xLPR Modular Code
A Probabilistic Approach to LBB

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GDC-4 and LBB

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- 10CFR50 Appendix A GDC-4 allows local dynamic effects of pipe ruptures to be excluded from design basis if pipe ruptures have extremely low probability of occurrence

- Local dynamic effects include pipe whipping and discharging fluids

- Commission-approved conservative flaw tolerance analyses developed and incorporated in SRP3.6.3 to demonstrate leak-before-break and satisfy GDC-4

- One screening criterion in SRP3.6.3 requires no active degradation mechanism

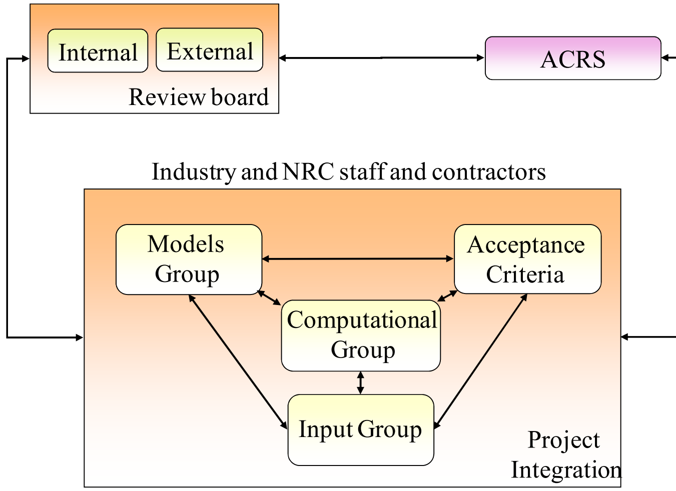
xLPR

Problem / Motivation

- PWSCC is an active degradation mechanism
- LBB approved for piping systems prior to PWSCC operational experience
- LBB systems still in compliance with regulations
- Qualitative: mitigations and inspections
- Quantitative: probabilistic evaluation to assess compliance (xLPR)

xLPR Development

- NRC goal to develop "Modular" code for addressing issues related to Risk of Pressure Boundary Integrity Failure
- Currently focusing on piping issues (xLPR) to solve current LBB need. May be applicable to other needs



- Working cooperatively with EPRI through a Memorandum of Understanding Addendum
- NRC and Industry staff participation in all aspects of code development
- Initial pilot study to assess effectiveness of approach

Team Members

Computational Group
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Nathan Palm – Westinghouse
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xLPR – NRC Intended Use

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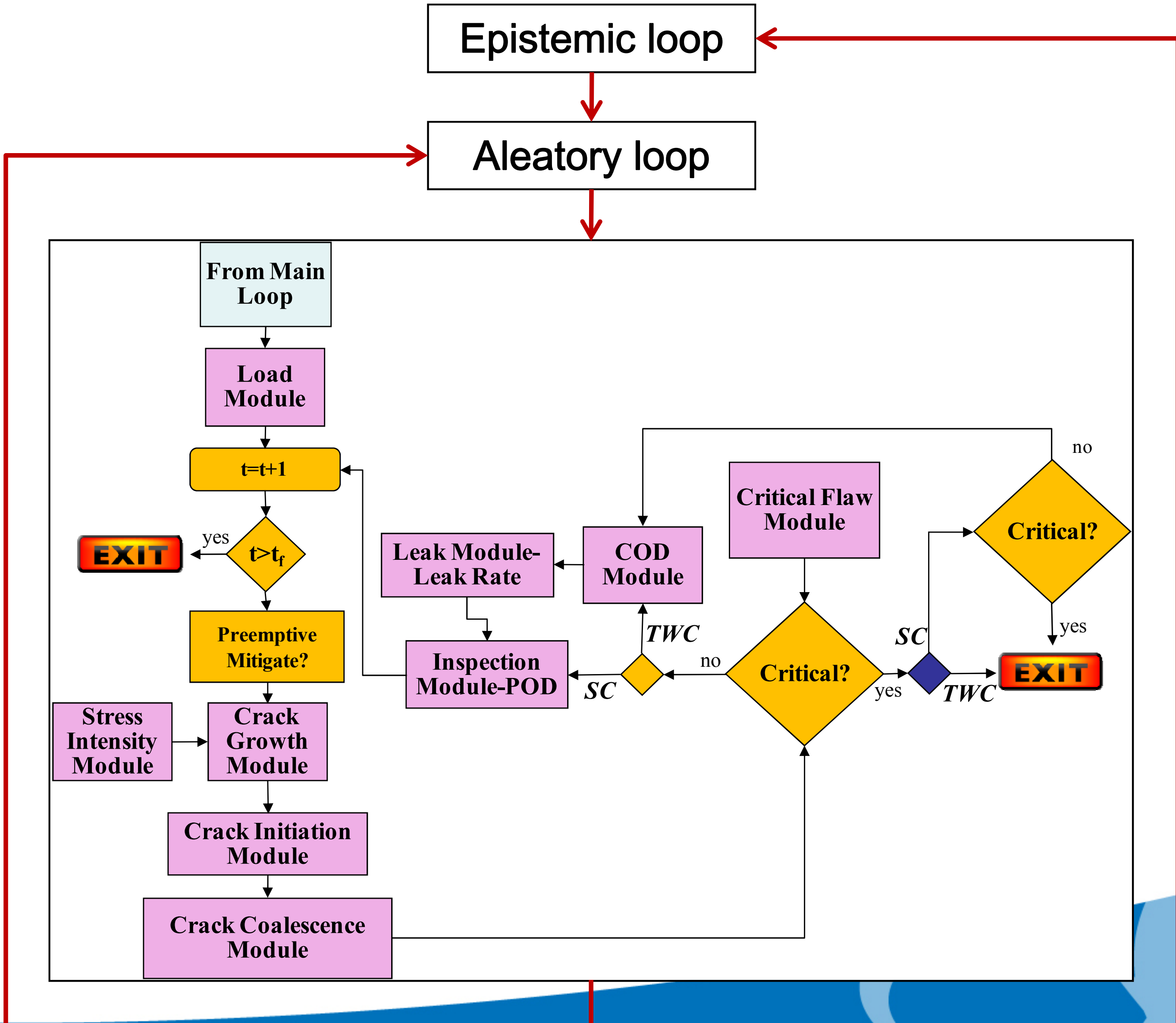
- Version 1.0 – Pilot study – Surge nozzle DM weld
  - To demonstrate feasibility
  - Determine appropriate probabilistic framework
  - Develop plan for future version
- Version 2.0 – Primary piping
  - Support LBB Regulation Guide development
  - Assess compliance with GDC-4
  - Prioritize future research efforts
- Version 3.0 – Reactor coolant pressure boundary
  - Combine piping with reactor vessel, steam generator, etc.
  - Analyze probability of failure for all coolant pressure boundary components

xLPR Process



Purple boxes represent self-contained, independent modules

Epistemic – Lack of Knowledge uncertainty

Aleatory – Irreducible uncertainty

Probability of leak/rupture

Version 1.0 Models Description

Crack Initiation

Several models are available for initiation probability

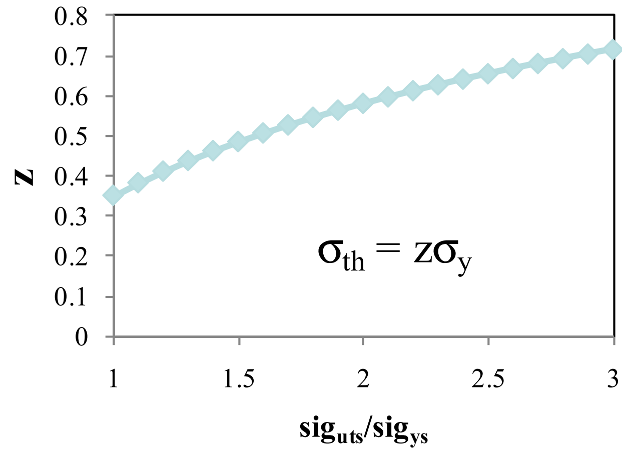
A.) Direct Approach

$$\frac{1}{t_I} = Ae^{-Q/RT}\sigma^n \quad (\sigma > \sigma_{th})$$

σ_{th} = 137MPa (20ksi)

$$t_I = Be^{Q/RT}\ln[(D-z)/(\sigma/\sigma_{ys}-z)]$$

$$where\ B = B_I m^q \ln[D]/\ln[(D-z)/(1-z)]$$



B.) Weibull

$$P(t_I < t) = 1 - e^{-(t/C)^3}$$

$$C = C_1 e^{Q/RT}\sigma^{-n}$$

- Capable of handling zinc/hydrogen changes, but not implemented

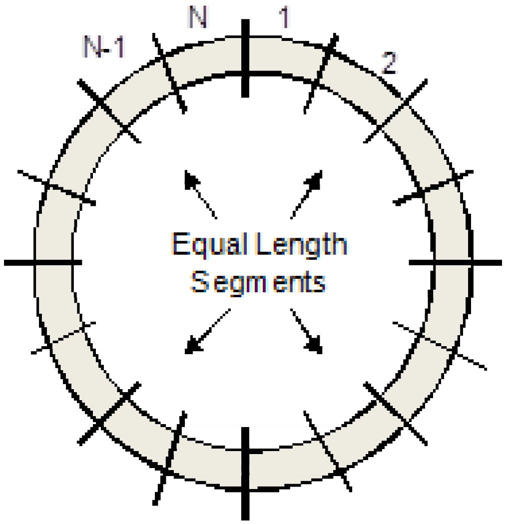
Models Description

Crack Initiation

- For Version 1.0, models are "calibrated" to MRP-216 surge nozzle data and base WRS

Pressurizer Nozzle DMW Inspections (mid 2007)			
Nozzle	# inspected	# circ cracks	# axial cracks
Surge	10	5	2
Safety	20	1	4
Relief	6	1	2
Spray	7	0	0

0.01 cracks/year



- Multiple circumferential crack initiation allowed
- Axial cracks added in Version 2.0

Models Description

Crack Growth from MRP-263

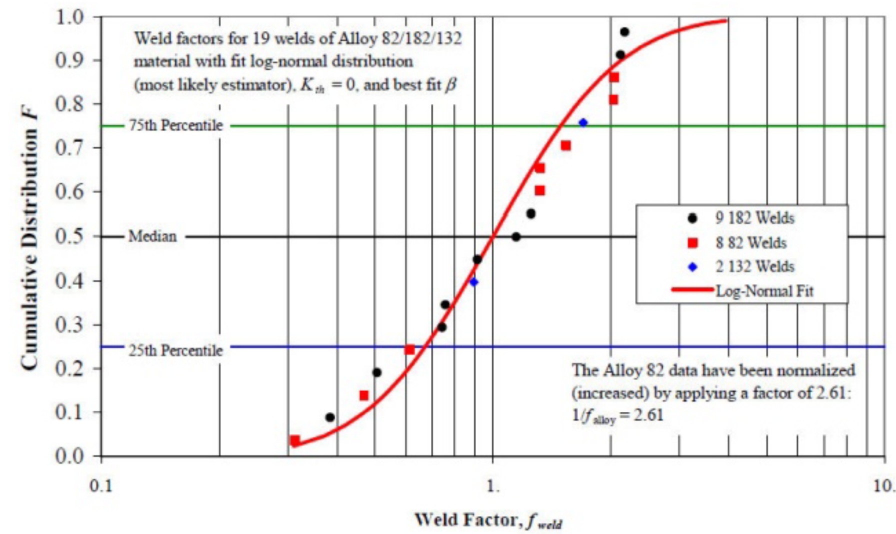
$$CGR = \exp\left[-\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]\alpha f_{weld}(K-K_{th})^{\beta}\left[\frac{1}{P}+\frac{(P-1)}{P}\exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^{2}\right)\right]$$

For $K<K_{th}$, CGR=0

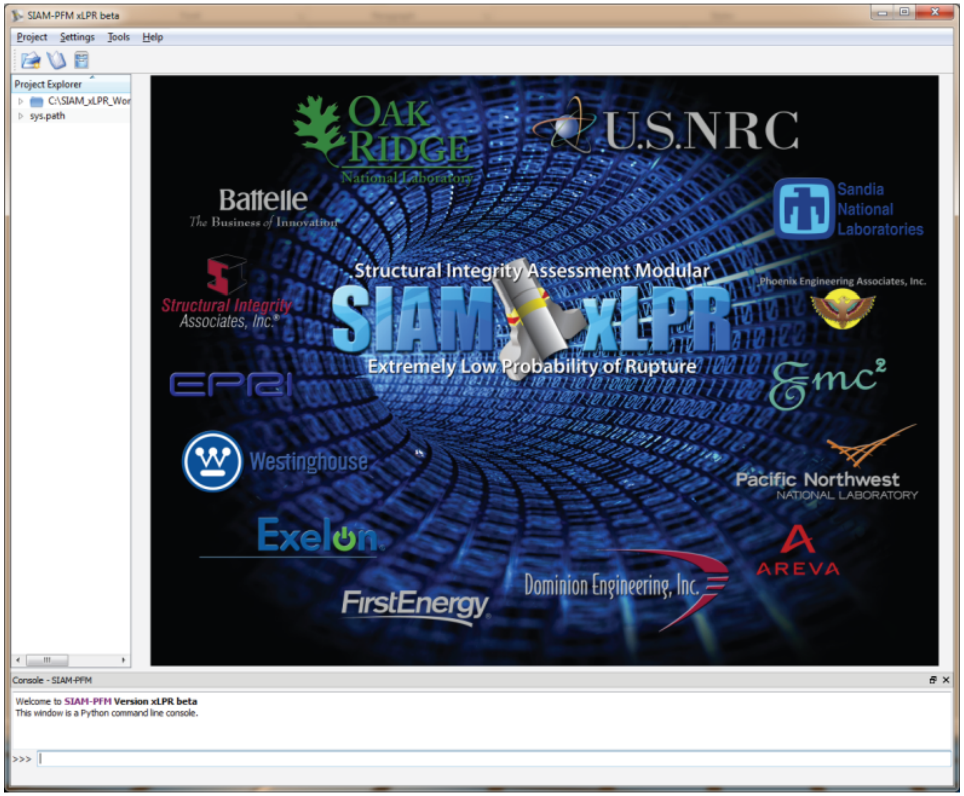
$$\Delta ECP_{Ni/NiO} = 29.58\left(\frac{T+273.15}{298.15}\right)\log\left(\frac{[H_2]}{[H_2]_{Ni/NiO}}\right)$$

$$[H_2]_{Ni/NiO} = 10^{(0.0111T-2.59)}$$

CGR	=	crack growth rate at temperature T in m/s
Q_g	=	thermal activation energy for crack growth = 130 kJ/mole
R	=	universal gas constant = 8.314×10^{-3} kJ/mole-K
T	=	absolute operating temperature at the crack location in K
T_{ref}	=	absolute reference temperature to normalize data = 598.15K
α	=	power law constant = 2.01×10^{-12}
K_{th}	=	threshold crack stress intensity factor = 0.0 $MPa\text{-}m^{0.5}$
β	=	exponent = 1.6
H_2	=	25 cc/kg-STP



xLPR Framework



Fully Open Source

GoldSim Commercial Code

Pilot Study Problems

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Analysis	Description
Probabilistic Base Case	Probabilistic base case analysis using Monte Carlo sampling.
Sensitivity Study	
Stress Mitigation	Analyses evaluate different mitigation times, for the same stress-based mitigation.
Chemical Mitigation	Chemical effects of increasing the hydrogen concentration in the water on the crack growth module. Three hydrogen concentrations were evaluated.
Crack Initiation	Considers the crack initiation model uncertainty.
Safe End Evaluation	Considers stainless steel safe end weld, which causes a through-thickness bending stress that can reduce the tensile inner-diameter stress.

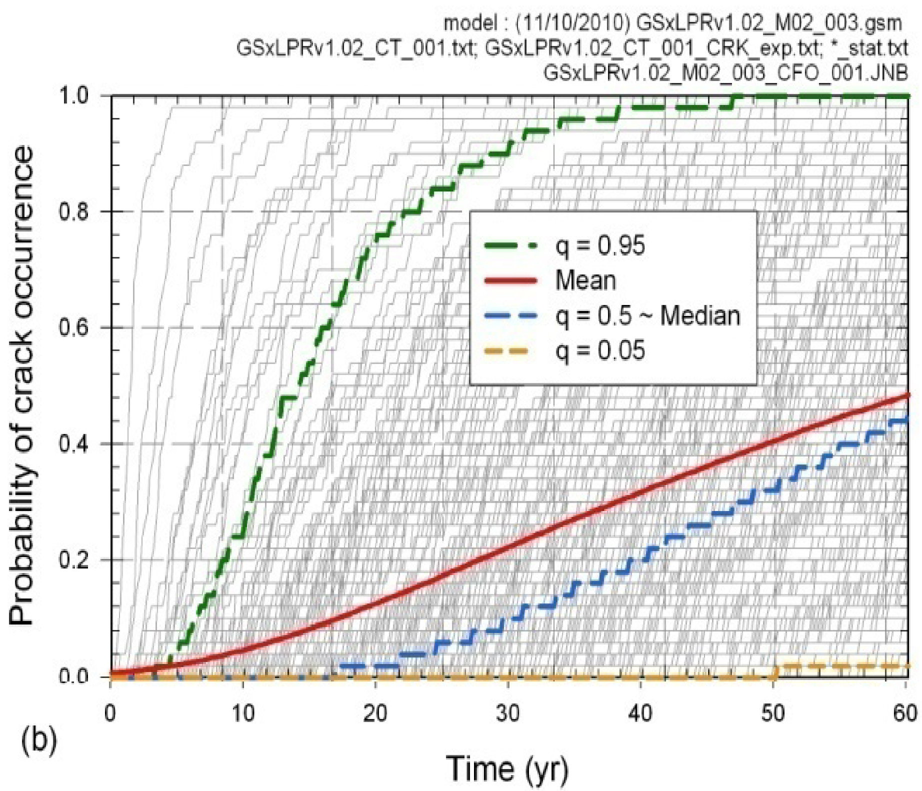
Uncertainty

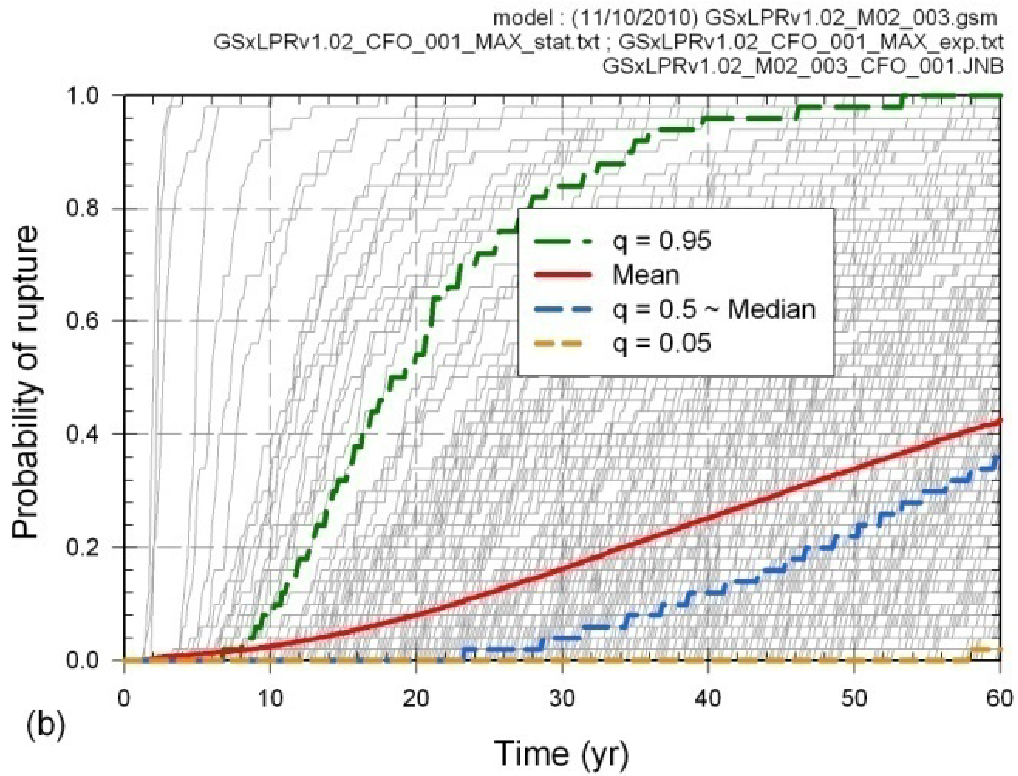
- Uncertainties were classified by models/inputs group
- More discussion needed, but satisfactory for pilot study

Epistemic (Lack of knowledge)	Aleatory (Irreducible)
• Loads • WRS • Crack growth (fweld) • Crack initiation parameters • POD parameters	• Crack size • POD detection • Material properties • Crack growth parameters (Q/R,c,P)

- Currently uses LHS (epistemic) and MC (aleatory)
- Importance sampling was demonstrated

Base Case Results





Problem is driven by crack initiation!!

Grey lines represent individual epistemic realizations

Base Case Results

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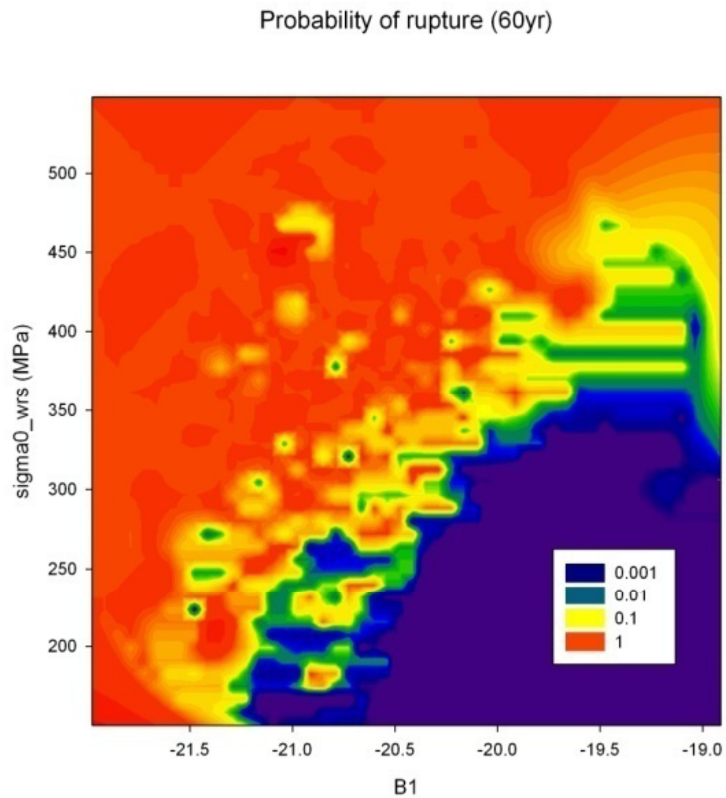
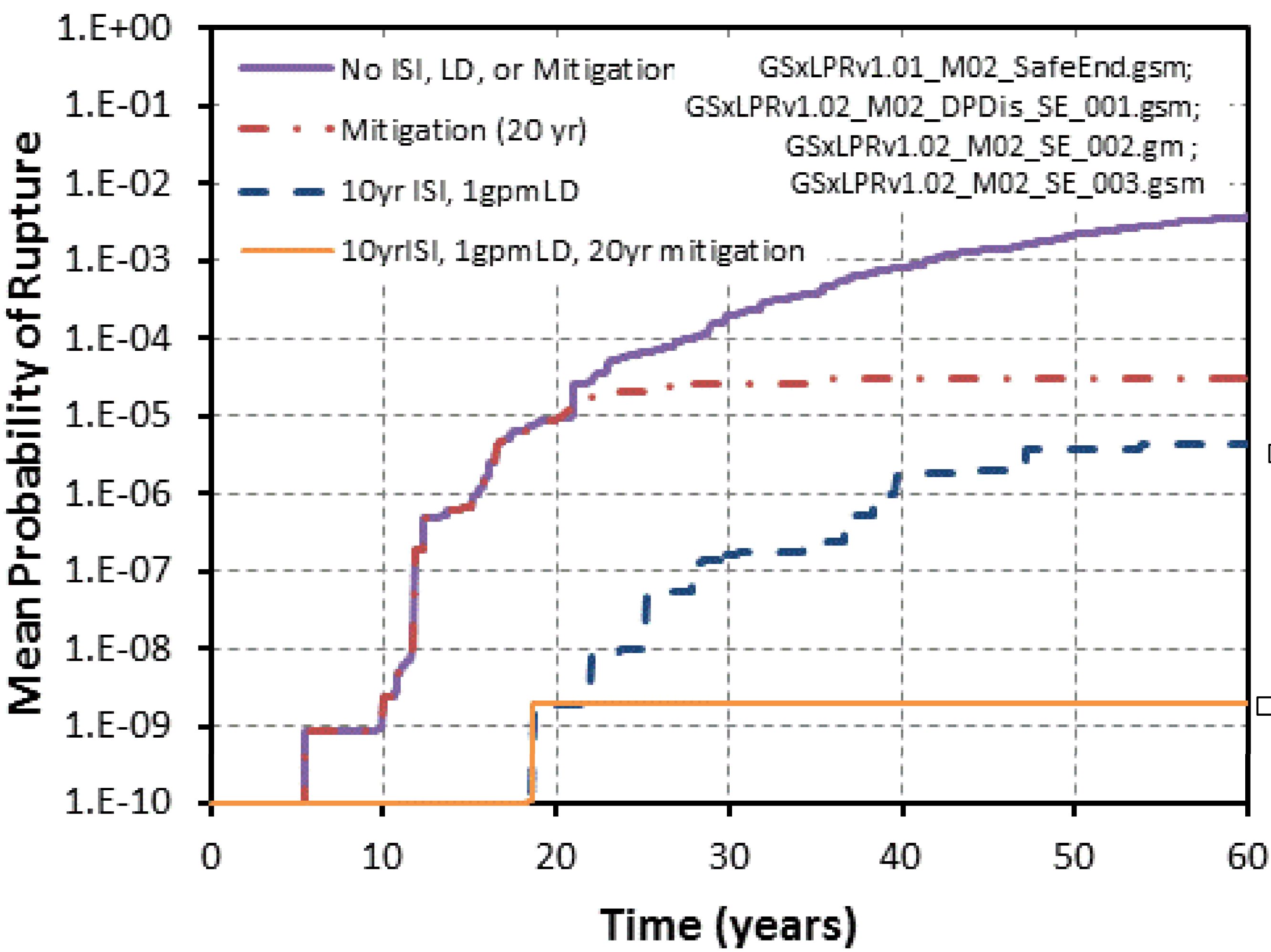
Sensitivity analyses were conducted to determine driving variables

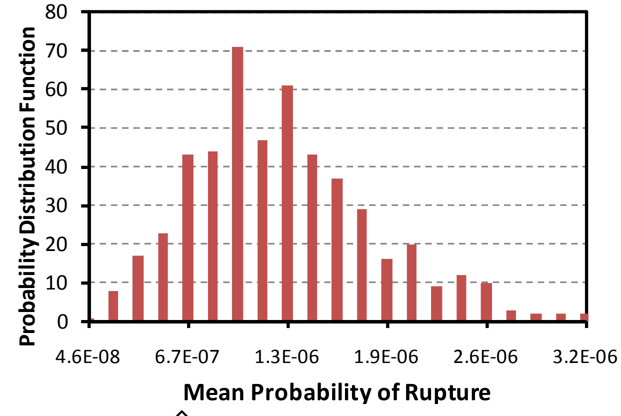
EXPCFO: 50 yr				EXPCFO: 60 yr			
var.	R^2	R^2 inc.	SRRC	var.	R^2	R^2 inc.	SRRC
SIG0WRS	41.80%	41.80%	0.5363	SIG0WRS	43.90%	43.90%	0.5764
B1	57.10%	15.30%	-0.3299	B1	60.70%	16.80%	-0.3568
FWELD	57.80%	0.70%	0.0701	FWELD	61.60%	0.90%	0.0853
RANDL17	58.00%	0.20%	0.0369	RANDP05	61.80%	0.20%	0.0391
				ODRAND	62.00%	0.20%	-0.0358

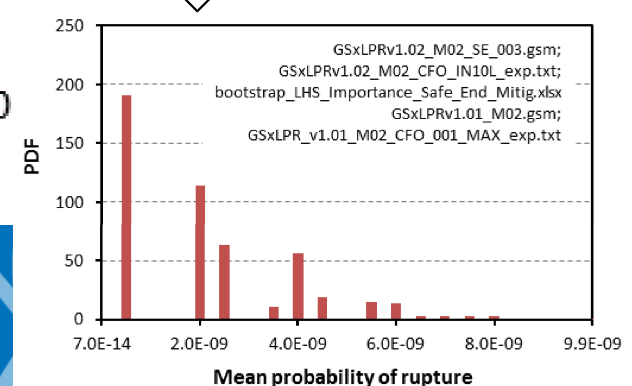


- R^2 - how much of the output variance is explained with the current input and all previous inputs
- The incremental R^2 - how much variance is explained by the addition of this input
- SIG0WRS – ID weld residual stress
- B1 – crack initiation parameter

Safe End Sensitivity Case







Pilot Study Results

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- The project team demonstrated that **it is feasible** to develop a modular-based probabilistic fracture mechanics code within a cooperative agreement while properly accounting for the problem uncertainties

- The project team demonstrated that the cooperative management structure was promising, but recommends a code development leader be selected and the PIB be restructured as an advisory committee

Pilot Study Results

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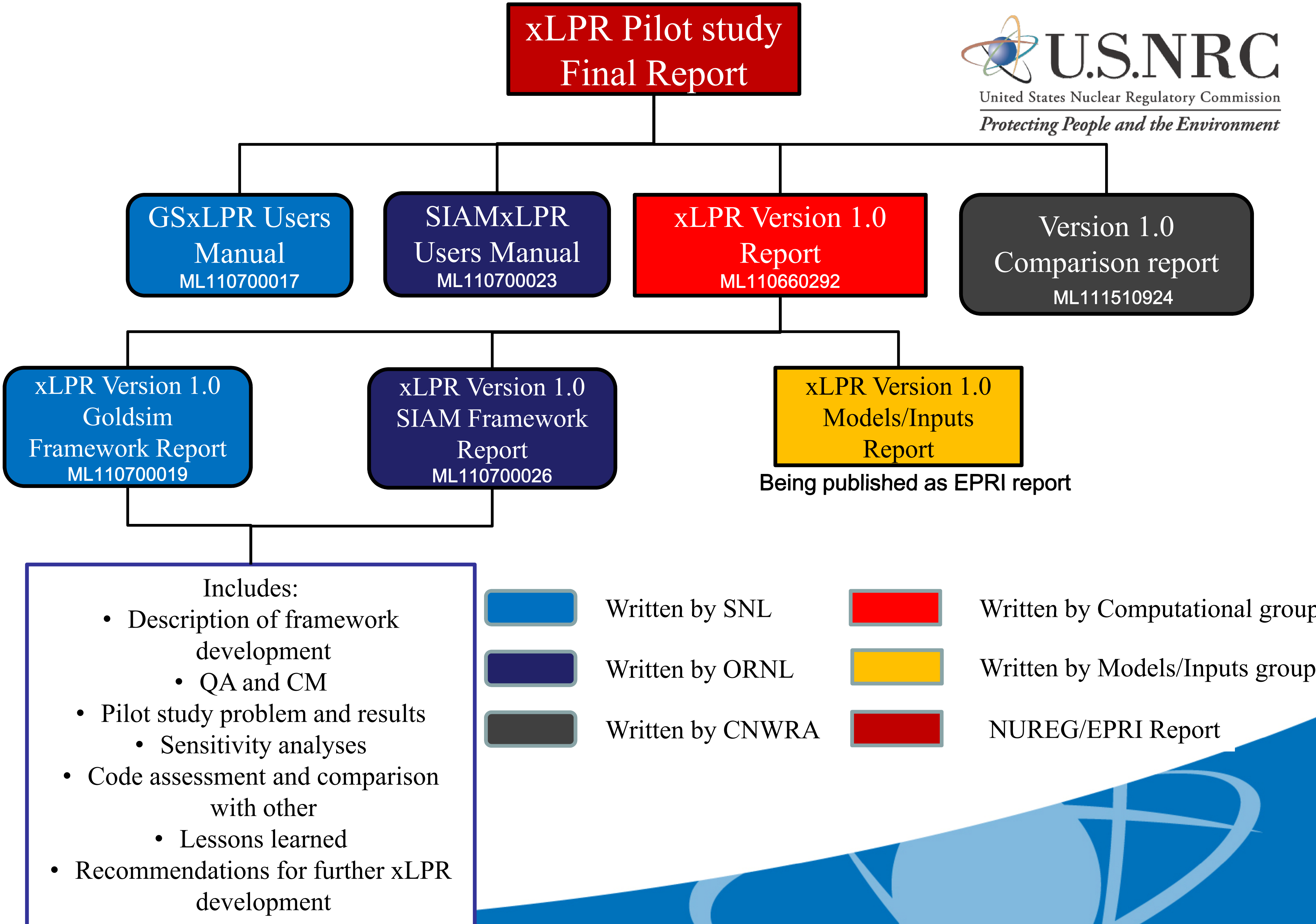
- Based on the framework code comparison, a cost analysis, and long term prospects, the xLPR project team recommends that the future versions of xLPR be developed using the GoldSim commercial software as the computational framework


xLPR Pilot study Final Report
GSxLPR Users Manual ML110700017
SIAMxLPR Users Manual ML110700023
xLPR Version 1.0 Report ML110660292
Version 1.0 Comparison report ML111510924
xLPR Version 1.0 Goldsim Framework Report ML110700019
xLPR Version 1.0 SIAM Framework Report ML110700026
xLPR Version 1.0 Models/Inputs Report
Being published as EPRI report
Includes:
• Description of framework development
• QA and CM
• Pilot study problem and results
• Sensitivity analyses
• Code assessment and comparison with other
• Lessons learned
• Recommendations for further xLPR development
Written by SNL
Written by ORNL
Written by CNWRA
Written by Computational group
Written by Models/Inputs group
NUREG/EPRI Report

Path Forward

- Project management restructuring - underway
- Version 2.0 QA program development – underway
- Version 2.0 Model and capability discussions – underway – Focus first on SCC initiation
- Version 2.0 Model development – Sept 2011
- Version 2.0 Framework implementation – April 2012
- Version 2.0 V&V – April 2013
- Version 2.0 release – End 2013