Developmental Efforts for the PRO-LOCA (Piping PFM) Code

Engineering Mechanics Corporation of Columbus

and

Battelle-Columbus

Presented by

David L. Rudland

Prepared by D. Rudland, G. Wilkowski (Emc²), P. Scott and R. Kurth (B-C)

Workshop on LBB in PWSCC Systems

January 9-11 2008

Hilton Washington DC/Rockville, Executive Meeting Center

drudland@emc-sq.com

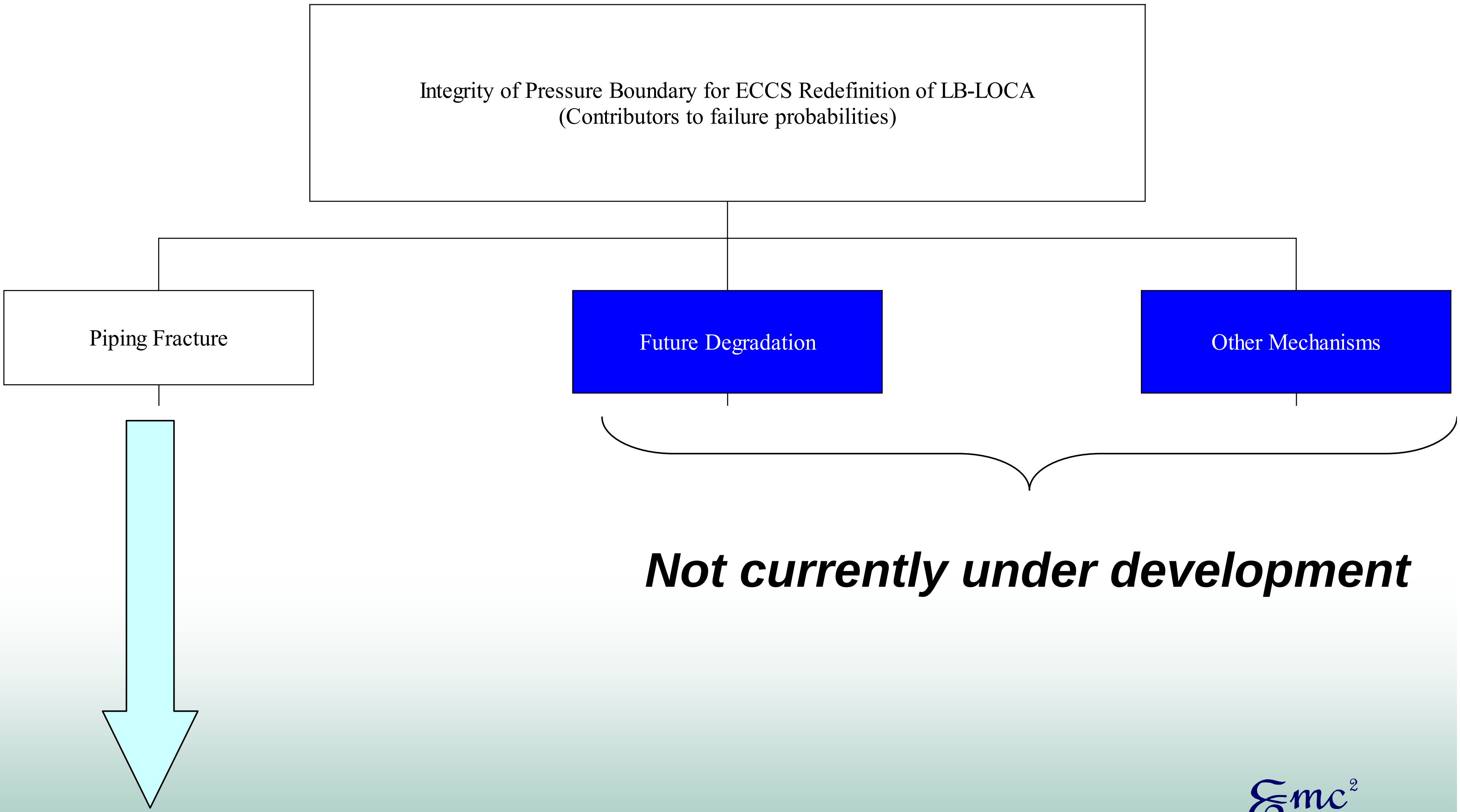
Reasons for Developing PRO-LOCA

- ***NRC is considering a <u>proposed</u> risk-informed revision of the design-basis break size requirements for operating commercial nuclear power plants (<u>draft</u> rule 50.46a)***
- ***Limiting condition considers leak from DEGB of largest piping system in plant – a highly unlikely event***
- ***Need to understand leakage and rupture probabilities as a function of break size to develop a risk-informed design basis break size***
- ***PRO-LOCA is being developed and benchmarked to assist NRC in revision of the break frequencies to support risk-informed activities***
- ***Staff to reassess break frequencies every 10 years, "living estimate"***

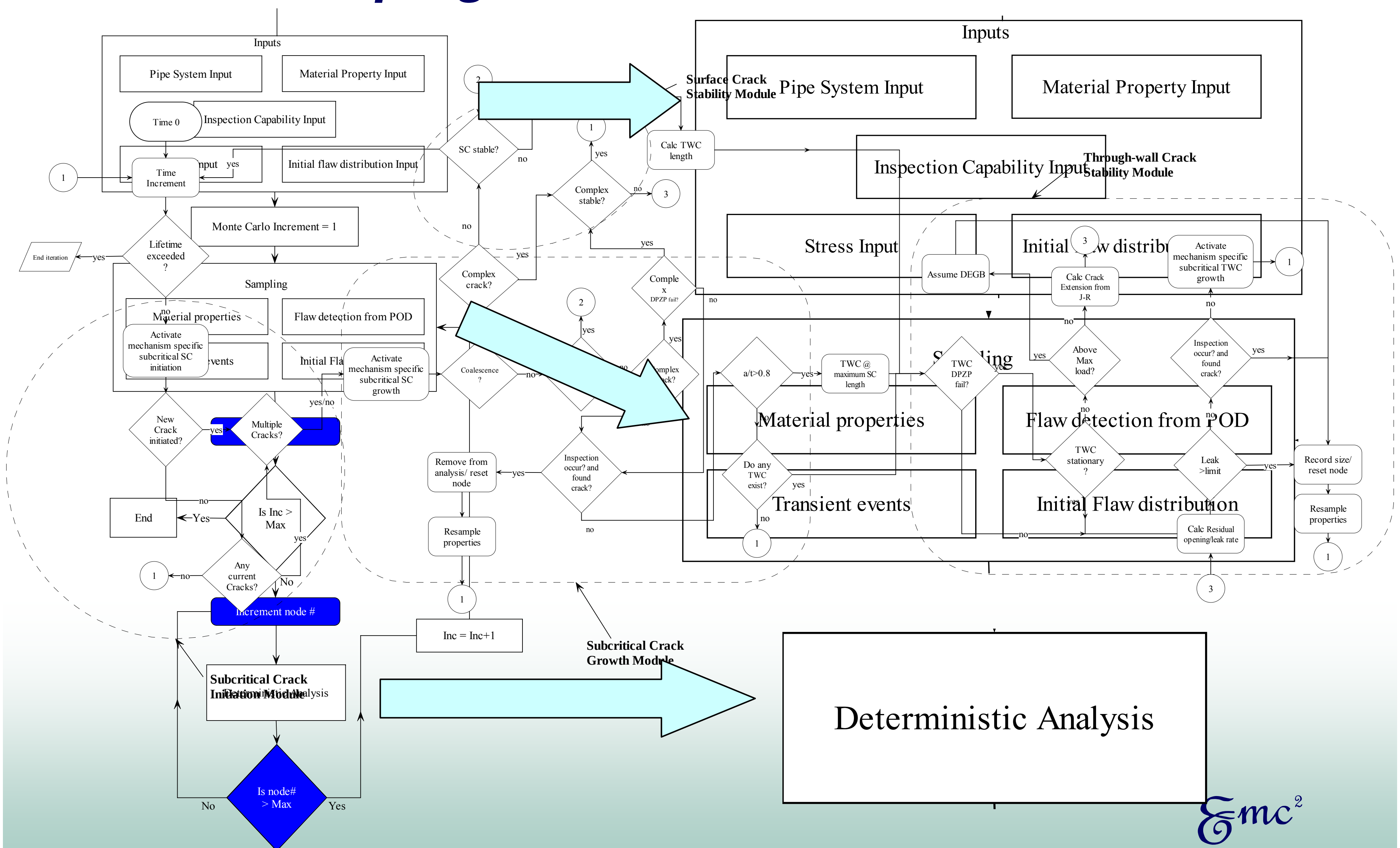
PRO-LOCA Chronology

- ***Late 2002 - NRC asked Battelle/Emc2 to develop PRO-LOCA to aid in a 50.46a revision – LBLOCA Project***
- ***June 2004 – First version of PRO-LOCA delivered to NRC – very basic code***
- ***December 2005 – FY05 version of PRO-LOCA delivered to NRC – Welding residual stress solutions, material property library, advanced transients, multiple crack initiation biasing and other enhancement made.***
- ***February 2006 – MERIT (Maximizing Enhancements in Risk Informed Technology) program started with focus on updating PRO-LOCA***
- ***December 2007 – FY07 version of PRO-LOCA released with Importance Sampling and other updates.***

PRO-LOCA Flow Chart



Detailed Piping Fracture Flow Chart



Emc²

Innovative Structural Integrity Solutions

High Level Comparison of Piping PFM codes

Code	Developer	Mechanisms	Failure probabilities	Notes
PROST	***GRS***	***F***	***L, R***	***Preexisting defects***
PRODIGAL	***Rolls Royce***	***F***	***L, R***	***Preexisting defects***
PROSACC	***DNV***	***F, I***	***L,R***	***In plates***
STRUREL	***Germany***	***F, I***	***R***	***No predefined initiation growth or failure criteria***
SRRA	***Westinghouse***	***F, I***	***L,R***	***Known limitations, MRP116 (WCAP-14572 Rev 1 Sup 1) suggests Praise for better analyses per (2004)***
NURBIT	***DNV***	***I***	***L,R***	***2000***
PRAISE	***Engineering Mechanics Technology***	***F, I***	***L, R***	***1980s – updated continuously***
PRO-LOCA	***Battelle/Emc^2***	***F, I, P***	***L, R***	***2004-5 (Beta only)***

F = fatigue, I = IGSCC, P = PWSCC, L = leak, R = Rupture

Emc^2
Innovative Structural Integrity Solutions

Comparison of Codes

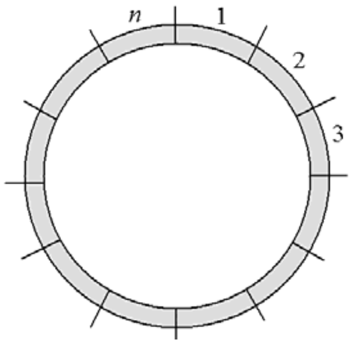
Item	NURBIT	PRAISE	PRO-LOCA
Years in development	***5***	***25***	***3***
PWSCC	***No***	***No****	***Yes***
SCC Crack initiation	***No***	***Yes (questionable)***	***Yes – Statistical based – very conservative***
Multiple crack initiation	***No***	***Yes***	***Yes***
Crack initiation biasing	***No***	***No***	***Yes***
Surface crack K	***Unique K solutions***	***Elliptical – RMS - Harris***	***Elliptical - Anderson***
Surface crack growth	***Driven by unique K***	***Length and depth by*** K_{RMS}	***Length and depth by K – may use correction factors for arbitrary growth***
Crack interaction	***No***	***ASME***	***ASME***

Comparison of Codes

Item	NURBIT	PRAISE	PRO-LOCA
Random SCC crack growth rate?	***No***	***Yes***	***Yes***
SC stability	***R6***	***Limit load/T_{mat}***	***SC.TNP/DPZP***
TWC stability	***R6***	***Limit load/T_{mat}***	***LBB.ENG2/DPZP***
Leak rate/CMOD	***SQUIRT (old Version)***	***Simple model***	***SQUIRT***
Bimetal WRS?	***No***	***No***	***Yes – Library of results***
Probabilistic method	***FORM/SORM***	***MC***	***MC***
Importance sampling	***N/A***	***Yes***	***Yes***
Material Library?	***No***	***No***	***Yes***
Modular code?	***No***	***No***	***Yes***
Analyze past and future behavior?	***No***	***No***	***Yes***

Time Scale and Geometry

- PRO-LOCA Code is divided into time categories
  - Years in operation, Year at design life, Year at extended life
  - Code uses one month time increments with growth rates, etc. assumed constant during time increment



- "Node" or pipe weld is divided into equal subunits

- PRO-LOCA uses a normalized subunit size
  - Size must be based on service experience – very sensitive parameter
  - Currently based on analysis of Nine-Mile Point plant IGSCC data – reviewed in PVP paper, 7.14% of pipe diameter –
  - Needs to be defined per cracking mechanism, i.e., IGSCC, PWSCC may have different subunit size
  - Only one crack is initiated per subunit
  - Subunits are tracked independently

Material Properties

- ***User has two choices for material property inputs – user input or library***
  - ***Material library (PIFRAC) is available (to MERIT TAG) to be used via web***
  - ***Data will be added as received***

	Base Metals	**Weld Metals**
Carbon Steels	A106B	A106B SAW
	A106C	A53 Grade A SAW
	A53 Grade A	A516 Grade 70 SAW
	A333 Grade 6	A106C TIG
	A155	STS 410 TIG
	A516 Grade 70	Generic Carbon Steel Weld
	A710 Grade A	
	STS49	
	STS410	
	Generic Carbon Steel	
Stainless Steel	Type 304	Type 304 SAW
	Type 316	Type 304 SAW (annealed)
	Type 316L	Type 304L SAW
	Generic Stainless Steel	Type 316 SAW
		Type 304 TIG
		Generic Stainless Steel Weld

	Base Metals	**Weld Metals**
Cast Stainless Steel	CF3	CF8M SAW
	CF3A	Generic Cast Stainless Steel Weld
	CF8	
	CF8A	
	CF8M	
	Generic Cast Stainless Steel	
Nickel Alloy	Alloy 600	Alloy 182 Weld
		Alloy 600 TIG
		Generic Nickel Based Alloy Weld

Operating Loads and Stresses

- ***The component stress is defined by***

$$\sigma = \sigma_0 + \sigma_1\left(\frac{x}{t}\right) + \sigma_2\left(\frac{x}{t}\right)^2 + \sigma_3\left(\frac{x}{t}\right)^3 + \sigma_4\left(\frac{x}{t}\right)^4 + \sigma_5$$

where

σ_0 to σ_4 represent the through thickness membrane stress

σ_5 – represents global bending stress – Currently maximum bending stress assumed constant around the circumference

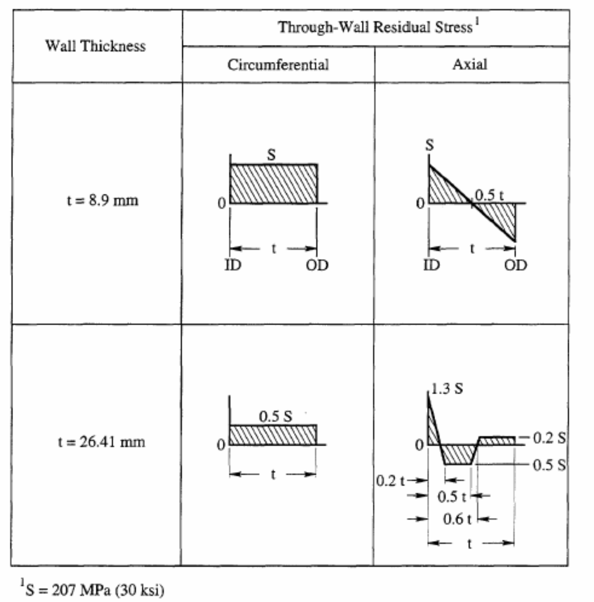
t = wall thickness

x = distance from ID

- ***Total stress is elastic summation of stress components***

Welding Residual Stress

- *Several options are currently available*
  - ***ASME Section XI Article IWB-3660 Rev. A →***
  - ***User input 4th order polynomial***
  - ***Unique solutions developed***
    - ***Hot-leg bimetal weld***
    - ***Surge-line bimetal weld***
    - ***Spray-nozzle bimetal weld***
    - ***Stainless steel weld***
    - ***Solutions with and without last pass welding on ID***
    - ***More to be added***
  - ***Currently all except user input are normalized by yield strength – incorporates a distribution (More precise distribution to being developed)***



Innovative Structural Integrity Solutions

Transients

- ***All transients affect crack initiation, growth and stability***
- ***The transients PRO-LOCA considers includes:***
  - ***Earthquakes***
    - ***Input as constant amplitude (added to normal operating loads) with R = -1, with probability of occurrence per year is input.***
  - ***Vibrations***
    - ***Assumed to be continuous, constant amplitude, constant frequency, R = -1 with Probability of occurrence***
  - ***Start-up and Shut Downs***
    - ***Assumed to occur over one time step***
  - ***Generic Transient***
    - ***Input number of cycles per year, rise time, probability of occurrence, stress ratio (R), assumed constant amplitude***

Pre-existing Flaws

- ***User has option to include pre-existing flaws in welds***
  - ***Flaw frequencies and size distribution are based on M Khaleel, Vic Chapman, Dave Harris, and Fred Simonen "Flaw Size Distribution and Flaw Existence Frequencies in Nuclear Piping" PVP Vol. 386, 1999***
  - ***For arc welding and inert gas welding with both austenitic and ferritic welds***
  - ***With or without pre-service inspection (without inspection frequency = with inspection frequency*12.8)***
  - ***Pre-existing flaw distributions for DM welds to be added***

Deterministic Models

- ***Cracking mechanisms active include corrosion fatigue, IGSCC and PWSCC***

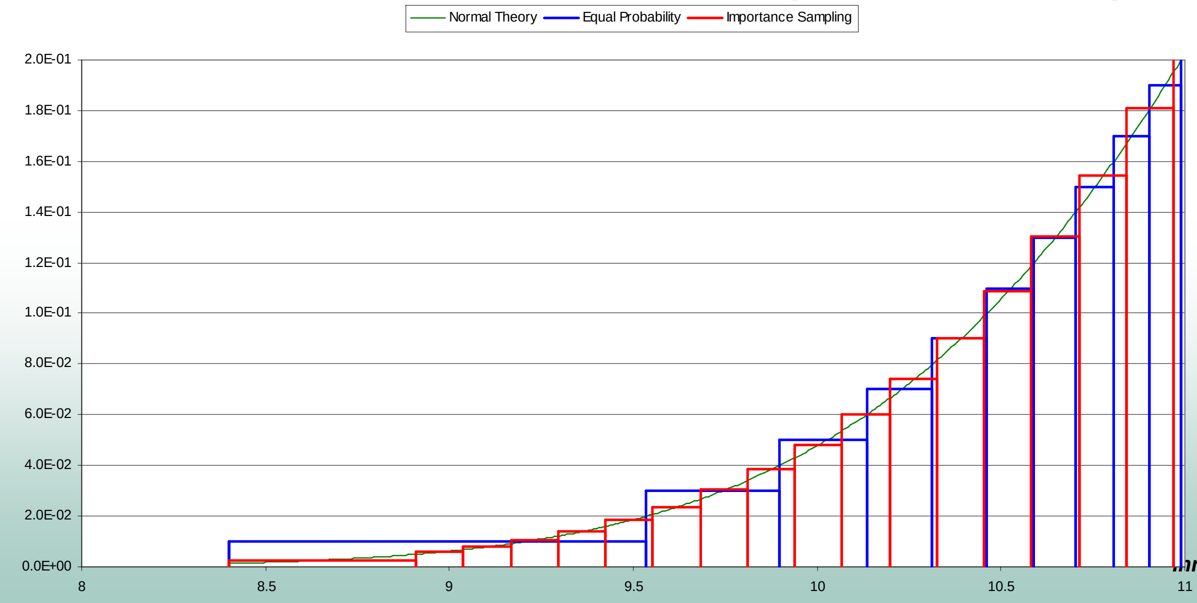
- ***Subcritical Crack Initiation***
  - ***SCC time to initiation models***
    - ***Developed from service history***
    - ***Data fit Weibull distribution – PVP2007-26731***
  - ***Fatigue initiation models developed by ANL (NUREG/CR-6335)***
  - ***Multiple crack initiations***
    - ***Based on service history***
    - ***See PVP2006-ICPVT11-93966***
  - ***User input model, and number of cracks per inch of susceptible material per year to be added.***

Deterministic Models, Cont

- ***Subcritical Crack Growth***
  - ***K-solutions from Anderson (modification for arbitrary crack growth to be added)***
  - ***ANL fatigue crack growth law with distributions (NUREG-6674, and NUREG-6721)***
  - ***MRP SCC crack growth laws with distributions (MRP-115 data may be added) - PVP2007-26731***
  - ***Crack coalescence – per ASME***
  - ***User defined model to be added***
- ***Crack Stability***
  - ***J-estimation scheme from NRC programs (NUREG/CR-6540)***
  - ***LBB.ENG2, SC.TNP, DPZP***
- ***Leak rate limit and inspections***
  - ***SQUIRT – for leak rate predictions***
  - ***User selected inspection periods – Currently crack removal is employed – repair may be added***

Probabilistic Framework

- *FY05 version used Monte-Carlo Simulation only*
- *FY07 version incorporates Importance Sampling as an option*
  - *The* **Probability Density Function** *(PDF) is replaced by a discrete representation of the PDF*
  - *Rather than using* **equal** *probability intervals we use* **unequal** *probability intervals to perform importance sampling*
  - *Since we randomly sample the* bin *not the probability, bins with lower probabilities will be sampled as frequently as higher probability bins*
  - *This allows the stratified PDF to be sampled more frequently in the tails*



Innovative Structural Integrity Solutions

Code Outputs

- ***PRO-LOCA's main output is the probability of occurrence for several size crack opening areas (COA).***
- ***The COA values are binned into categories as shown***

COA	*Effective Opening Diameter*	*LOCA Category*
93.5 mm^2 (0.145 inch^2)	***11 mm (0.43 inch)***	***1***
1,406 mm^2 (2.18 inch^2)	***42.4 mm (1.67 inch)***	***2***
4,690 mm^2 (7.27 inch^2)	***77.3 mm (3.04 inch)***	***3***
23,477 mm^2 (36.4 mm^2)	***173 mm (6.81 inch)***	***4***
100,645 mm^2 (156 mm^2)	***358 mm (14.1 inch)***	***5***
503,225 mm^2 (780 mm^2)	***800 mm (31.5 inch)***	***6***

- ***In addition, the code outputs the probability of crack initiation, and the occurrence of a TWC (Category 0)***

Benchmarking

- **All code modules, i.e., crack growth, stability, leakage, etc. were QA'ed against spreadsheets and other codes.**
- **Some limited benchmarking of PRO-LOCA against PRAISE and NURBIT was conducted with FY05 code.**
- **Further PRAISE benchmarking occurred in NRC program conducted through PNNL and published in PVP2007-26373, PVP2007-26374.**
- **More benchmarking will occur in MERIT program.**

Current Plans for PRO-LOCA

- **PRO-LOCA upcoming enhancements will include**
  - ***Continued work on SCC crack initiation and growth – updated models, subunit work, arbitrary crack shapes, etc.***
  - ***Additional WRS library solutions and development of distributions.***
  - ***A working leak rate model for the transition flow regime between single-phase and two-phase flow conditions and improved crack morphology parameter distributions.***
  - ***New statistically-based material properties will be added.***
  - ***More flexible user inputs.***
  - ***Updated importance sampling and run-time improvements.***
  - ***Benchmarking with other codes and service experience.***
  - ***Any many others!***