Probabilistic Fracture Mechanics Analysis of CRDM Nozzles

Presented at:

NRC – MRP Alloy 600 Meeting
Rockville, MD

Presented by:
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Outline of Presentation

- **Overview of Methodology**
- **Software Modifications**

  (to address comments from 2/21/02 NRC meeting)
- **PFM Analyses in support of MRP RPV Head Penetration Inspection Plan**
  - Susceptibility Categories
  - Inspection Types and Frequencies

Key Elements of RPV Head Nozzle PFM Analysis

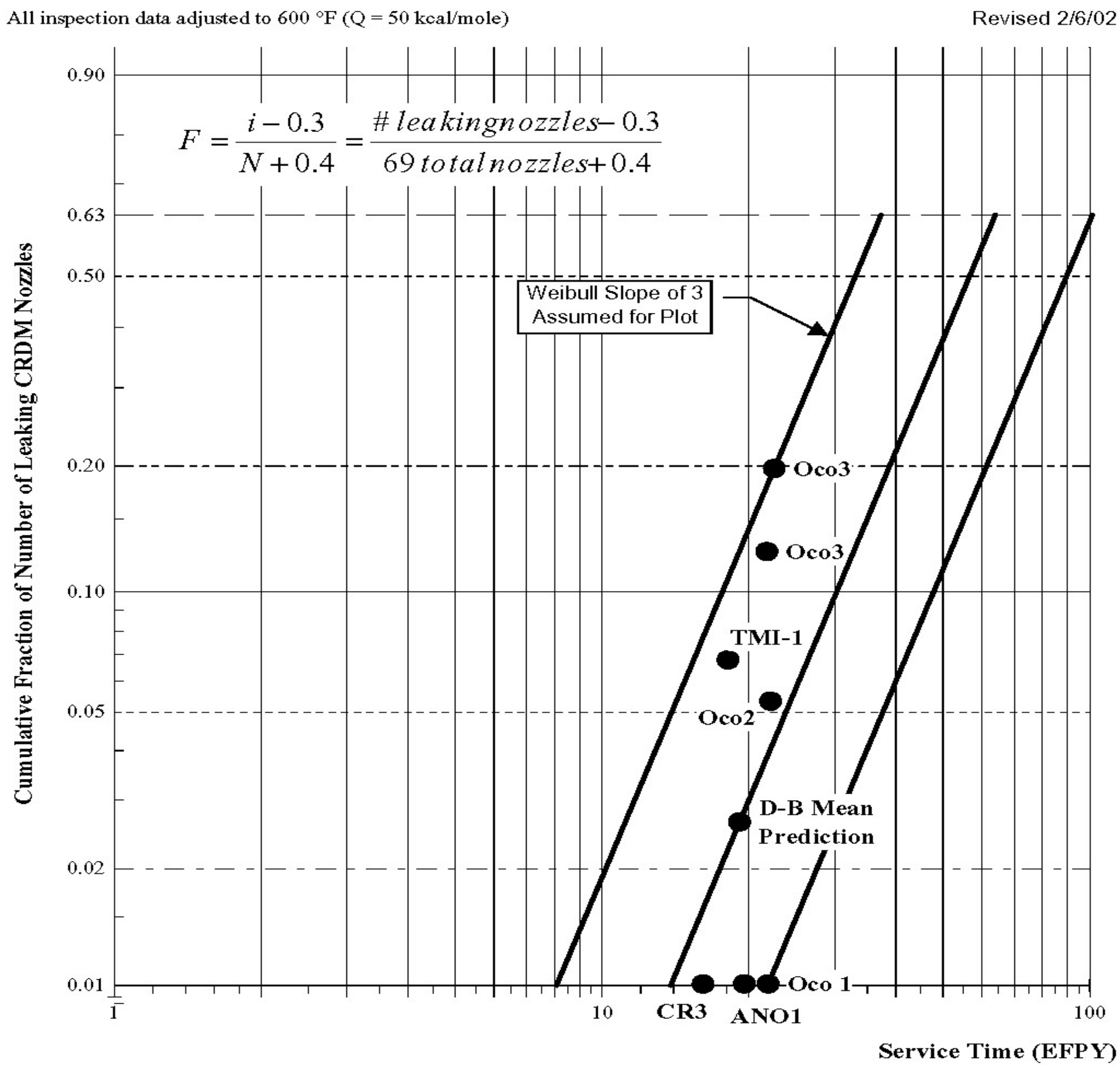
- **Probability of Leakage**
  - Weibull Model based on Experience to Date
  - Incorporated into Monte Carlo Model
- **Fracture mechanics modeling for Stress Intensity Factors**
  - Through-Wall Cracks
  - Part Through Wall Cracks
- **Stress Corrosion Crack Growth Statistics**
- **Effect of Inspections**
  - Inspection Interval
  - Inspection Reliability

Weibull Models for Leakage

- **Analysis by Dominion Engineering – B&W plants w/ Weibull slope of 3**
  - Weibull Slope = 3.0
  - Weibull Theta* = 15.36 (avg.) ; 9.094 (worst case)

*Theta = Characteristic time to 63.3% probability of at least one leak in a head.

Dominion Engineering Weibull Analysis (Beta = 3)



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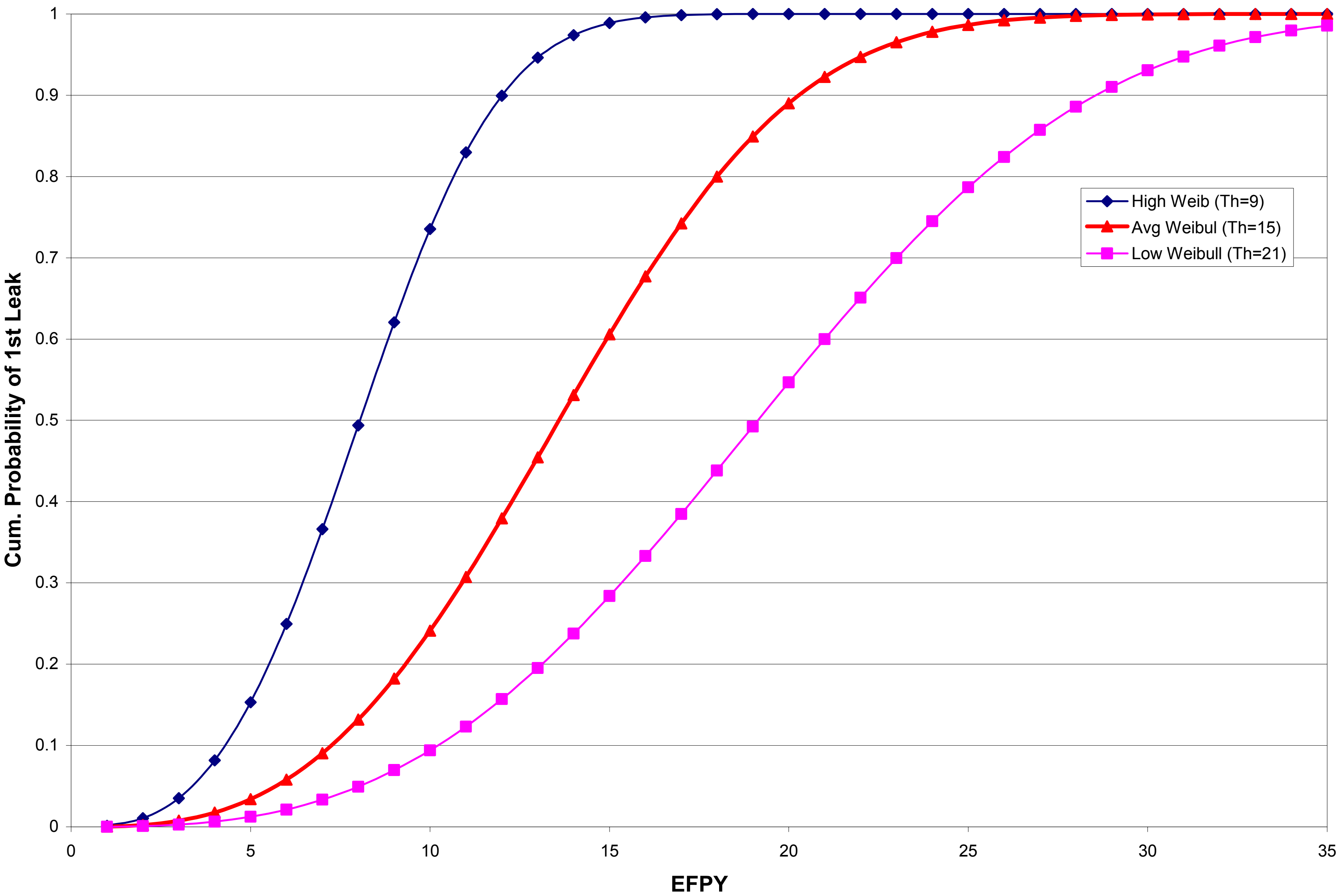
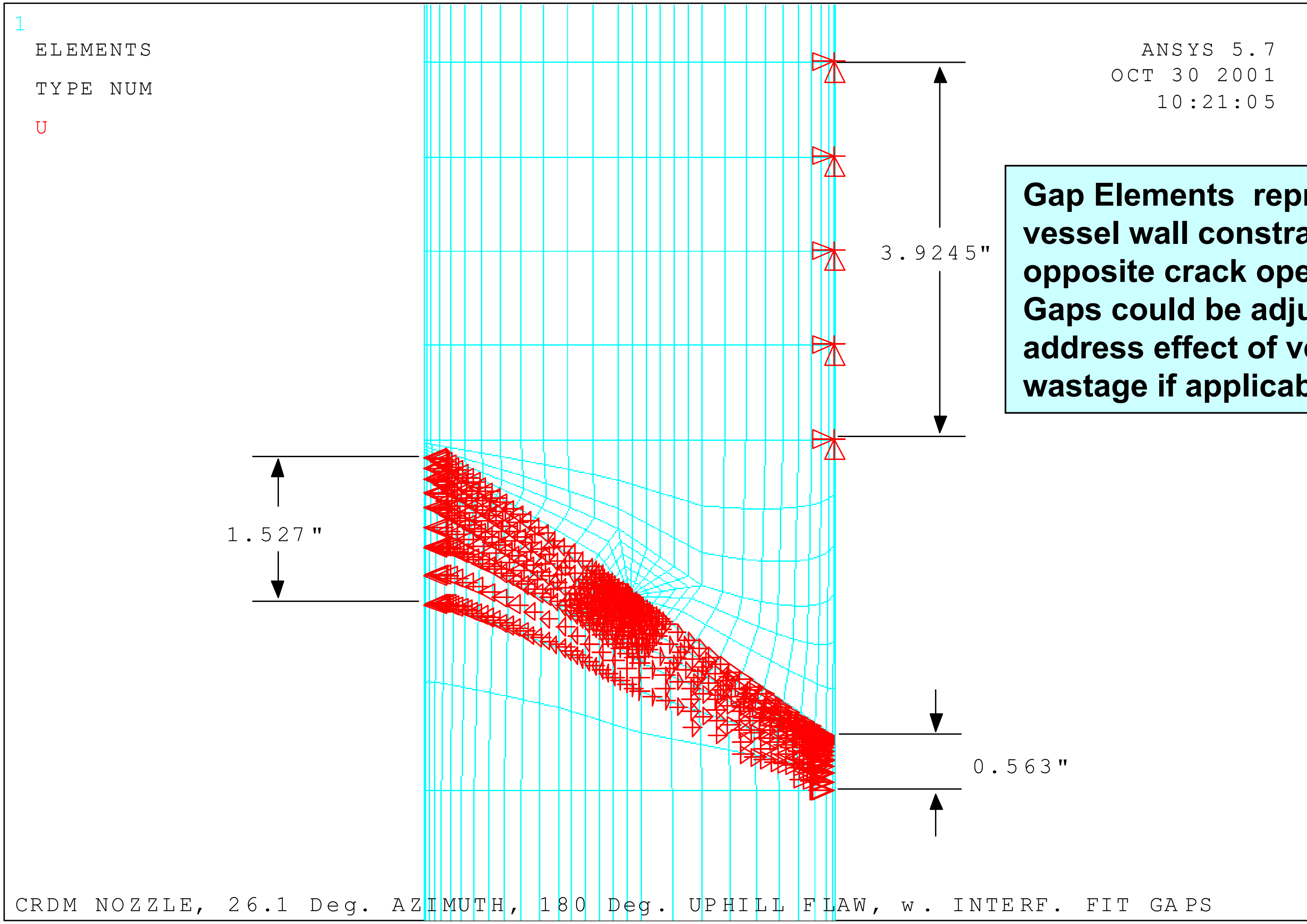
Weibull Distributions used in PFM

β=3; θ=15 $\pm$ 6

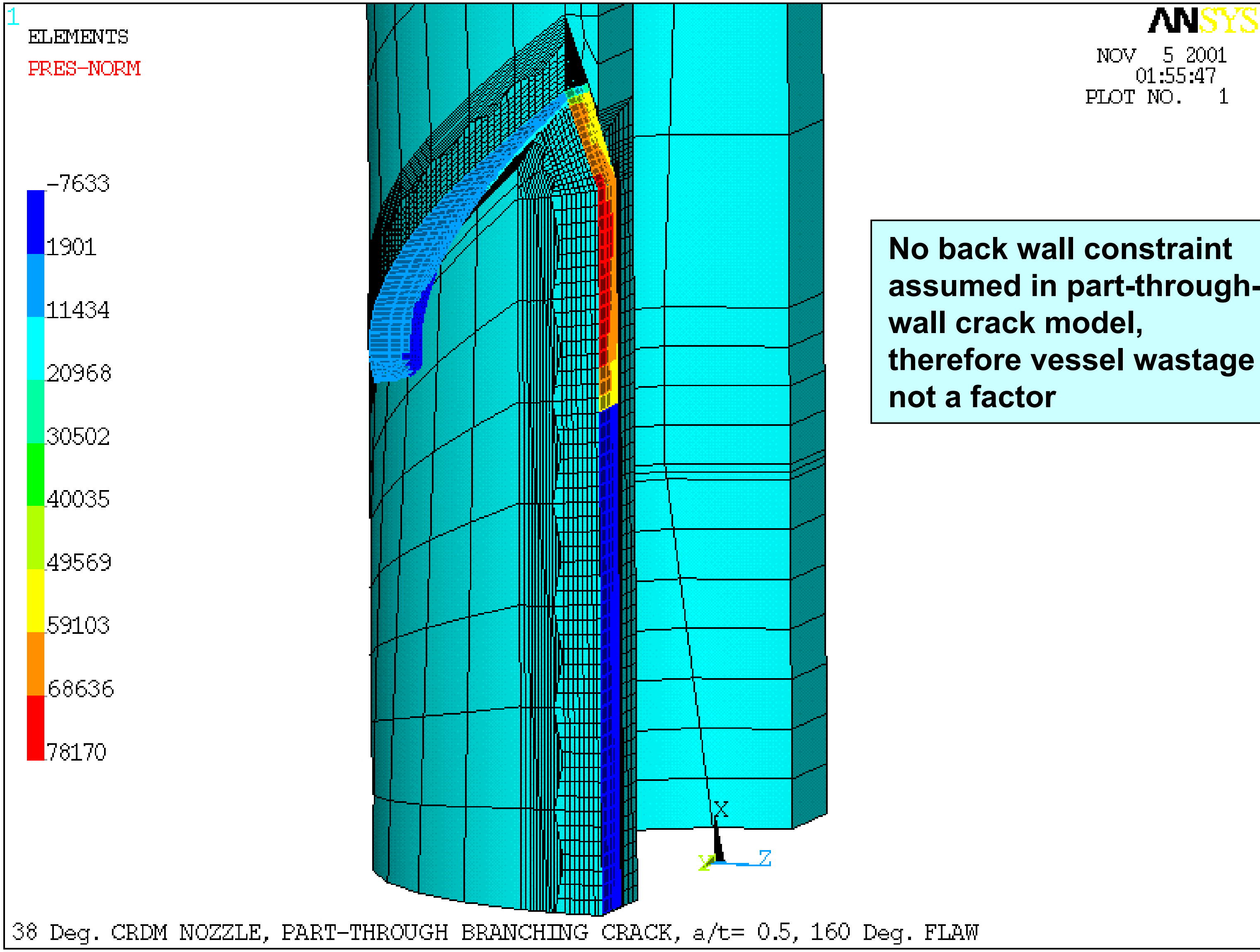


Fracture Mechanics Model
Through-Wall Crack



Gap Elements represent vessel wall constraint opposite crack opening – Gaps could be adjusted to address effect of vessel wastage if applicable.

Part-Through-Wall Flaw Model



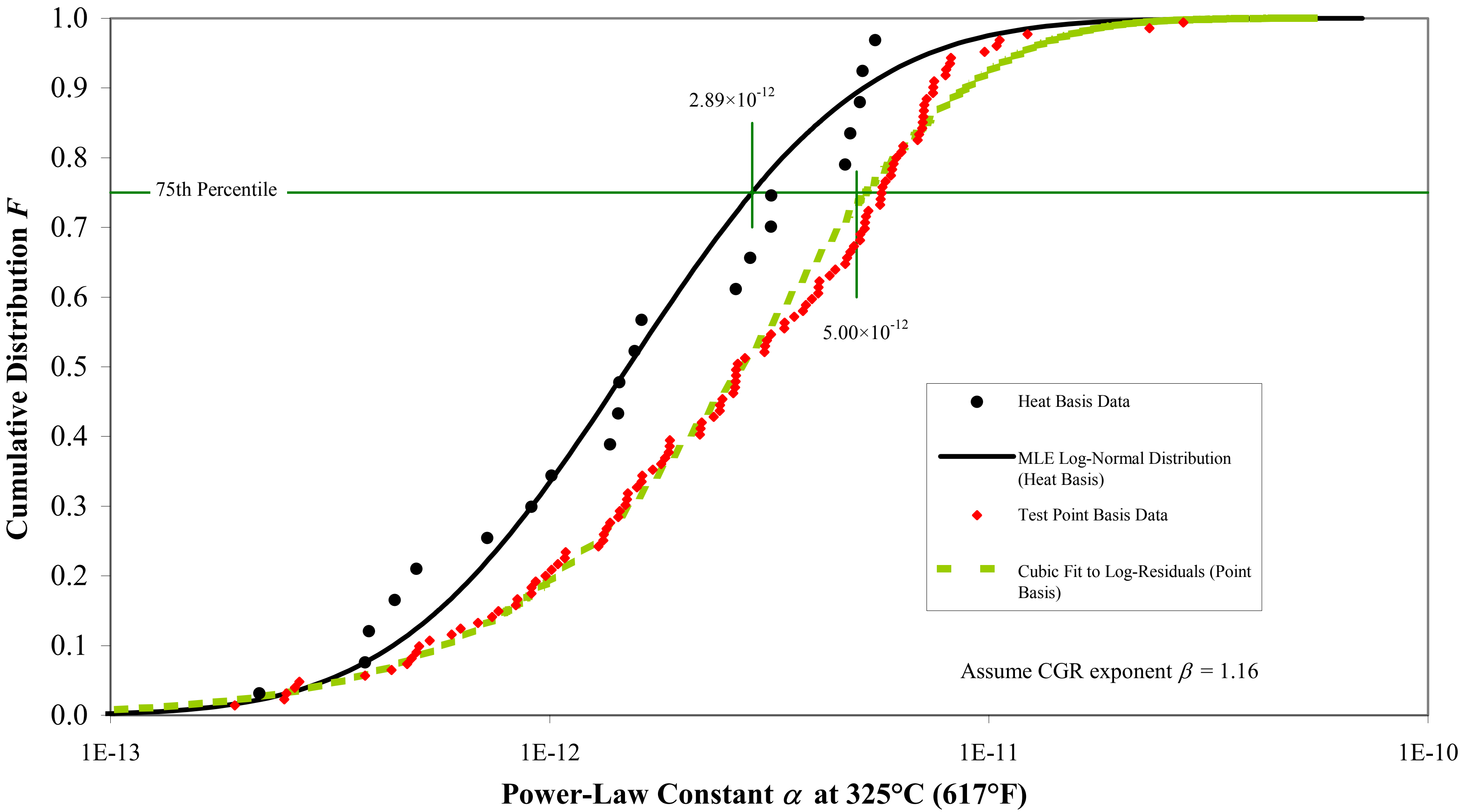
No back wall constraint assumed in part-through-wall crack model, therefore vessel wastage not a factor

Stress Intensity Factor Results
B&W Type Plant

High Yield, Large Gap Case

Nozzle Angle	Circumferential Crack Length		Stress Intensity Factor (ksi*(in)$^{1/2}$)	
	Degrees	Inches	Uphill	Downhill
0°	30	0.9664	20.8	N/A
	70	2.2550	18.8	N/A
	160	5.1540	20.3	N/A
	180	5.3140	0.64	N/A
	220	6.4950	0.63	N/A
	260	7.6760	0.63	N/A
	300	8.8570	0.62	N/A
18°	30	1.0170	27.2	27.2
	70	2.3730	24.0	24.0
	160	5.4240	24.5	24.5
	180	5.5920	23.4	1.0
	220	6.8350	23.8	2.4
	260	8.0770	26.9	6.0
	300	9.3200	26.5	11.5
26°	30	1.0830	29.7	29.7
	70	2.5260	26.1	26.1
	160	5.7750	26.5	26.5
	180	5.9530	28.4	0.4
	220	7.2760	23.2	1.7
	260	8.5990	23.6	7.5
	300	9.9220	24.9	16.6
38°	30	1.2380	34.4	34.4
	70	2.8830	27.1	27.1
	160	6.6020	29.2	29.2
	180	6.8060	37.7	4.5
	220	8.3190	31.2	6.7
	260	9.8310	26.6	12.7
	300	11.3440	29.9	25.9

SCC Crack Growth Data for Nozzle Material in Reactor Environment



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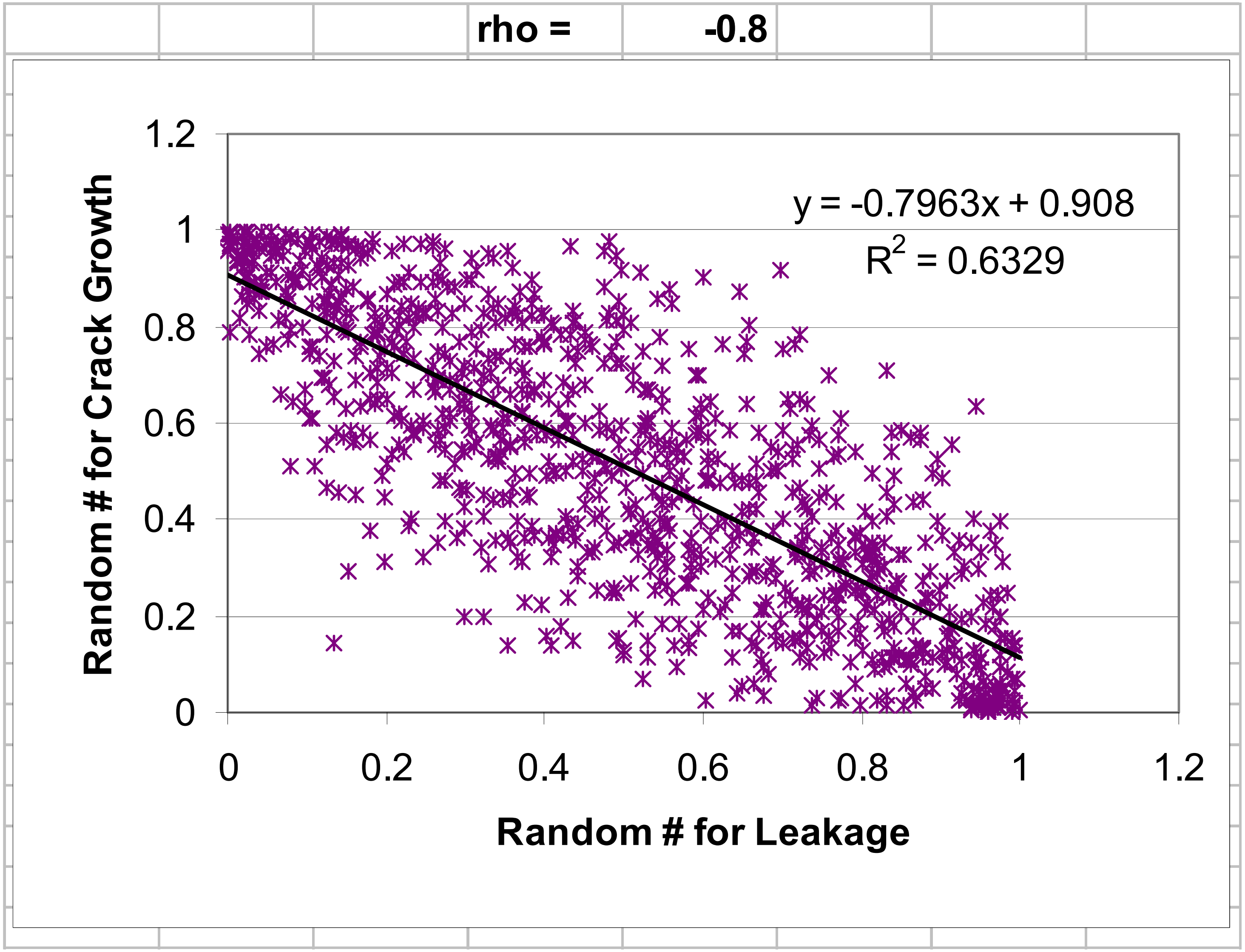
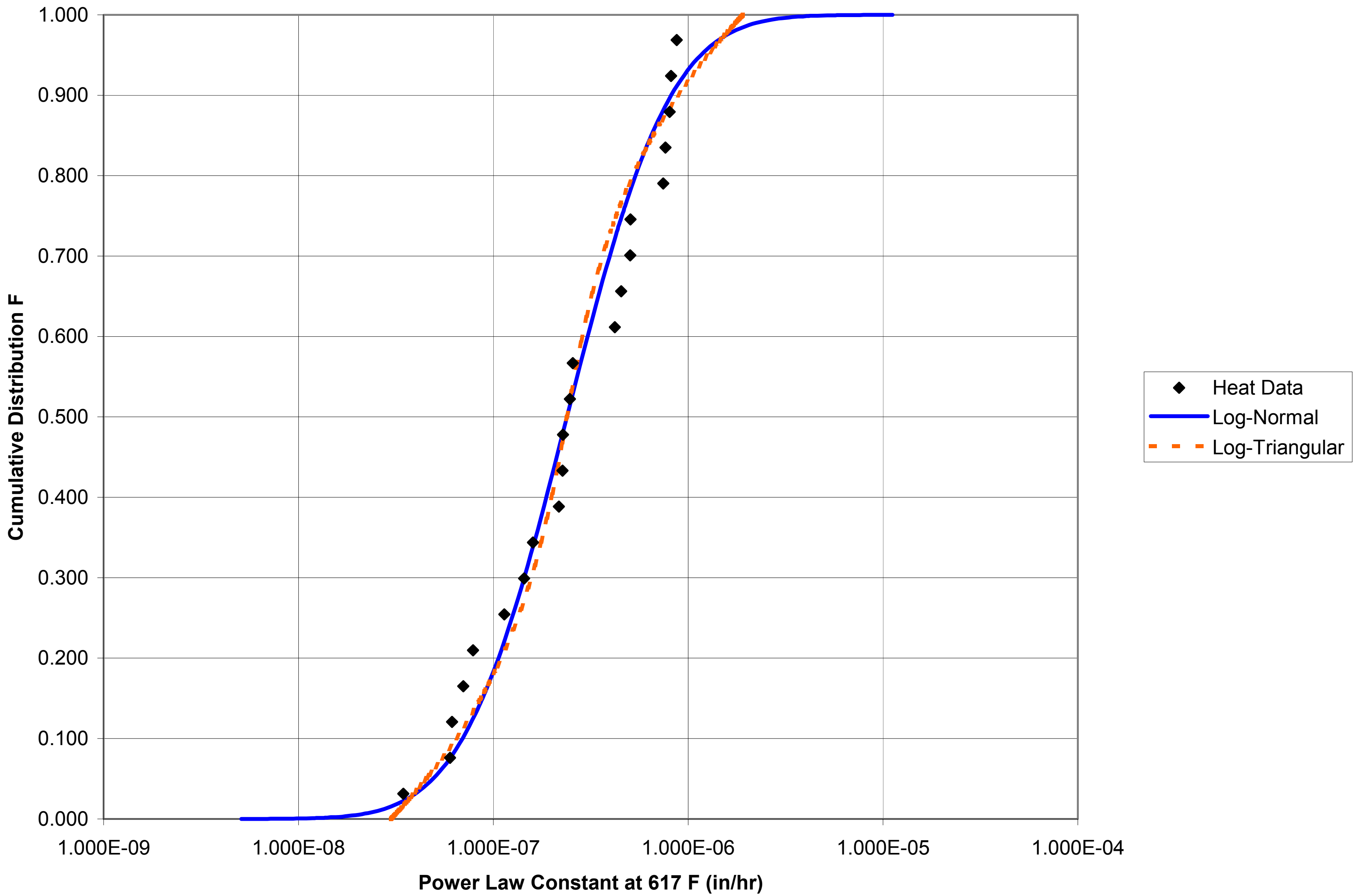
CGR Initiation vs. Growth Correlation



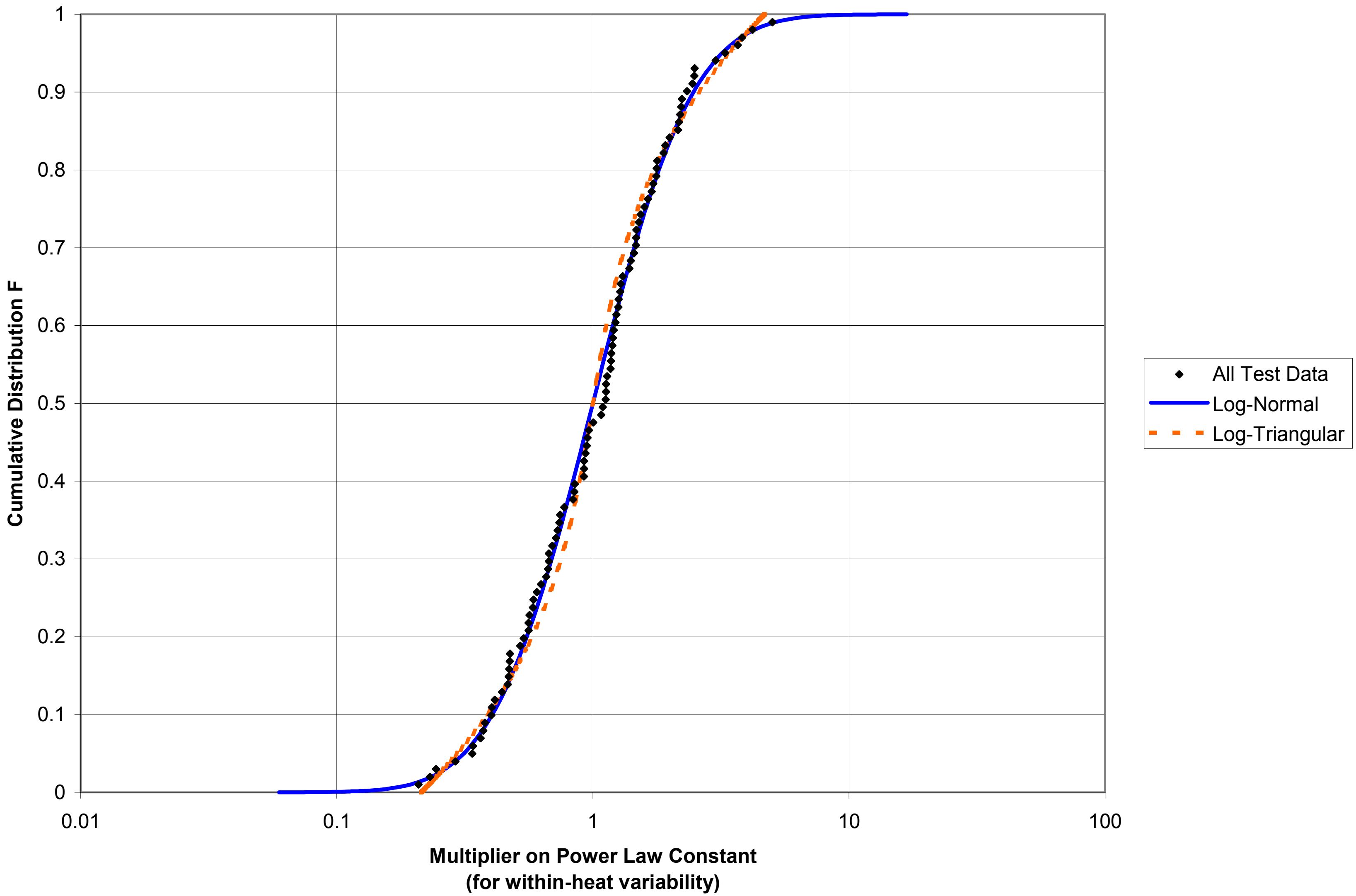
Software Modifications
(to Address Comments from 2/21/02 NRC Meeting)

- **Model Heats of Tubes rather than Individual Tubes**
  - Head modeled by finite number of heats (1 to N_{tubes})
  - Random variables for nozzle leakage and crack growth rate first determined for each heat
  - Second set of random variables then determined for individual tubes within a heat.
  - Correlation factor between leakage and crack growth rates applied to both sets of random variables
- **Truncation of Tails of Distributions**
  - Crack Growth Rate Distributions (both heat-to-heat and within-heat) can be specified as either Log-Normal (un-truncated) or Log-Triangular (truncated)
- **Degraded POD for Subsequent Inspections**
  - Software now accepts "degradation factor" input for subsequent inspections of leaking tubes which were previously inspected and missed

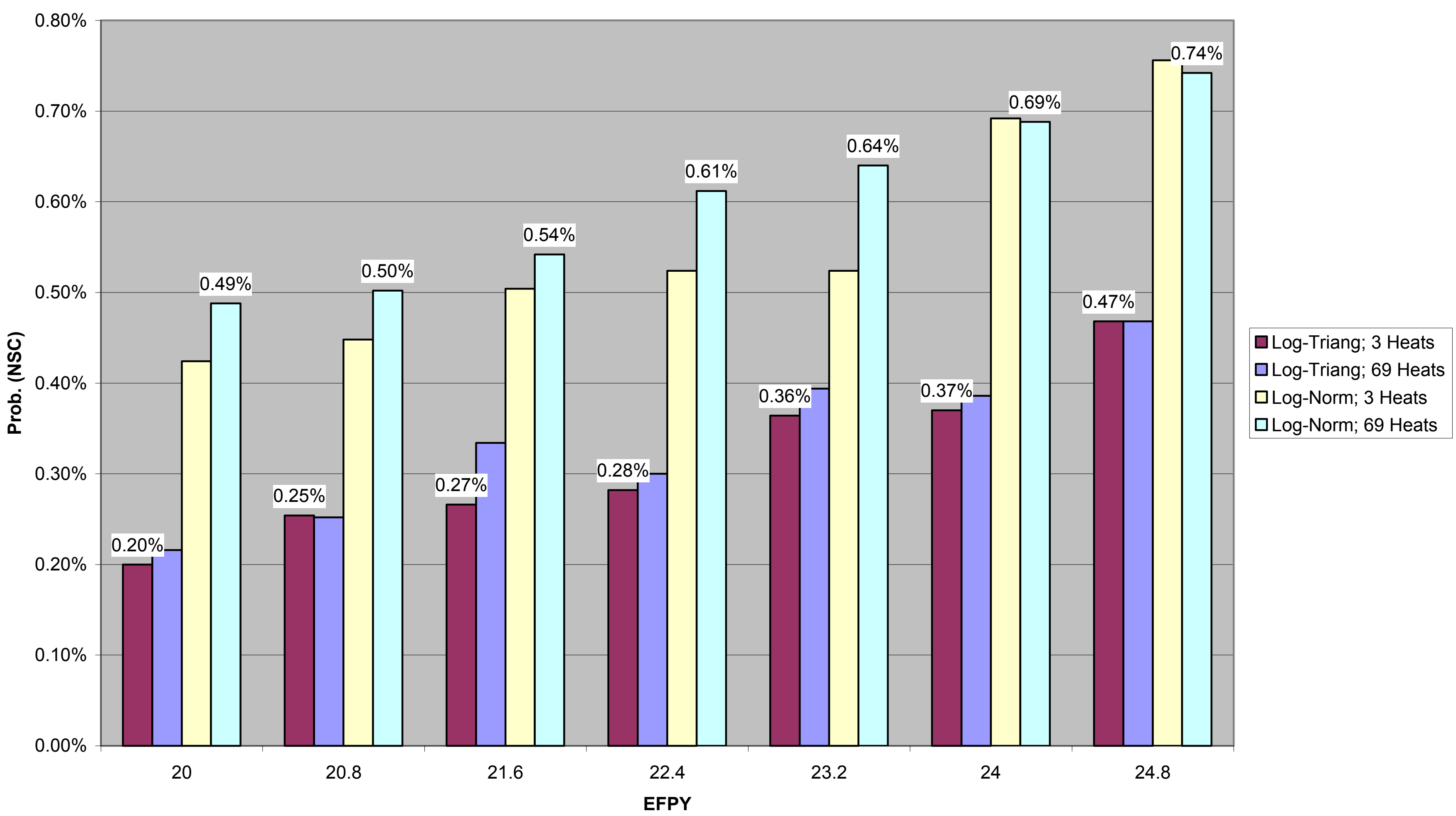
CGR Distributions Based on Heat Data



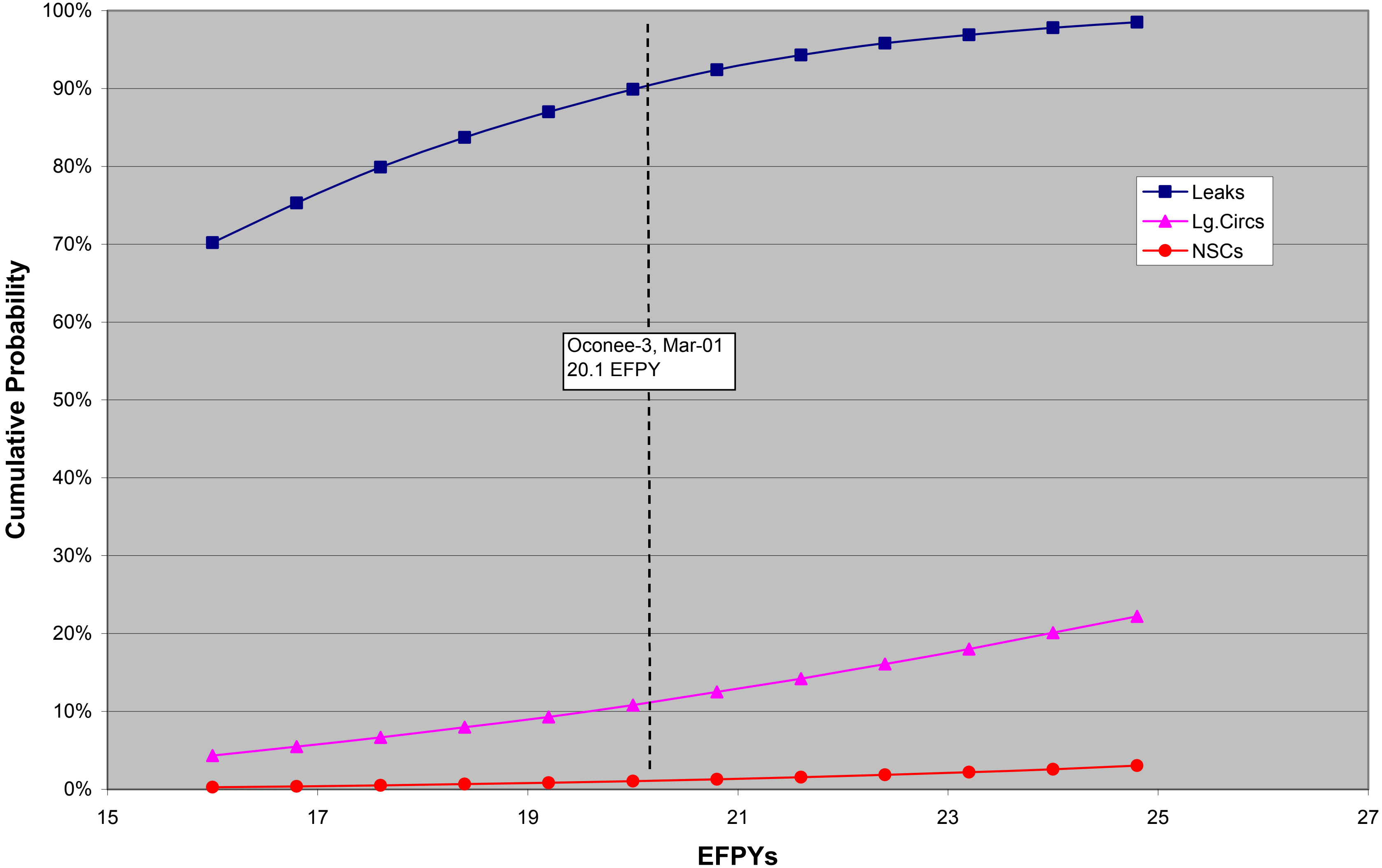
Multiplier on CGR Distribution for Within-Heat Variability



PFM Results w/ Modified Software (602°F Head Temp.; No Inspection)



Benchmarking of PFM Results with respect to B&W Plants



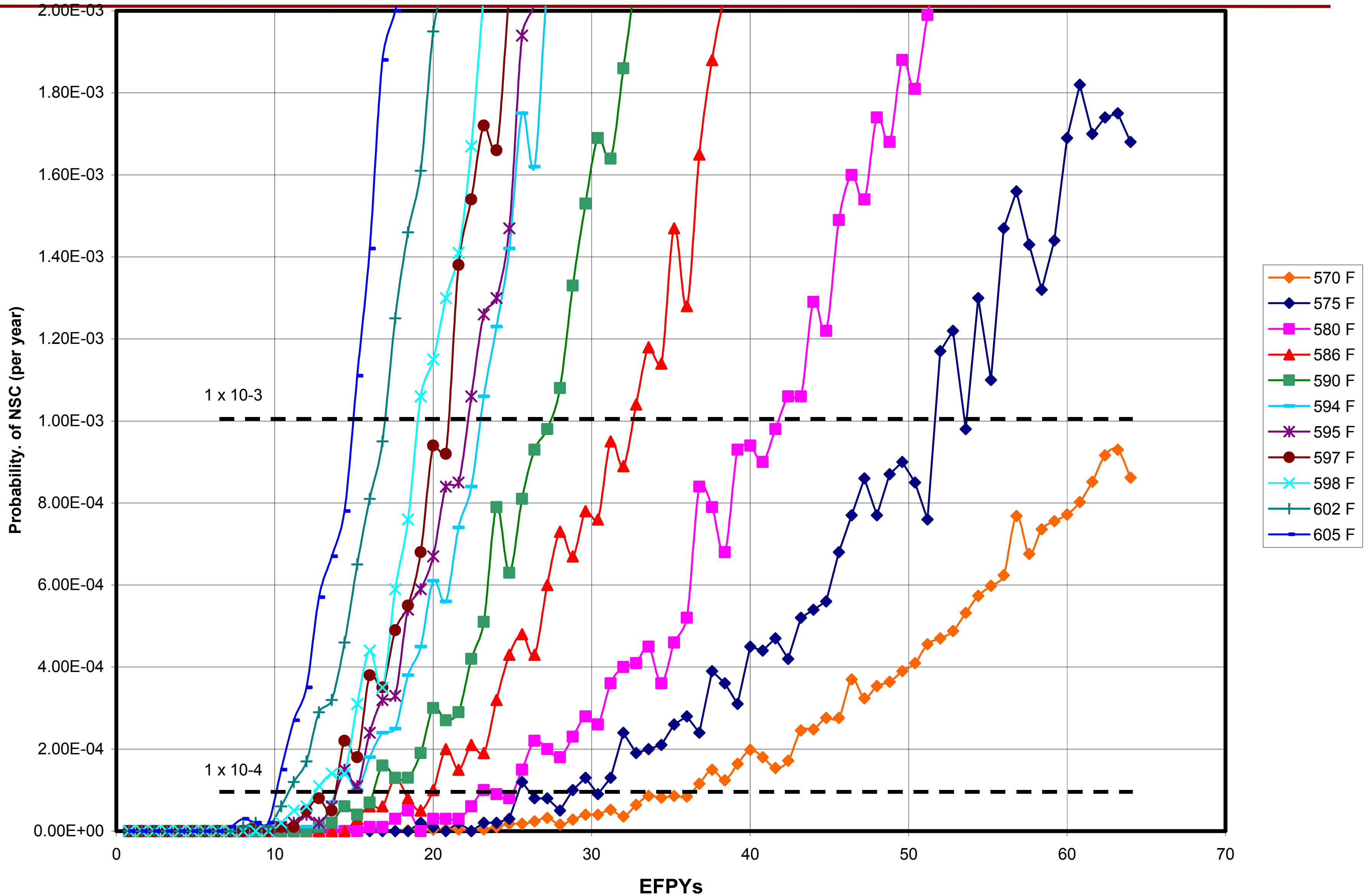
Technical Basis for Inspection Plan
- Basic Concept -

- Start with “benchmarked” analysis parameters from B&W plant analysis
- Analyze plants at various head temperatures
- Set risk categories based on probability of Net Section Collapse (per year) and cumulative leakage probability
- Set inspection intervals based on effect of various inspections on probability of Net Section Collapse (per year)

“Benchmarked” Analysis Parameters

- **Head Temperature: Various from 560°F to 605°F**
- **Weibull Parameters:**
  - ♦ Slope = 3
  - ♦ Beta = 15 ± 6 (Triangular)
- **Crack Growth Rate Statistics**
  - ♦ Heat-to-Heat - Log-Triangular: -15.25 ± 2.212
  - ♦ Within Heat – Log-Triangular: 0 ± 1.6
- **Crack Growth vs. Leakage Correlation Factors**
  - ♦ 0.8 – Heat-to-Heat
  - ♦ 0.8 – Within-Heat
- **Acceptability Criteria: PDF of NSC < 1 x 10^{-3} per year**

Inspection Plan PFM Runs: Probability of NSC (per year)



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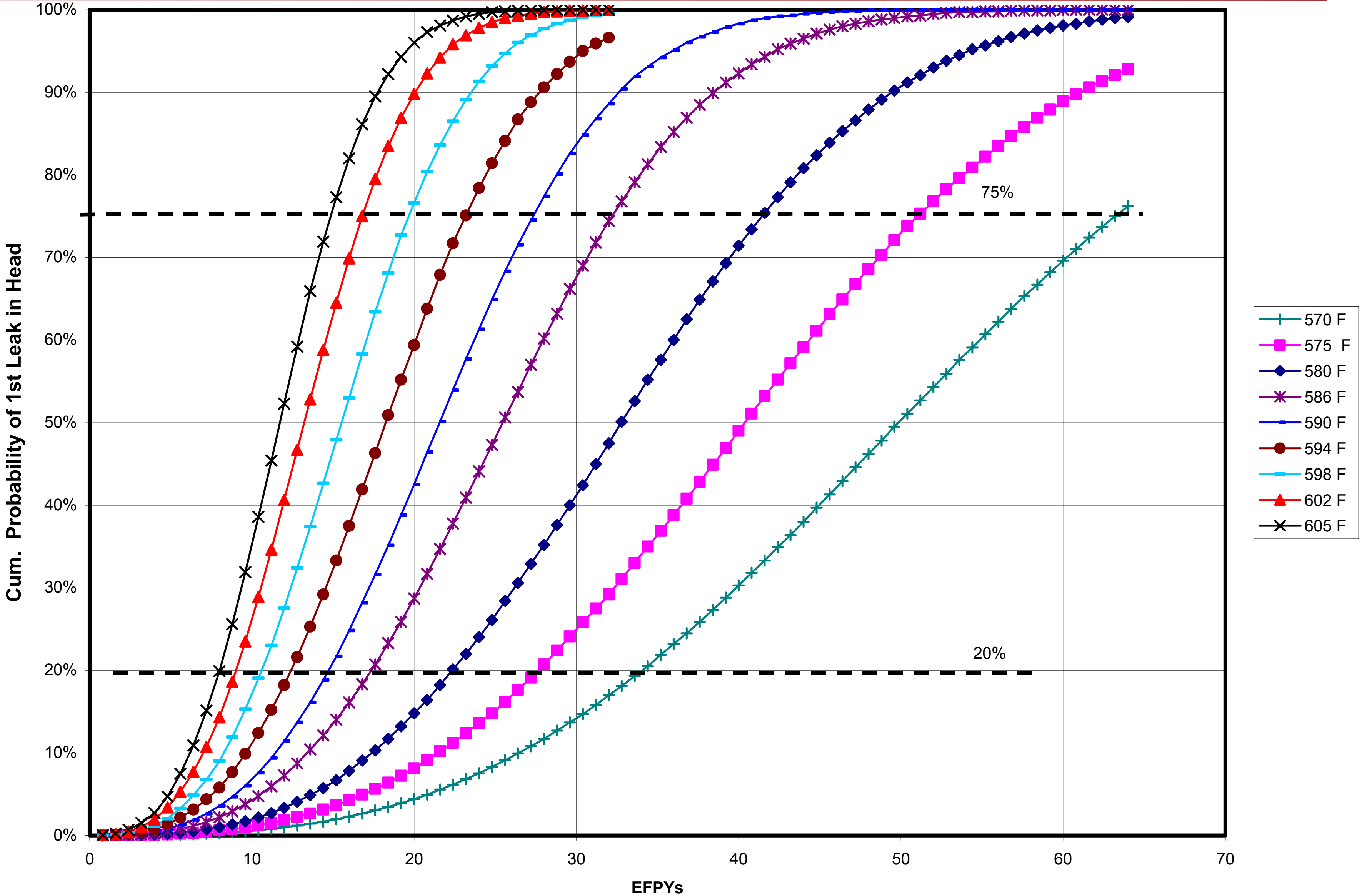
Inspection Plan PFM Runs: Cum. Probability of Leakage



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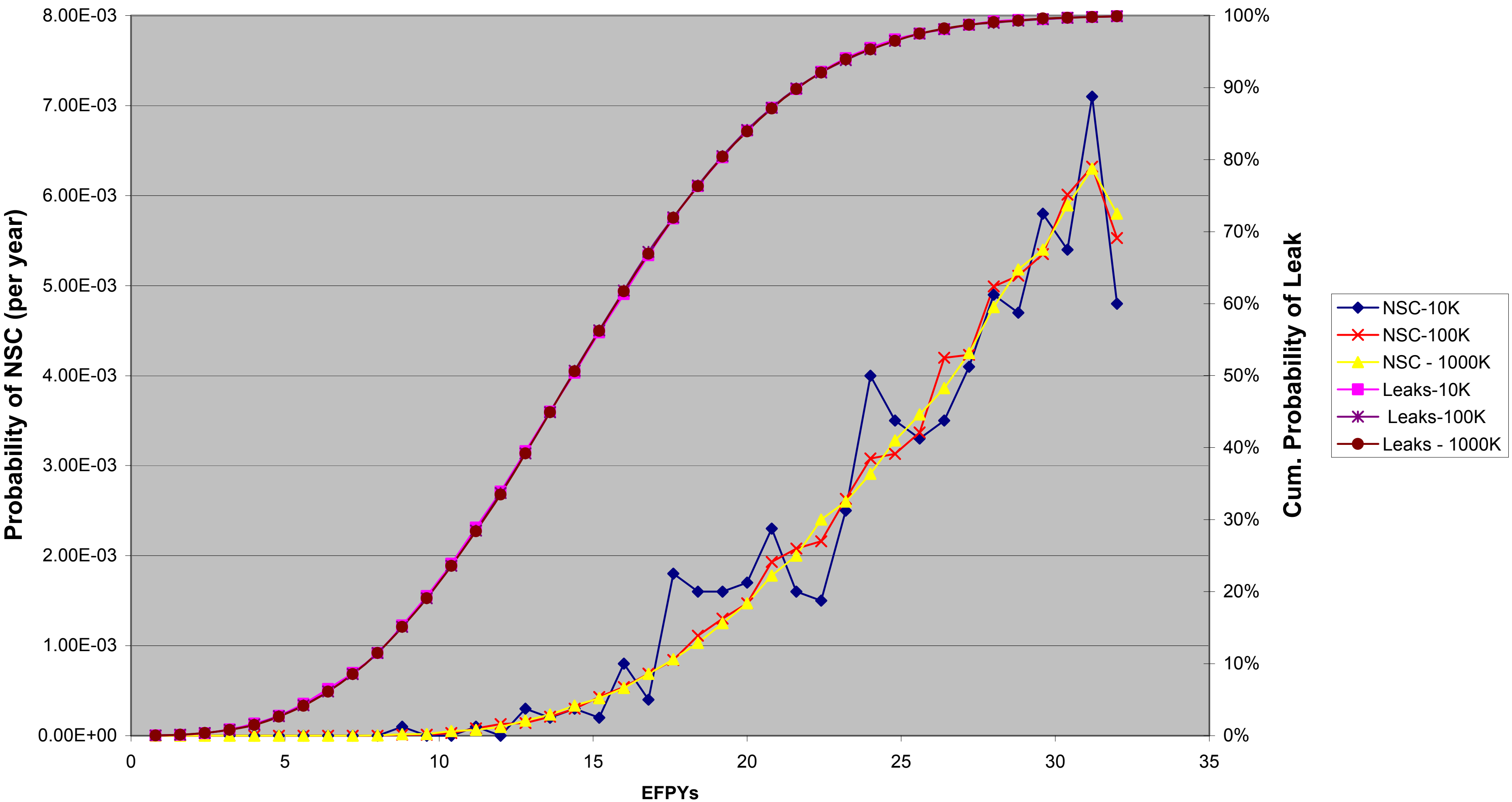
PFM Convergence Study (@ 600°F)



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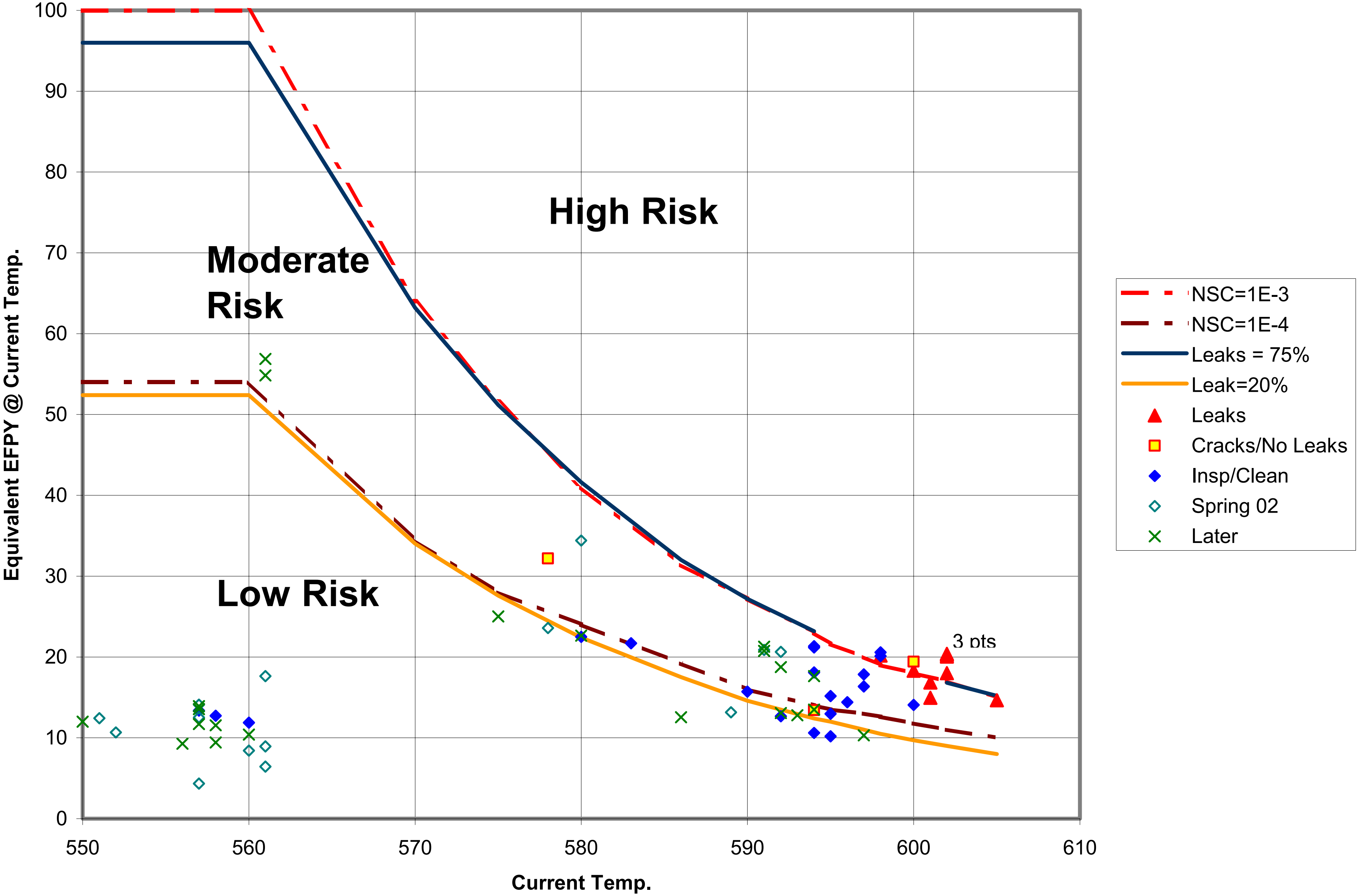
Definition of Susceptibility Categories Based on PFM Results



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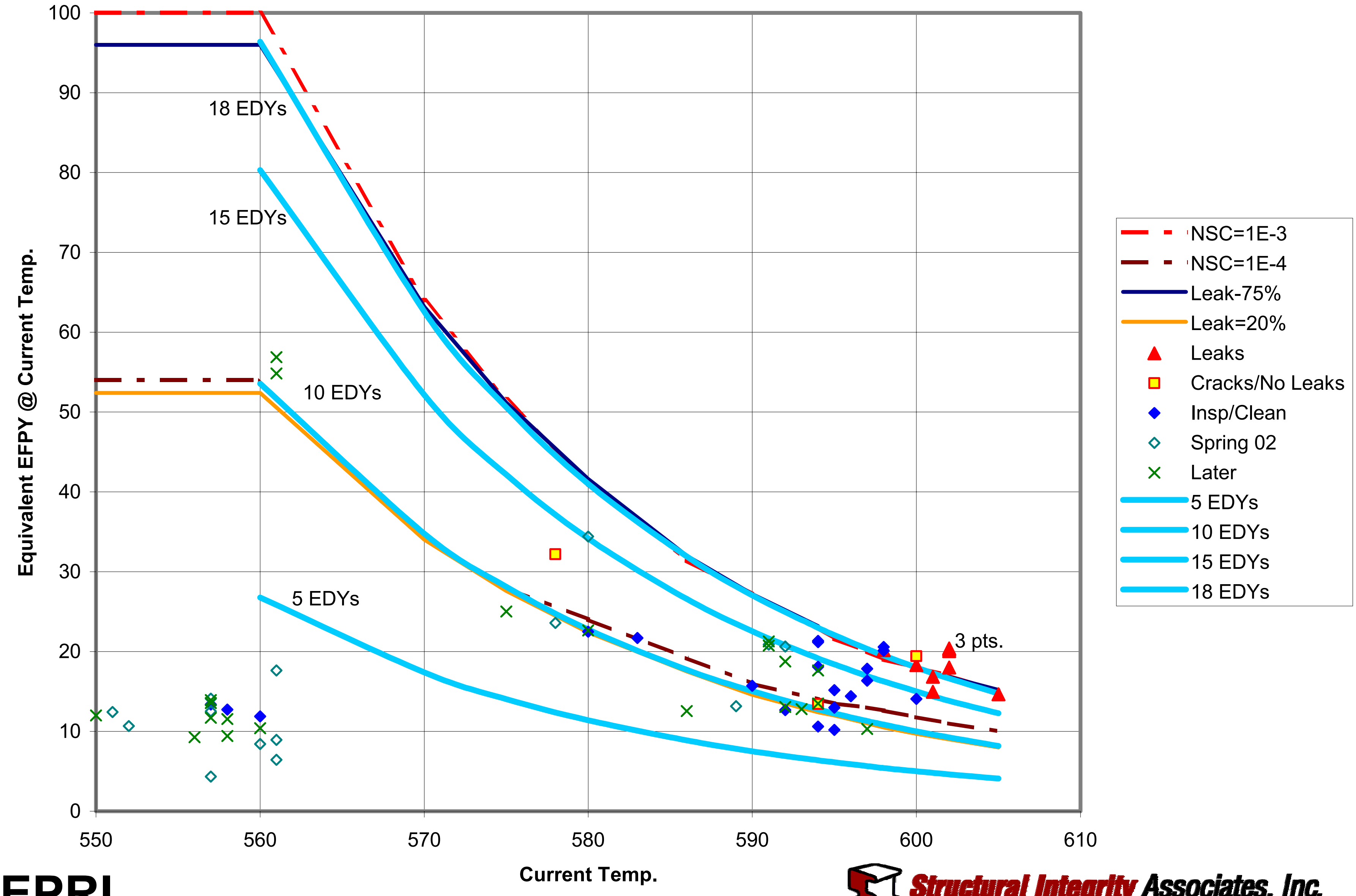
Correspondence of Susceptibility Categories to EDYs



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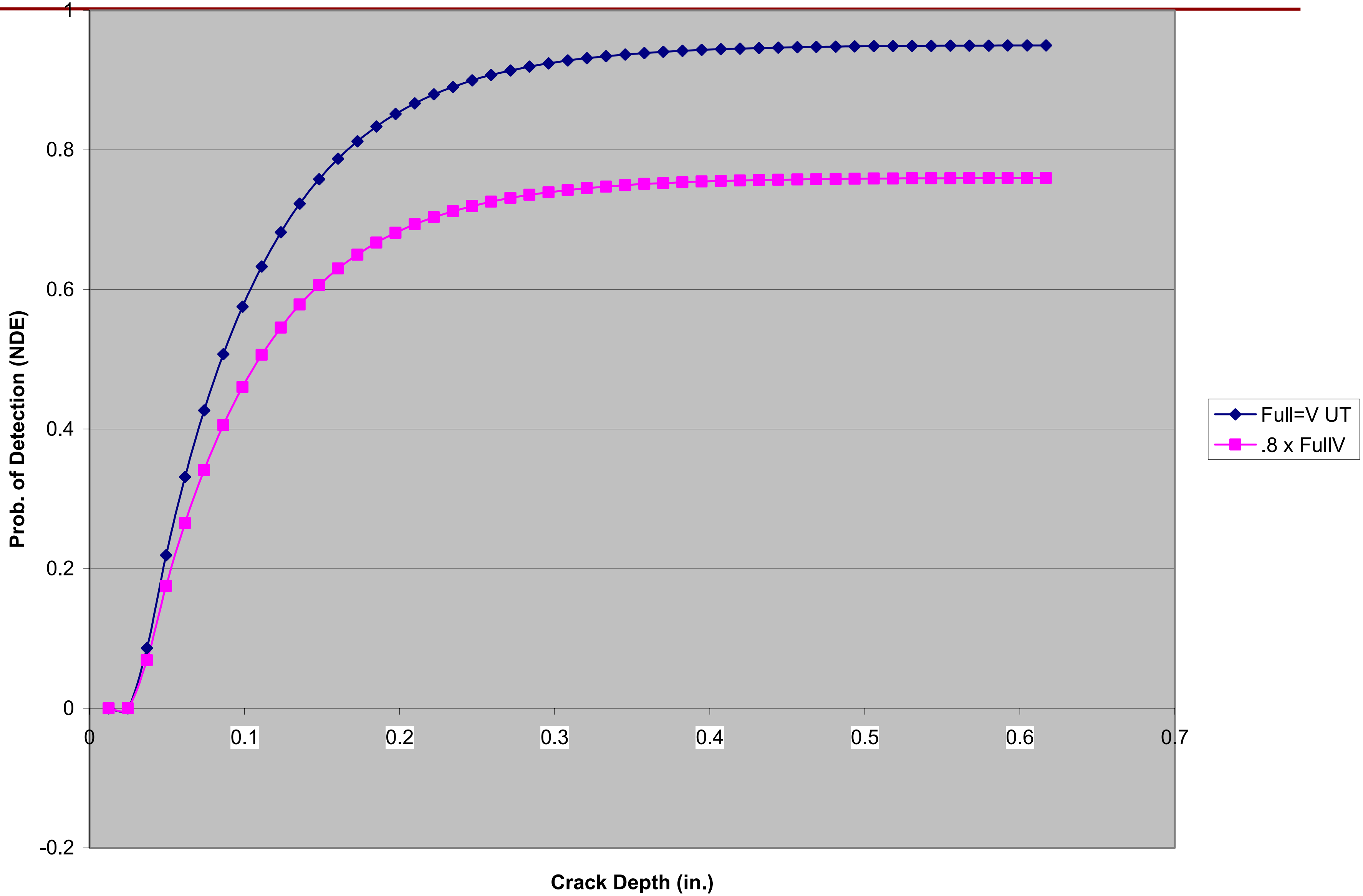
Inspection Frequency Runs: Probabilities of Detection

- **Bare Metal Visual Inspections (BMV)**
  - Initial POD = 0.6
  - POD for Subsequent Exams = 0.2 x Initial POD (when Leakage missed)
- **Non-Destructive Examinations (NDE)**
  - POD = f(crack depth) per EPRI-TR-102074[1]
  - 80% Coverage Assumed

[1]Dimitrijevic, V. and Ammirato, F., "Use of Nondestructive Evaluation Data to Improve Analysis of Reactor Pressure Vessel Integrity, " EPRI Report TR-102074, Yankee Atomic Electric Co. March 1993

Probability of Detection Curves for NDE



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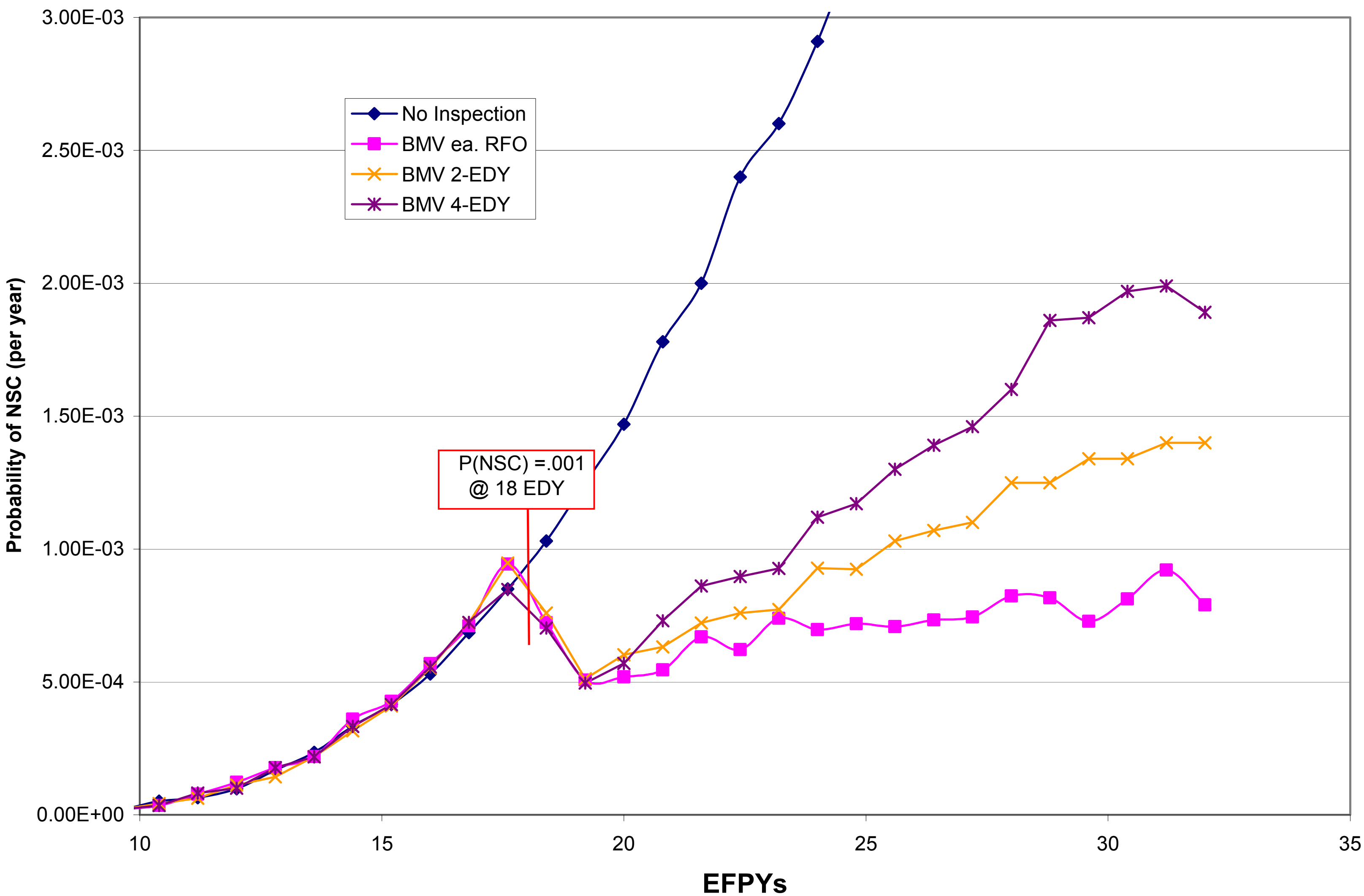
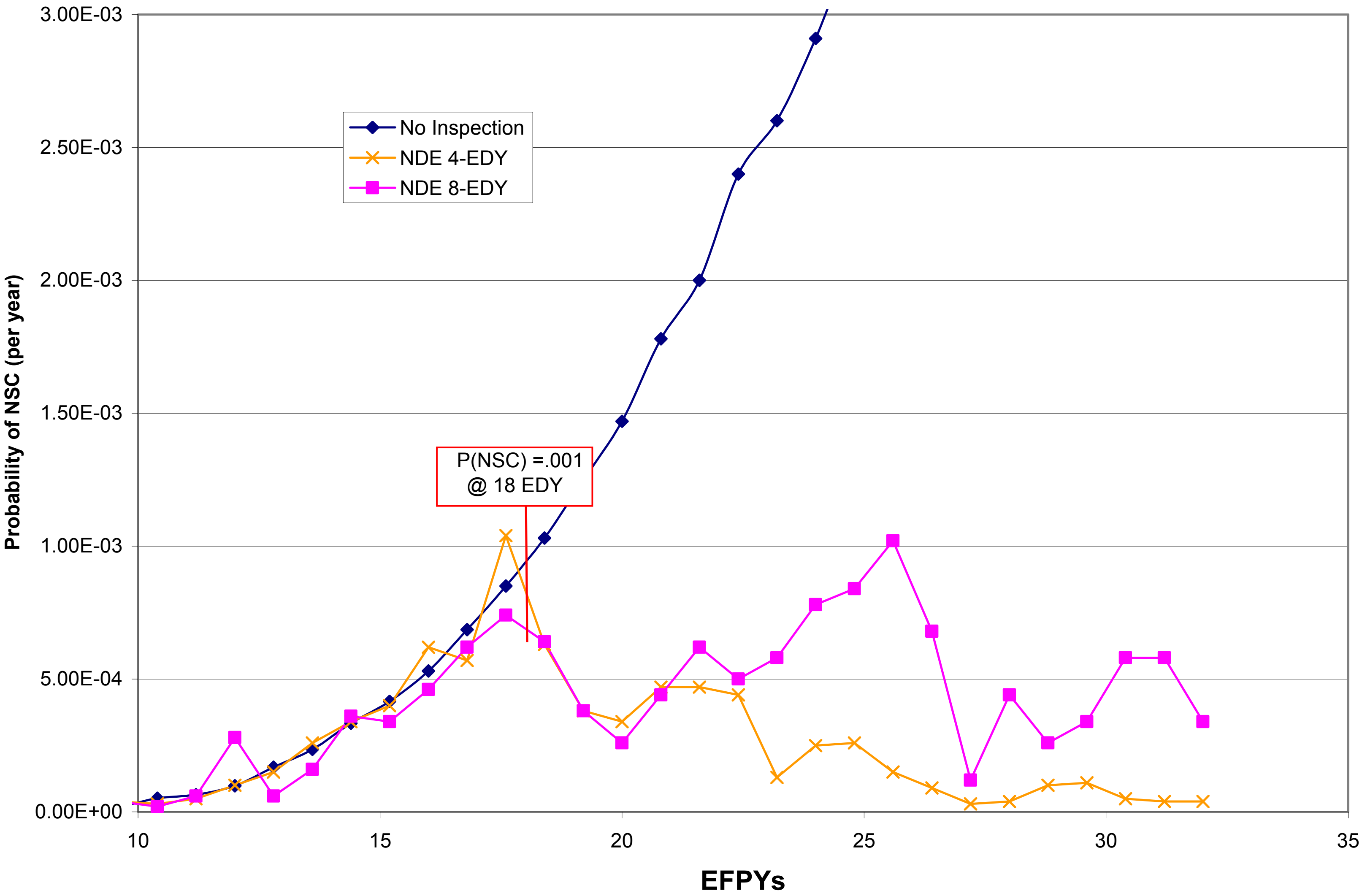
Inspection Plan Technical Basis: Effect of Visual Inspection Runs



Inspection Plan Technical Basis: Effect of NDE Inspection



Deterministic Crack Growth Analyses

- **Uses Expert Panel recommended crack growth law**
  - 2 x 75th Percentile of all data
  - da/dt = C(K-8.19)1.16

Temperature (ºF)	C
580	3.604×10^{-7}
590	4.665×10^{-7}
600	6.008×10^{-7}
602	6.316×10^{-7}
605	6.806×10^{-7}

Deterministic Crack Growth Analyses

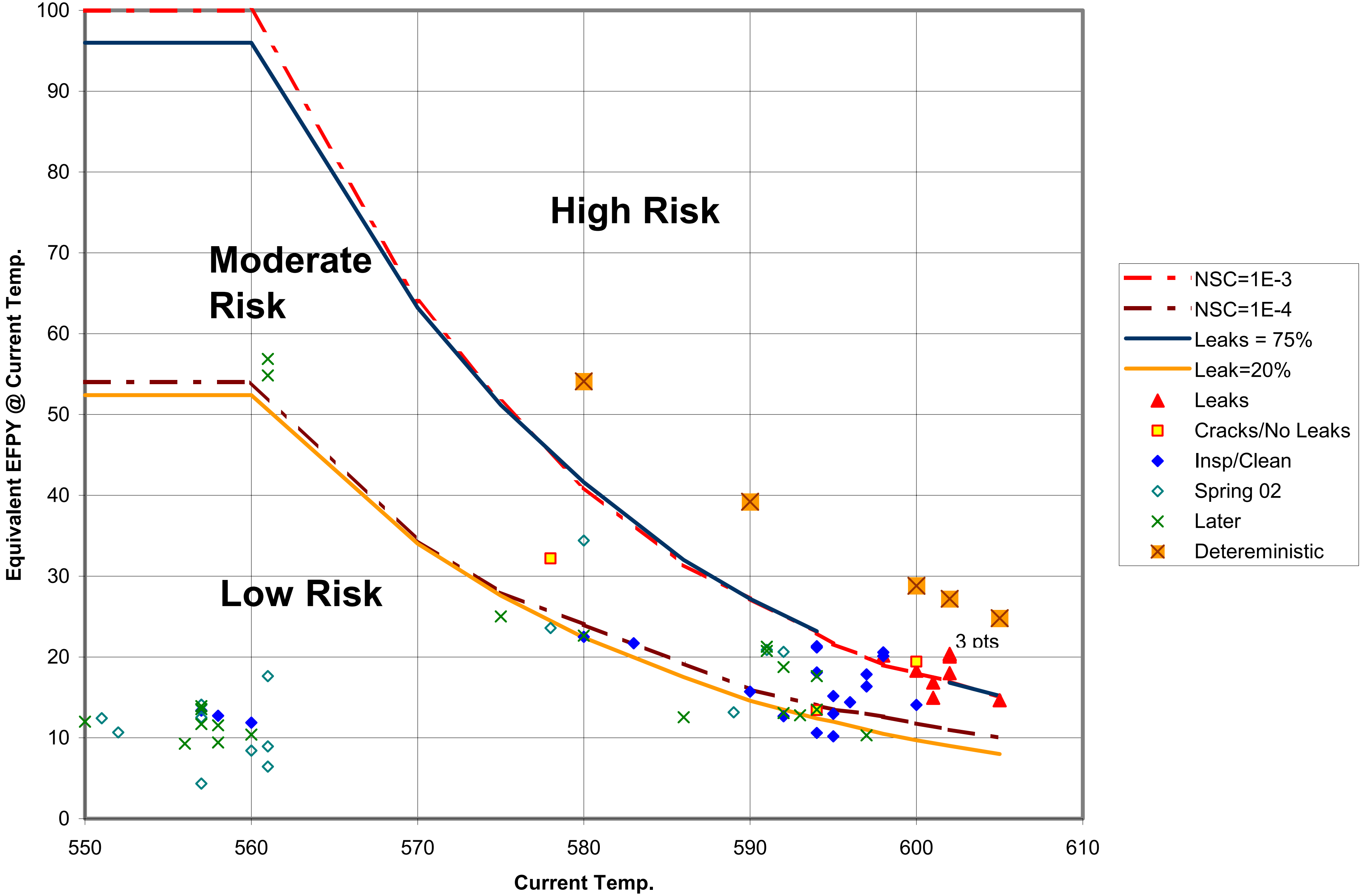
- **Uses Stress Intensity Factors from plant specific analysis of Westinghouse plant**
  - High Angle Nozzle (43.5° nozzle angle)
  - Higher Ks than B&W plant results

Circ. Crack Length		K
Degrees	Inches	Ksi*in $^{1/2}$
30	1.16	34.4
70	2.70	27.1
160	6.16	29.2
180	6.34	47.2
220	7.75	51.9
260	9.16	58.1
300	10.57	63.7

Deterministic Crack Growth Analysis Results

Temperature (ºF)	Time for Initial Flaw Size of 30º Circumference to Grow to 165º and 300º (EFPY)	
	Westinghouse-Type Plant	
	165º	300º
580	23.7	31.7
590	18.3	24.6
600	14.2	19.1
602	13.5	18.2
605	12.5	16.8

Deterministic Crack Growth Results Added to Susceptibility Category Plot



Conclusions

- **PFM Incorporates:**
  - Weibull model of time to leakage
  - Finite Element Fracture Mechanics model for B&W type head
  - Crack growth rate statistics from Expert Panel
  - Effect of various inspection types, intervals and POD
  - Heat-basis analysis from NRC Comments
  - Log-Triangular and Log-Normal CGR Distributions
- **Inspection Plan Technical Basis Runs:**
  - Start with "benchmarked" analysis parameters from B&W plant analysis
  - Analyze plants at various head temperatures
  - Set risk categories based on probability of Net Section Collapse (per year) and cumulative leakage probability
  - Set inspection intervals based on effect of various inspection types and frequency on probability of Net Section Collapse (per year)

Conclusions (cont'd)

- **Susceptibility Categories Based on PFM Results**
  - ♦ Low –Risk:: 0 < EDYs < 10
  - ♦ Moderate Risk: 10 < EDYs < 18
  - ♦ High Risk: 18 < EDYs
- **Inspection Type and Frequency Results**
  - ♦ Inspection cases run with conservative POD assumptions
  - ♦ BMV each RFO upon entering High Risk Category reduces probability of NSC to acceptable level indefinitely
  - ♦ NDE every 4 EDYs upon entering High Risk Category reduces probability of NSC to essentially nil
- **Deterministic Crack Growth Results**
  - ♦ Conservatively bounds times from moderate to high risk susceptibility regions