LOCA Initiating Event Frequencies Final Results for 2011

Risk Informed GSI-191 Resolution
Monday, August 22, 2011
1:00 pm - 4:30 p.m EDT
Public Meeting with STP Nuclear Operating Company

Karl N. Fleming
KNF Consulting Services LLC
Bengt O. Y. Lydell
SCANDPOWER
Risk Management

Discussion Topics

- Briefing on Final Results for 2011
- Review of technical approach with focus on recent refinements
- Highlights of Results
  - Component level for CASAGRANDE
  - Total LOCA frequencies for RISKMAN
  - Comparison with NUREG-1829
- Issues to Complete in 2012

LOCA Frequencies Objectives

- Incorporate insights from previous work on LOCA frequencies
- Characterize LOCA initiating events and their frequencies with respect to:
  - Specific components, materials, dimensions
  - Specific locations
  - Range of break sizes
  - Damage / Degradation mechanisms and mitigation effectiveness
  - Other break characteristics, e.g. speed
- Quantify both aleatory and epistemic uncertainties; augment with sensitivity studies
- Support interfaces with other parts of the GSI-191 evaluation
  - LOCA initiating event frequencies for PRA modeling
  - Break characterization for evaluation of debris formation
- Participate in NRC workshops

Current Status

- Defined homogenous pipe failure rate categories
- Refined method for deriving conditional rupture probabilities vs. break size
- Obtained final 2011 results for each pipe category and provided to CASAGRANDE
- Obtained final 2011 results for total LOCA frequencies from pipe failures with comparisons to NUREG-1829
- Incorporated independent review comments and recommendations by MIT and Ali Mosleh

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

Pipe Rupture Model

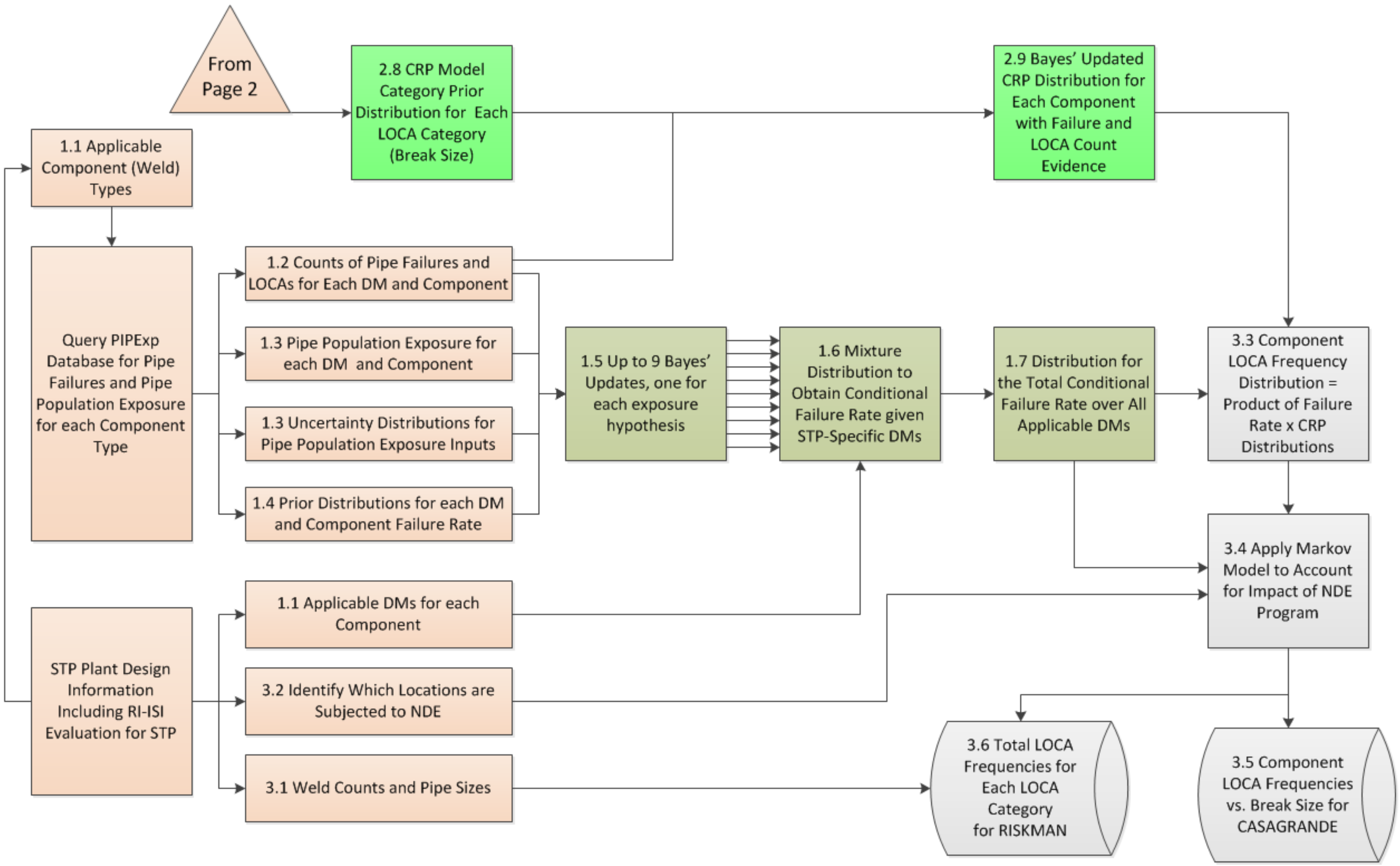
$$F(LOCA_x) = \sum_i m_i \rho_{ix} \quad (2.1)$$

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

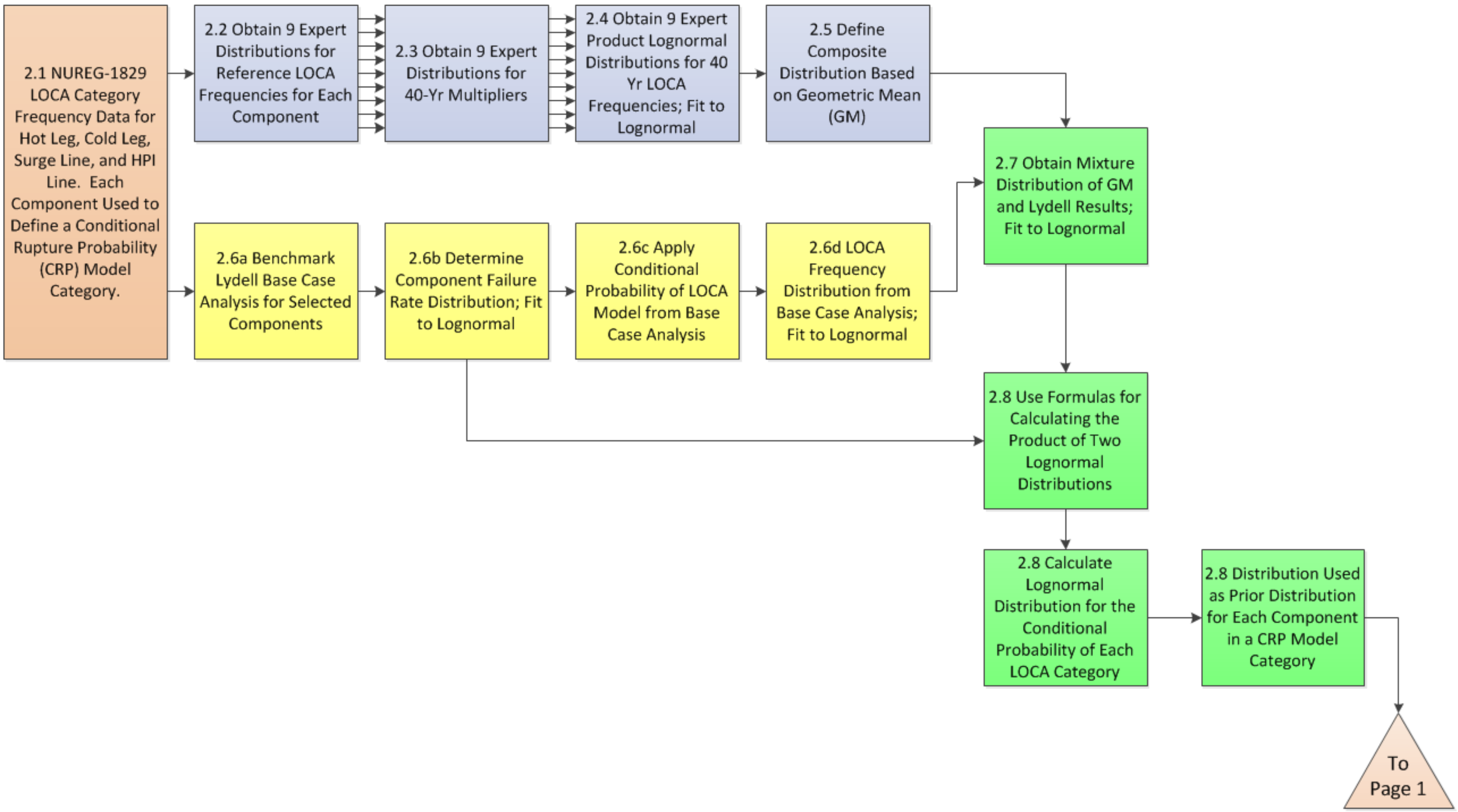
where:

$F(LOCA_x) =$	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

Step-by-Step Procedure 1 of 2



Step-by-Step Procedure 2 of 2



Step 1 Failure Rate 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 - $\Sigma\lambda_{ik}$

Step 1.1 Definition of Component Types

- Goal is to define homogeneous groups of components that may be characterized by a single failure rate estimate
- Fundamental to any PRA data analysis
- Criteria
  - Pipe materials
  - Pipe size
  - Applicable damage mechanisms (DMs)
  - Unusual distribution of component failures
  - In-service inspection program status
- STP Class 1 Pipe Weld Categories
  - 8 System Groups
  - 25 Categories based on combinations of DMs
  - 45 Categories based on DMs and Pipe Sizes
  - 775 Total number of Class 1 pipe welds at STP

Homogeneous Pipe Failure Rate 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

Component Categories 1 of 3

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

Component Categories 2 of 3

System Case	System	Component Case	Weld Type	Applicable DM	STP Total No. of Welds	Pipe Size (in.)	DEGB Size (in.)
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

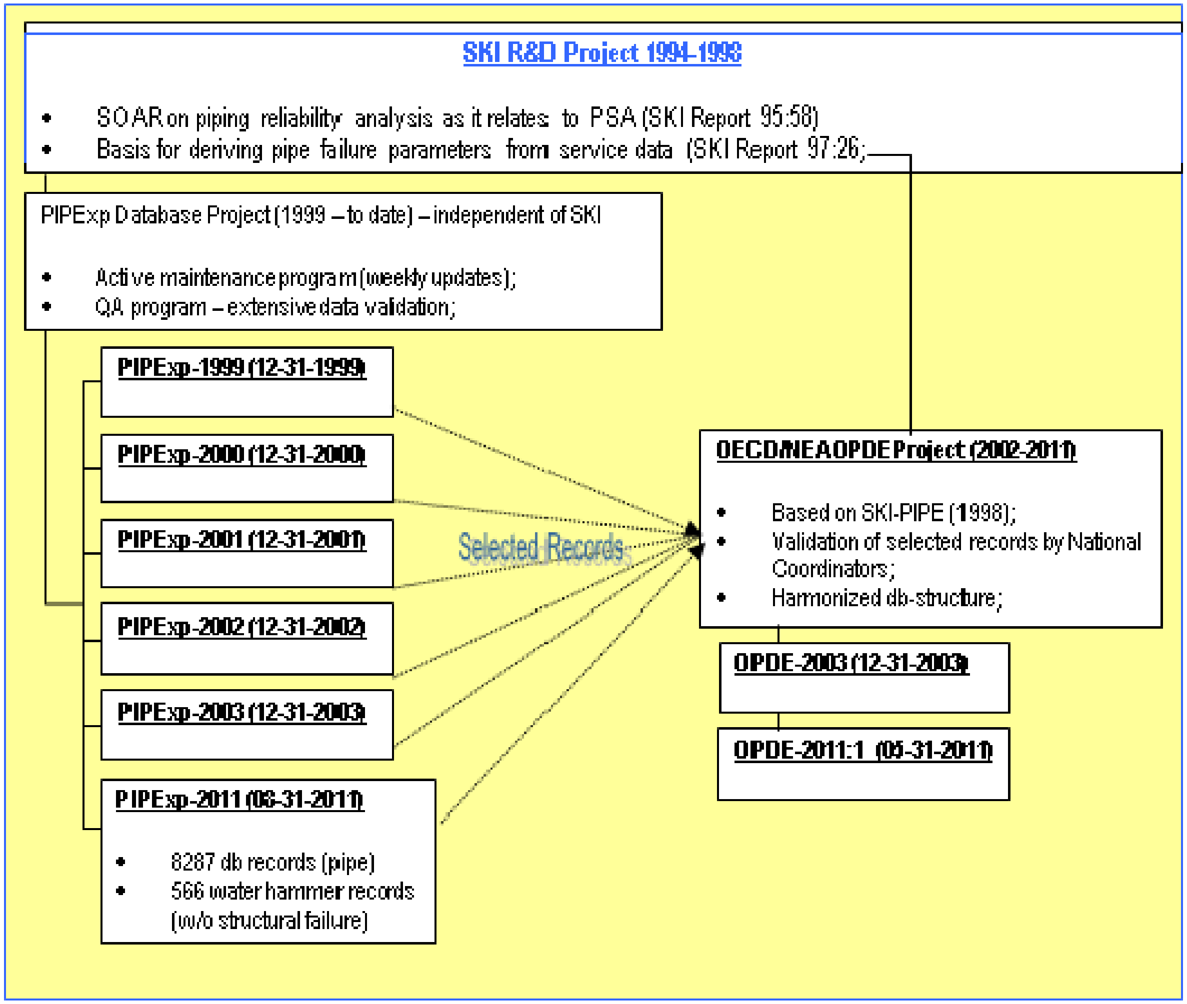
Component Categories 3 of 3

System Case	System	Component Case	Weld Type	Applicable DM	STP Total No. of Welds	Pipe Size (in.)	DEGB Size (in.)
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
	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		

Step 1.2 Failure Data Query

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

PIPExp Database



Step 1.3 Component Exposure

- Component Exposure includes
  - Reactor-years of service data (little uncertainty)
  - Number of components per reactor (almost always uncertain)
  - Fraction of the components susceptible to a DM (sometimes uncertain)
- Components per reactor for Hot Leg Welds

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

Damage Mechanisms (DM)

- Damage Mechanism Assessment
  - All welds susceptible to D&C
  - All BF welds susceptible to PWSCC
  - Many DMs can be ruled out for certain categories
  - In some cases some unknown fraction of a component category is susceptible to DMs (e.g. TF and SC)
- DM 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

Uncertainty Model for Hot Leg B-J Welds Subject to Thermal Fatigue

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 High (1.12 x Base)	p=.25 High (.08 x Base)	0.0625	0.08972	2,898 weld-yrs
	p=.50 Medium (.02 x Base)	0.125	0.02243	724 weld-yrs
	p=.25 Low (.01 x Base)	0.0625	0.011215	362 weld-yrs
p=.50 Medium (1.0 x Base)	p=.25 High (.08 x Base)	0.125	0.08	2,584 weld-yrs
	p=.50 Medium (.02 x Base)	0.25	0.02	646 weld-yrs
	p=.25 Low (.01 x Base)	0.125	0.01	323 weld-yrs
p=.25 Low (0.75 x Base)	p=.25 High (.08 x Base)	0.0625	0.059813	1,932 weld-yrs
	p=.50 Medium (.02 x Base)	0.125	0.014953	483 weld-yrs
	p=.25 Low (.01 x Base)	0.0625	0.007477	241 weld-yrs

Summary of Component Exposure Estimates

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

Steps 1.4 and 1.5 Select Priors and Perform Bayes' Updates - Hot Leg Welds

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

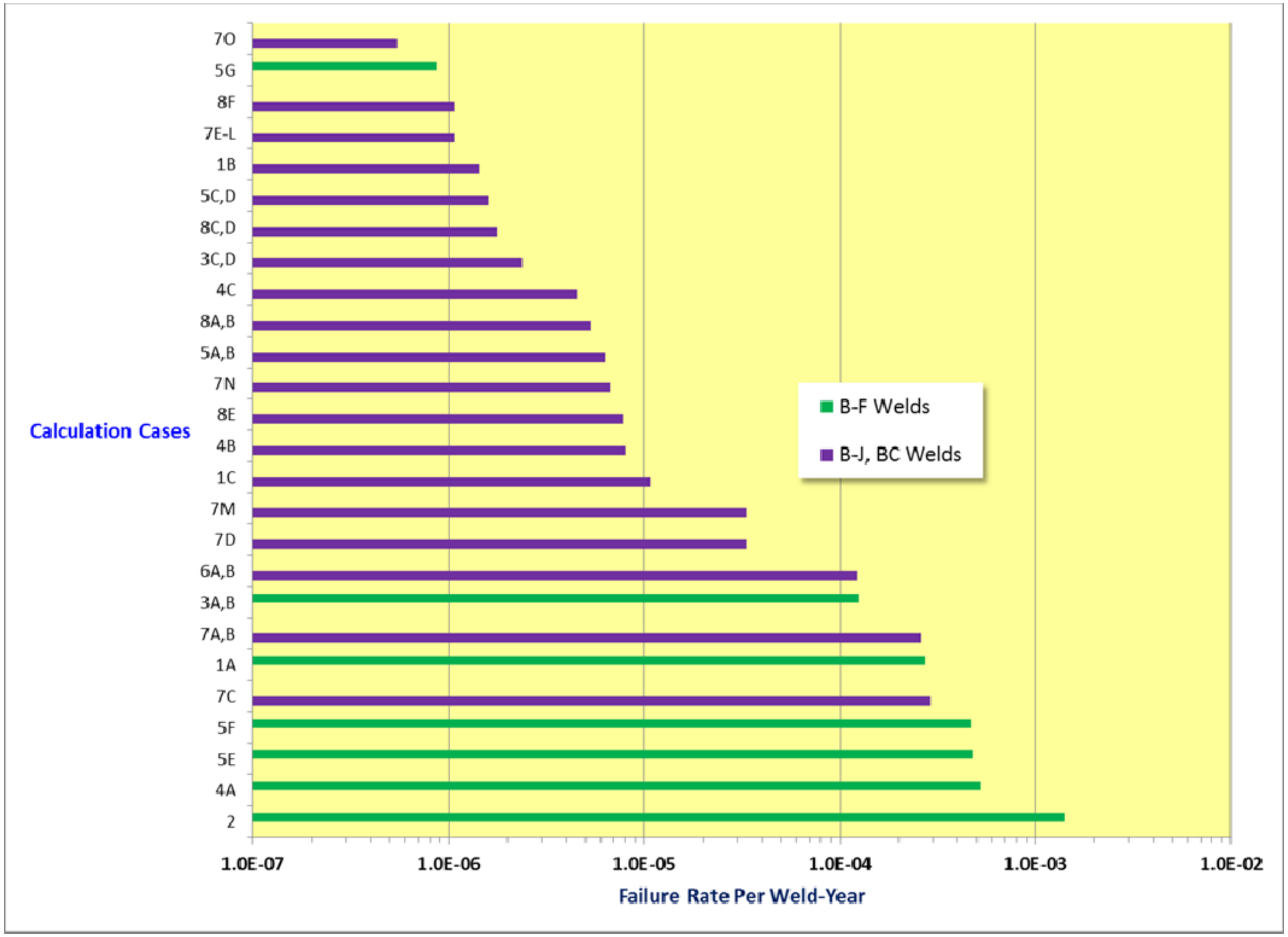
Notes:
(1) Failure rates expressed in failures per weld-year.
(2) Exposure expressed in weld-years.
(3) DM = Damage Mechanism; SC = stress corrosion cracking; TF = thermal fatigue; DC = design and construction defects.
(4) RF = Range Factor = SQRT (95%tile/5%tile).

Steps 1.6 and 1.7 Apply Mixture Distribution and Sum over applicable DMs

- Hot Leg Weld Categories

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

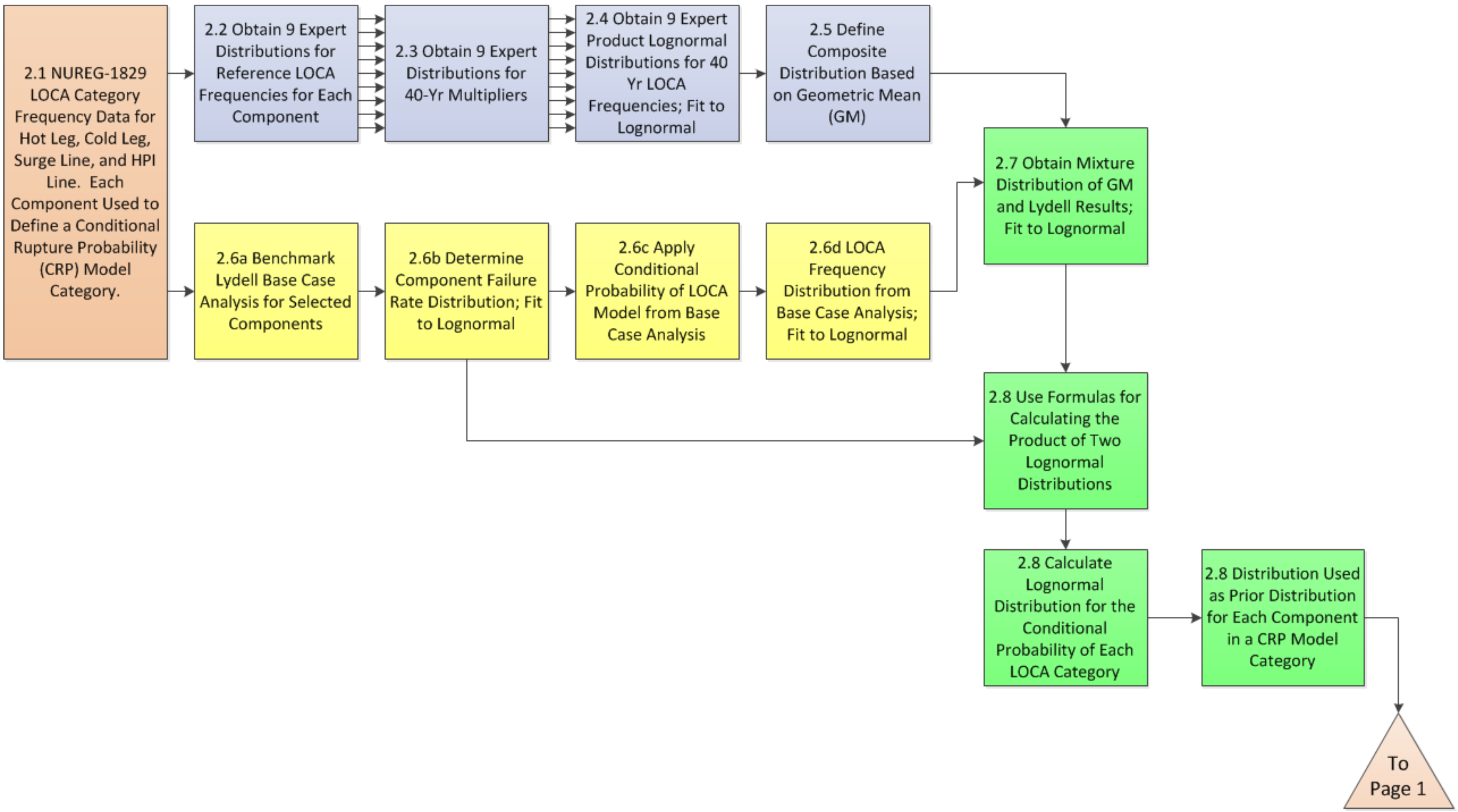
Mean Failure Rate Results for STP Class 1 Components



Step 2 CRP Development

1.	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

Step-by-Step Procedure 2 of 2



CRP Model Development

- Goal is to make use of NUREG-1829 data in the characterization of epistemic uncertainty
- Our technical approach is based on converting LOCA frequencies to CRPs to facilitate separate failure rate treatment
  - Our method is based on calculating LOCA frequency as the product of a failure rate and a CRP
  - Failure rate is established independent of NUREG-1829 data in Step 1 for all component categories
  - NUREG-1829 data is used to set target LOCA frequencies for each CRP model to be developed
  - CRP distributions are derived from target LOCA frequencies using formulas for the product of two lognormal distributions and the Lydell Base Case failure rate distributions
- Two distinct sources of NUREG-1829 data
  - Base case analyses of specific PWR components (hot leg, surge line, HPI line for a specific 3-loop PWR design by Lydell using methodology similar to that being used for STP
  - Questionnaires provided by 9 experts with estimates of LOCA frequencies vs. break size for many PWR components for the entire fleet of U.S. PWRs

Step 2.1 Define CRP Model Categories

- The following CRP models are used for all STP model Categories
  - 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:
  - Sufficient data in NUREG-1829 and supporting input data to support estimation of the CRPs
  - Categories provide a unique model for all the categories with large pipe sizes
  - 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 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. Developing variants within this category would not be expected to have different results

Application of the CRP Models to the 8 System 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

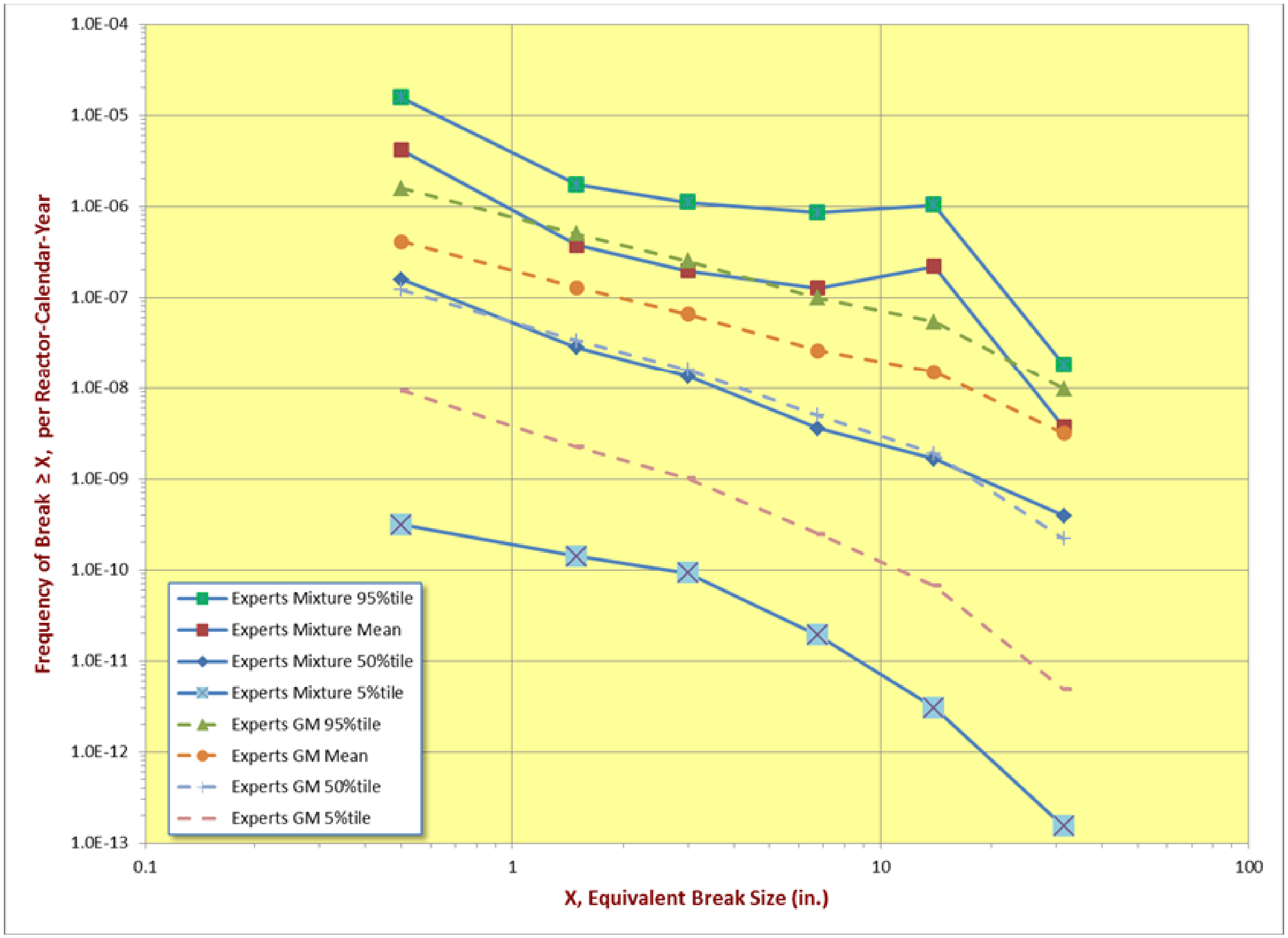
Steps 2.2 thru 2.5
Expert Composite Distributions

- Goal is to derive a single composite distribution that represents the inputs provided by 9 experts for LOCA frequencies for key components
- Some experts provided asymmetric inputs but most provided symmetric inputs for lower, middle, and upper values
- We investigated two approaches for forming composite distributions
  - Mixture Distribution Method; each expert is given equal weight in a sampling scheme in which an expert is selected and then a sample is randomly chosen from a lognormal distribution of LOCA frequency
  - Geometric Mean Method: a composite distribution is formed by taking the geometric means of two parameters of the experts lognormal distributions: the parameters chosen are the medians and range factors.
  - Both Methods require the combination of two distributions provided by each expert; one for a reference LOCA frequency and another for multipliers to reflect plant operation for 40 years

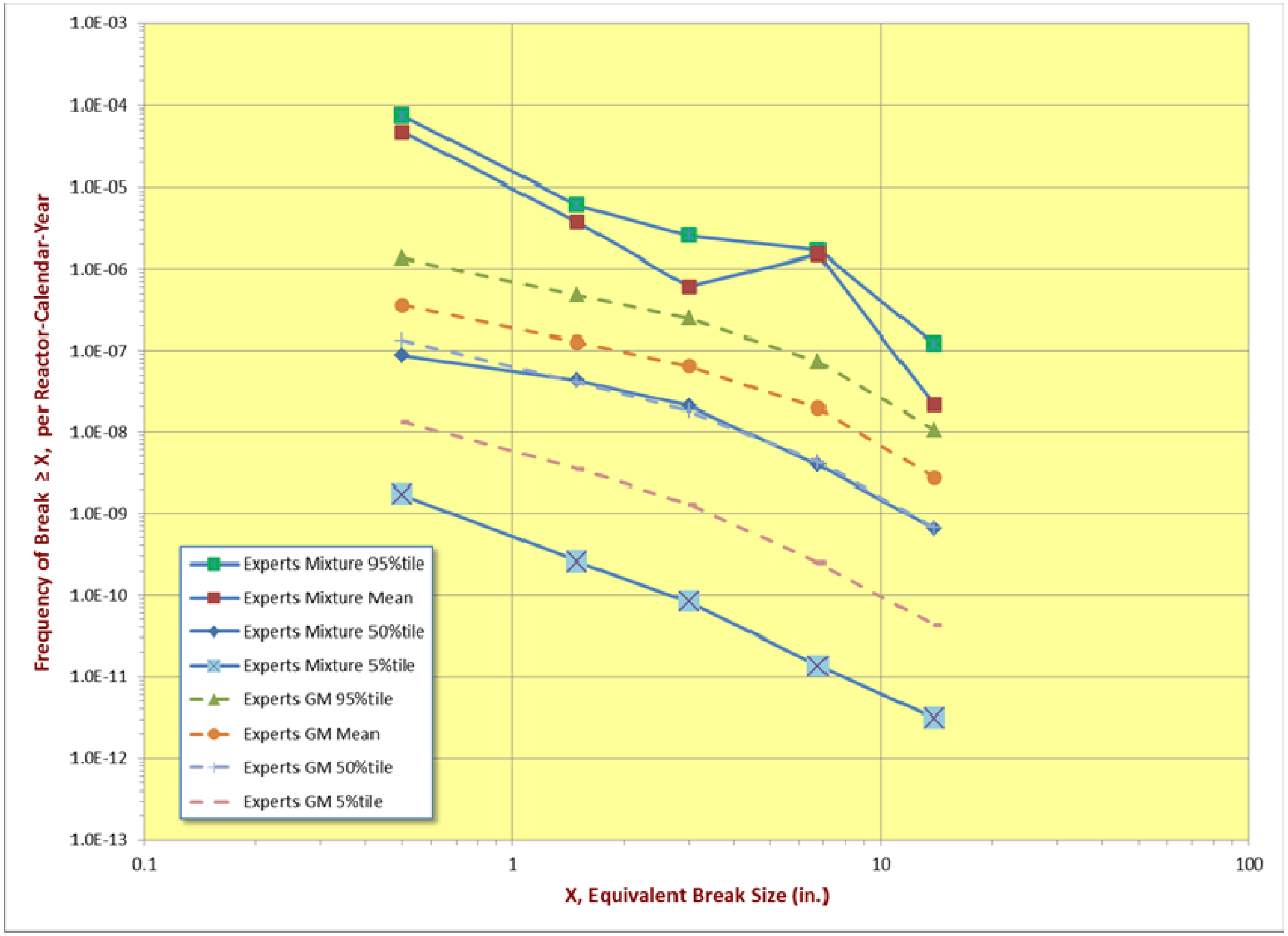
Treatment of Asymmetric Inputs

- Raw data provided by the 9 experts is comprised of a lower value, mid value and upper value with understanding they are treated as the parameters of a lognormal distribution
- In most cases the inputs are symmetric, i.e. Upper/Mid = Mid/Lower; in a few cases Mid/Lower > Upper/Mid
- In NUREG-1829 split lognormal distributions were used to treat this asymmetry.
- In this study we fit the asymmetric cases to lognormal using two methods: 1. RF = SQRT(Upper/Lower); 2. RF = Upper/Mid. We adopted 2 per recommendation from Dr. Mosleh
- We rejected split lognormals as our tools do not support it and we adopted a different approach to treating the lower tails that is applied when we select our target LOCA frequencies

Comparison of Geometric Mean and Mixture Distributions for RCS Hot Leg



Comparison of Geometric Mean and Mixture Distributions for RCS Surge Line



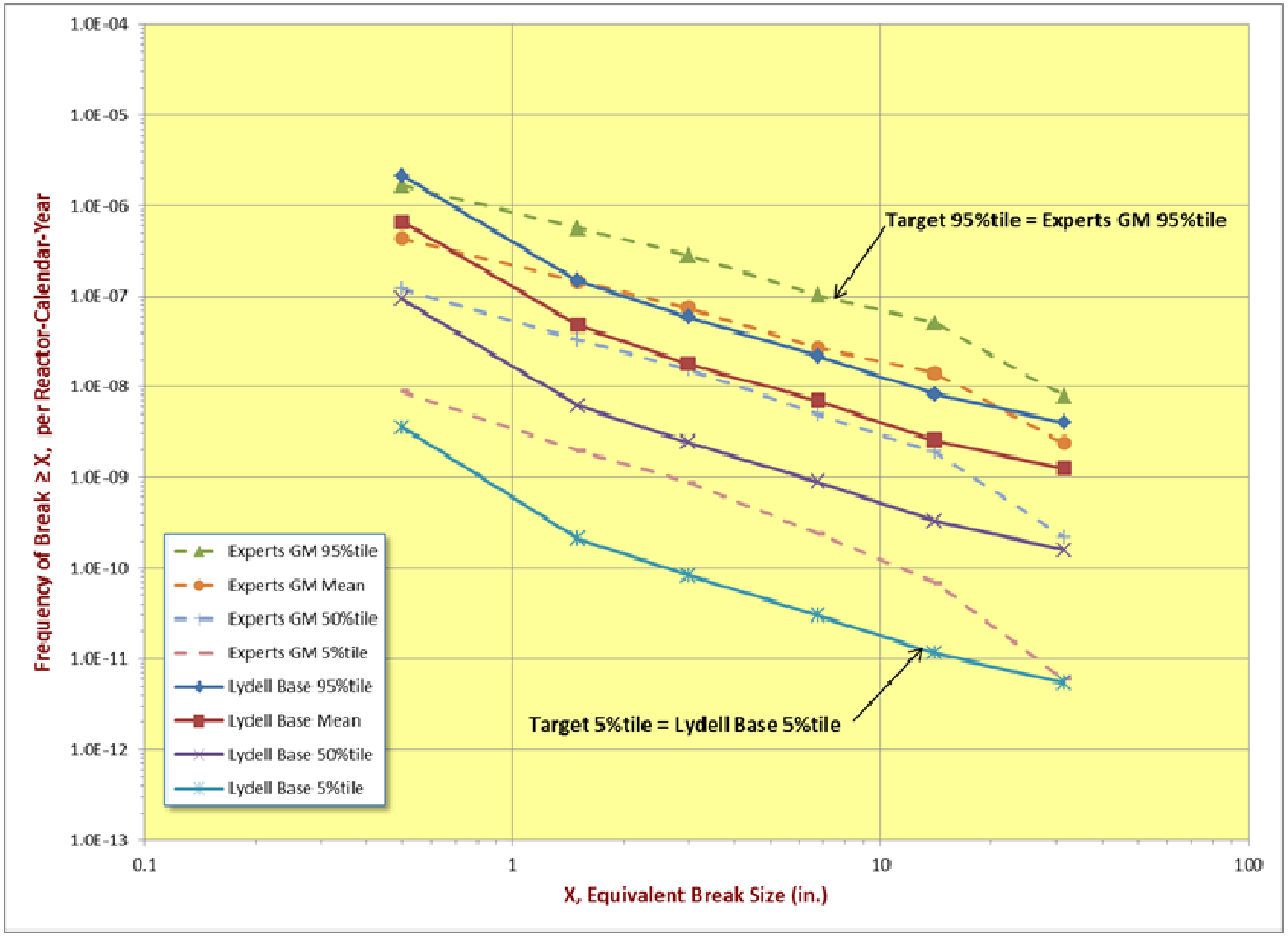
Geometric Mean Composite Distributions

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

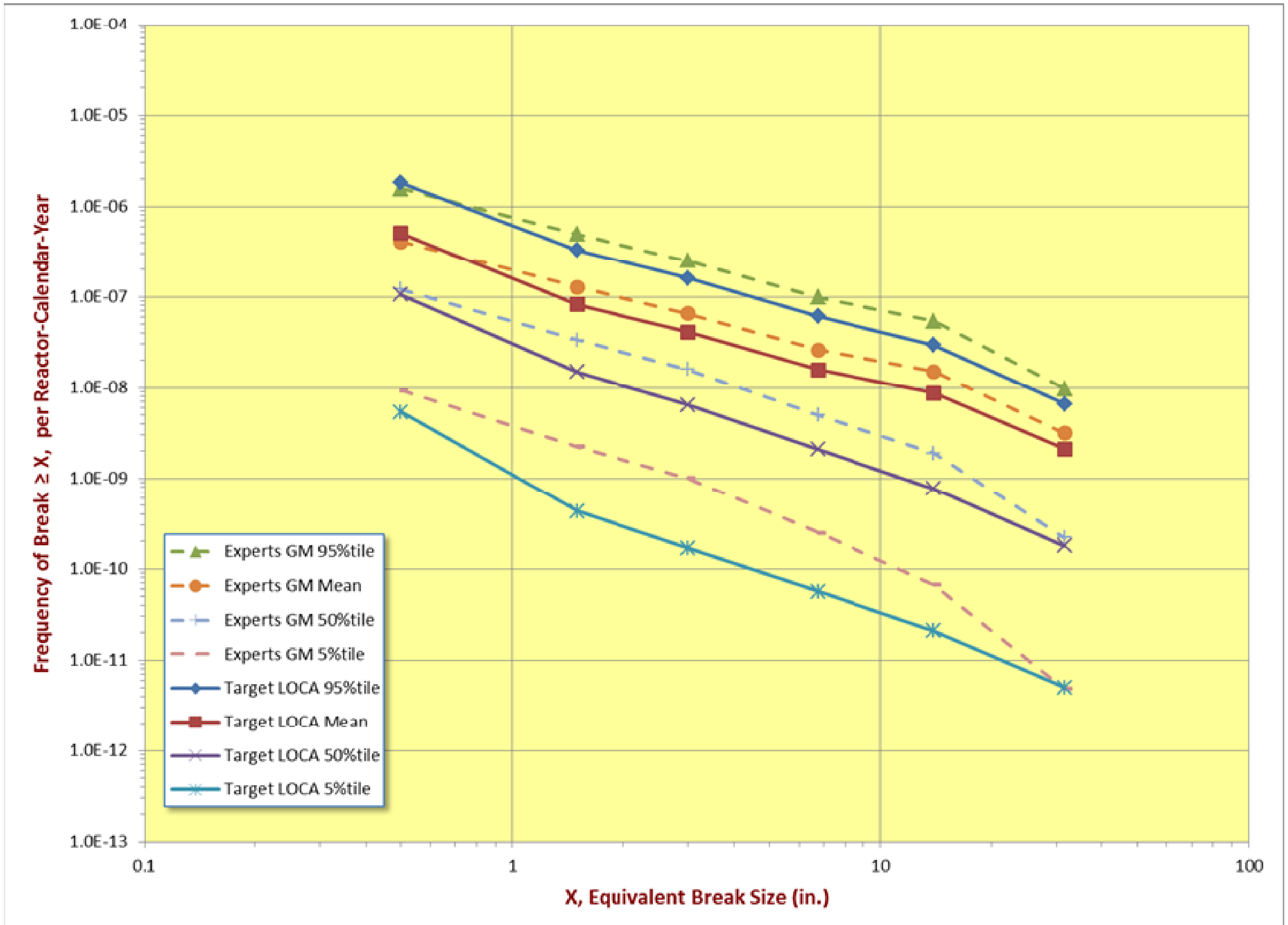
Step 2.7 Selection of Target LOCA Frequencies

- Four Options 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 rejected as based on only 1 expert
- Option 2 rejected as too sensitive to extreme values from 2 experts
- Option 4 preferred over Option 3 as providing a more complete representation of both model and expert opinion aspects of epistemic Uncertainty
- Two methods evaluated for Option 4
  - Worst case percentile method previously presented to the NRC
  - Mixture distribution method recommended by Dr. Mosleh as more consistent with established method for combining two distributions (selected)

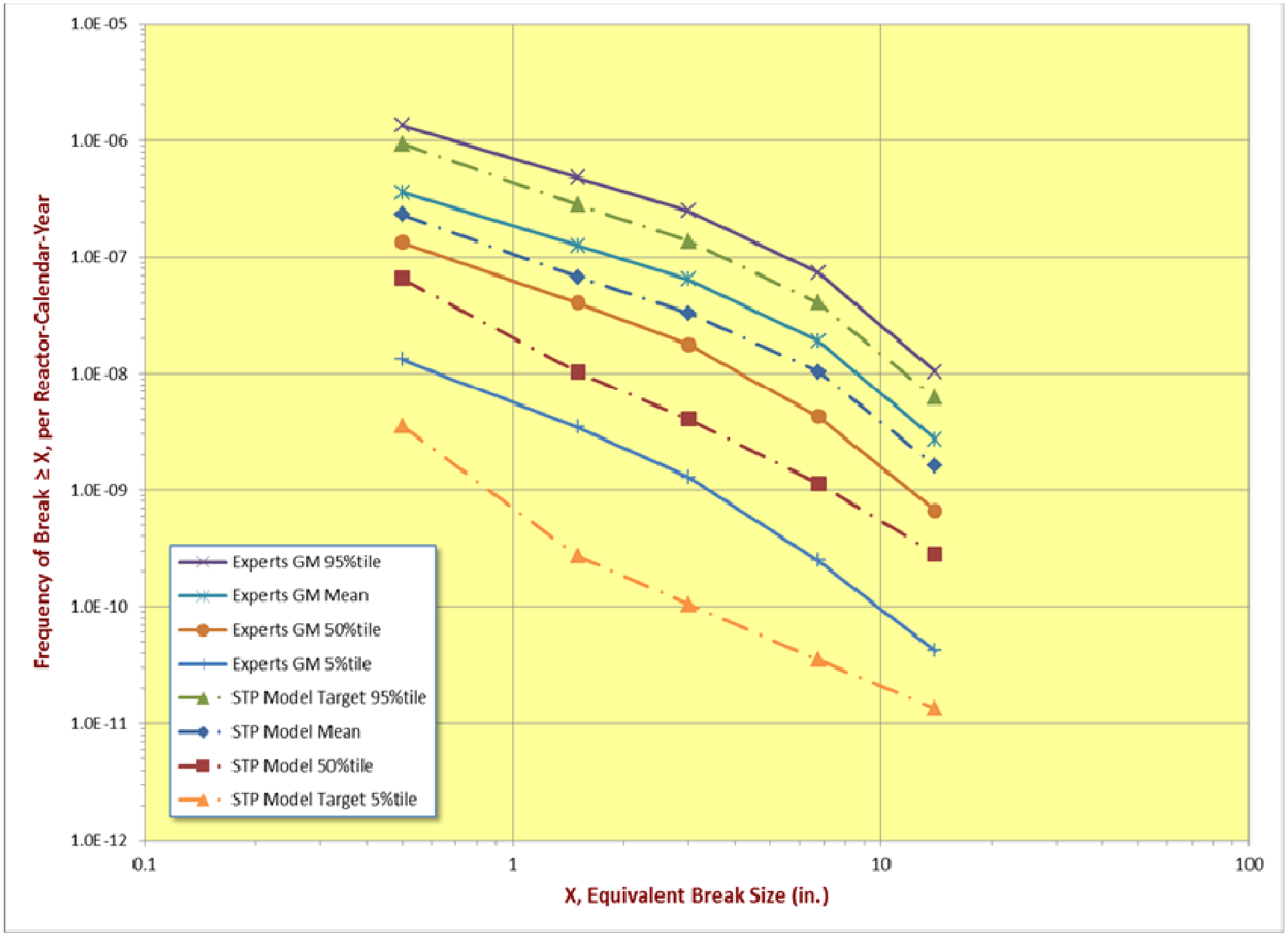
Use of Worst-Case Percentiles from NUREG-1829 GM and Lydell Base Case



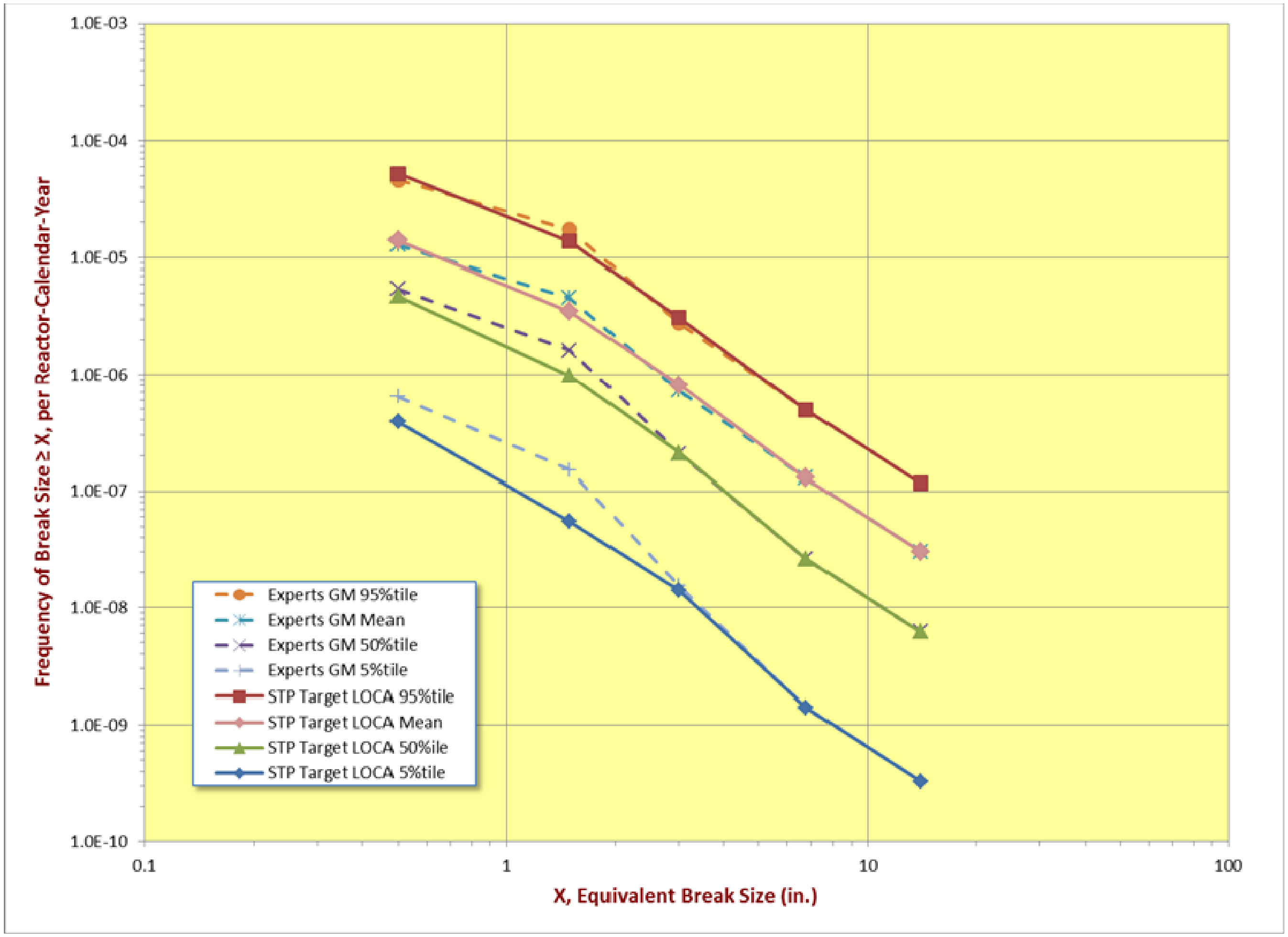
Comparison of GM and Mixture of GM and Lydell Base – Hot Leg



Comparison of GM and Mixture of GM and Lydell Base – Surge Line



Comparison of GM and Mixture of GM and Lydell Base – HPI Line



Comparison of Hybrid Methods

STP Hot Leg Target LOCA Model - Worst Case 5%tile and 95%tile						
LOCA Cat.	**Break Size**	**Mean**	**5%tile**	**50%tile**	**95%tile**	**RF**
1	0.5	5.79E-07	3.55E-09	8.72E-08	2.14E-06	24.6
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	6.76	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
STP Hot Leg Target LOCA Model - Probabilistic Mixture						
1	0.5	5.08E-07	5.30E-09	1.05E-07	1.91E-06	19.0
2	1.5	9.32E-08	3.91E-10	1.46E-08	3.68E-07	30.7
3	3	4.54E-08	1.60E-10	6.39E-09	1.76E-07	33.1
4	6.76	1.64E-08	5.73E-11	2.05E-09	6.32E-08	33.2
5	14	8.37E-09	2.03E-11	7.64E-10	2.92E-08	37.9
6	31.5	1.80E-09	5.85E-12	1.80E-10	5.83E-09	31.6

Selected Approach for Target LOCA Frequencies

- Probabilistic mixture of two models
  - Model 1 Geometric mean of 9 expert distributions
    - Develop 40 year composite distribution of 9 experts using geometric mean method
    - Combined lognormal distribution for Current day and 40yr multipliers for each expert preserving median and RF=Upper/Mid
    - Developed composite distribution based on geometric means of each experts medians and range factors
  - Model 2 Bengt Lydell Base Case analysis
  - Results of Models 1 and 2 combined giving equal weight to each yielding a mixture distribution of the two models
  - This method produces somewhat greater uncertainties than using Model 1 by itself mostly by extending the lower tails of the distributions

Step 2.8 Develop CRP Distributions from Target LOCA Distributions

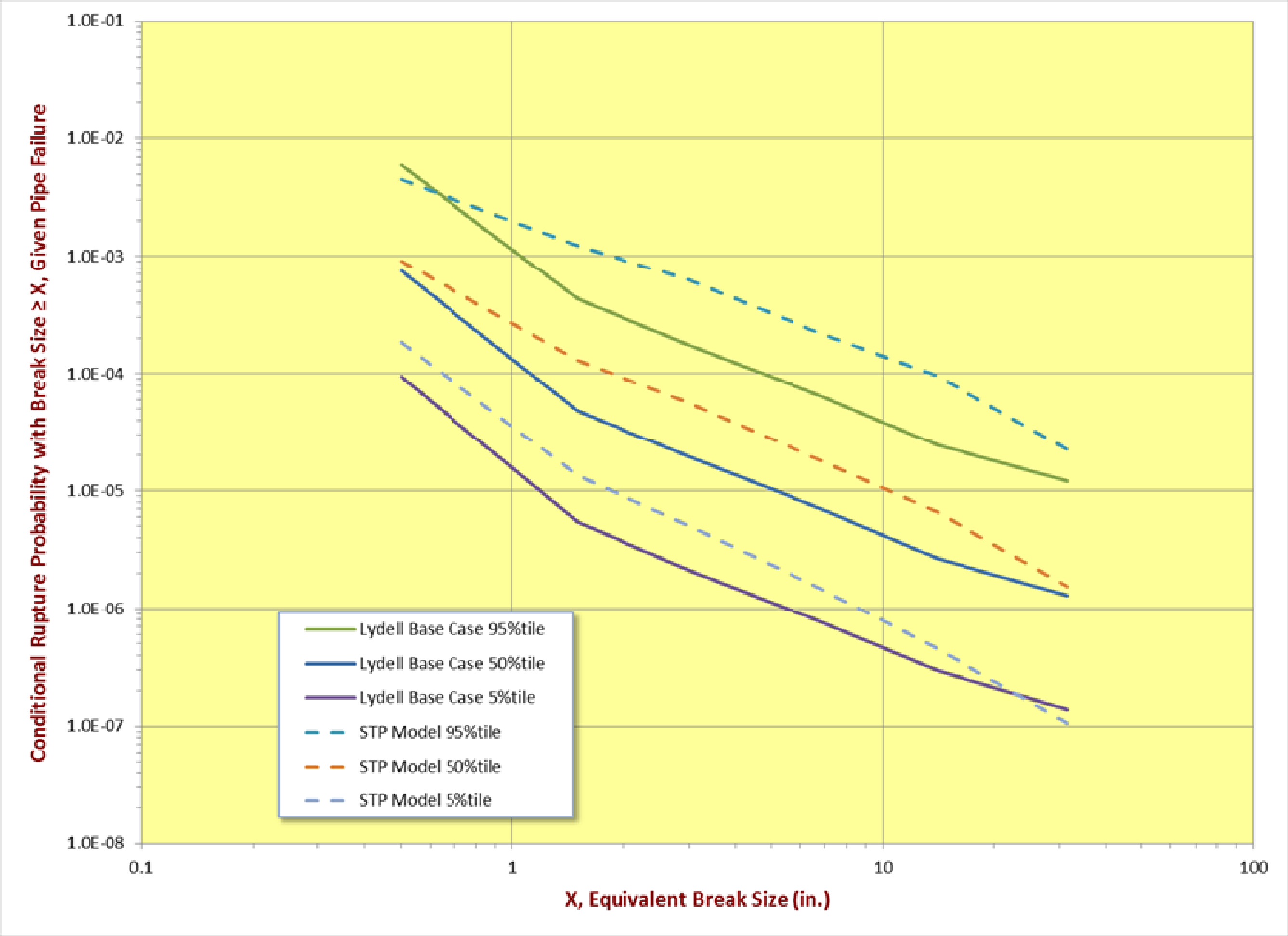
- Target LOCA frequency distributions defined as lognormal distributions
- CRP distributions assumed to be lognormal distributions
- Lydell Base Case failure rate distributions fit to lognormal distributions
- Formulas based on lognormal properties used to calculate CRP distribution parameters

Step 2.8 CRP Distribution Parameters

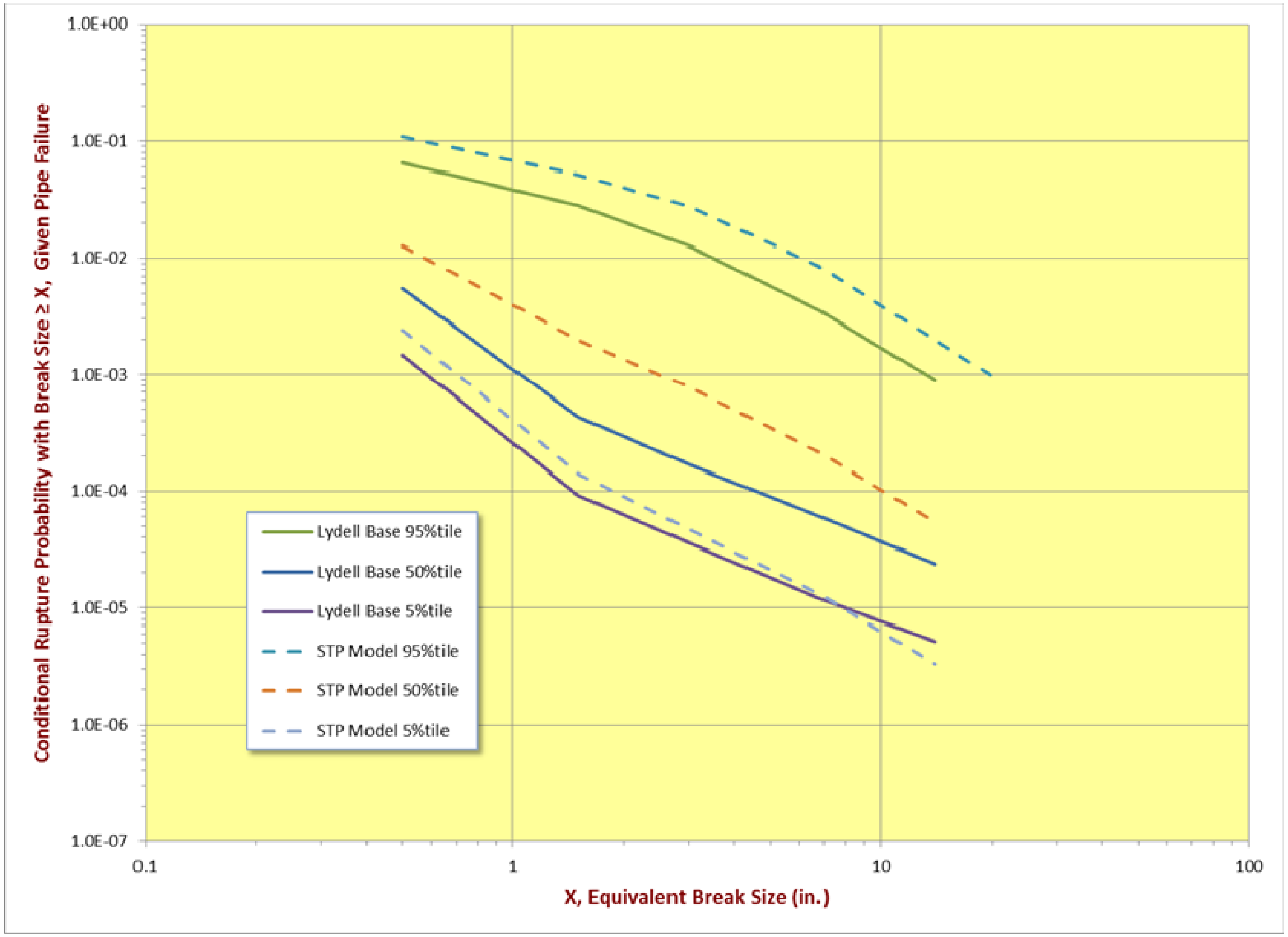
Component	LOCA Category	Break Size (in.)	Conditional Rupture Probability Distribution Parameters				
			Median	Mean	5th Percentile	95th Percentile	Range Factor[1]
Hot Leg	1	≥ 0.5	1.46E-03	1.84E-04	9.10E-04	4.50E-03	4.9
	2	≥ 1.5	3.31E-04	1.35E-05	1.29E-04	1.23E-03	9.6
	3	≥ 3	1.65E-04	5.01E-06	5.61E-05	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
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.

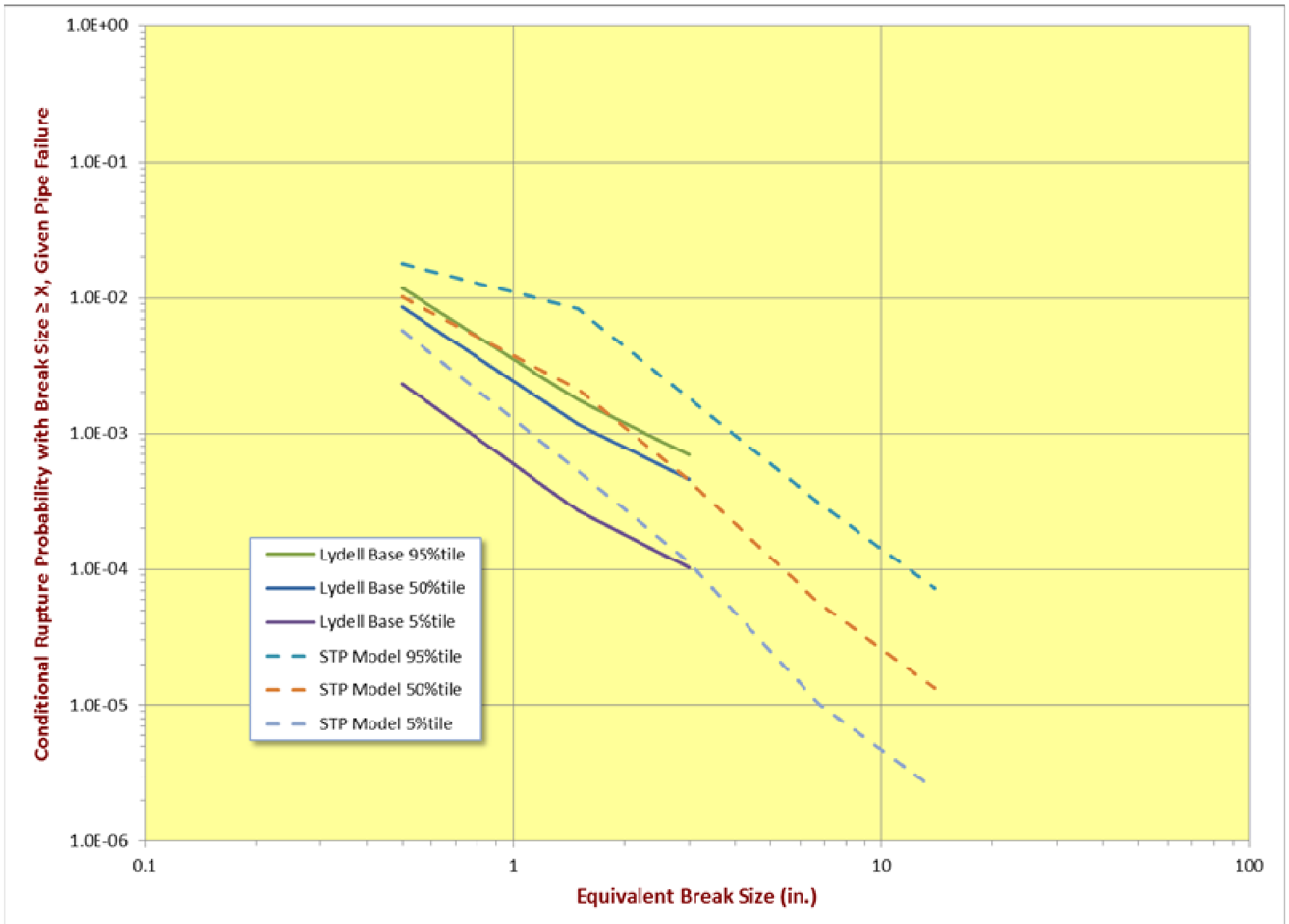
Comparison of CRP Models for Hot Leg – STP vs. Lydell Base Case



Comparison of CRP Models for Surge Line – STP vs. Lydell Base Case



Comparison of CRP Models for HPI Line – STP vs. Lydell Base Case



Step 2.9 Bayes' Update of CRP Distributions

- CRPs from Step 2.8 used as priors
- Bayes' update for each of 8 systems using CRP models
- Evidence is 0 LOCAs out of number of failures for system
- Hot Leg CRP used for Hot leg and SG Inlet

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

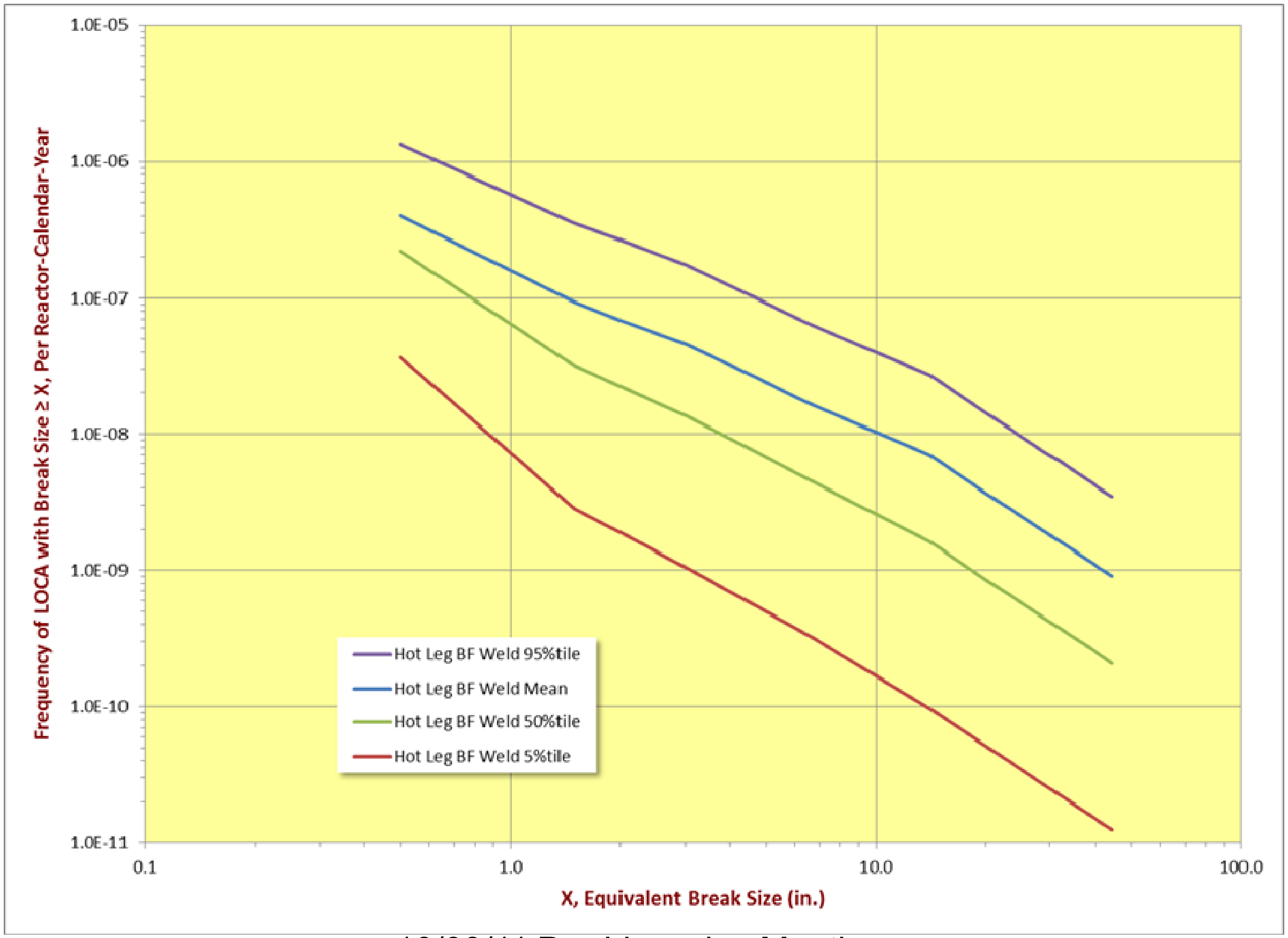
Step 3 STP-Specific LOCA Frequencies

1.	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 - $F(LOCA_x)$

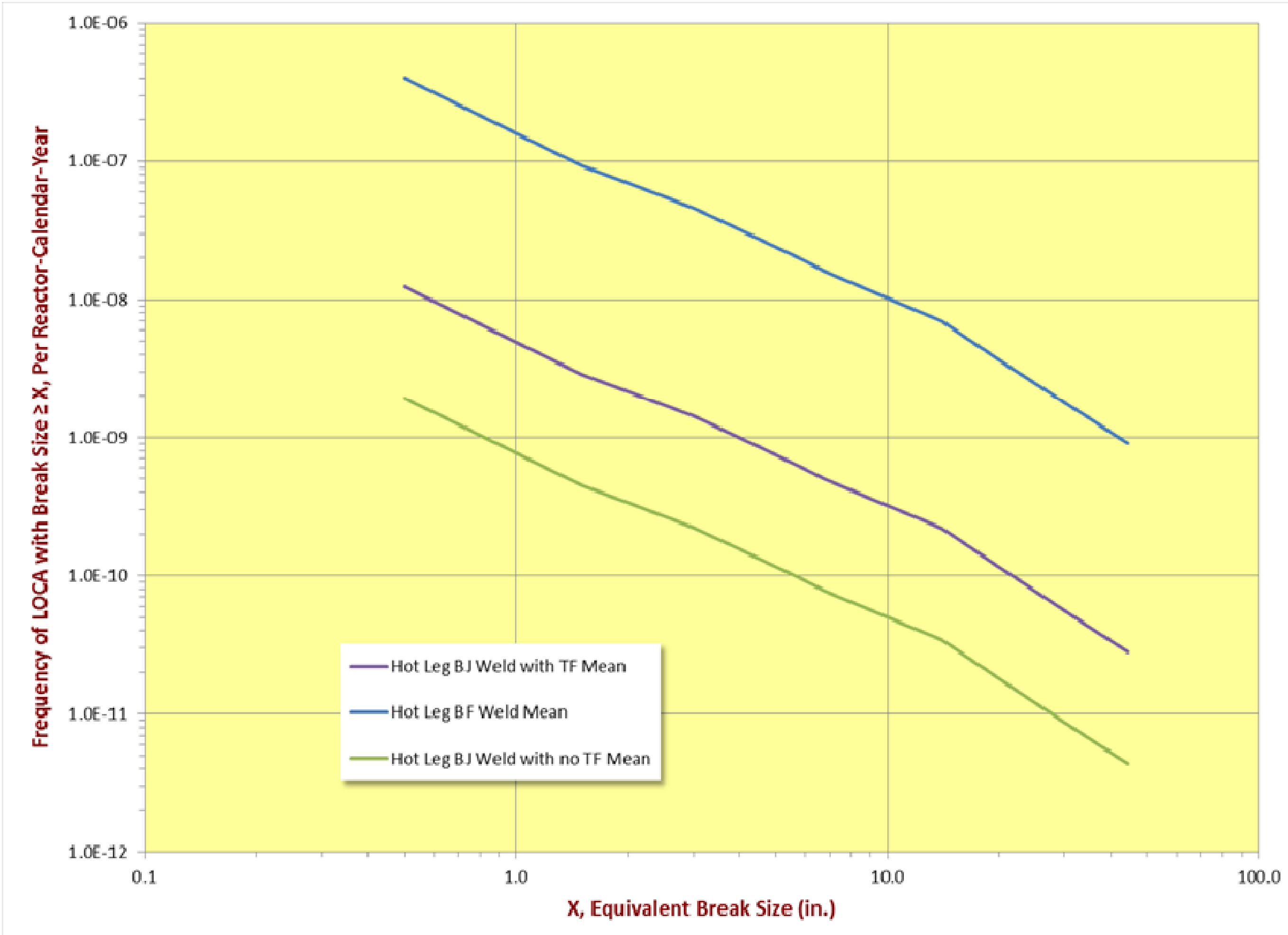
Step 3.3 Combine Failure Rates and CRPs to Produce LOCA Frequencies

- Two methods used:
  - Monte Carlo simulation integrated with failure rate analysis
  - Use of formulas for combining two lognormal distributions
- Calculation of total LOCA frequencies based on correlation of CRP model distributions (use of common CRP models)

Example Results – Hot Leg B-F Weld at RPV Nozzle



Comparison of Mean LOCA Frequencies for Hot Leg Weld Types



Form of LOCA Frequencies for CASAGRANDE

- Different results for each of 45 component categories
- Example results for large pipes

Calc. Case	1A		1B		1C		2		3A		3B		3C		3D	
System	Hot Leg		Hot Leg		Hot Leg		SG Inlet		Cold Leg		Cold Leg		Cold Leg		Cold Leg	
Size Case (in.)	29		29		29		29		27.5		31		27.5		31	
DEGB (in.)	41.01		41.01		41.01		41.01		38.89		43.84		38.89		43.84	
Weld Type	B-F		B-J		B-J		B-F		B-F		B-F		B-J		B-J	
DM	SC, D&C		D&C		TF, D&C		SC, D&C		SC, D&C		SC, D&C		D&C		D&C	
No. Welds	4		11		1		4		4		4		12		24	
	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	4.02E-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
	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
	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
	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
	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
	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
	6.75	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
	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
	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
	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
	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
	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

(Highlighted) DEGB Frequency

STP Results for Initiating Event Frequencies LOCAs from Pipe Breaks

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

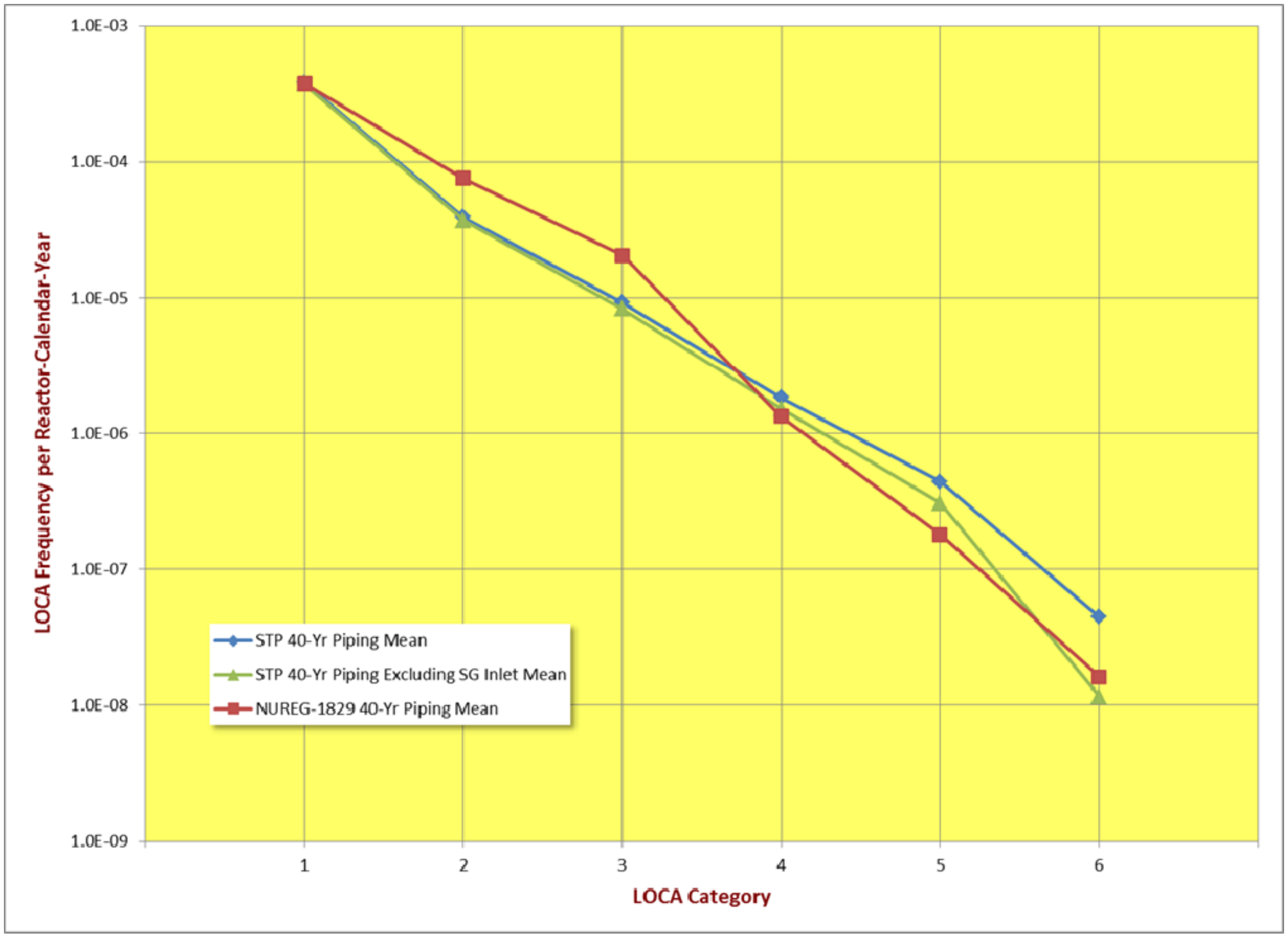
Notes:

[1] Small, Medium, and Large LOCA categories consistent with STP PRA model; Categories 1-6 defined in NUREG-1829 (see Table 4-1).

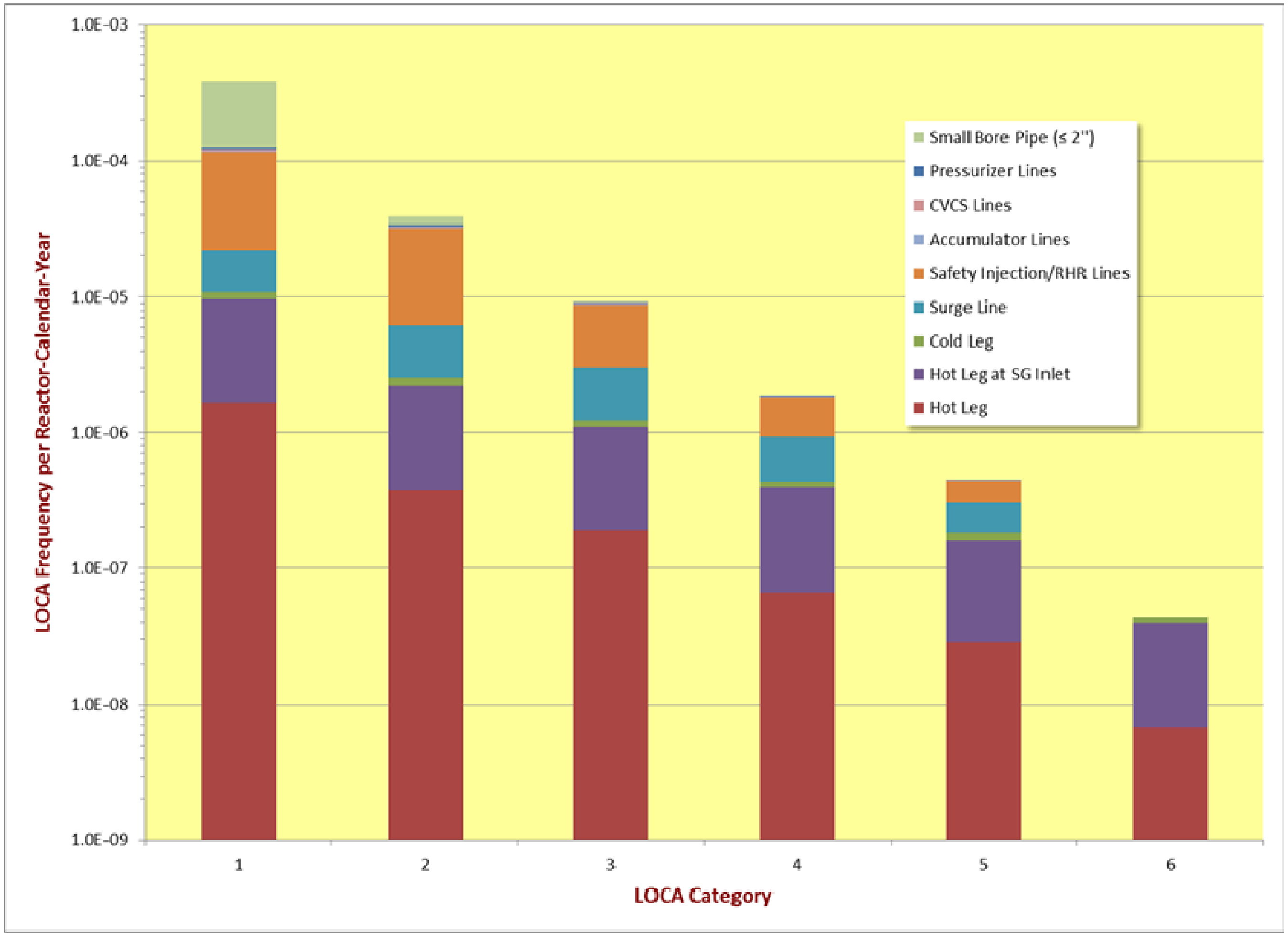
[2] Point estimate obtained with mean failure rate and CRP lognormal distributions and weld counts.

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

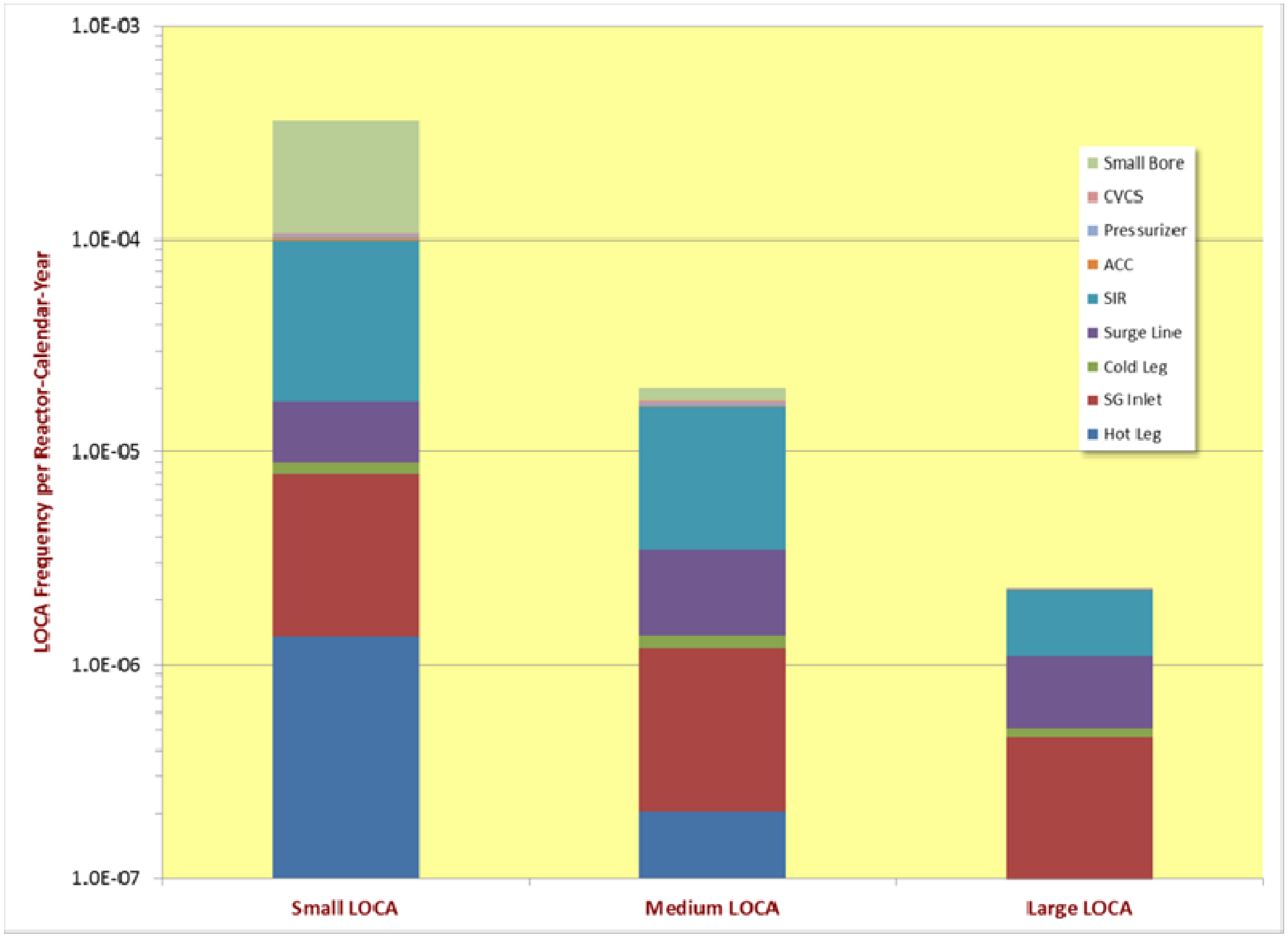
Comparison STP Pipe Induced Mean LOCA Frequencies with NUREG-1829



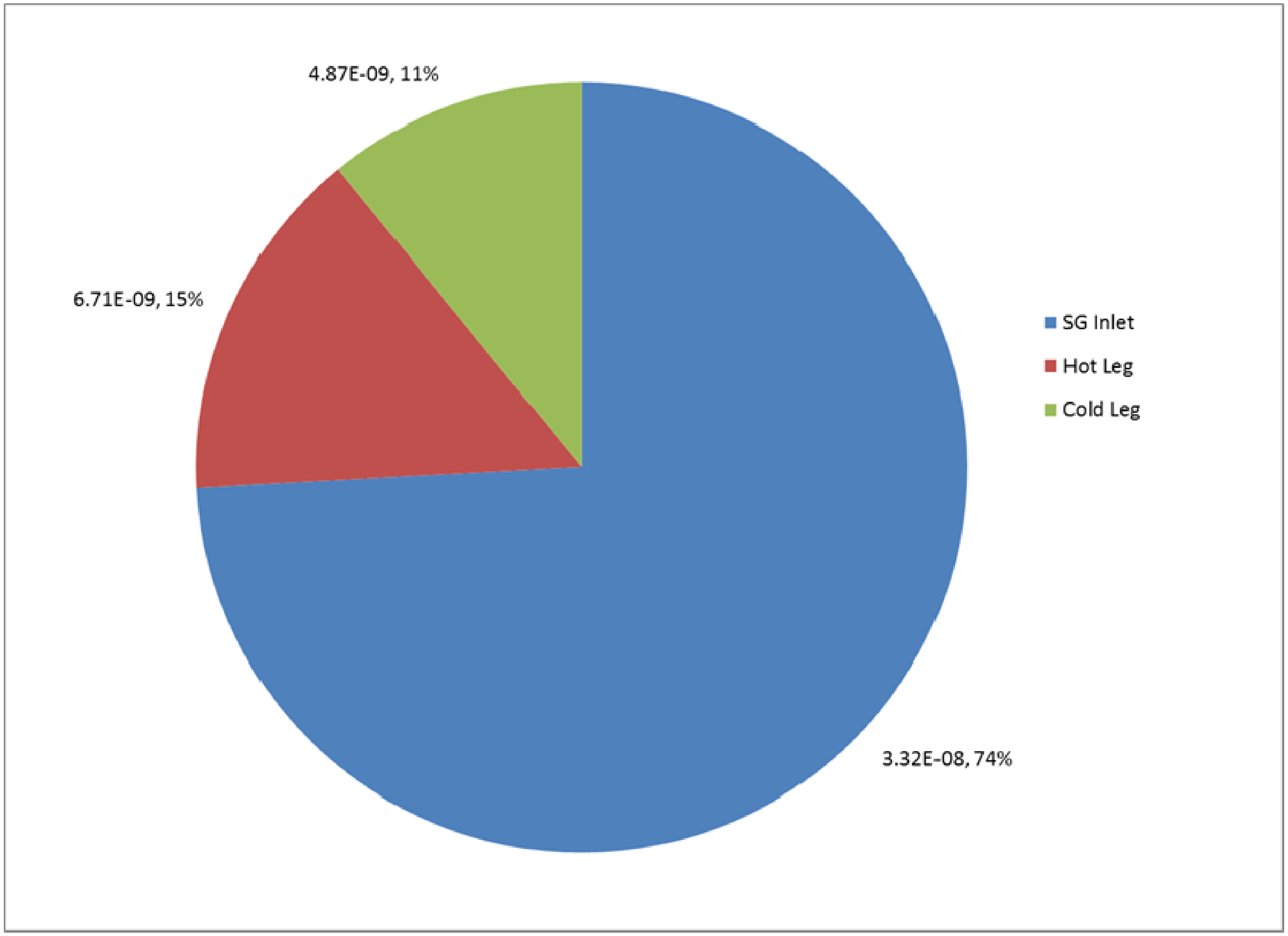
System Contributions to STP LOCA Category Frequency



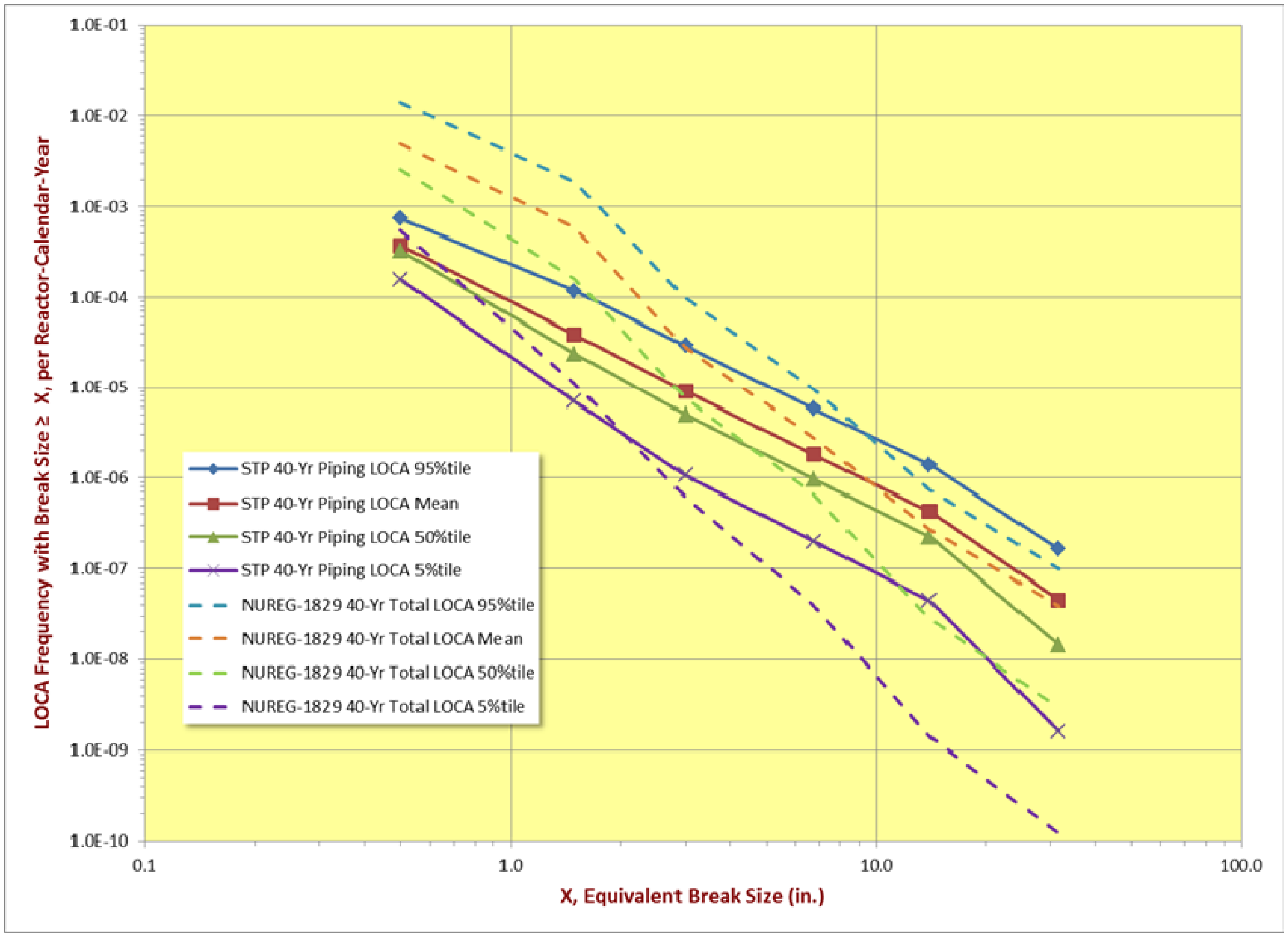
System Contributions to STP LOCA Initiating Events



Contributions to LOCA Category 6 Frequency



Comparison of Uncertainties STP Pipe vs. NUREG-1829 Total LOCA Frequency



Key Results Demonstrated

- 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.

Major Tasks for 2012

- 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.