation, most of the experts provided input to the estimation of LOCA frequencies for specific components on the RCS pressure boundary, including the components that were evaluated in the base case results as well as essentially all the major components on the Class 1 pressure boundary. Selected component-level results of this elicitation are found in Appendix L of NUREG-1829. For PWRs, these results are presented for LOCA Categories 1, 3, and 5. An example of the form of this information for LOCA Category 1 is shown in Figure 4-1. There is also component-level expert elicitation information presented in that appendix for hot leg piping for LOCA Category 6. The NUREG-1829 supporting information that was just recently released has additional information on component-level LOCA estimates for LOCA frequencies that covers all applicable LOCA categories for each component [14].
- In the evaluation of service data that was performed in support of NUREG-1829, which includes the base case analyses performed by Bill Gallean and Bengt Lydell, none of the reviewed service data involved the occurrence of any LOCAs. The service data we have collected in Table 3-3 for these systems, encompassing a total of 166 pipe failures, include flaws, cracks, and rather small leaks, but no leaks that would constitute even a Small LOCA, which corresponds to LOCA Category 1. The pipe rupture models used in the base case studies of Gallean and Lydell , as well as the one used in this study, assume that each pipe failure is a precursor to a LOCA. Each of these models starts with an estimate of the failure rate, which includes all pipe failures requiring repair or replacement. The model integrates the failure rates, which are estimated using service data, with the more significant pipe failures that produce LOCAs. This is accomplished by defining the conditional probability of a break of a given size given a pipe failure. Another way to look at this model is that pipe failures are assumed to represent challenges to the system and that upon each challenge, there is a probability of experiencing a break of a given size. By considering the full range of different break sizes, all the LOCA frequency categories can be quantified.
- The pipe break frequency model described in Section 2 and Equations (2.1) and (2.2) provide the capability to estimate failure rates at each location in the Class 1 piping system pressure boundary, which is needed for this GSI-191 risk-informed evaluation. Conversion of the LOCA frequency inputs in NUREG-1829 from a LOCA frequency basis to a conditional probability of LOCA basis was necessitated by this model. This required establishing target LOCA frequencies for key components and then deriving the equivalent CRP model that when combined with the failure rate model will produce the same target LOCA frequencies.

Based on the above information and insights, we will use information from NUREG-1829 to convert information that was presented in the form of LOCA frequencies vs. LOCA category, to conditional probabilities vs. break size. This approach is applied to the four PWR components that were included in the base case results as well as in the expert elicitation: the RCS hot leg, the RCS cold leg, the RCS surge line, and the HPI injection line. These span a representative range of nominal pipe sizes on the PWR Class 1 pressure boundary of 30", 30”, 14”, and 3.75”, respectively.

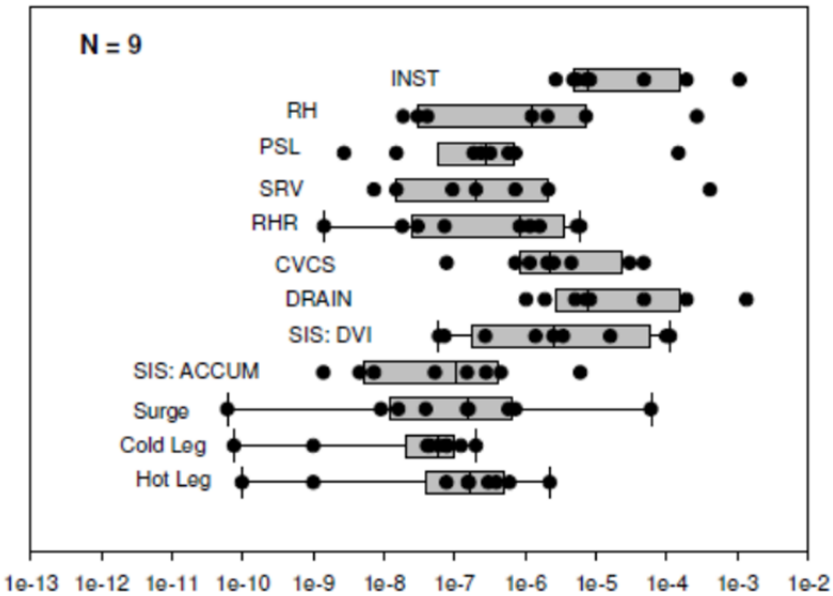

Figure 4-1 Category 1 LOCA Frequencies for PWR Piping Systems at 25 Years of Plant Operation (Reproduced from Figure L.13 in NUREG-1829)

4.3 Model for Deriving Conditional Probabilities from Rupture Frequencies

The model used to convert information on unconditional rupture frequencies to conditional failure probabilities makes use of the base case results of Lydell for each of the four selected PWR components (hot leg, cold leg, surge line, HP injection line) and the following equation:

$$F(LOCA_j) = \sum_l m_l \lambda_l P(R_j|F) \tag{4.1}$$

Where:

$F(LOCA_j) =$ Unconditional frequency of LOCA Category *j* due to pipe failures in selected component, per reactor calendar-year

$m_l =$ Number of pipe welds of type l in selected component having the same failure rate

$\lambda_l =$ Failure rate per weld-year for pipe weld type l within the selected component in Lydell's Base Case Analysis from Appendix D in NUREG-1829

$P(R_j|F) =$ Conditional rupture probability (CRP) in LOCA Category *j* given failure in selected component

Each term in this model is subject to epistemic uncertainty, which is to be estimated. Therefore, this model and the base case analysis of the failure rates from Lydell are used to derive epistemic uncertainties for the CRPs in each LOCA category. This produces a set of target LOCA frequency distribution parameters that have been selected to incorporate the epistemic uncertainties developed in NUREG-1829. This approach makes use of there being a technical basis for the failure rate estimates

from service data and a well-reviewed and extensively applied Bayes' uncertainty analysis method. These estimates were part of the information that was available to each NUREG-1829 expert to anchor his inputs. Since there have been no Category 1, 2, 3, 4, 5, or 6 LOCAs, the expert elicitation results of all the experts constitute an extrapolation from the existing service data. Therefore, our approach simply assumes that the variability in the expert elicitation inputs for LOCA frequency represents the epistemic uncertainty in the LOCA frequency for each component. This epistemic uncertainty is then assumed to result from the combination of the epistemic uncertainty in the failure rate and the epistemic uncertainty in the conditional probability of each LOCA category.

This model is somewhat simplified from the Lydell Base Case Analysis in Appendix D of NUREG-1829. Lydell's Base Case Analysis uses different conditional LOCA category probabilities for different loading conditions and then combines them to produce his base case results. So, as part of Step 2.6, we shall derive an equivalent conditional probability model using equations described in the following in order to benchmark this model against the slightly different model of Lydell. Then we shall adjust the epistemic uncertainties in the conditional probability of a LOCA in a manner that matches target LOCA frequencies that are set to incorporate the variability among experts' estimates in NUREG-1829.

4.4 Select Components to Define CRP Model Categories (Step 2.1)

As shown in the previous section, 45 failure rate categories were used to characterize the pipe failure rates for 775 distinct weld locations for all the Class 1 piping systems at STP. The failure rate categories cover all combinations of systems, weld types, damage mechanisms, and pipe sizes that are defined by the component categories. In order to estimate CRP, the following CRP Model categories were selected:

- Hot Leg CRP model
- Cold Leg CRP model
- Surge Line CRP model
- High Pressure Injection CRP model

This selection was based on the following considerations:

- There are sufficient data in NUREG-1829 and supporting input data to support estimation of the CRPs and the associated epistemic uncertainties using the technical approach adopted in this study.
- The above categories provide a unique model for all the categories with large pipe sizes, i.e., those with pipe diameters at least 12", which are expected to be the most prone to debris generation. Further detail in the treatment of smaller pipes is not warranted for this application, nor is it supported by sufficient pipe failure data.
- The SG Inlet categories are a special case of the welds in the hot leg and constitute a separate category solely to capture any "outliers" in the failure rate data. The conditional probability of pipe rupture for the SG Inlet is not expected to differ from that for the other welds in the hot leg.
- The High Pressure Injection CRP category is representative of the medium and small bore pipe with pipe diameter up to 12". They are all stainless steel lines connected to the larger pipe sizes and are subject to a similar range of DMs. This category includes both bimetallic (B-F) and similar metal (B-J and BC) welds and covers a full range of DMs that are found in Class 1 piping.

- In combination with the 45 unique failure rate cases developed in Section 3, the above CRP model categories provide a reasonably complete set to characterize the LOCA frequencies in all 775 weld locations in Table 3-3.
- The above four models will be used to develop prior distributions for the CRP epistemic uncertainties. Applying them to specific components will entail the Bayes' update in Step 2.9, in which the number of failures and ruptures for each failure rate case will be used as the evidence for updating these base priors. Hence, the four CRP models will actually produce eight different sets of CRPs, one for each system. These will be expanded further to apply to different pipe sizes, where the maximum break size for each pipe size is set to the DEGB size.

A summary of the mapping of CRP model categories to the piping system categories is shown in Table 4-2

Table 4-2 Assignment of Piping System Categories to CRP Model Categories

Case	Description	Weld Type	Damage Mechanism (DM)	CRP Model and Bayes' Update Evidence
1	RCS Hot Leg Excl. SG Inlet	B-F	PWSCC, D&C	Hot Leg CRP Model, updated with 0 ruptures in 6 failures
		B-J	TF, D&C	
2	RCS Cold Leg	B-F	PWSCC, D&C	Cold Leg CRP Model, updated with 0 ruptures in 3 failures
		B-J	D&C	
3	RCS Hot Leg SG Inlet	B-F	PWSCC, D&C	Hot Leg CRP Model, updated with 0 ruptures in 19 failures
4	PZR Surge Line	B-F	PWSCC, TF, D&C	Surge Line CRP Model, updated with 0 ruptures in 3 failures
		B-J, BC	TF, D&C	
5	PZR Medium Bore Piping	B-F	PWSCC, TF, D&C	HPI CRP Model, updated with 0 ruptures in 12 failures
		B-J, BC	TF, D&C	
6	Class 1 Small Bore Piping	B-J	TF, D&C, TGSCC, VF	HPI CRP Model, updated with 0 ruptures in 106 failures
7	Class 1 Medium Bore SIR Piping	B-J	TF, D&C, IGSCC	HPI CRP Model, updated with 0 ruptures in 14 failures
8	Class 1 Medium Bore CVCS Piping	B-J, BC	TF, D&C, TGSCC, VF	HPI CRP Model Updated with 0 ruptures in 14 failures

B-F ASME Category B-F welds (bimetallic)
B-J ASME Category B-J welds (single metal)
BC Branch Connection Weld, B-J welds used at branch connections
CVCS Chemical, Volume, and Control System
D&C Design and Construction Defects
IGSCC Intergranular Stress Corrosion Cracking
PWSCC Primary Water Stress Corrosion Cracking
PZR Pressurizer

Case	Description	Weld Type	Damage Mechanism (DM)	CRP Model and Bayes' Update Evidence
RCS	Reactor Coolant System			
SIR	Safety Injection and Recirculation Systems			
TF	Thermal Fatigue			
TGSCC	Transgranular Stress Corrosion Cracking			
VF	Vibration Fatigue			

4.5 Use of Data from NUREG-1829 Expert Elicitation (Steps 2.2 and 2.3)

The expert elicitation that was performed for NUREG-1829 included a request for estimates of LOCA frequencies for specific pipe- and non-pipe-related components [14]. Nine experts provided input at this level, and Steps 2.1 through 2.5 involve analysis of these data for selected components, namely the hot leg, cold leg, surge line, and HPI line components in PWRs. One set of numbers provided by the experts was LOCA frequencies by LOCA category in terms of a mid-value (Mid), an upper bound (UB), and a lower bound (LB), with the understanding that those would be interpreted as medians, 95%tiles, and 5%tiles of a lognormal uncertainty distribution. For symmetric inputs (i.e., when UB/Mid = Mid/LB), which were provided in most cases, these distributions were assumed to be lognormal distributions. For asymmetric inputs provided by the experts, a specific split lognormal distribution was assumed.

The first set of LOCA frequencies was for the existing fleet of plants, which involves a mixture of plant ages and an average plant age of about 25 years at the time the elicitation was performed. The experts provided multipliers for normalizing these LOCA frequencies to plant ages of 25 years, 40 years, and 60 years prior to the occurrence of a LOCA. These multipliers enabled the experts to express whether LOCA frequencies could be affected by aging effects and whether such effects might be mitigated. This study is intended to develop LOCA frequencies that will be valid over the 40 years of the current plant license. Therefore, only the 40-year values are used here.

The expert elicitation inputs for the hot leg pipes are provided in Table 4-3. The nine experts are labeled A through L, with D, F, and K unassigned. The data highlighted in yellow are copied directly from the questionnaire sheets in Reference [14]. Similar tables were developed for the cold leg, surge line, and HPI line (the variant of the HPI line with volume injection was selected for consistency with the Lydell HPI Base Case Analysis in Appendix D of NUREG-1829). This completes Steps 2.2 and 2.3 for each CRP model component.

4.6 Development of 40-Year LOCA Frequency Distributions (Step 2.4)

In Step 2.4, the "LOCA Frequencies for System" distributions are multiplied by the 40-year multiplier distributions, to obtain the 40-year LOCA frequency distributions. This is straightforward because the product of two lognormal distributions is also a lognormal distribution.

When the two input distributions are lognormal, the parameters of the lognormal distribution for the 40-year LOCA frequencies can be directly computed using the following formulas.

$$median_{40YLF} = median_{Base} * median_{40YM} \tag{4.2}$$

$$RF_{40YLF} = e^{1.645\sigma_{40YLF}} \tag{4.3}$$

Where:

$$\sigma_{40YLF} = \sqrt{\left(\frac{\ln(RF_{Base})}{1.645}\right)^2 + \left(\frac{\ln(RF_{40YM})}{1.645}\right)^2} \tag{4.4}$$

$median_{40YLF} =$ Median of the lognormal distribution for the 40-year LOCA frequency, evaluated for each combination of expert and LOCA Category

$median_{Base} =$ Median of the lognormal distribution for the base LOCA frequency ("LOCA Frequency for System" provided by each expert for each LOCA Category)

$median_{40YM} =$ Median of the lognormal distribution for the 40-year multiplier provided by each expert for each LOCA Category

$RF_{40YLF} =$ Range factor of the lognormal distribution for the 40-year LOCA frequency, equal to SQRT(95%tile/5%tile) of the lognormal distribution

$\sigma_{40YLF} =$ Logarithmic standard deviation for the lognormal distribution for the 40-year LOCA frequency, evaluated for each combination of expert and LOCA Category

$RF_{Base} =$ Range factor of the lognormal distribution for the base LOCA frequency provided by each expert for each LOCA Category

$RF_{40YM} =$ Range factor of the lognormal distribution for the 40-year multiplier provided by each expert for each LOCA Category

When the experts provided asymmetric inputs, NUREG-1829 utilized a split lognormal formulation for calculating the 40-year LOCA frequency distributions. In this study, the inputs provided by the experts were fit to lognormals by preserving the medians and the 95%tiles of the input distributions, while ignoring the asymmetries on the left side of the distributions. An alternative procedure was also tested, in which the median and the range factor defined as the square root of the ratio of the 95%tile to the 5%tile were preserved in the input distributions, which were again assumed to be lognormal. In his independent review of an earlier draft of this report, Dr. Ali Mosleh recommended the former procedure, which was adopted in this report. The adopted approach retains the simplicity of using lognormals in lieu of the more complicated split lognormals, retains the identification of the best estimates with the medians of the distributions, and by preserving the 50th and higher percentiles is more effective in preserving the means of the underlying input distributions.

In Table 4-3, the first procedure is applied as indicated in the blue-shaded cells. The RF95 values were calculated based on UB/Mid for the base LOCA frequencies and the 40-year multipliers, and the RF95 values for the 40-year LOCA frequencies were calculated from Equation (4.4).

As a result of the above procedure, there is a single lognormal distribution defined for each LOCA category frequency at 40 years of operation. This distribution is applicable to each component provided

by each of the 9 experts who provided component level inputs in Reference [14]. In some cases, experts provided fixed values for one parameter (base LOCA frequency or multiplier) and a distribution for the other, in which case the distribution for the 40-year LOCA frequency was found simply by scaling the provided distribution parameters with the supplied fixed values. The results in the last column of Table 4-3 reflect the execution of Step 2.4 for the hot leg.

Table 4-3 NUREG-1829 Expert Distributions for Hot Leg LOCA Frequencies

Expert ID	LOCA Category	LOCA Frequency for System[1] (Per Reactor-Calendar Year)				40-Yr Multiplier[1]				40-Yr LOCA Frequency[1] (Per Reactor-Calendar Year)	
		LB	Mid	UB	RF95=UB/Mid[2]	LB	Mid	UB	RF95=UB/Mid[2]	Mid[3]	RF95[4]
A	1 (> 100)	5.33E-08	1.60E-07	4.80E-07	3.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.60E-07	3.00E+00
	2 (> 1,500)	5.33E-08	1.60E-07	4.80E-07	3.00E+00	1.50E-02	3.00E-01	5.85E-01	1.95E+00	4.80E-08	3.62E+00
	3 (> 5,000)	5.33E-08	1.60E-07	4.80E-07	3.00E+00	5.00E-03	1.00E-01	1.95E-01	1.95E+00	1.60E-08	3.62E+00
	4 (> 25,000)	5.33E-08	1.60E-07	4.80E-07	3.00E+00	1.50E-03	3.00E-02	5.85E-02	1.95E+00	4.80E-09	3.62E+00
	5 (> 100,000)	5.33E-08	1.60E-07	4.80E-07	3.00E+00	5.00E-04	1.00E-02	1.95E-02	1.95E+00	1.60E-09	3.62E+00
	6 (> 500,000)	5.33E-08	1.60E-07	4.80E-07	3.00E+00	1.50E-04	3.00E-03	5.85E-03	1.95E+00	4.80E-10	3.62E+00
B	1 (> 100)	3.00E-07	3.00E-07	3.00E-07	1.00E+00	1.00E-01	1.00E+00	1.00E+01	1.00E+01	3.00E-07	1.00E+01
	2 (> 1,500)	1.20E-07	1.20E-07	1.20E-07	1.00E+00	1.00E-01	1.00E+00	1.00E+01	1.00E+01	1.20E-07	1.00E+01
	3 (> 5,000)	4.80E-08	4.80E-08	4.80E-08	1.00E+00	1.00E-01	1.00E+00	1.00E+01	1.00E+01	4.80E-08	1.00E+01
	4 (> 25,000)	1.92E-08	1.92E-08	1.92E-08	1.00E+00	1.00E-01	1.00E+00	1.00E+01	1.00E+01	1.92E-08	1.00E+01
	5 (> 100,000)	7.68E-09	7.68E-09	7.68E-09	1.00E+00	1.00E-01	1.00E+00	1.00E+01	1.00E+01	7.68E-09	1.00E+01
	6 (> 500,000)	3.07E-09	3.07E-09	3.07E-09	1.00E+00	1.00E-01	1.00E+00	1.00E+01	1.00E+01	3.07E-09	1.00E+01
C	1 (> 100)	6.00E-07	6.00E-07	6.00E-07	1.00E+00	3.00E-02	1.00E+00	3.00E+01	3.00E+01	6.00E-07	3.00E+01
	2 (> 1,500)	5.00E-08	5.00E-08	5.00E-08	1.00E+00	3.00E-02	1.00E+00	3.00E+01	3.00E+01	5.00E-08	3.00E+01
	3 (> 5,000)	2.00E-08	2.00E-08	2.00E-08	1.00E+00	3.00E-02	1.00E+00	3.00E+01	3.00E+01	2.00E-08	3.00E+01
	4 (> 25,000)	3.00E-09	3.00E-09	3.00E-09	1.00E+00	5.00E-02	1.67E+00	1.67E+02	1.00E+02	5.01E-09	1.00E+02
	5 (> 100,000)	1.00E-09	1.00E-09	1.00E-09	1.00E+00	6.00E-02	2.00E+00	2.00E+03	1.00E+03	2.00E-09	1.00E+03
	6 (> 500,000)	2.00E-10	2.00E-10	2.00E-10	1.00E+00	6.00E-02	2.00E+00	2.00E+03	1.00E+03	4.00E-10	1.00E+03
E	1 (> 100)	3.07E-07	9.22E-07	2.77E-06	3.00E+00	3.33E-04	2.83E-02	3.33E-01	1.18E+01	2.61E-08	1.49E+01
	2 (> 1,500)	3.07E-07	9.22E-07	2.77E-06	3.00E+00	3.33E-04	2.83E-02	3.33E-01	1.18E+01	2.61E-08	1.49E+01
	3 (> 5,000)	3.07E-07	9.22E-07	2.77E-06	3.00E+00	3.33E-04	2.83E-02	3.33E-01	1.18E+01	2.61E-08	1.49E+01
	4 (> 25,000)	3.67E-09	1.10E-08	3.30E-08	3.00E+00	1.00E-03	1.00E-01	1.50E+00	1.50E+01	1.10E-09	1.86E+01
	5 (> 100,000)	1.27E-09	3.80E-09	1.14E-08	3.00E+00	1.00E-04	5.00E-02	1.00E+00	2.00E+01	1.90E-10	2.43E+01

Expert ID	LOCA Category	LOCA Frequency for System[1] (Per Reactor-Calendar Year)				40-Yr Multiplier[1]				40-Yr LOCA Frequency[1] (Per Reactor-Calendar Year)	
		LB	Mid	UB	RF95=UB/Mid[2]	LB	Mid	UB	RF95=UB/Mid[2]	Mid[3]	RF95[4]
	6 (> 500,000)	4.33E-10	1.30E-09	3.90E-09	3.00E+00	1.00E-04	3.00E-02	3.00E+00	1.00E+02	3.90E-11	1.14E+02
G	1 (> 100)	5.13E-08	1.54E-07	4.62E-07	3.00E+00	1.00E-01	1.14E+00	1.00E+01	8.77E+00	1.76E-07	1.14E+01
	2 (> 1,500)	7.50E-09	2.25E-08	6.75E-08	3.00E+00	1.00E-01	1.14E+00	1.00E+01	8.77E+00	2.57E-08	1.14E+01
	3 (> 5,000)	2.78E-09	8.33E-09	2.50E-08	3.00E+00	1.00E-01	1.14E+00	1.00E+01	8.77E+00	9.50E-09	1.14E+01
	4 (> 25,000)	9.50E-10	2.85E-09	8.55E-09	3.00E+00	1.00E-01	1.14E+00	1.00E+01	8.77E+00	3.25E-09	1.14E+01
	5 (> 100,000)	1.71E-10	8.53E-10	4.27E-09	5.01E+00	1.00E-01	1.14E+00	1.00E+01	8.77E+00	9.72E-10	1.49E+01
	6 (> 500,000)	1.58E-11	1.58E-10	1.58E-09	1.00E+01	1.00E-01	1.14E+00	1.00E+01	8.77E+00	1.80E-10	2.37E+01
H	1 (> 100)	1.48E-07	4.45E-07	1.34E-06	3.01E+00	2.50E+00	2.50E+01	2.50E+02	1.00E+01	1.11E-05	1.28E+01
	2 (> 1,500)	2.03E-08	6.10E-08	1.83E-07	3.00E+00	1.00E+00	1.00E+01	1.00E+02	1.00E+01	6.10E-07	1.28E+01
	3 (> 5,000)	7.33E-09	2.20E-08	6.60E-08	3.00E+00	5.00E-01	5.00E+00	5.00E+01	1.00E+01	1.10E-07	1.28E+01
	4 (> 25,000)	2.60E-09	7.80E-09	2.34E-08	3.00E+00	5.00E-01	5.00E+00	5.00E+01	1.00E+01	3.90E-08	1.28E+01
	5 (> 100,000)	8.83E-10	2.65E-09	7.95E-09	3.00E+00	5.00E-01	5.00E+00	5.00E+01	1.00E+01	1.33E-08	1.28E+01
	6 (> 500,000)	2.93E-10	8.80E-10	2.64E-09	3.00E+00	5.00E-01	5.00E+00	5.00E+01	1.00E+01	4.40E-09	1.28E+01
I	1 (> 100)	4.00E-11	2.00E-09	1.00E-07	5.00E+01	5.00E-01	5.00E-01	5.00E-01	1.00E+00	1.00E-09	5.00E+01
	2 (> 1,500)	4.00E-11	2.00E-09	1.00E-07	5.00E+01	5.00E-01	5.00E-01	5.00E-01	1.00E+00	1.00E-09	5.00E+01
	3 (> 5,000)	4.00E-11	2.00E-09	1.00E-07	5.00E+01	5.00E-01	5.00E-01	5.00E-01	1.00E+00	1.00E-09	5.00E+01
	4 (> 25,000)	4.00E-11	2.00E-09	1.00E-07	5.00E+01	5.00E-01	5.00E-01	5.00E-01	1.00E+00	1.00E-09	5.00E+01
	5 (> 100,000)	4.00E-11	2.00E-09	1.00E-07	5.00E+01	5.00E-01	5.00E-01	5.00E-01	1.00E+00	1.00E-09	5.00E+01
	6 (> 500,000)	4.00E-11	2.00E-09	1.00E-07	5.00E+01	5.00E-01	5.00E-01	5.00E-01	1.00E+00	1.00E-09	5.00E+01
J	1 (> 100)	9.25E-12	9.80E-11	2.88E-09	2.94E+01	3.19E+01	3.19E+01	3.19E+01	1.00E+00	3.13E-09	2.94E+01
	2 (> 1,500)	5.78E-13	1.03E-11	7.61E-10	7.39E+01	5.24E+01	5.24E+01	5.24E+01	1.00E+00	5.40E-10	7.39E+01
	3 (> 5,000)	1.40E-13	3.21E-12	3.38E-10	1.05E+02	6.04E+01	6.04E+01	6.04E+01	1.00E+00	1.94E-10	1.05E+02
	4 (> 25,000)	1.53E-14	4.82E-13	9.75E-11	2.02E+02	7.50E+01	7.50E+01	7.50E+01	1.00E+00	3.62E-11	2.02E+02
	5 (> 100,000)	2.42E-15	6.99E-14	1.93E-11	2.76E+02	9.81E+01	9.81E+01	9.81E+01	1.00E+00	6.86E-12	2.76E+02
	6 (> 500,000)	1.44E-17	6.28E-16	7.56E-13	1.20E+03	1.14E+02	1.14E+02	1.14E+02	1.00E+00	7.16E-14	1.20E+03

Expert ID	LOCA Category	LOCA Frequency for System[1] (Per Reactor-Calendar Year)				40-Yr Multiplier[1]				40-Yr LOCA Frequency[1] (Per Reactor-Calendar Year)	
		LB	Mid	UB	RF95=UB/Mid[2]	LB	Mid	UB	RF95=UB/Mid[2]	Mid[3]	RF95[4]
L	1 (> 100)	2.62E-06	9.60E-06	3.52E-05	3.67E+00	1.27E-01	1.27E-01	1.27E-01	1.00E+00	1.22E-06	3.67E+00
	2 (> 1,500)	1.58E-06	6.34E-06	2.53E-05	3.99E+00	1.27E-01	1.27E-01	1.27E-01	1.00E+00	8.05E-07	3.99E+00
	3 (> 5,000)	3.84E-07	1.92E-06	9.60E-06	5.00E+00	4.19E-01	4.19E-01	4.19E-01	1.00E+00	8.04E-07	5.00E+00
	4 (> 25,000)	1.54E-07	7.68E-07	3.84E-06	5.00E+00	1.01E+00	1.01E+00	1.01E+00	1.00E+00	7.76E-07	5.00E+00
	5 (> 100,000)	6.40E-08	3.20E-07	1.60E-06	5.00E+00	2.41E+00	2.41E+00	2.41E+00	1.00E+00	7.71E-07	5.00E+00
	6 (> 500,000)	3.20E-11	3.20E-10	3.20E-09	1.00E+01	2.61E+00	2.61E+00	2.61E+00	1.00E+00	8.35E-10	1.00E+01

Notes:

[1] Data shaded in yellow are taken from NUREG-1829 expert questionnaires in Reference [14]. Data shaded in blue were calculated in this study per Notes [2] through [4].

[2] RF = Range Factor of a lognormal distribution defined by the Mid value as the median and by the UB value as the 95%tile.

[3] Median of a lognormal distribution for the 40-year LOCA frequency created by the product of two lognormal distributions: the medians of the lognormal distributions for LOCA frequency for system and the 40-year multiplier (see Equation [4.1]).

[4] Range Factor of the 40-year LOCA frequency lognormal distribution (see Equation [4.2]).

4.7 Develop Expert Composite Distributions from NUREG-1829 (Step 2.5)

In this step, the nine expert distributions for 40-year LOCA frequencies obtained in Step 2.4 are combined into a single composite distribution.

NUREG-1829 discussed two approaches for developing expert composite distributions: the Mixture Distribution Method and the Geometric Mean Method. NUREG-1829 adopted the latter approach, whereas this study evaluated both approaches, briefly described below.

Mixture Distribution Method

The expert elicitation input sheets that are found in Reference [14] furnished each expert with input on the LOCA frequencies in each of the six applicable LOCA categories for each component in the RCS pressure boundary, the same components as shown in Figure 4-1.

A single mixture distribution was developed for each combination of component and LOCA category by combining the 40-year LOCA frequency distributions provided by each expert. A single mixture distribution was developed by sampling a discrete distribution on each Monte Carlo trial to determine which expert's lognormal distribution for the 40-year LOCA frequency to be sampled for that trial. The discrete distribution has a value for each expert, with each value's being assigned the same probability in order to give all experts equal weight. In the several cases where experts did not provide inputs for each LOCA category, the mixture distribution was developed only for those experts providing inputs for that category. In all cases, a minimum of seven experts provided input, and the vast majority of cases had nine. This method is discussed in NUREG-1829 but was rejected in favor of the Geometric Mean method.

Geometric Mean Method

When this method was used in NUREG-1829, it was oriented toward the calculation of the total LOCA frequency rather than the LOCA frequency for many locations. Another contrast was the use in NUREG-1829 of split lognormals, whereas this study used lognormal fitting based on preserving medians and 95%tiles. In this study, a single lognormal distribution for each component and each LOCA category was defined by taking the geometric mean of the medians of the experts' lognormal distributions as the composite distribution median, and the geometric means of the range factors of the experts' lognormal distributions for the 40-year LOCA frequencies as the composite distribution range factor. As with the Mixture Method, in this study the input lognormal distributions provided by the experts were fit to lognormal distribution by matching the 50th and 95th percentiles. A summary of the derived composite distribution parameters is provided in Table 4-4, which completes Step 2.5 of our LOCA frequency procedure.

A comparison of the resulting composite distributions using both methods is provided in Figures 4-2 and 4-3, for the RCS hot leg and RCS surge line, respectively. As seen in these figures, the composite distributions generated by the Mixture Distribution method produce much broader ranges of uncertainty than those obtained by the Geometric Mean method. As discussed in NUREG-1829 and

confirmed by our study, the upper and lower bounds of the mixture distributions are heavily influenced by the experts' extreme high-side and low-side inputs, respectively, whereas the distribution percentiles from the Geometric Mean method more fairly represent the experts' inputs. However, in the selection of target LOCA frequencies, this study departs from NUREG-1829 by employing both the Geometric Mean Model of LOCA frequencies and a re-creation of the Lydell Base Case Analysis in NUREG-1829 Appendix D for the same group of components.

Table 4-4 Composite Distributions for NUREG-1829 Experts Based on Geometric Mean Method

Component	LOCA Cat.	Break Size (Inches)	Geometric Mean Distribution Parameters Events per Reactor-Calendar Year				
			Mean	5%tile	50%tile	95%tile	RF
Hot Leg	1	≥ 0.5	4.08E-07	9.32E-09	1.21E-07	1.57E-06	13.0
	2	≥ 1.5	1.28E-07	2.25E-09	3.34E-08	4.95E-07	14.8
	3	≥ 3	6.51E-08	1.01E-09	1.59E-08	2.52E-07	15.8
	4	≥ 6.75	2.59E-08	2.49E-10	4.96E-09	9.88E-08	19.9
	5	≥ 14	1.50E-08	6.70E-11	1.90E-09	5.37E-08	28.3
	6	≥ 31.5	3.16E-09	4.84E-12	2.18E-10	9.78E-09	45.0
Cold Leg	1	≥ 0.5	1.47E-07	3.27E-09	4.30E-08	5.66E-07	13.2
	2	≥ 1.5	5.20E-08	9.07E-10	1.35E-08	2.01E-07	14.9
	3	≥ 3	2.19E-08	3.33E-10	5.31E-09	8.48E-08	16.0
	4	≥ 6.75	7.85E-09	7.41E-11	1.49E-09	2.99E-08	20.1
	5	≥ 14	4.54E-09	1.94E-11	5.60E-10	1.62E-08	28.9
	6	≥ 31.5	1.10E-09	1.56E-12	7.23E-11	3.36E-09	46.4
Surge Line	1	≥ 0.5	3.60E-07	1.33E-08	1.34E-07	1.35E-06	10.1
	2	≥ 1.5	1.26E-07	3.46E-09	4.09E-08	4.83E-07	11.8
	3	≥ 3	6.45E-08	1.29E-09	1.79E-08	2.49E-07	13.9
	4	≥ 6.75	1.92E-08	2.47E-10	4.28E-09	7.41E-08	17.3
	5	≥ 14	2.72E-09	4.22E-11	6.66E-10	1.05E-08	15.8
HPI Line	1	≥ 0.5	1.27E-05	6.40E-07	5.45E-06	4.65E-05	8.5
	2	≥ 1.5	4.58E-06	1.51E-07	1.62E-06	1.74E-05	10.7
	3	≥ 3	7.21E-07	1.53E-08	2.06E-07	2.78E-06	13.5
	4	≥ 6.75	1.29E-07	1.41E-09	2.64E-08	4.95E-07	18.8
	5	≥ 14	3.03E-08	3.30E-10	6.20E-09	1.16E-07	18.8

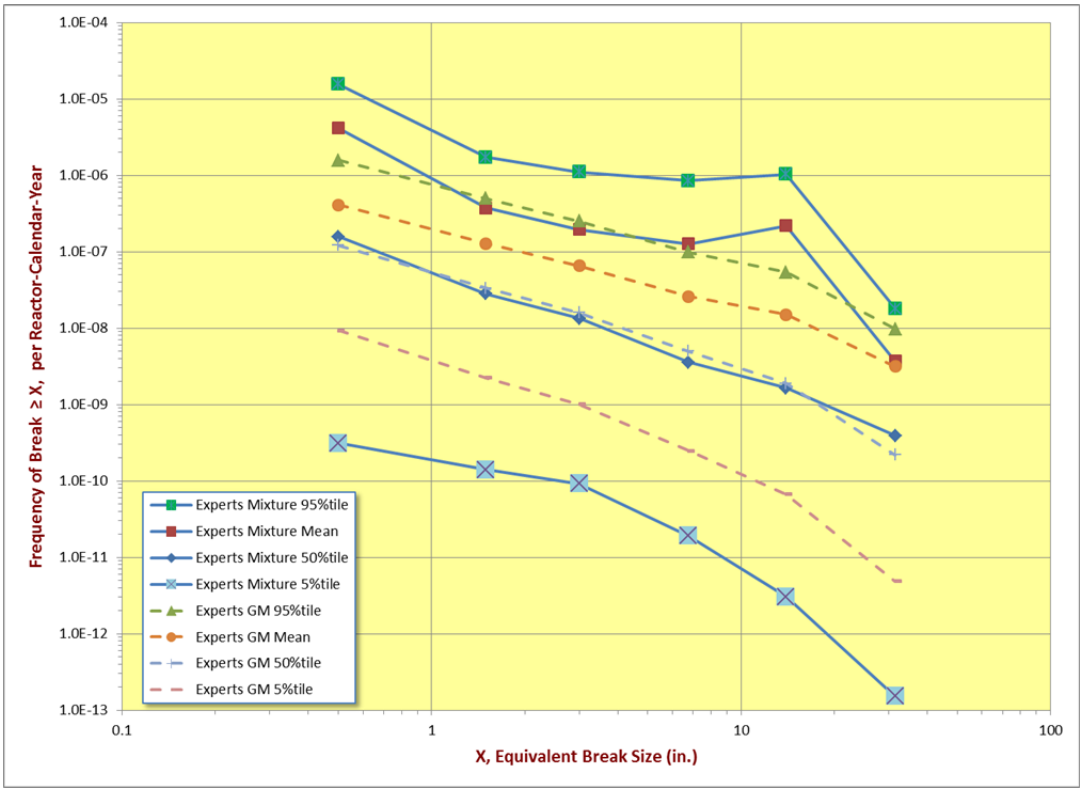

Figure 4-2 Comparison of Mixture and Geometric Mean Composite Distributions – RCS Hot Leg

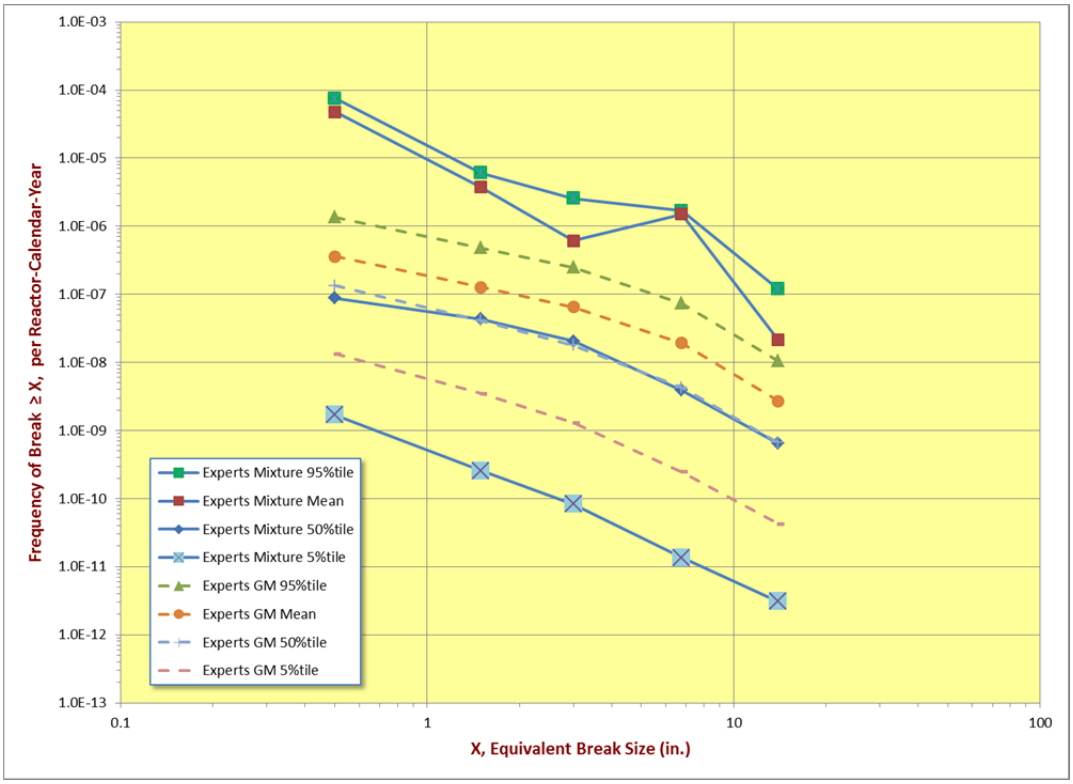

Figure 4-3 Comparison of Mixture and Geometric Mean Composite Distributions – RCS Surge Line

4.8 Benchmark of Lydell's Base Case Analysis (Step 2.6)

This step establishes inputs to the selection of target LOCA frequencies from the Lydell Base Case Analysis. A secondary purpose is to establish the corresponding failure rate and CRP distributions that are responsible for the Base Case results. The failure rate distribution parameters will be used in Step 2.8 to convert the target LOCA frequency distributions to CRP distributions.

Using the same Microsoft Excel™ and Oracle Crystal Ball™ files that Lydell used to develop his Base Case results, the simplified model of Equation (4.1) was applied to the same failure rate estimates that Lydell derived and documented in Appendix D of NUREG-1829, assuming a lognormal distribution for the conditional LOCA category probability for each component. This resulted in lognormal parameters that essentially reproduce Lydell's Appendix D results, as shown in Figures 4-4, 4-5, and 4-6, for the HPI injection line, RCS surge line, and RCS hot leg, respectively. The CRP distribution parameters were obtained by first developing the LOCA frequencies and then calculating the CRP distribution parameters using formulas for calculating the parameters for the product of two lognormal distributions – similar to Equations (4.2) and (4.3). The figures comparing the Base Case results from Appendix D in NUREG-1829 with the results obtained using the equivalent lognormal distributions indicate excellent agreement. The underlying lognormal distribution parameters for the conditional LOCA probabilities in Table 4-5 appear to the authors to be reasonable, i.e. they are neither very large nor very small. The conditional probability of a given break size is indicated to be inversely proportional to pipe size which is in agreement with previous estimates of LOCA frequencies.

The uncertainty distribution parameters for the LOCA frequencies from this reconstruction of the Lydell Base Case results are shown in Table 4-6. This completes Step 2.6 of the LOCA frequency procedure.

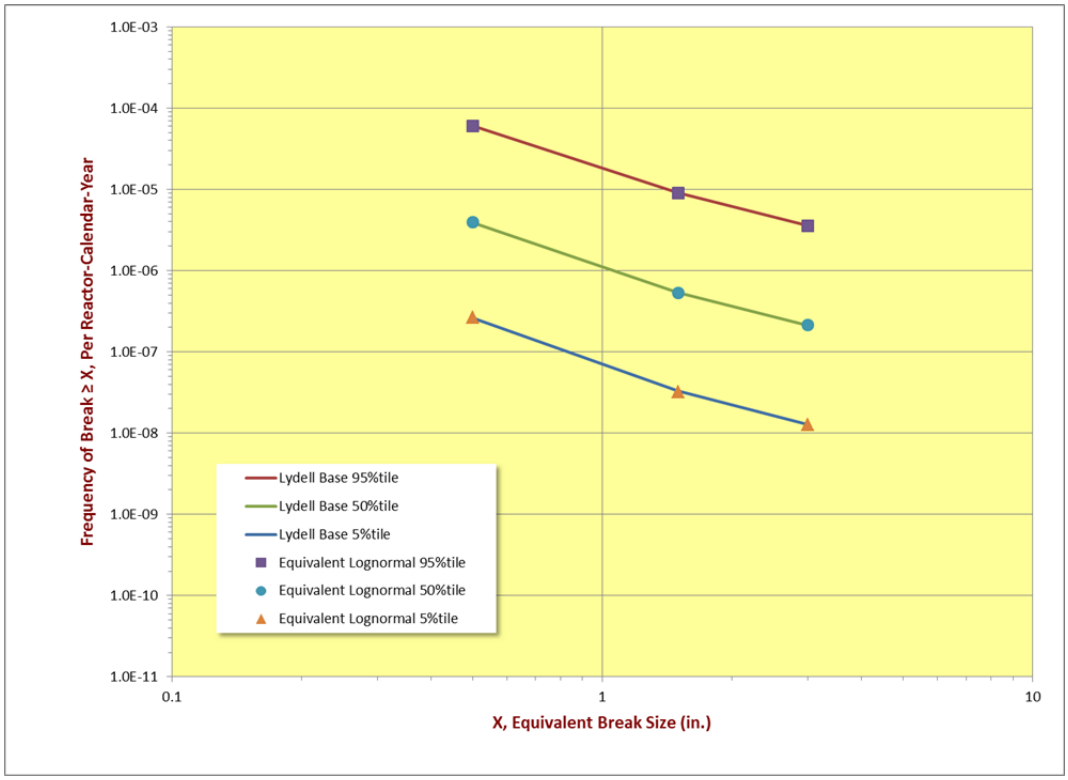

Figure 4-4 Benchmarking of Lognormal Distributions to Lydell Base Case Results – HPI Injection Line

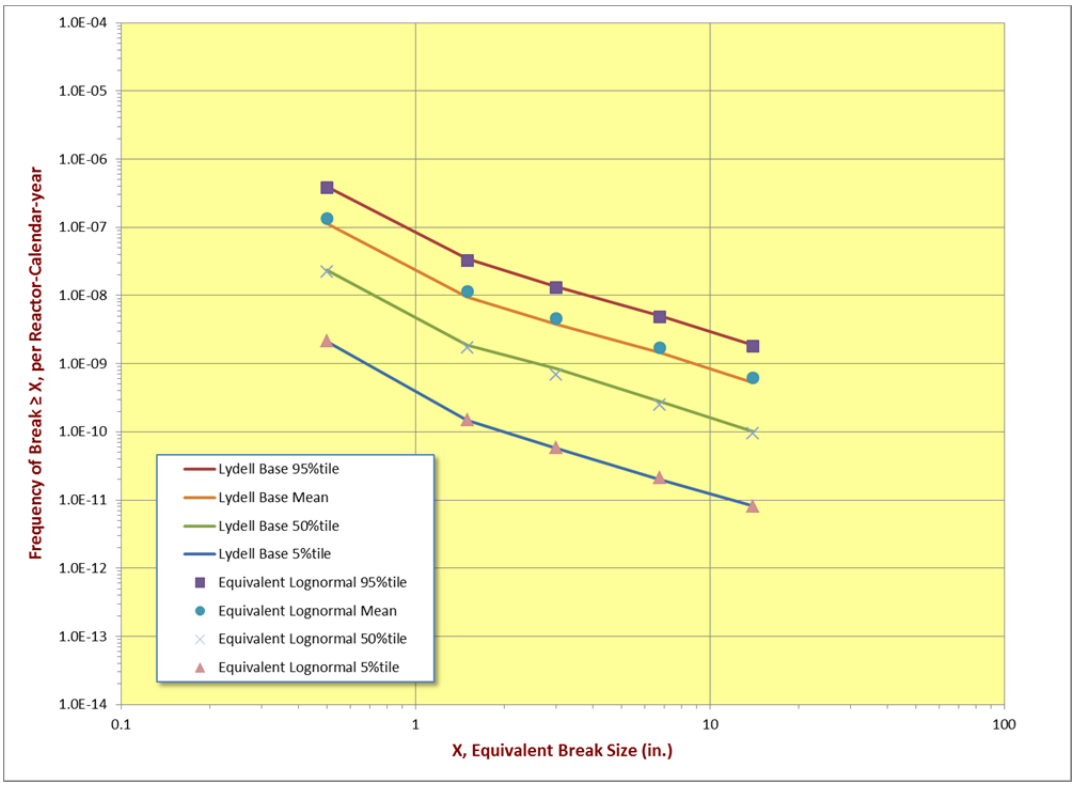

Figure 4-5 Benchmarking of Lognormal Distributions to Lydell Base Case Results – RCS Surge Line

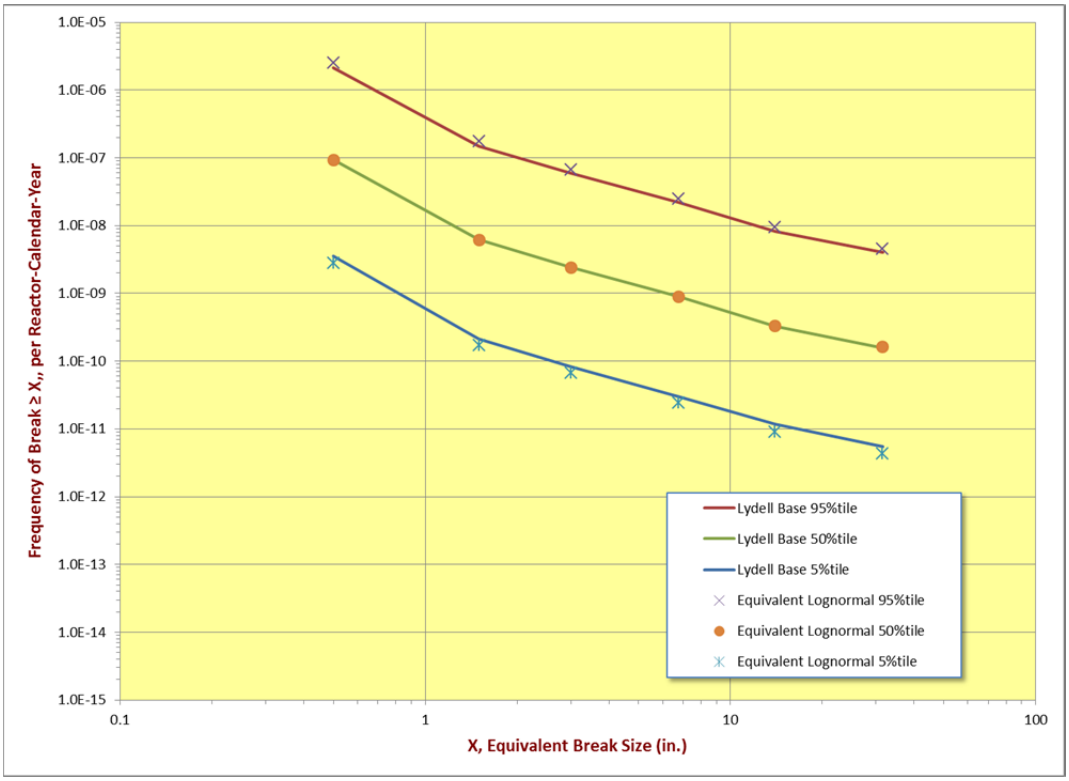

Figure 4-6 Benchmarking of Lognormal Distributions to Lydell Base Case Results – RCS Hot Leg

Table 4-5 Lognormal Distributions for Failure Rates and Conditional Rupture Probabilities (CRPs) Matching Lydell's Base Case Results

Component	LOCA Category	Break Size (in.)	Mean	5%tile	Median	95%tile	Range Factor
RCS – Hot Leg	Failure Rate		3.46E-04	1.01E-05	1.15E-04	1.32E-03	11.4
	1	≥ .5	1.67E-03	9.49E-05	7.55E-04	6.01E-03	8.0
	2	≥ 1.5	1.18E-04	5.38E-06	4.85E-05	4.37E-04	9.0
	3	≥ 3	4.73E-05	2.13E-06	1.93E-05	1.75E-04	9.1
	4	≥ 6.75	1.76E-05	7.71E-07	7.09E-06	6.52E-05	9.2
	5	≥ 14	6.59E-06	2.97E-07	2.69E-06	2.43E-05	9.1
	6	≥ 31.5	3.23E-06	1.38E-07	1.28E-06	1.20E-05	9.3
RCS – Cold Leg	Failure Rate		1.73E-04	5.04E-06	5.77E-05	6.61E-04	11.4
	1	≥ .5	1.67E-03	9.49E-05	7.55E-04	6.01E-03	8.0
	2	≥ 1.5	1.18E-04	5.38E-06	4.85E-05	4.37E-04	9.0
	3	≥ 3	4.73E-05	2.13E-06	1.93E-05	1.75E-04	9.1
	4	≥ 6.75	1.76E-05	7.71E-07	7.09E-06	6.52E-05	9.2
	5	≥ 14	6.59E-06	2.97E-07	2.69E-06	2.43E-05	9.1
	6	≥ 31.5	3.23E-06	1.38E-07	1.28E-06	1.20E-05	9.3

Component	LOCA Category	Break Size (in.)	Mean	5%tile	Median	95%tile	Range Factor
RCS – Surge Line	Failure Rate		1.33E-05	5.55E-07	5.25E-06	4.96E-05	9.5
	1	≥ .5	7.65E-03	1.46E-03	5.52E-03	2.08E-02	3.8
	2	≥ 1.5	6.70E-04	9.19E-05	4.31E-04	2.02E-03	4.7
	3	≥ 3	2.62E-04	3.59E-05	1.68E-04	7.89E-04	4.7
	4	≥ 6.75	9.81E-05	1.21E-05	6.08E-05	3.04E-04	5.0
	5	≥ 14	3.62E-05	5.17E-06	2.36E-05	1.08E-04	4.6
HPI	Failure Rate		1.33E-03	4.27E-05	4.65E-04	5.07E-03	10.9
	1	≥ .5	1.18E-02	2.32E-03	8.59E-03	3.18E-02	3.7
	2	≥ 1.5	1.75E-03	2.69E-04	1.17E-03	5.11E-03	4.4
	3	≥ 3	6.97E-04	1.03E-04	4.61E-04	2.06E-03	4.5

Table 4-6 LOCA Frequency Distributions from Benchmarking of Lydell Base Case Results

Component	LOCA Cat.	Break Size (in.)	Lydell Base Case Distribution Parameters Events per Reactor-Calendar Year				
			Mean	5%tile	50%tile	95%tile	RF
Hot Leg	1	≥ 0.5	6.65E-07	3.55E-09	9.39E-08	2.14E-06	24.6
	2	≥ 1.5	4.87E-08	2.10E-10	6.15E-09	1.49E-07	26.6
	3	≥ 3	1.83E-08	8.33E-11	2.42E-09	5.95E-08	26.7
	4	≥ 6.75	6.99E-09	3.03E-11	8.93E-10	2.21E-08	27.0
	5	≥ 14	2.55E-09	1.16E-11	3.29E-10	8.29E-09	26.7
	6	≥ 31.5	1.26E-09	5.44E-12	1.58E-10	4.04E-09	27.3
Cold Leg	1	≥ 0.5	3.33E-07	1.78E-09	4.70E-08	1.07E-06	24.6
	2	≥ 1.5	2.44E-08	1.05E-10	3.08E-09	7.45E-08	26.6
	3	≥ 3	9.15E-09	4.17E-11	1.21E-09	2.98E-08	26.7
	4	≥ 6.75	3.50E-09	1.52E-11	4.47E-10	1.11E-08	27.0
	5	≥ 14	1.28E-09	5.80E-12	1.65E-10	4.15E-09	26.7
	6	≥ 31.5	6.30E-10	2.72E-12	7.90E-11	2.02E-09	27.3
Surge Line	1	≥ 0.5	1.14E-07	2.13E-09	2.36E-08	3.94E-07	13.6
	2	≥ 1.5	9.60E-09	1.48E-10	1.88E-09	3.46E-08	15.3
	3	≥ 3	3.84E-09	5.78E-11	8.50E-10	1.35E-08	15.3
	4	≥ 6.75	1.44E-09	2.01E-11	2.77E-10	5.06E-09	15.9
	5	≥ 14	5.31E-10	8.23E-12	1.01E-10	1.87E-09	15.1
HPI Line	1	≥ 0.5	1.60E-05	2.62E-07	3.93E-06	6.09E-05	15.2
	2	≥ 1.5	2.33E-06	3.30E-08	5.40E-07	9.02E-06	16.5
	3	≥ 3	9.22E-07	1.28E-08	2.14E-07	3.59E-06	16.7

4.9 Select Target LOCA Frequencies from NUREG-1829 Data (Step 2.7)

In selecting the target LOCA frequencies, four options were considered.

- Option 1: use only the Lydell Base Case results
- Option 2: use only the Experts' Mixture Distribution results
- Option 3: use only the Experts' Geometric Mean results
- Option 4: use a hybrid of the Experts' Geometric Mean and Lydell Base Case results

Option 1 would be consistent with the STP approach to LOCA frequency assessment but would not be making full use of the expert elicitation results of NUREG-1829. Option 2 would be making use of the expert elicitation but would produce unreasonably large spreads between the upper and lower percentiles, which would overemphasize the most extreme expert inputs. Option 3 would be superior to Options 1 and 2 in that it would better represent the diverse inputs of the expert panel and would include the input of Lydell. The option selected, Option 4, is a hybrid of Options 1 and 3 and is comprised of a mixture distribution of the LOCA frequencies produced by those options.

Option 4 places equal weight on the Lydell Base Case results and the Expert Geometric Mean results. This option's mixture distribution was developed by Monte Carlo simulation, which involved a binary variable to select either Lydell Base Case results or Expert Geometric Mean results, after which a random sample was obtained from that selected distribution. The use of the mixture distribution method to provide a composite target LOCA distribution was recommended by Dr. Ali Mosleh, who performed an independent review of an earlier draft where a different method was used to develop the hybrid of the two LOCA frequency models. In the earlier approach, a hybrid distribution was constructed using the worst case 95%tiles and 5%tiles of the distributions from Options 1 and 3, and the 95%tile and 5%tile were then selected from that hybrid distribution.

Option 4 is preferred over Option 3 as it exhibits a larger degree of epistemic uncertainty while providing mean values that are very close to those of Option 3. These target LOCA frequencies are used in the next step to derive CRPs for LOCAs in each of the LOCA break size categories given a pipe failure.

The parameters of the target LOCA frequency distributions for the Hot Leg, Cold Leg, Surge Line, and HPI Line selected using this method were shown in Table 2-11. Figures 4-7, 4-8 and 4-9 compare the resulting target LOCA frequencies and those for Option 3, for the RCS Hot Leg, Surge Line, and HPI Line, respectively. The net effect is to increase the uncertainty with slight reductions in the mean and 95%tile and larger reductions for the 5%tiles compared to Option 3 for the Hot Leg and Surge Line. In the case of the HPI line, the Lydell Base Case was for a small pipe size so only Categories 1, 2, and 3 were included. Hence the target LOCA frequencies for Categories 4 and 5 are the same as those for the GM method and the impact of incorporating the Lydell Base inputs to the mixture distribution is much smaller for this case when compared to the hot leg and surge line. The cold leg results are very similar to the hot leg results except that the frequencies are scaled down somewhat. This completes Step 2.7.

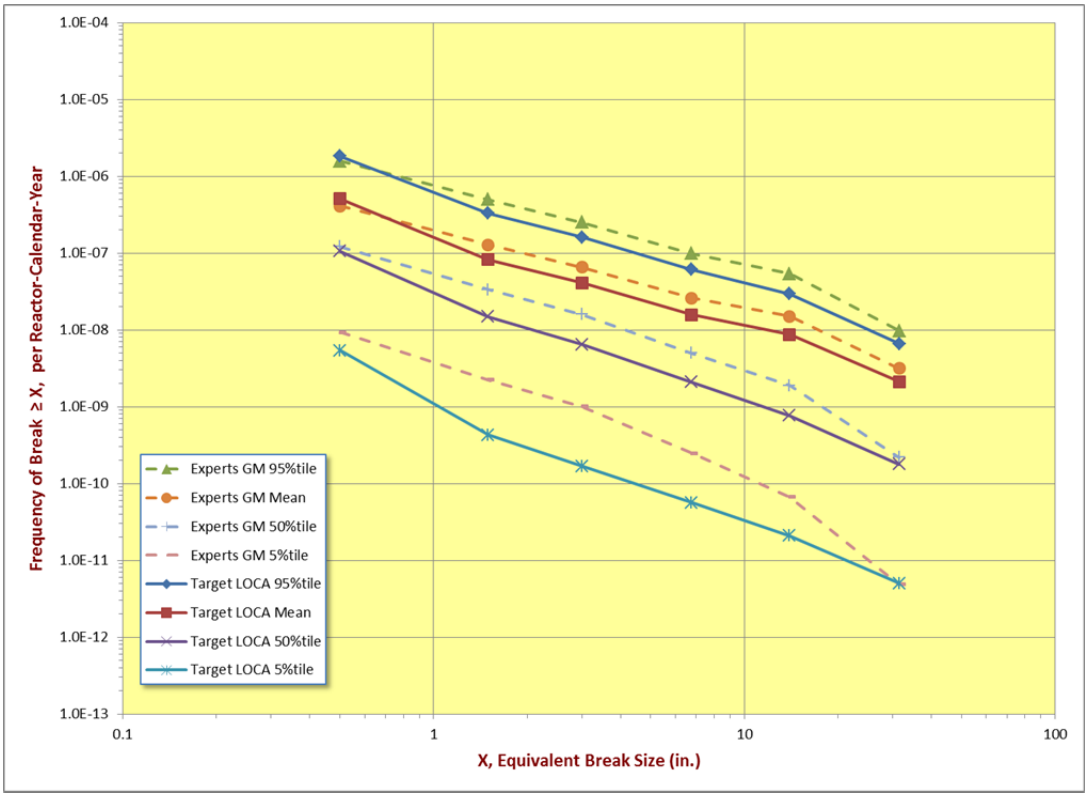

Figure 4-7 Comparison of Experts' Geometric Mean and STP Target LOCA Model-Hot Leg

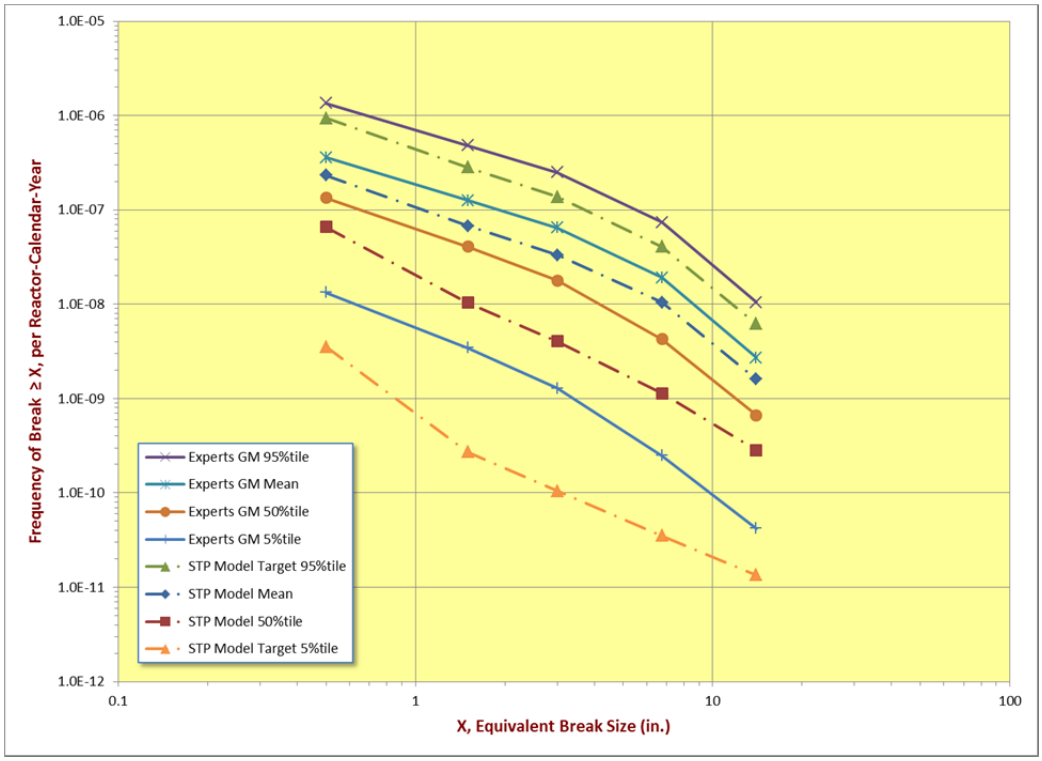

Figure 4-8 Comparison of Experts' Geometric Mean and STP Target LOCA Model – Surge Line

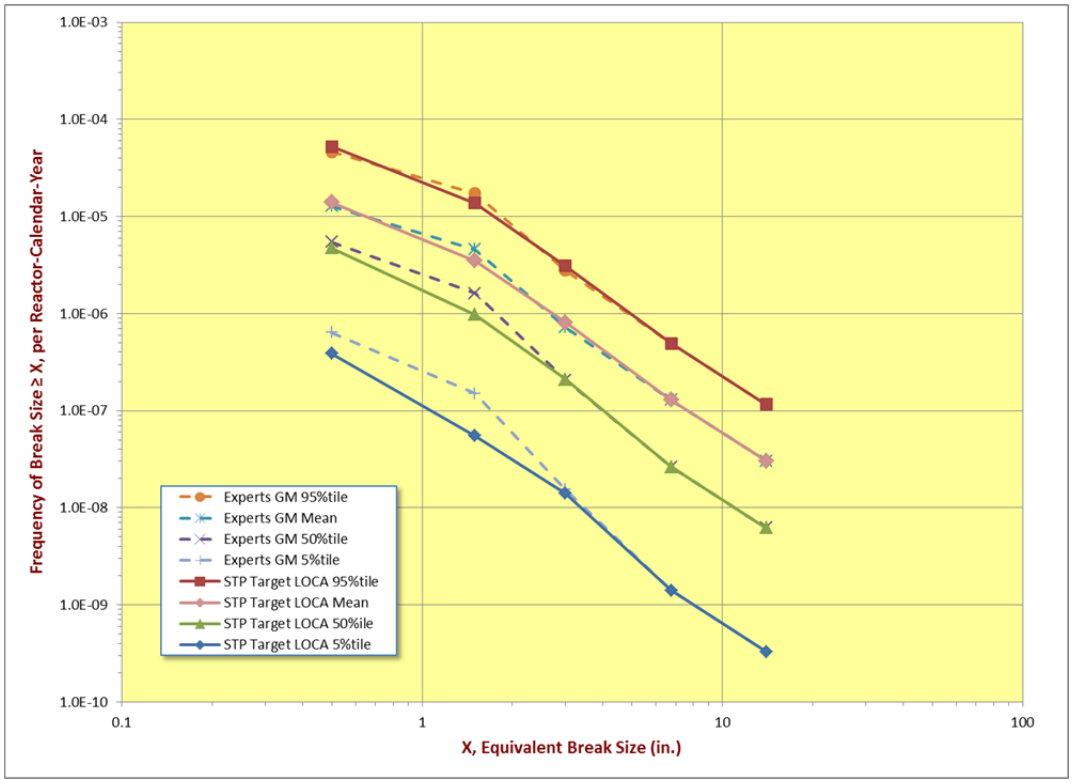

Figure 4-9 Comparison of Experts' Geometric Mean and STP Target LOCA Model- HPI Line

Table 4-7 Mixture Distribution of Geometric Mean and Lydell Base Case for STP Target LOCA Frequencies

Component	LOCA Cat.	Break Size (in.)	Target LOCA Frequency Distribution Parameters Events per Reactor-Calendar Year				
			Mean	5%tile	50%tile	95%tile	RF
Hot Leg	1	≥ 0.5	5.07E-07	5.39E-09	1.05E-07	1.83E-06	18.4
	2	≥ 1.5	8.22E-08	4.29E-10	1.49E-08	3.30E-07	27.7
	3	≥ 3	4.10E-08	1.68E-10	6.47E-09	1.60E-07	30.9
	4	≥ 6.75	1.57E-08	5.65E-11	2.09E-09	6.07E-08	32.8
	5	≥ 14	8.69E-09	2.09E-11	7.64E-10	2.93E-08	37.4
	6	≥ 31.5	2.11E-09	5.01E-12	1.79E-10	6.63E-09	36.4
	6D[1]	≥ 44.5	1.05E-09	2.72E-12	9.80E-11	3.52E-09	36.0
Cold Leg	1	≥ 0.5	2.28E-07	2.36E-09	4.32E-08	8.08E-07	18.5
	2	≥ 1.5	3.71E-08	2.09E-10	6.63E-09	1.43E-07	26.1
	3	≥ 3	1.53E-08	8.09E-11	2.62E-09	5.92E-08	27.1
	4	≥ 6.75	5.38E-09	2.68E-11	8.13E-10	2.03E-08	27.5
	5	≥ 14	2.72E-09	8.97E-12	2.94E-10	9.45E-09	32.5
	6	≥ 31.5	8.03E-10	2.05E-12	7.27E-11	2.64E-09	35.8
	6D	≥ 44.5	4.63E-10	1.10E-12	4.10E-11	1.53E-09	37.4
Surge Line	1	≥ 0.5	2.34E-07	3.55E-09	6.60E-08	9.35E-07	16.2
	2	≥ 1.5	6.78E-08	2.72E-10	1.04E-08	2.83E-07	32.3
	3	≥ 3	3.33E-08	1.05E-10	4.04E-09	1.38E-07	36.2
	4	≥ 6.75	1.05E-08	3.52E-11	1.14E-09	4.06E-08	34.0
	5	≥ 14	1.61E-09	1.35E-11	2.84E-10	6.17E-09	21.4
	5D[2]	≥ 19.8	6.53E-10	8.56E-12	1.47E-10	2.52E-09	17.2
HPI Line	1	≥ 0.5	1.39E-05	3.88E-07	4.73E-06	5.26E-05	11.6
	2	≥ 1.5	3.51E-06	5.50E-08	9.78E-07	1.37E-05	15.8
	3	≥ 3	8.11E-07	1.41E-08	2.11E-07	3.11E-06	14.9
	4	≥ 6.75	1.29E-07	1.41E-09	2.64E-08	4.95E-07	18.8
	5	≥ 14	3.03E-08	3.30E-10	6.20E-09	1.16E-07	18.8

Notes:
[1] LOCA Category 6D is introduced in this study to denote a double ended break of a 31.5 in. pipe
[2] LOCA Category 5D is introduced in this study to denote a double ended break of a 14 in. pipe

4.10 Develop Conditional Rupture Probabilities from Target LOCA Frequencies (Step 2.8)

This step uses the target LOCA frequencies from Step 2.7 and information from the Lydell Base Case results on the underlying failure rates for each component, to derive a CRP model that when linked with the Lydell Base Case failure rate model, will reproduce the target LOCA frequencies that were developed in Step 2.7. The Lydell failure rate analysis that was performed in Appendix D of NUREG-1829 used the same methodology for failure rate development as used here, using an earlier set of PIPExp failure data. The results for his Base Case failure rates for the components associated with the target LOCA frequencies are shown in Table 4-8. This includes the three PWR components analyzed in NUREG-1829 as well as the RCS cold leg, whose results have been developed using a set of assumptions that are comparable to that used for the RCS hot leg. In order to derive the model for conditional probability of rupture, the Lydell failure rates were fit to lognormal distributions by matching the 5th and 95th percentiles and the range factor calculated from these percentiles.

Since the use of lognormal distributions enables the LOCA frequency to be expressed as the product of a lognormally distributed failure rate and a lognormally distributed CRP, the parameters of the CRP distributions may be calculated directly. Using the same methodology as used in Equations (4.2, (4.3), and (4.4), the following relations are established.

$$median_{CRP_k} = \frac{median_{TLF_k}}{median_{FR}} \tag{4.5}$$

$$RF_{CRP_k} = e^{1.645\sigma_{CRP_k}} \tag{4.6}$$

where

$$\sigma_{CRP_k} = \sqrt{\left(\frac{\ln(RF_{TLF_k})}{1.645}\right)^2 - \left(\frac{\ln(RF_{FR})}{1.645}\right)^2} \tag{4.7}$$

$median_{CRP_k}$ = Median of the lognormal distribution for the conditional probability of pipe rupture in LOCA Category *k* given pipe failure

$median_{TLF_k}$ = Median of the lognormal distribution for the target LOCA frequency for LOCA Category *k*

$median_{FR}$ = Median of the lognormal distribution for the pipe failure rate

RF_{CRP_k} = Range factor of the lognormal distribution for the conditional probability of pipe rupture in LOCA Category *k* given pipe failure, equal to SQRT(95%tile/5%tile) of the lognormal distribution

σ_{CRP_k} = Logarithmic standard deviation for the lognormal distribution for the conditional probability of pipe rupture in LOCA Category *k* given pipe failure

RF_{TLF_k} = Range factor of the lognormal distribution for the target LOCA frequency for LOCA Category *k*

RF_{FR} = Range factor of the lognormal distribution for the pipe failure rate

The medians and range factors of the CRP distributions were computed from the medians and range factors of the target LOCA frequency distributions using the above formulas. Then, using the properties of the lognormal distribution, the remaining parameters of the distributions may be directly computed.

Table 4-8 Parameters of Target LOCA Frequencies Selected for STP Model

Component	LOCA Category	Break Size (in.)	Cumulative LOCA Frequency[1], per Reactor-Calendar-Year				RF[2]
			Mean	5%tile	50%tile	95%tile	
Hot Leg	1	≥ 0.5	4.45E-07	3.55E-09	7.72E-08	1.68E-06	21.7
	2	≥ 1.5	1.95E-07	2.10E-10	1.09E-08	5.68E-07	52.0
	3	≥ 3	1.05E-07	8.33E-11	4.89E-09	2.87E-07	58.7
	4	≥ 6.75	3.75E-08	3.03E-11	1.77E-09	1.03E-07	58.3
	5	≥ 14	2.02E-08	1.16E-11	7.75E-10	5.17E-08	66.8
	6	≥ 31.5	2.41E-09	5.44E-12	2.08E-10	7.94E-09	38.2
Cold Leg	1	≥ 0.5	1.52E-07	1.78E-09	3.22E-08	5.85E-07	18.2
	2	≥ 1.5	7.47E-08	1.05E-10	4.89E-09	2.28E-07	46.6
	3	≥ 3	3.17E-08	4.17E-11	1.99E-09	9.55E-08	47.9
	4	≥ 6.75	1.00E-08	1.52E-11	6.85E-10	3.09E-08	45.2
	5	≥ 14	5.27E-09	5.80E-12	2.99E-10	1.54E-08	51.5
	6	≥ 31.5	7.60E-10	2.72E-12	8.51E-11	2.66E-09	31.3
Surge Line	1	≥ 0.5	3.85E-07	2.13E-09	5.48E-08	1.41E-06	25.7
	2	≥ 1.5	1.94E-07	1.48E-10	8.84E-09	5.27E-07	59.7
	3	≥ 3	1.10E-07	5.78E-11	4.00E-09	2.77E-07	69.2
	4	≥ 6.75	2.86E-08	2.01E-11	1.24E-09	7.64E-08	61.7
	5	≥ 14	3.01E-09	8.23E-12	2.89E-10	1.02E-08	35.2
HPI Line	1	≥ 0.5	1.57E-05	2.62E-07	3.99E-06	6.09E-05	15.2
	2	≥ 1.5	5.31E-06	3.30E-08	8.05E-07	1.96E-05	24.4
	3	≥ 3	9.30E-07	1.28E-08	2.14E-07	3.59E-06	16.7
	4	≥ 6.75	1.36E-07	1.34E-09	2.64E-08	5.17E-07	19.6
	5	≥ 14	3.19E-08	3.16E-10	6.20E-09	1.22E-07	19.6

Notes:
[1] Frequency of LOCA with break size greater than or equal to the indicated value.
[2] RF = SQRT(95%tile/5%tile).

Comparisons of the STP Model CRP distributions with those used in the Lydell Base Case are shown in Figures 4-11, 4-12, and 4-13. The net result of the procedure is to produce somewhat more pessimistic CRP values with larger epistemic uncertainties than those used in the Lydell Base Case Analysis. This completes Step 2.8 of the LOCA frequency procedure.

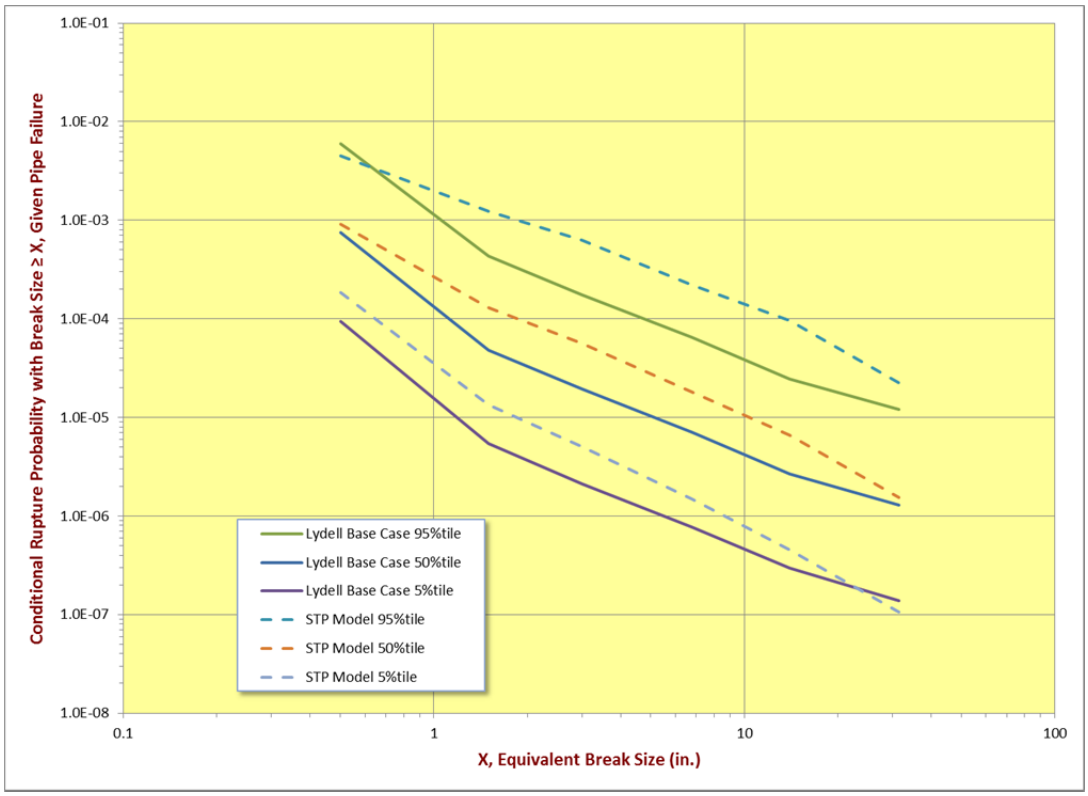

Figure 4-10 Comparison of Lydell and STP Models for CRP – RCS Hot Leg

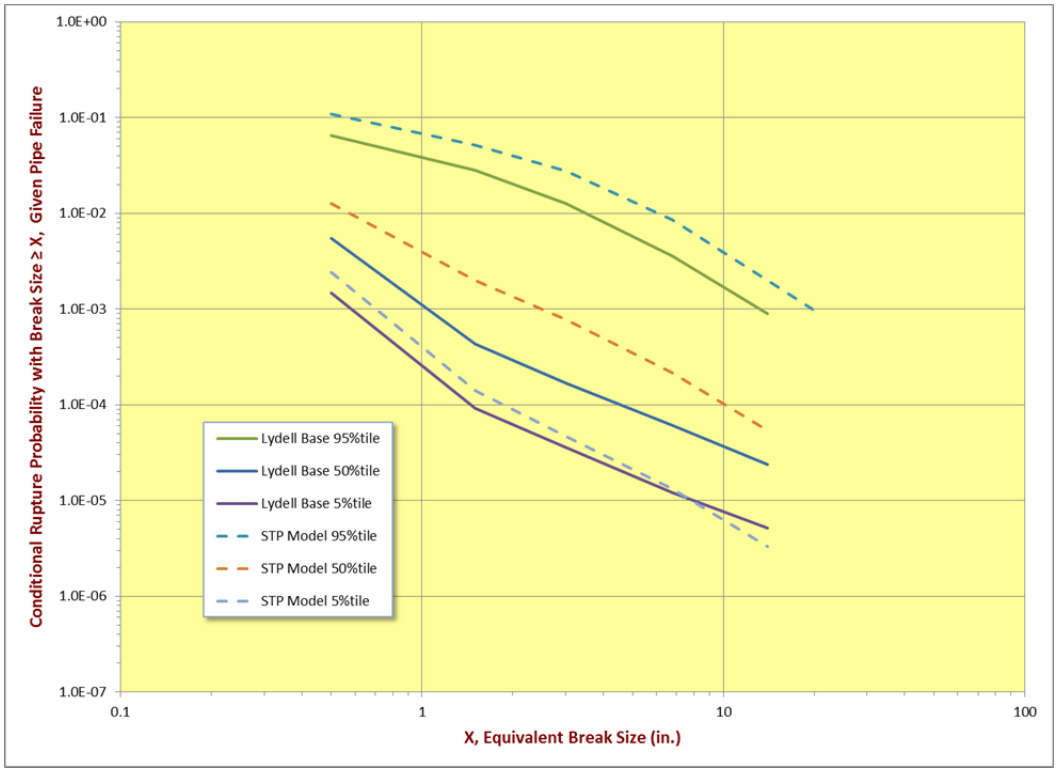

Figure 4-11 Comparison of Lydell and STP Models for CRP – RCS Surge Line

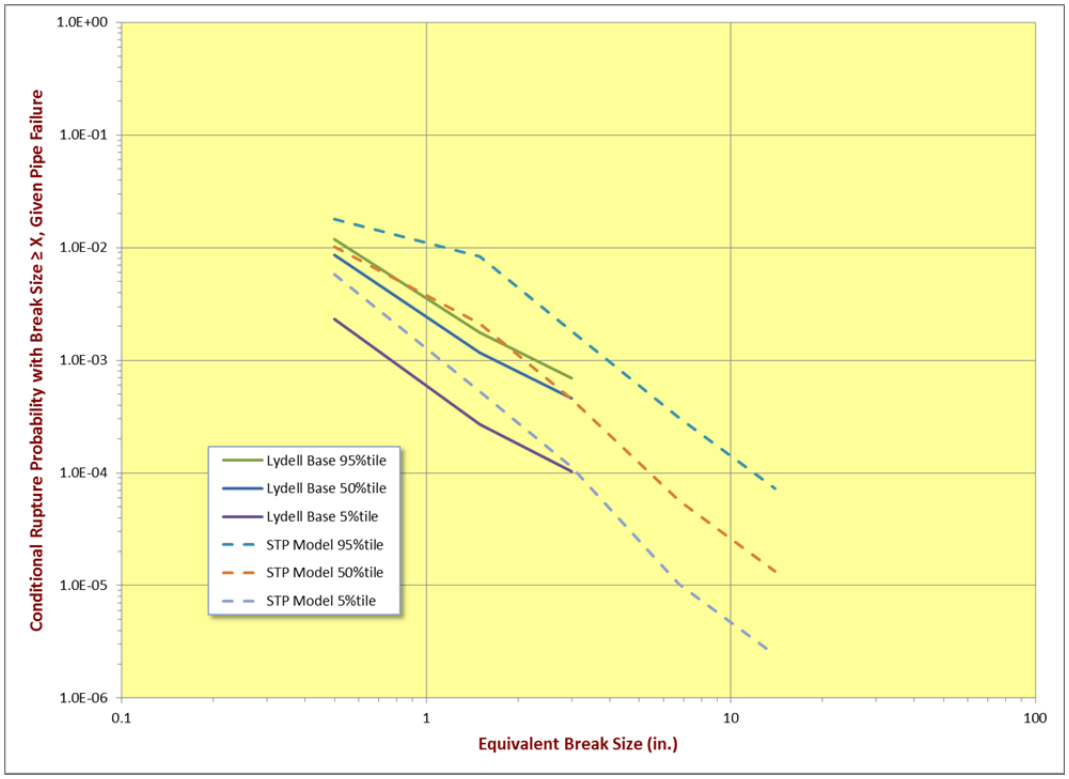

Figure 4-12 Comparison of Lydell and STP Models for CRP – HPI Line

Table 4-9 STP CRP Distribution Priors Derived from Target LOCA Frequencies

Component	LOCA Category	Break Size (in.)	Conditional Rupture Probability Distribution Parameters				
			Median	Mean	5th Percentile	95th Percentile	Range Factor[1]
Hot Leg	1	≥ 0.5	1.46E-03	1.84E-04	9.10E-04	4.50E-03	4.9
	2	≥ 1.5	3.31E-04	1.35E-05	1.29E-04	1.23E-03	9.6
	3	≥ 3	1.65E-04	5.01E-06	5.61E-05	6.28E-04	11.2
	4	≥ 6.75	5.74E-05	1.49E-06	1.81E-05	2.20E-04	12.2
	5	≥ 14	2.49E-05	4.54E-07	6.62E-06	9.65E-05	14.6
	6	≥ 31.5	5.84E-06	1.06E-07	1.55E-06	2.26E-05	14.6[4]
	6D[2]	44.5	3.20E-06	5.82E-08	8.49E-07	1.24E-05	14.6[4]
Cold Leg	1	≥ 0.5	1.20E-03	1.50E-04	7.48E-04	3.72E-03	5.0
	2	≥ 1.5	2.74E-04	1.31E-05	1.15E-04	1.00E-03	8.7
	3	≥ 3	1.13E-04	4.92E-06	4.54E-05	4.18E-04	9.2
	4	≥ 6.75	3.58E-05	1.49E-06	1.41E-05	1.33E-04	9.5
	5	≥ 14	1.59E-05	4.25E-07	5.09E-06	6.10E-05	12.0
	6	≥ 31.5	4.48E-06	9.17E-08	1.26E-06	1.73E-05	13.7
	6D[2]	44.5	2.67E-06	4.88E-08	7.10E-07	1.03E-05	14.6

Component	LOCA Category	Break Size (in.)	Conditional Rupture Probability Distribution Parameters				
			Median	Mean	5th Percentile	95th Percentile	Range Factor[1]
Surge Line	1	≥ 0.5	2.08E-02	2.42E-03	1.26E-02	6.53E-02	5.2
	2	≥ 1.5	7.24E-03	1.40E-04	1.98E-03	2.80E-02	14.1
	3	≥ 3	3.28E-03	4.68E-05	7.70E-04	1.27E-02	16.4
	4	≥ 6.75	9.24E-04	1.32E-05	2.17E-04	3.57E-03	16.4[4]
	5	≥ 14	2.30E-04	3.29E-06	5.41E-05	8.90E-04	16.4[4]
	5D[3]	19.8	1.19E-04	1.70E-06	2.80E-05	4.60E-04	16.4[4]
HPI Line	1	≥ 0.5	1.08E-02	5.77E-03	1.02E-02	1.80E-02	1.8
	2	≥ 1.5	3.00E-03	5.27E-04	2.10E-03	8.39E-03	4.0[4]
	3	≥ 3	6.45E-04	1.13E-04	4.53E-04	1.81E-03	4.0
	4	≥ 6.75	9.67E-05	1.03E-05	5.67E-05	3.11E-04	5.5
	5	≥ 14	2.27E-05	2.43E-06	1.33E-05	7.30E-05	5.5[4]

Notes:
[1] Range Factor = SQRT(95%tile/5%tile).
[2] 6D corresponds to a double-ended break of a 31.5” pipe.
[3] 5D corresponds to a double-ended break of a 14” pipe.
[4] Range factors adjusted upwards to ensure no RF decrease with decreasing LOCA frequency.

4.11 Bayes’ Update of the Conditional Probability Distributions (Step 2.9)

The conditional probability models developed in the previous section are used as the basis for a prior distribution, which we then update with the evidence from the service data on the number of experienced pipe failures with no LOCAs for each system. During the Bayes’ updating, the lognormal distributions developed in Step 2.8 as the prior distributions, were truncated to avoid CRP values greater than 1.0. However, this truncation only impacts the extreme right-hand tails of the distribution and therefore does not significantly affect the major quoted parameters (mean, median, 5%tile, and 95%tile). The Bayes’ updates were performed using R-DAT Plus™ Version 1.5.8 (Build 1691) software. The truncated lognormal distributions described in Table 4-9 were used as prior distributions and then updated with 0 LOCAs in each LOCA category out of the number of observed failures for each system. The results are summarized in Table 4-10. The final Bayes’ updated distributions for the CRP distributions in Table 4-10 show a small decrease relative to the values in Table 4-9. This completes Step 2.9 and all the steps associated with developing the CRP model for the STP LOCA frequencies.

Table 4-10 STP CRP Distributions after Bayes' Updating

Component	Bayes' Update Evidence	LOCA Category	Break Size (in.)	Conditional Rupture Probability Distribution Parameters				
				Mean	5%tile	Median	95%tile	RF[1]
Hot Leg	0 Ruptures/ 6 Failures; Hot Leg CRP Model	1	≥ 0.5	1.43E-03	1.85E-04	9.04E-04	4.39E-03	4.9
		2	≥ 1.5	3.28E-04	1.34E-05	1.29E-04	1.23E-03	9.6
		3	≥ 3	1.64E-04	5.01E-06	5.60E-05	6.25E-04	11.2
		4	≥ 6.75	5.74E-05	1.48E-06	1.81E-05	2.20E-04	12.2
		5	≥ 14	2.49E-05	4.53E-07	6.62E-06	9.66E-05	14.6
		6	≥ 31.5	5.85E-06	1.06E-07	1.55E-06	2.26E-05	14.6
		6D[2]	44.5	3.20E-06	5.82E-08	8.49E-07	1.24E-05	14.6
Hot Leg at SG Inlet	0 Ruptures/ 19 Failures; Hot Leg CRP Model	1	≥ 0.5	1.39E-03	1.84E-04	8.91E-04	4.25E-03	4.8
		2	≥ 1.5	3.22E-04	1.34E-05	1.28E-04	1.20E-03	9.5
		3	≥ 3	1.61E-04	5.00E-06	5.58E-05	6.18E-04	11.1
		4	≥ 6.75	5.70E-05	1.48E-06	1.81E-05	2.19E-04	12.2
		5	≥ 14	2.35E-05	4.29E-07	6.26E-06	9.11E-05	14.6
		6	≥ 31.5	5.84E-06	1.06E-07	1.55E-06	2.26E-05	14.6
		6D[2]	44.5	3.20E-06	5.82E-08	8.49E-07	1.24E-05	14.6
Cold Leg	0 Ruptures/ 3 Failures; Cold Leg CRP Model	1	≥ 0.5	1.20E-03	1.49E-04	7.46E-04	3.71E-03	5.0
		2	≥ 1.5	2.72E-04	1.32E-05	1.15E-04	9.97E-04	8.7
		3	≥ 3	1.13E-04	4.93E-06	4.54E-05	4.17E-04	9.2
		4	≥ 6.75	3.60E-05	1.48E-06	1.41E-05	1.34E-04	9.5
		5	≥ 14	1.59E-05	4.24E-07	5.09E-06	6.11E-05	12.0
		6	≥ 31.5	4.47E-06	9.20E-08	1.26E-06	1.73E-05	13.7
		6D[2]	44.5	2.68E-06	4.86E-08	7.10E-07	1.04E-05	14.6
Surge Line	0 Ruptures/ 3 Failures; Surge Line CRP Model	1	≥ 0.5	1.89E-02	2.36E-03	1.20E-02	5.81E-02	5.0
		2	≥ 1.5	6.09E-03	1.38E-04	1.91E-03	2.46E-02	13.3
		3	≥ 3	2.92E-03	4.66E-05	7.56E-04	1.18E-02	15.9
		4	≥ 6.75	8.86E-04	1.32E-05	2.16E-04	3.49E-03	16.2
		5	≥ 14	2.27E-04	3.30E-06	5.40E-05	8.83E-04	16.4
		5D[3]	19.8	1.18E-04	1.71E-06	2.80E-05	4.58E-04	16.4
CVCS Line	0 Ruptures/ 14 Failures; HPI CRP Model	1	≥ 0.5	1.07E-02	5.59E-03	1.00E-02	1.79E-02	1.8
		2	≥ 1.5	2.88E-03	5.17E-04	2.05E-03	7.97E-03	3.9
		3	≥ 3	6.40E-04	1.13E-04	4.50E-04	1.79E-03	4.0
		4	≥ 6.75	9.68E-05	1.03E-05	5.66E-05	3.11E-04	5.5
		5	≥ 14	2.27E-05	2.42E-06	1.33E-05	7.31E-05	5.5

Component	Bayes' Update Evidence	LOCA Category	Break Size (in.)	Conditional Rupture Probability Distribution Parameters				
				Mean	5%tile	Median	95%tile	RF[1]
Safety Injection Recirculation (SIR) Lines	0 Ruptures/ 14 Failures; HPI CRP Model	1	≥ 0.5	1.07E-02	5.59E-03	1.00E-02	1.79E-02	1.8
		2	≥ 1.5	2.88E-03	5.17E-04	2.05E-03	7.97E-03	3.9
		3	≥ 3	6.40E-04	1.13E-04	4.50E-04	1.79E-03	4.0
		4	≥ 6.75	9.68E-05	1.03E-05	5.66E-05	3.11E-04	5.5
		5	≥ 14	2.27E-05	2.42E-06	1.33E-05	7.31E-05	5.5
Pressurizer Lines	0 Ruptures/ 12 Failures; HPI CRP Model	1	≥ 0.5	1.07E-02	5.60E-03	1.00E-02	1.80E-02	1.8
		2	≥ 1.5	2.89E-03	5.18E-04	2.05E-03	8.03E-03	3.9
		3	≥ 3	6.41E-04	1.13E-04	4.51E-04	1.79E-03	4.0
		4	≥ 6.75	9.68E-05	1.03E-05	5.66E-05	3.11E-04	5.5
		5	≥ 14	2.27E-05	2.42E-06	1.33E-05	7.31E-05	5.5
Small Bore	0 Ruptures/ 79 Failures; HPI CRP Model	1	≥ 0.5	8.21E-03	1.10E-02	2.26E-03	2.91E-02	3.6
		2	≥ 1.5	1.67E-03	3.60E-03	2.05E-04	1.30E-02	8
		3	≥ 3	4.57E-04	1.02E-03	5.53E-05	3.72E-03	8.2

Notes:

[1] Range Factor = SQRT(95%tile/5%tile).

[2] 6D corresponds to a double-ended break of a 31.5" pipe.

[3] 5D corresponds to a double-ended break of a 16" pipe.

5. LOCA Frequencies for STP GSI-191 Application (Step 3)

This section documents the quantification of LOCA frequencies for input to the CASAGRANDE model for evaluation of debris-induced failures of the recirculation cooling function and to the RISKMAN model for evaluation of the changes to core damage frequency and large early-release frequency for the GSI-191 application. In accordance with the step-by-step approach to LOCA frequency determination presented in Section 2, this section covers the following key tasks:

3. STP-Specific LOCA Frequency Development
   - 3.1 Determine weld counts and pipe sizes for each component m_i
   - 3.2 Identify which locations are in and out of the NDE program
   - 3.3 Combine the results of Step 1 and Step 2 for component LOCA frequencies
   - 3.4 Apply Markov Model to specialize rupture frequencies (I_{ik}) for NDE or no NDE
   - 3.5 Provide location-by-location LOCA frequencies vs. break size to CASAGRANDE – ρ_{jx}
   - 3.6 Provide Small, Medium, and Large LOCA frequencies ($F(LOCA_x)$) to RISKMAN

5.1 Weld Counts and Pipe Sizes for Each Component (Steps 3.1 and 3.2)

A detailed review of the piping system isometric diagrams was performed to establish the pipe sizes and weld counts for each of the component categories listed in Table 3-2. This review was done independently by the group at Alion that developed the CAD model of the STP LOCA sensitive piping systems and containment, and by another group at Scandpower that prepared a database of STP piping system components and supporting design information [15]. This database identifies which welds are being inspected in the NDE program both before and after the implementation of risk-informed in-service inspection at STP.

5.2 Component LOCA Frequency Distributions (Step 3.3)

The LOCA frequencies for each component category were developed by combining the results for the failure rate uncertainty distributions developed in Step 1 and documented in Section 3, with the results for the conditional rupture probability distributions developed in Step 2 and documented in Section 4. This was done using two methods: Method 1 is Monte Carlo simulation via Equation (2.2), and Method 2 is the use of formulas for computing the parameters of the arithmetic product of two lognormal distributions. The results of Method 2 are regarded as the official results, as these are not influenced by any Monte Carlo sampling uncertainty and are exact under the assumption that both the failure rate and CRP distributions are lognormal. In general, the results of Method 1 and 2 were in excellent agreement, which facilitated checking the results and debugging the spreadsheets (small differences in the second significant figure). The uncertainties in the frequency of LOCA vs. break size reflect the uncertainties in the failure rate estimation as well as in the CRP model estimates.

The component LOCA frequency vs. break size distributions for each of the 41 component categories are found in Tables 5-1 through 5-4. These tables have been customized to fit the various pipe sizes that are reflected in the component category definitions. The last entry in the table is the estimated frequency of a double-ended break of the pipe. The LOCA frequencies for the other entries are cumulative frequencies, i.e., frequencies of a break equal to or greater than the indicated break size.

In converting from LOCA category to break size in the CRP model, the frequencies for break sizes other than those indicated in Table 4-1 were developed using linear interpolation and extrapolation on a log frequency vs. log break-size curve. This approach is justified by the trends of the frequencies vs. break-size curves on a log-log plot being well behaved and showing limited curvature. The shape of these curves is driven by the assumptions underlying the CRP model.

The Monte Carlo calculations were carried out using Crystal Ball™ Version 11.1.2.1.000 (32 bit) and Microsoft Excel Office Professional 2010 Version 14.0.6106.5005. Straight Monte Carlo rather than Latin Hypercube was used, with 100,000 trials. The CRP distributions derived from each of the CRP component categories (hot leg, cold leg, surge line, HPI line) were assumed to correlate fully, i.e., to have a correlation coefficient of +1.0. The Monte Carlo analysis for the failure rate development and LOCA frequency analysis were fully integrated rather than done in stages.

Plots of the LOCA frequencies vs. break size for hot leg components are shown in Figures 5-1, 5-2, and 5-3. The first two figures show the epistemic uncertainties for component categories 1A (B-F welds in hot leg subject to stress corrosion cracking and design & construction defects) and 1C (B-J welds in hot leg susceptible to thermal fatigue and design & construction defects). As seen in these figures, the ratios between the 95th and 5th percentiles are two to three orders of magnitude, indicating great uncertainty. In Figure 5-3, the mean LOCA frequencies for the three types of hot leg welds (B-F, and B-J with and without thermal fatigue) are compared. There is significant variability in LOCA frequencies across these categories. The results for these cases are parallel because they use the same CRP model. Hence the variability is sourced to the variability in the failure rates, whose details were presented in Section 4.

The four B-F welds in the pressurizer at STP (excluding the B-F weld in the surge line at the pressurizer) have been repaired using weld overlays to address observed cracking. Prior to application of these weld overlays, these welds were in Categories 5F and 5G in Table 3-2. They are now assigned to Category 5H. The LOCA frequency model used for these welds is to apply the pressurizer failure rate for design & construction defects to the weld overlay itself, under the assumption that the underlying cracks and associated damage mechanisms have been adequately mitigated by the overlay.

5.3 Application of Markov Model to Address Impact of NDE Program (Step 3.4)

All the results presented to this point have included the effects of piping inspections and integrity management programs only implicitly. This is because the failure rate data and inputs from NUREG-1829 that form the basis for our conditional probability of the LOCA model have been based on an analysis that has implicitly reflected the effects of the industry reliability integrity management (RIM) programs. Such programs include testing and monitoring for leaks as well as non-destructive examinations that are performed in the various ISI programs on a periodic basis. Hence, the LOCA frequencies developed for STP component categories in Step 3.3 reflect an averaging of the effects of these RIM programs. For Class 1 welds, there is a variability in RIM because only a relatively small fraction of the weld population is subjected to NDE (approximately 10%), whereas all the Class 1 welds benefit from the same 100% coverage of leak testing.

Table 5-1 LOCA Frequencies vs. Break Size for Hot Leg, SG Inlet, Cold Leg, and Surge Line Component Categories 1A through 4B

Calc. Case	1A		1B		1C		2		3A		3B		3C		3D		4A		4B		4C		4D	
System	Hot Leg		Hot Leg		Hot Leg		SG Inlet		Cold Leg		Cold Leg		Cold Leg		Cold Leg		Surge Line		Surge Line		Surge Line		Surge Line	
Size Case (in.)	29		29		29		29		27.5		31		27.5		31		16		16		16		2.5	
DEGB (in.)	41.01		41.01		41.01		41.01		38.89		43.84		38.89		43.84		22.63		22.63		22.63		3.54	
Weld Type	B-F		B-J		B-J		B-F		B-F		B-F		B-J		B-J		B-F		B-J		BC		B-J	
DM	SC, D&C		D&C		TF, D&C		SC, D&C		SC, D&C		SC, D&C		D&C		D&C		SC, TF, D&C		TF, D&C		TF, D&C		TF, D&C	
No. Welds	4		11		1		4		4		4		12		24		1		7		2		6	
	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	
	0.50	4.02E-07	0.50	1.95E-09	0.50	1.25E-08	0.50	1.98E-06	0.50	1.51E-07	0.50	1.51E-07	0.50	2.79E-09	0.50	2.79E-09	0.50	9.75E-06	0.50	7.44E-08	0.50	1.21E-07	0.50	7.44E-08
	1.50	9.25E-08	1.50	4.49E-10	1.50	2.87E-09	1.50	4.59E-07	1.50	3.43E-08	1.50	3.43E-08	1.50	6.33E-10	1.50	6.33E-10	1.50	3.30E-06	1.50	2.52E-08	1.50	4.11E-08	1.50	2.52E-08
	2.00	6.92E-08	2.00	3.36E-10	2.00	2.15E-09	2.00	3.45E-07	2.00	2.38E-08	2.00	2.38E-08	2.00	4.39E-10	2.00	4.39E-10	2.00	2.43E-06	2.00	1.85E-08	2.00	3.02E-08	2.00	1.85E-08
	3.00	4.61E-08	3.00	2.24E-10	3.00	1.43E-09	3.00	2.31E-07	3.00	1.42E-08	3.00	1.42E-08	3.00	2.62E-10	3.00	2.62E-10	3.00	1.58E-06	3.00	1.20E-08	3.00	1.97E-08	3.00	1.20E-08
	4.00	3.19E-08	4.00	1.55E-10	4.00	9.90E-10	4.00	1.60E-07	4.00	9.49E-09	4.00	9.49E-09	4.00	1.75E-10	4.00	1.75E-10	4.00	1.03E-06	4.00	7.82E-09	4.00	1.28E-08	3.54	9.42E-09
	6.00	1.89E-08	6.00	9.19E-11	6.00	5.89E-10	6.00	9.52E-08	6.00	5.39E-09	6.00	5.39E-09	6.00	9.95E-11	6.00	9.95E-11	6.00	5.58E-07	6.00	4.26E-09	6.00	6.94E-09		
	6.75	1.61E-08	6.75	7.83E-11	6.75	5.01E-10	6.75	8.12E-08	6.75	4.53E-09	6.75	4.53E-09	6.75	8.36E-11	6.75	8.36E-11	6.75	4.68E-07	6.75	3.57E-09	6.75	5.82E-09		
	14.00	7.01E-09	14.00	3.40E-11	14.00	2.18E-10	14.00	3.35E-08	14.00	2.01E-09	14.00	2.01E-09	14.00	3.70E-11	14.00	3.70E-11	14.00	1.18E-07	14.00	9.03E-10	14.00	1.47E-09		
	20.00	3.70E-09	20.00	1.80E-11	20.00	1.15E-10	20.00	1.81E-08	20.00	1.15E-09	20.00	1.15E-09	20.00	2.11E-11	20.00	2.11E-11	16.00	9.19E-08	16.00	7.02E-10	16.00	1.15E-09		
	29.00	1.90E-09	29.00	9.24E-12	29.00	5.92E-11	29.00	9.57E-09	27.50	6.96E-10	27.50	6.96E-10	27.50	1.28E-11	27.50	1.28E-11	20.00	6.14E-08	20.00	4.69E-10	20.00	7.65E-10		
	31.50	1.64E-09	31.50	7.97E-12	31.50	5.11E-11	31.50	8.30E-09	31.50	5.63E-10	31.50	5.63E-10	31.50	1.04E-11	31.50	1.04E-11	22.63	4.77E-08	22.63	3.64E-10	22.63	5.93E-10		
	41.01	1.04E-09	41.01	5.03E-12	41.01	3.22E-11	41.01	5.24E-09	38.89	4.12E-10	43.80	3.38E-10	38.89	7.60E-12	43.80	6.23E-12								

Table 5-2 LOCA Frequencies vs. Break Size for Pressurizer and Small Bore Component Categories 5A through 6B

Calc. Case	5A		5B		5C		5D		5E		5F		5G		5H		5I		5J		6A		6B	
System	Pressurizer		Pressurizer		Pressurizer		Pressurizer		Pressurizer		Pressurizer		Pressurizer		Pressurizer		Pressurizer		Pressurizer		Small Bore		Small Bore	
Size Case (in.)	6		3		4		3		6		6		6		6		4		2		2		1	
DEGB (in.)	8.49		4.24		5.66		4.24		8.49		8.49		8.49		8.49		5.66		2.83		2.83		1.41	
Weld Type	B-J		B-J		B-J		B-J		B-J		B-F		B-F		B-F		BC		B-J		B-J		B-J	
DM	TF, D&C		TF, D&C		D&C		D&C		D&C		SC, TF, D&C		SC, D&C		D&C (Weld Overlay)		D&C		TF, D&C		VF, SC, D&C		VF, SC, D&C	
No. Welds	29		14		53		4		29		0		0		4		2		2		16		193	
	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)			X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)
	0.50	4.59E-08	0.50	4.59E-08	0.50	1.72E-08	0.50	1.72E-08	0.50	1.72E-08	0.50	5.09E-06	0.50	5.01E-06	0.50	1.74E-08	0.50	1.72E-08	0.50	4.59E-08	0.5	1.22E-06	0.5	1.22E-06
	0.75	2.76E-08	0.75	2.76E-08	0.75	1.03E-08	0.75	1.03E-08	0.75	1.03E-08	0.75	3.06E-06	0.75	3.01E-06	0.75	1.05E-08	0.75	1.03E-08	0.75	2.76E-08	0.75	7.18E-07	0.75	7.18E-07
	1.00	1.96E-08	1.00	1.96E-08	1.00	7.33E-09	1.00	7.33E-09	1.00	7.33E-09	1.00	2.17E-06	1.00	2.13E-06	1.00	7.42E-09	1.00	7.33E-09	1.00	1.96E-08	1	5.00E-07	1	5.00E-07
	1.50	1.24E-08	1.50	1.24E-08	1.50	4.64E-09	1.50	4.64E-09	1.50	4.64E-09	1.50	1.38E-06	1.50	1.35E-06	1.50	4.70E-09	1.50	4.64E-09	1.50	1.24E-08	1.4	3.30E-07	1.4	3.30E-07
	2.00	6.64E-09	2.00	6.64E-09	2.00	2.49E-09	2.00	2.49E-09	2.00	2.49E-09	2.00	7.36E-07	2.00	7.24E-07	2.00	2.52E-09	2.00	2.49E-09	2.00	6.64E-09	1.5	3.08E-07		
	3.00	2.75E-09	3.00	2.75E-09	3.00	1.03E-09	3.00	1.03E-09	3.00	1.03E-09	3.00	3.05E-07	3.00	3.00E-07	3.00	1.04E-09	3.00	1.03E-09	2.83	3.13E-09	1.99	1.75E-07		
	4.24	1.30E-09	4.24	1.30E-09	4.24	4.87E-10	4.24	4.87E-10	4.24	4.87E-10	4.24	1.44E-07	4.24	1.42E-07	4.24	4.94E-10	4.24	4.87E-10			2.0	1.73E-07		
	5.66	6.26E-10			5.66	2.34E-10			5.66	2.34E-10	5.66	6.94E-08	5.66	6.83E-08	5.66	2.37E-10	5.66	2.34E-10			2.8	8.66E-08		
	6.00	5.47E-10							6.00	2.05E-10	6.00	6.06E-08	6.00	5.96E-08	6.00	2.07E-10								
	6.75	4.16E-10							6.75	1.56E-10	6.75	4.61E-08	6.75	4.54E-08	6.75	1.58E-10								
	8.49	2.64E-10							8.49	9.89E-11	8.49	2.93E-08	8.49	2.88E-08	8.49	1.00E-10								

Table 5-3 LOCA Frequencies vs. Break Size for Safety Injection and Recirculation System Categories 7A through 7L

Calc. Case	7A		7B		7C		7D		7E		7F		7G		7H		7I		7J		7K		7L	
System	SIR		SIR		SIR		SIR		SIR		SIR		SIR		SIR		SIR		SIR		SIR		SIR	
Size Case (in.)	12		8		8		12		12		10		8		6		4		3		2		1.5	
DEGB (in.)	16.97		11.31		11.31		16.97		16.97		14.14		11.31		8.49		5.66		4.24		2.83		2.12	
Weld Type	B-J		B-J		B-J		B-J		BC, B-J		B-J		BC, B-J		B-J		BC		BC		BC		B-J	
DM	TF, D&C		TF, D&C		SC, TF, D&C		SC, D&C		D&C		D&C		D&C		D&C		D&C		D&C		D&C		D&C	
No. Welds	21		9		3		3		57		30		42		23		5		9		10		0	
	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)		X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)
	0.50	2.78E-06	0.50	2.78E-06	0.50	3.10E-06	0.50	3.54E-07	0.50	1.14E-08	0.50	1.14E-08	0.50	1.14E-08	0.50	1.14E-08	0.50	1.14E-08	0.50	1.14E-08	0.50	1.14E-08	0.50	1.14E-08
	0.75	1.67E-06	0.75	1.67E-06	0.75	1.86E-06	0.75	2.12E-07	0.75	6.84E-09	0.75	6.84E-09	0.75	6.84E-09	0.75	6.84E-09	0.75	6.84E-09	0.75	6.84E-09	0.75	6.84E-09	0.75	6.84E-09
	1.00	1.18E-06	1.00	1.18E-06	1.00	1.32E-06	1.00	1.51E-07	1.00	4.85E-09	1.00	4.85E-09	1.00	4.85E-09	1.00	4.85E-09	1.00	4.85E-09	1.00	4.85E-09	1.00	4.85E-09	1.00	4.85E-09
	1.50	7.48E-07	1.50	7.48E-07	1.50	8.34E-07	1.50	9.54E-08	1.50	3.07E-09	1.50	3.07E-09	1.50	3.07E-09	1.50	3.07E-09	1.50	3.07E-09	1.50	3.07E-09	1.50	3.07E-09	1.50	3.07E-09
	2.00	4.01E-07	2.00	4.01E-07	2.00	4.48E-07	2.00	5.12E-08	2.00	1.65E-09	2.00	1.65E-09	2.00	1.65E-09	2.00	1.65E-09	2.00	1.65E-09	2.00	1.65E-09	2.00	1.65E-09	2.00	1.65E-09
	2.83	1.67E-07	2.83	1.67E-07	2.83	1.86E-07	2.83	2.13E-08	2.83	6.85E-10	2.83	6.85E-10	2.83	6.85E-10	2.83	6.85E-10	2.83	6.85E-10	2.83	6.85E-10	2.83	6.85E-10		
	4.00	8.50E-08	4.00	8.50E-08	4.00	9.48E-08	4.00	1.08E-08	4.00	3.49E-10	4.00	3.49E-10	4.00	3.49E-10	4.00	3.49E-10	4.00	3.49E-10	4.00	3.49E-10				
	4.24	7.41E-08	4.24	7.41E-08	4.24	8.26E-08	4.24	9.45E-09	4.24	3.04E-10	4.24	3.04E-10	4.24	3.04E-10	4.24	3.04E-10	4.24	3.04E-10	4.24	3.04E-10				
	5.66	3.79E-08	5.66	3.79E-08	5.66	4.23E-08	5.66	4.84E-09	5.66	1.56E-10	5.66	1.56E-10	5.66	1.56E-10	5.66	1.56E-10	5.66	1.56E-10						
	6.00	3.31E-08	6.00	3.31E-08	6.00	3.70E-08	6.00	4.23E-09	6.00	1.36E-10	6.00	1.36E-10	6.00	1.36E-10	6.00	1.36E-10								
	6.75	2.52E-08	6.75	2.52E-08	6.75	2.81E-08	6.75	3.22E-09	6.75	1.04E-10	6.75	1.04E-10	6.75	1.04E-10	6.75	1.04E-10								
	7.20	2.22E-08	7.20	2.22E-08	7.20	2.48E-08	7.20	2.83E-09	7.20	9.12E-11	7.20	9.12E-11	7.20	9.12E-11	7.20	9.12E-11								
	8.49	1.60E-08	8.49	1.60E-08	8.49	1.79E-08	8.49	2.04E-09	8.49	6.58E-11	8.49	6.58E-11	8.49	6.58E-11	8.49	6.58E-11								
	10.00	1.16E-08	10.00	1.16E-08	10.00	1.29E-08	10.00	1.47E-09	10.00	4.75E-11	10.00	4.75E-11	10.00	4.75E-11										
	11.31	9.11E-09	11.31	9.11E-09	11.31	1.02E-08	11.31	1.16E-09	11.31	3.74E-11	11.31	3.74E-11	11.31	3.74E-11										
	14.14	5.93E-09					14.14	7.56E-10	14.14	2.44E-11	14.14	2.44E-11												
	16.97	4.05E-09					16.97	5.16E-10	16.97	1.66E-11														

Table 5-4 LOCA Frequencies vs. Break Size for Accumulator Injection and CVCS Categories 7M through 8F

Calc. Case	7M		7N		7O		8A		8B		8C		8D		8E		8F	
System	ACC		ACC		ACC		CVCS		CVCS		CVCS		CVCS		CVCS		CVCS	
Size Case (in.)	12		12		12		2		4		2		4		4		4	
DEGB (in.)	16.97		16.97		16.97		2.83		5.66		2.83		5.66		5.66		5.66	
Weld Type	B-J		B-J		BC, B-J		B-J		B-J		B-J		B-J		BC		BC	
DM	SC, D&C		TF, D&C		D&C		TF, VF, D&C		TF, VF, D&C		VF, D&C		VF, D&C		TF, D&C		D&C	
No. Welds	0		35		15		10		19		47		6		4		1	
	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)	X, Break Size (in.)	F(LOCA ≥X)
	0.50	3.54E-07	0.50	5.18E-08	0.50	6.26E-09	0.50	4.28E-08	0.50	4.28E-08	0.50	1.87E-08	0.50	1.87E-08	0.50	7.98E-08	0.50	1.87E-08
	0.75	2.12E-07	0.75	3.11E-08	0.75	3.75E-09	0.75	2.57E-08	0.75	2.57E-08	0.75	1.12E-08	0.75	1.12E-08	0.75	4.79E-08	0.75	1.12E-08
	1.00	1.51E-07	1.00	2.21E-08	1.00	2.66E-09	1.00	1.82E-08	1.00	1.82E-08	1.00	7.97E-09	1.00	7.97E-09	1.00	3.40E-08	1.00	7.97E-09
	1.50	9.54E-08	1.50	1.40E-08	1.50	1.69E-09	1.50	1.15E-08	1.50	1.15E-08	1.50	5.04E-09	1.50	5.04E-09	1.50	2.15E-08	1.50	5.04E-09
	2.00	5.12E-08	2.00	7.49E-09	2.00	9.04E-10	2.00	6.03E-09	2.00	6.03E-09	2.00	2.64E-09	2.00	2.64E-09	2.00	1.12E-08	2.00	2.64E-09
	2.83	2.13E-08	2.83	3.12E-09	2.83	3.76E-10	3.00	2.42E-09	3.00	2.42E-09	3.00	1.06E-09	3.00	1.06E-09	3.00	4.51E-09	3.00	1.06E-09
	4.00	1.08E-08	4.00	1.67E-09	4.00	2.02E-10			4.00	1.26E-09			4.00	5.49E-10	4.00	2.34E-09	4.00	5.49E-10
	4.24	9.45E-09	5.66	7.09E-10	5.66	8.55E-11			5.66	5.77E-10			5.66	2.52E-10	5.66	1.08E-09	5.66	2.52E-10
	5.66	4.84E-09	6.00	6.19E-10	6.00	7.47E-11												
	6.00	4.23E-09	6.80	4.71E-10	6.80	5.69E-11												
	6.75	3.22E-09	7.20	4.14E-10	7.20	5.00E-11												
	7.20	2.83E-09	10.00	2.16E-10	10.00	2.61E-11												
	8.49	2.04E-09	14.14	1.11E-10	14.14	1.34E-11												
	10.00	1.47E-09	16.97	7.56E-11	16.97	9.12E-12												
	11.31	1.16E-09																
	14.14	7.56E-10																
	16.97	5.16E-10																

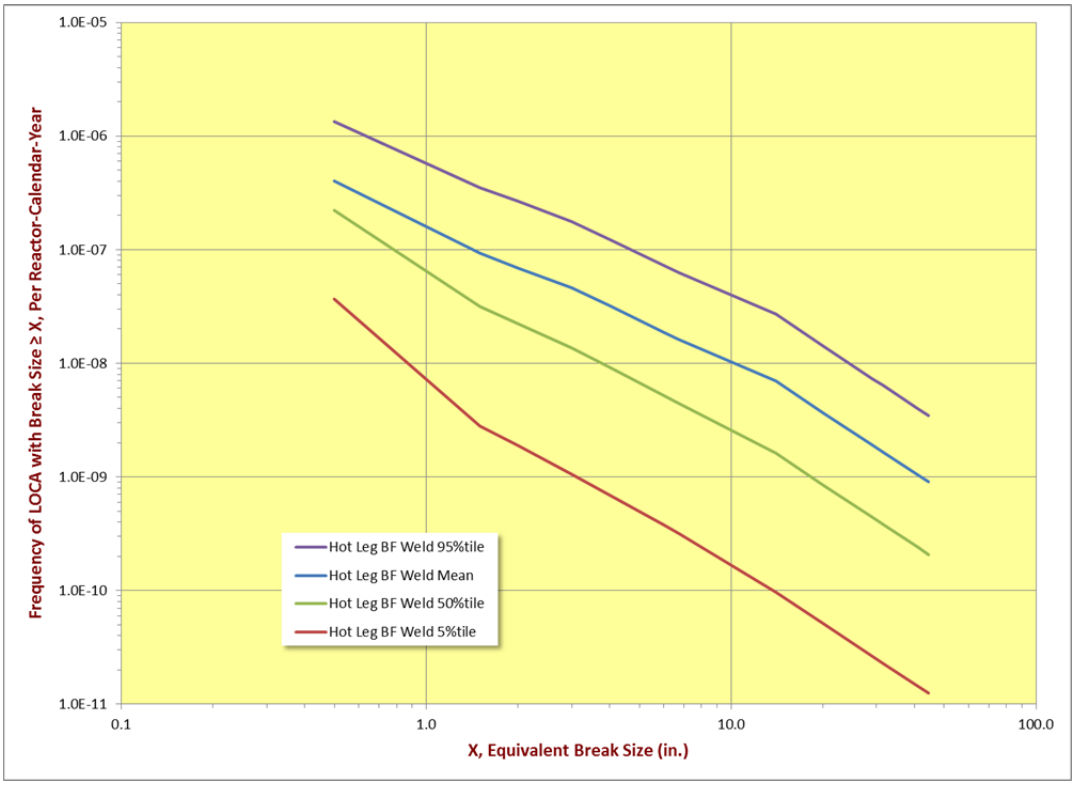

Figure 5-1 LOCA Frequencies vs. Break Size for B-F Welds in Hot Leg (Category 1A)

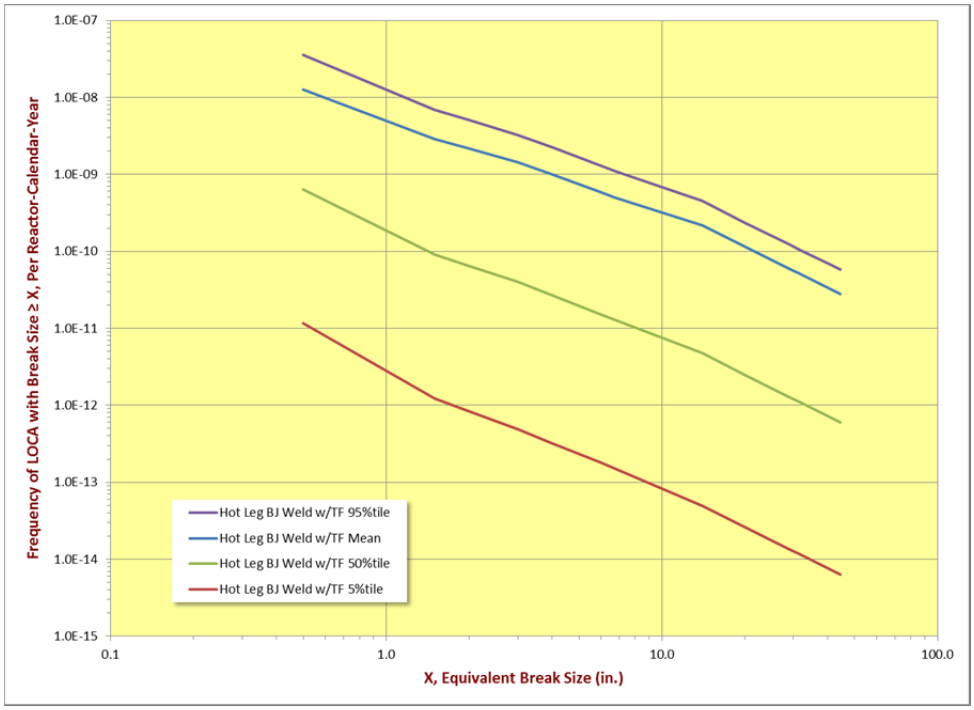

Figure 5-2 LOCA Frequencies vs. Break Size for B-J Welds in Hot Leg Subject to Thermal Fatigue (Category 1C)

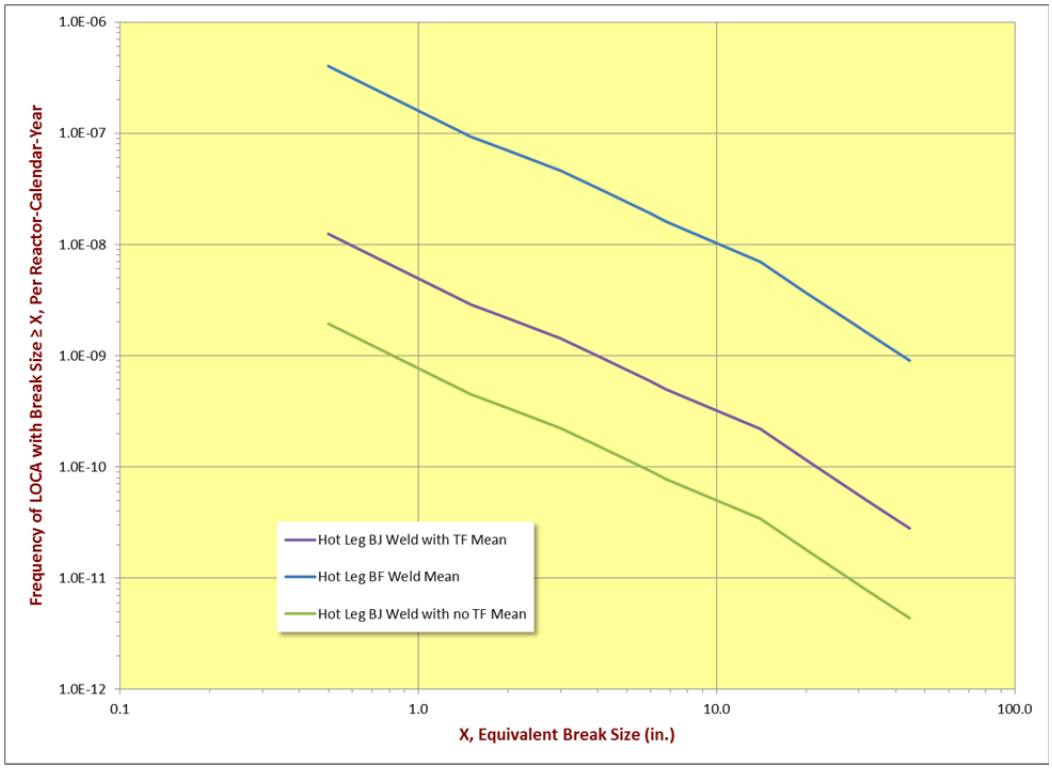

Figure 5-3 Comparison of Mean Frequencies for Hot Leg Welds

An example of the kind of change in LOCA frequencies that can result from location-by-location changes in the pipe inspection and leak monitoring program is shown in Figure 5-4 for an RCS weld subject to stress corrosion cracking [13]. As seen in this figure, the frequency of a pipe break may vary by more than an order of magnitude based on the reliability integrity management program, all other factors being equal.

The application of the Markov model to STP components is deferred until more information is available to identify which locations are risk-significant with respect to debris formation. Because the number of input parameters needed to quantify the Markov model is significant, it is impractical to apply that model to all 41 unique component categories at STP. The analysis presented in Figure 5-4 would be representative of B-F welds in the large bore pipes, such as Categories 1A, 2, 3A, and 3B. When the Markov model is applied to STP components, the LOCA frequencies for those welds not subjected to NDE will be increased by a small and not significant amount, and the LOCA frequencies for those subjected to NDE will be decreased by factors ranging from 3 to 10. This will also provide an opportunity to modify the selections of welds for the NDE program to offset significant risk impacts that are associated with debris-induced failure of recirculation cooling. Because Step 3.4 in the LOCA frequency procedure is deferred, the results to be used in the 2011 GSI-191 evaluation will not reflect weld to weld variations due to the welds included and excluded from the NDE program.

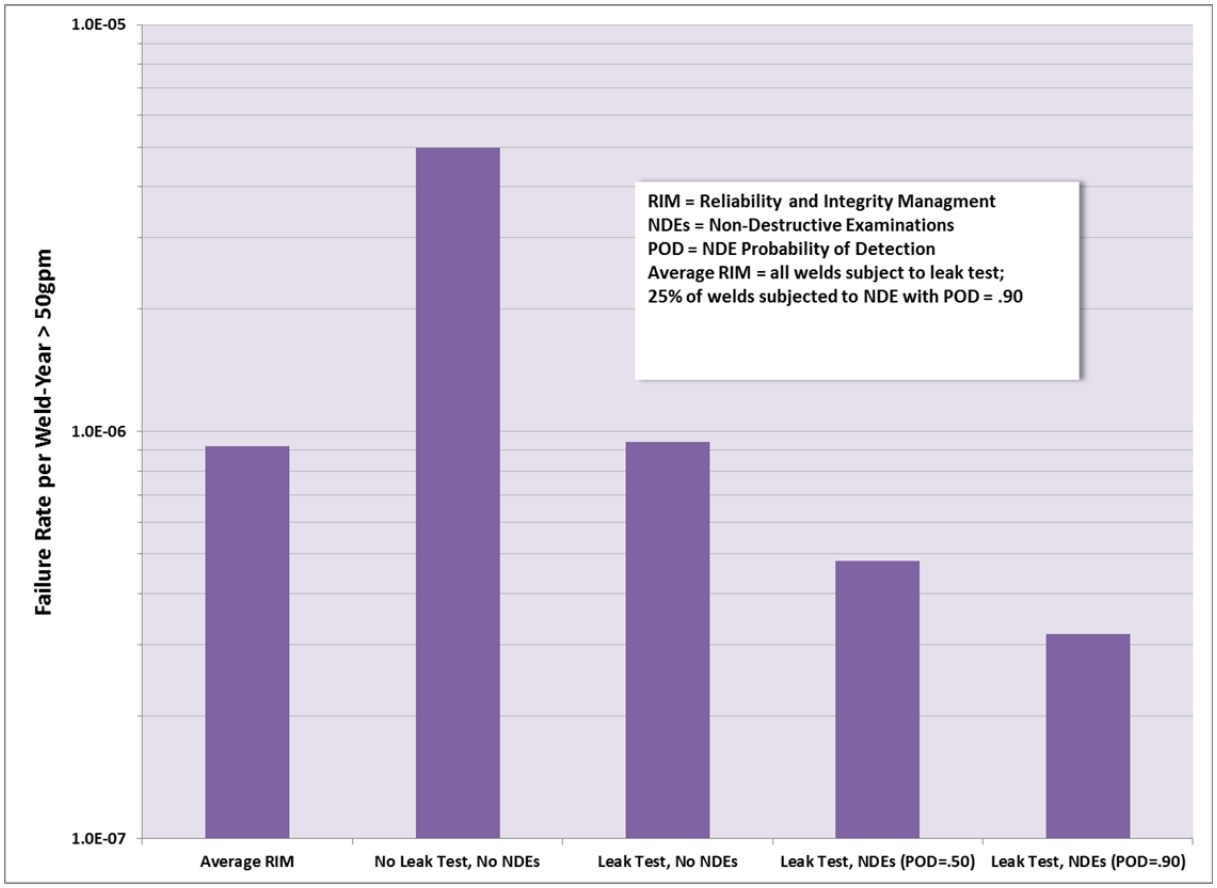

Figure 5-4 Comparison of Weld Failure Rates Determined by Markov Model for Different Reliability Integrity Management Approaches

5.4 Total LOCA Frequencies for RISKMAN (Step 3.6)

The total LOCA frequencies were calculated using Equation (2.1) by multiplying the number of components in each category by the LOCA frequencies per category from Step 3.3. This was done using two methods. Method 1 is a mean point estimate in which the means of the failure rate, means of the CRP model distributions, and weld counts were multiplied on an Excel spreadsheet. Method 2 was an integrated Monte Carlo simulation that included the steps in the failure rate development, application of the CRP lognormal distributions, and weld counts. As noted earlier, the CRP distributions within a CRP component category were treated as fully correlated in the Monte Carlo calculations. The results are summarized in Table 5-5.

In Figure 5-5, the STP mean pipe-induced LOCA frequencies are compared against the results from NUREG-1829 for pipe-induced LOCAs. As seen in this comparison, the results are in excellent agreement for Categories 1 and 4 and within a factor of 3 of each other over the whole range of LOCA categories. For Categories 2 and 3, the STP results track somewhat lower, whereas for Categories 5 and 6, the STP results track somewhat higher. To conduct a sensitivity study, a case is plotted with the contributions from the SG inlet removed to investigate the impact of this “outlier” component that was observed in the failure data. There was an unusually high incidence of failures at this weld location (19 failures vs. 6

failures for the entire remaining hot leg welds in the database), all occurring in Japanese PWRs following steam generator replacement. When these outlier contributions are removed, the Category 5 and 6 results from STP and NUREG-1829 are in excellent agreement.

Figure 5-5 is based on mean values, whereas Figure 5-6 compares the uncertainty distribution results, with the caveat that the STP results are for pipe-induced LOCAs and that the NUREG-1829 data in this figure include both pipe- and non-pipe-induced LOCAs. While there is information in NUREG-1829 that breaks down pipe and non-pipe contributions, which is used in Figure 5-5, there is no information on uncertainty distributions for the pipe-only contributions. However, it is reasonable that the uncertainties calculated for STP are somewhat smaller than those estimated in NUREG-1829, given that the STP results are for a specific plant and NUREG-1829 reflects the uncertainty and variability for entire fleet of US PWR plants.

Figures 5-7 and 5-8 present the major contributions to LOCA frequency by system, using a logarithmic scale on the Y-axis. A linear perspective (i.e. not with the distortion of logarithmic scales) on the contributions to Category 6 LOCA frequencies is provided in Figure 5-9, which shows that the SG Inlet B-F welds contribute about 74% to the total Category 6 LOCA frequency.

When making comparisons with NUREG-1829, the following differences between that and the present study should be taken into account:

- NUREG-1829 results are from a generic study for the population of PWRs in the U.S. This includes 2-loop, 3-loop, and 4-loop PWR plants, almost all of which have only two trains of ECCSs connected to the loop piping. The base case analyses that were performed in NUREG-1829 that were available for use as anchors for the expert elicitation were for a 3-loop PWR plant. This document's results are specific to STP, a 4-loop PWR plant with interfacing piping for three trains of ECCSs.
- NUREG-1829 results are produced from expert elicitation. The STP results have utilized NUREG-1829 information to develop the CRP distributions, but have been calculated using a different methodology and based on generic pipe failure information from the PIPExp database and from STP-specific weld counts, pipe sizes, and damage mechanisms.

Given the differences, it is interesting that the results are so comparable in magnitude. That the total LOCA frequencies calculated for STP are comparable to the NUREG-1829 results provides a sanity check on the methodology used in this study and its application to STP. More specifically this comparison shows that assumptions made in using NUREG-1829 data to develop the CRP distributions, in combination of the failure rate treatment and LOCA frequency methodology, have produced a set of results that do not differ appreciably from the pipe induced LOCA frequencies in NUREG-1829.

Table 5-5 Results for Total Pipe Break-Induced LOCA Frequencies

LOCA Category[1]	Break Size (in.)	Point Estimate[2]	LOCA Frequency per Reactor-Calendar Year				Range Factor[3]
			Mean	5%tile	50%tile	95%tile	
Small LOCA	0.5 to 2.0	3.59E-04	3.54E-04	1.42E-04	3.11E-04	7.03E-04	2.2
Medium LOCA	2.0 to 6.0	2.01E-05	2.00E-05	1.44E-06	1.14E-05	6.53E-05	6.7
Large LOCA	> 6.0	2.29E-06	2.09E-06	1.80E-07	9.53E-07	7.18E-06	6.3
Category 1	≥ 0.5	3.82E-04	3.76E-04	1.57E-04	3.30E-04	7.39E-04	2.2
Category 2	≥ 1.5	3.91E-05	3.90E-05	7.00E-06	2.37E-05	1.18E-04	4.1
Category 3	≥ 3	9.24E-06	9.09E-06	1.07E-06	5.04E-06	2.94E-05	5.2
Category 4	≥ 6.75	1.84E-06	1.82E-06	2.00E-07	9.69E-07	5.83E-06	5.4
Category 5	≥ 14	4.40E-07	4.31E-07	4.45E-08	2.25E-07	1.39E-06	5.6
Category 6	≥ 0.5	4.48E-08	4.50E-08	1.61E-09	1.44E-08	1.65E-07	10.1

Notes:
[1] Small, Medium, and Large LOCA categories consistent with STP PRA model; Categories 1-6 defined in NUREG-1829 (see Table 4-1).
[2] Point estimate obtained with mean failure rate and CRP lognormal distributions and weld counts.
[3] Range Factor = SQRT(95%tile/5%tile).

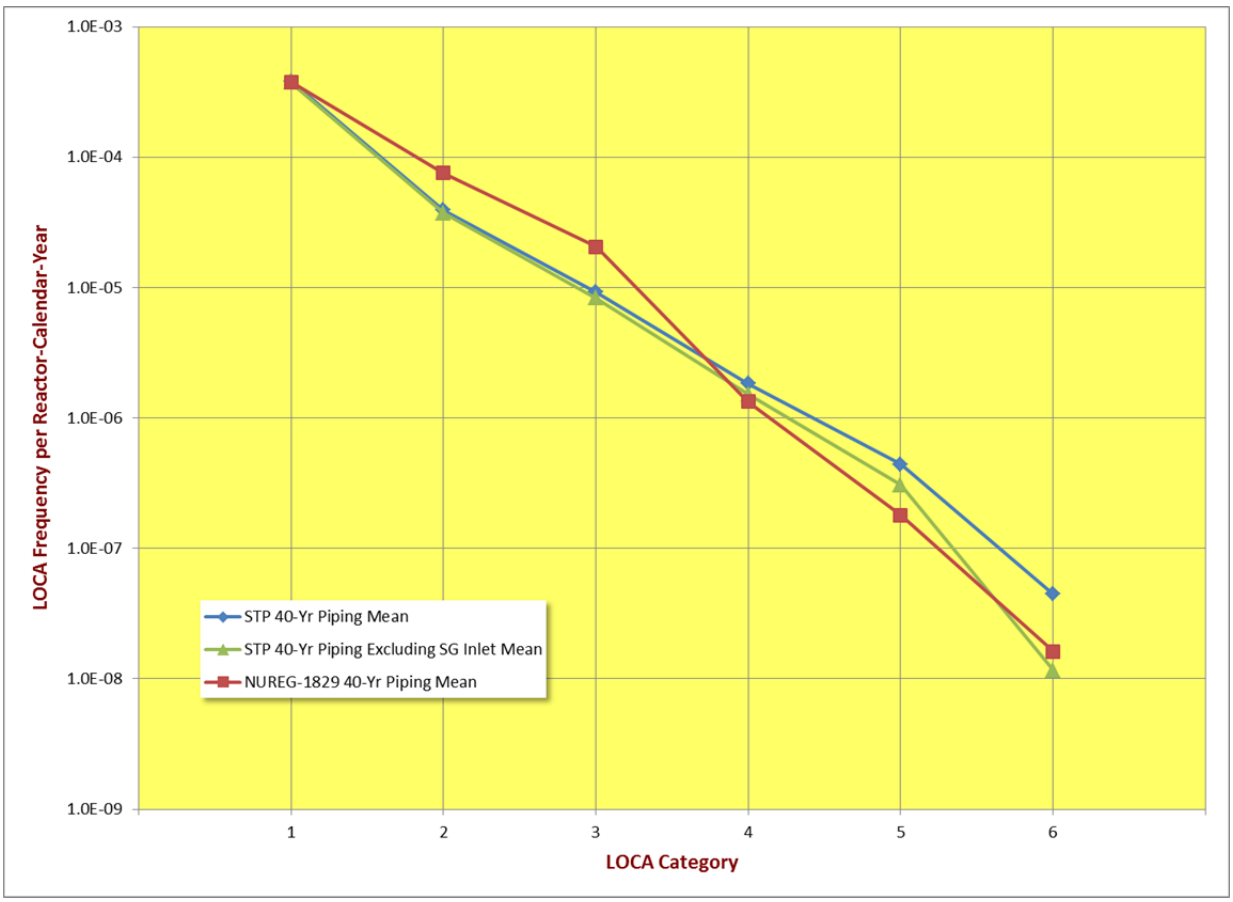

Figure 5-5 Comparison of LOCA Frequencies for Pipes: STP vs. NUREG-1829

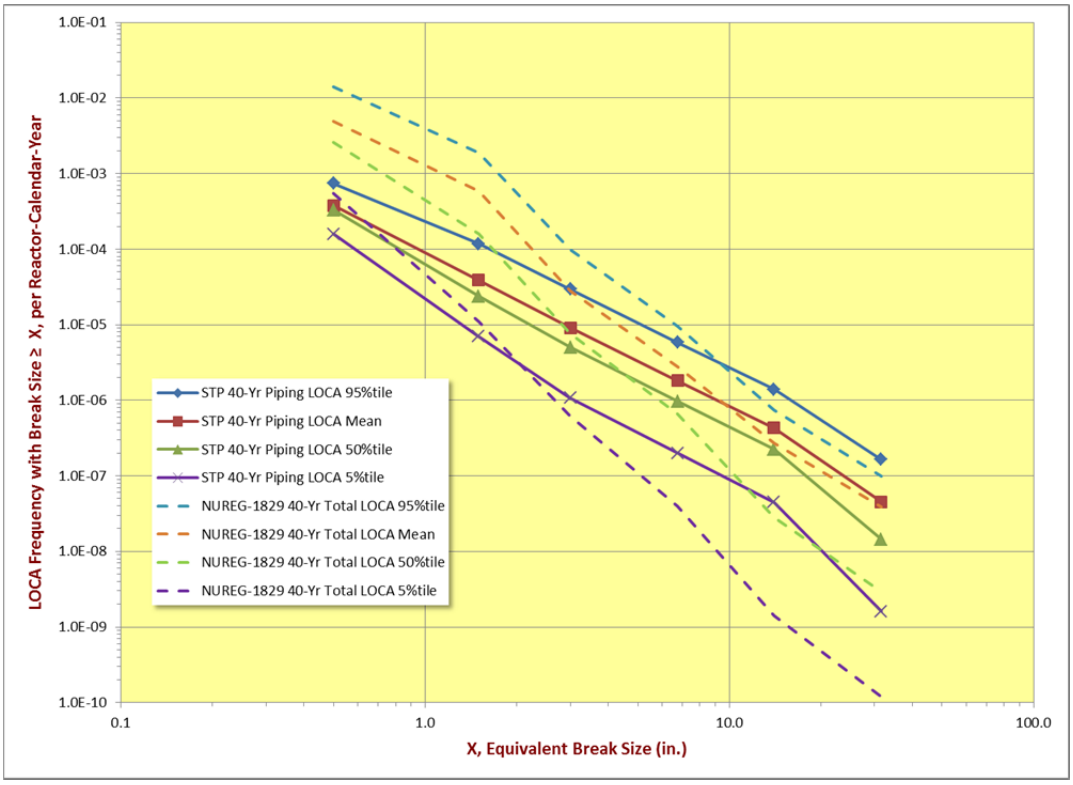

Figure 5-6 Comparison of Uncertainty Distributions for STP Pipe-Induced LOCA and NUREG-1829 Total LOCA Frequencies

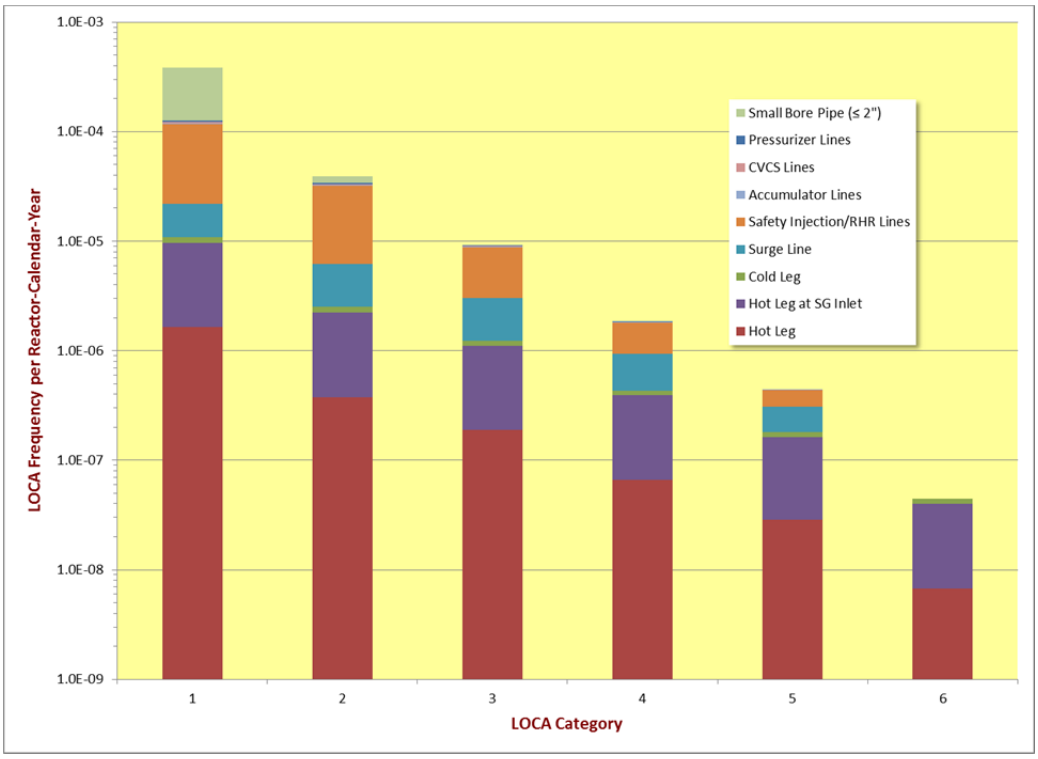

Figure 5-7 Contributions to Mean LOCA Category Frequencies by System

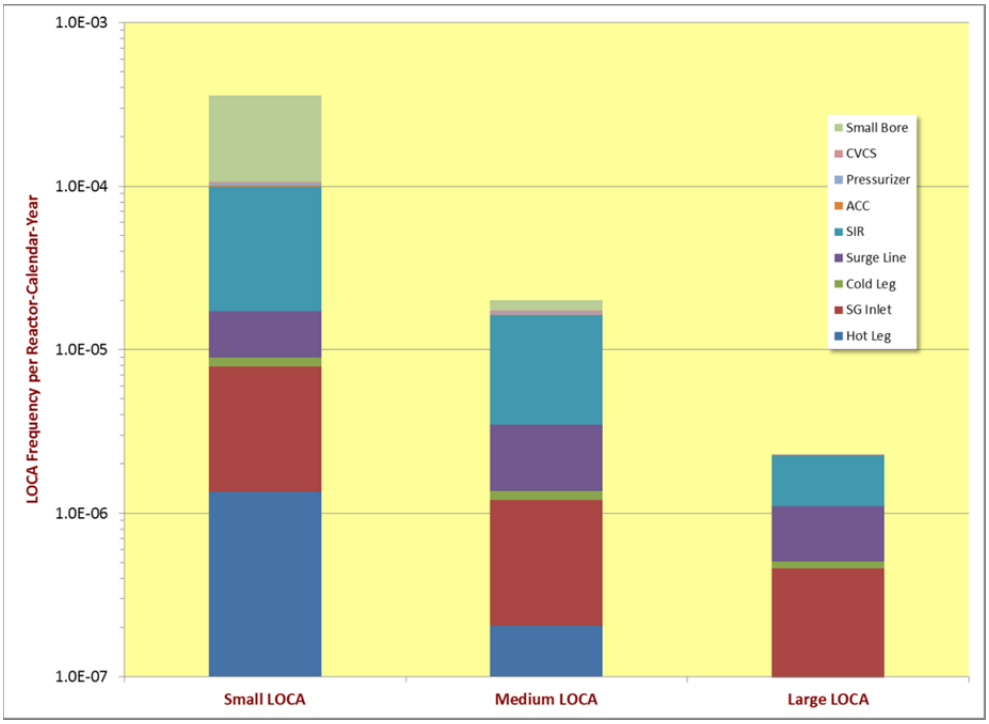

Figure 5-8 System Contributions to Mean LOCA Initiating Event Frequencies

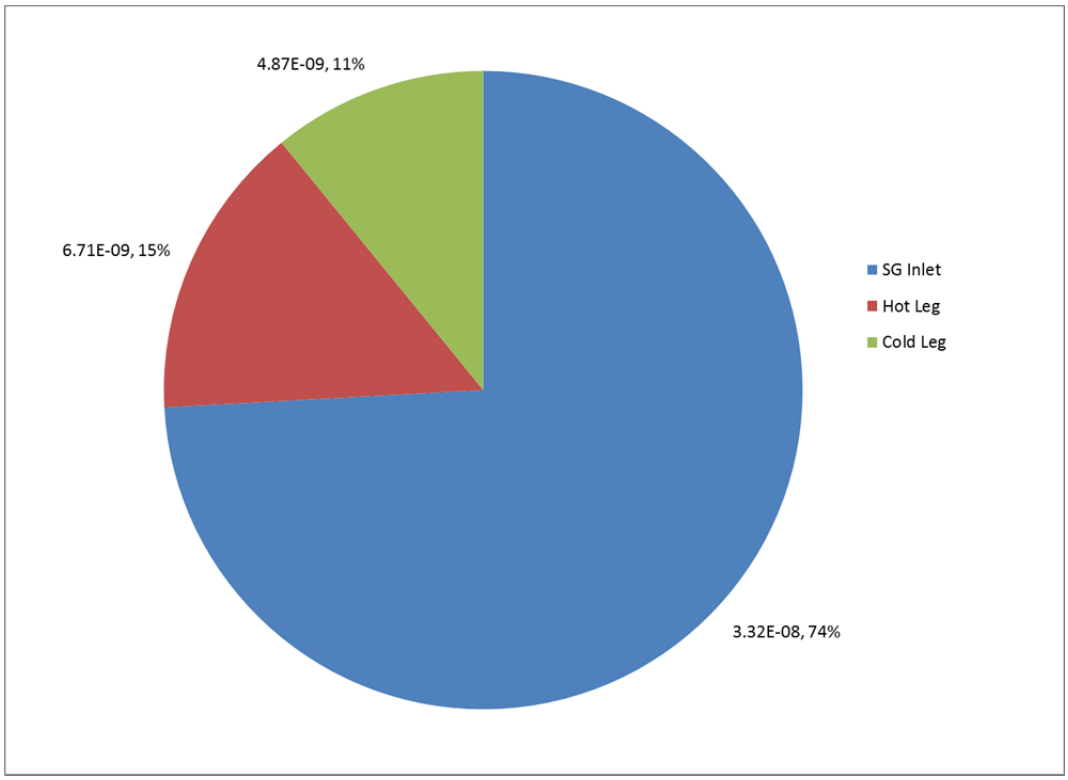

Figure 5-9 System Contribution to LOCA Category 6 Frequencies

5.5 LOCA Frequency Summary

The technical approach to estimation of LOCA frequencies for the STP GSI-191 project has been described in section 5, with results for each step. The specific capabilities that have been demonstrated include:

- The capability to estimate LOCA frequencies as a function of break size at each location.
- The capability to utilize information from NUREG-1829 to characterize epistemic uncertainty associated with LOCA frequencies.
- A method that incorporates via Bayes' uncertainty analysis the service data on pipe failures and component exposures.
- A quantification of epistemic uncertainties associated with estimating the input parameters in the model equations, including both parametric and modeling sources of uncertainty.
- The capability to quantify the impacts of information on degradation mechanism susceptibility at each location, based on insights from service data and results of RI-ISI evaluation.

The results that have been generated for LOCA-specific as well as total LOCA frequencies are reasonable and consistent with those developed in previous studies.

Prior to completion of the LOCA frequency task for GSI-191, the following issues need to be and will be addressed in a future update of this report.

- Non-isolatable LOCAs caused by failures of non-pipe components need to be addressed. These include control rod drive standpipes, instrument lines, and other components welded to the reactor pressure vessel, pump and valve bodies, pressurizer safety and relief valve leaks, and reactor coolant pump seals.
- Isolatable LOCAs need to be addressed. These involve failures in Class 2 piping systems that can be isolated, including CVCS charging and letdown lines, RCP seal return lines, etc.
- Pipe breaks in steam and feed-water lines inside the containment that could generate debris and lead to a need for recirculation cooling and/or containment spray actuation need to be addressed.
- Execution of Step 3.4 to apply the Markov model to evaluate the impact of inspected and non-inspected NDE locations on the LOCA frequencies needs to be completed.
- The current study is based on rough estimates of weld counts and pipe sizes for small bore pipes. If small bore pipes are found to contribute significantly to the risk of debris-induced ECCS failures, more detailed review of the small bore piping configurations needs to be completed.

6. References

[1] Tregoning, R., L. Abramson, and P. Scott, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies through the Elicitation Process", NUREG-1829, U.S. Nuclear Regulatory Commission, Washington, DC, April 2008.

[2] Lydell, B. O. Y., "PIPExp/PIPE-2010: Monthly Summary of Database Content (Status as of 31-July-2011)," Sigma-Phase Inc., Vail AZ. Monthly summary reports have been issued since January 1999.

[3] Fleming, K. N. and B. O. Y. Lydell, "Database Development and Uncertainty Treatment for Estimating Pipe Failure Rates and Rupture Frequencies," Reliability Engineering and System Safety, 86: 227–246, 2004.

[4] Fleming, K. N. and B. O. Y. Lydell, "Pipe Rupture Frequencies for Internal Flooding PRAs," Revision 1. EPRI, Palo Alto, CA: 2006. 1013141.

[5] Fleming, K. N. and B. O. Y. Lydell, "Pipe Rupture Frequencies for Internal Flooding PRAs," Revision 2. EPRI, Palo Alto, CA: 2010. 1021086.

[6] Fleming, K. N. et al., "Piping System Reliability and Failure Rate Estimation Models for Use in Risk-Informed In-Service Inspection Applications," EPRI, Palo Alto, CA: 1998. TR-110161.

[7] Fleming, K. N. and T.J. Mikschl, "Piping System Failure Rates and Rupture Frequencies for Use in Risk-Informed In-Service Inspection Applications," EPRI, Palo Alto, CA: 1999. TR-111880.

[8] Mosleh, A. and F. Groen, "Technical Review of the Methodology of EPRI TR-110161," University of Maryland report for EPRI, published as an Appendix to EPRI TR-110161 (Reference [6]).

[9] Electric Power Research Institute, "Revised Risk-Informed In-Service Inspection Procedure", EPRI, Palo Alto, CA: 1999. TR-112657, Rev. B-A.

[10] U.S. Nuclear Regulatory Commission, Safety Evaluation Report Related to Revised Risk-Informed In-Service Inspection Evaluation Procedure: EPRI TR-112657, Rev. B, July 1999, Washington, DC, 1999. Published as a forward to TR-112657 (Reference [9]).

[11] Martz, H., "Final (Revised) Review of the EPRI-Proposed Markov Modeling/Bayesian Updating Methodology for Use in Risk-Informed In-Service Inspection of Piping in Commercial Nuclear Power Plants," Los Alamos National Laboratory, June 1999. TSA-1/99-164.

[12] Fleming, K. N., "Markov Models for Evaluating Risk-Informed In-Service Inspection Strategies for Nuclear Power Plant Piping Systems," Reliability Engineering and System Safety, 83(1): 27–45, 2004.

[13] Fleming, K. N. et al., "Treatment of Passive Component Reliability in Risk-Informed Safety Margin Characterization – Fiscal Year 2010 Status Report," INL/EXT-10-20013, report prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy, September 2010.

[14] U.S. Nuclear Regulatory Commission, Supporting information for NUREG-1829 (Reference [1]) on Individual Expert's Estimates of LOCA Frequencies for Specific Components and LOCA Categories, available on ADAMS Accession Numbers ML080560008, ML080560010, ML080560011, ML080560013.

[15] Scandpower Risk Management, Inc., "GSI-191 Component Database," Microsoft Access Database of South Texas Project Components considered in LOCA Frequency Analysis, September 16, 2011.

[16] Andresen, P.L. et al, 2007. Expert Panel Report on Proactive Materials Degradation Assessment, NUREG/CR-6923, U.S. Nuclear Regulatory Commission, Washington (DC).

[17] OECD Nuclear Energy Agency, 2011. Technical Basis for Commendable Practices on Ageing Management – SCC and Cable Ageing Project (SCAP), NEA/CSNI/R(2010)5, Issy-les-Moulineaux (France).

[18] Scott, P.M., 2010. Primary Water Stress Corrosion Cracking of Nickel-base Alloys, Technical Report Prepared for the SCAP-SCC Working Group, Noisy le Roi (France).

[19] OECD Nuclear Energy Agency, 1998. Proc. Specialists Meeting on Experience with Thermal Fatigue in LWR Piping Caused by Mixing and Stratification, NEA/CSNI/R(1998)8, Issy-les-Moulineaux (France).

[20] Lydell, B. and Olsson, A., 2008. Reliability Data for Piping Components in Nordic Nuclear Power Plants. "R-Book" Project Phase I, SKI Report 2008:1, Swedish nuclear Power Inspectorate, Stockholm (Sweden).

[21] Letter, dated December 30, 1999, as supplemented April 17, 2000, T. J. Jordan (South Texas Project, Units 1 and 2, Manager, Systems Engineering), to U.S. Nuclear Regulatory Commission, containing Risk-Informed Inservice Inspection Program Plan -South Texas Project Units 1 and 2.