Probabilistic Fracture Mechanics Analysis of CRDM Nozzles

Presented at:

NRC Meeting

Rockville, MD

Presented by:

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Structural Integrity Associates

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Meeting Objectives

- Discuss new MRP analyses performed to address NRC comments on prior analyses plus new data
- Establish agreement on major assumptions in PFM analysis
- Demonstrate use of probabilistic and deterministic fracture mechanics analyses to establish re-inspection intervals for non-visual NDE

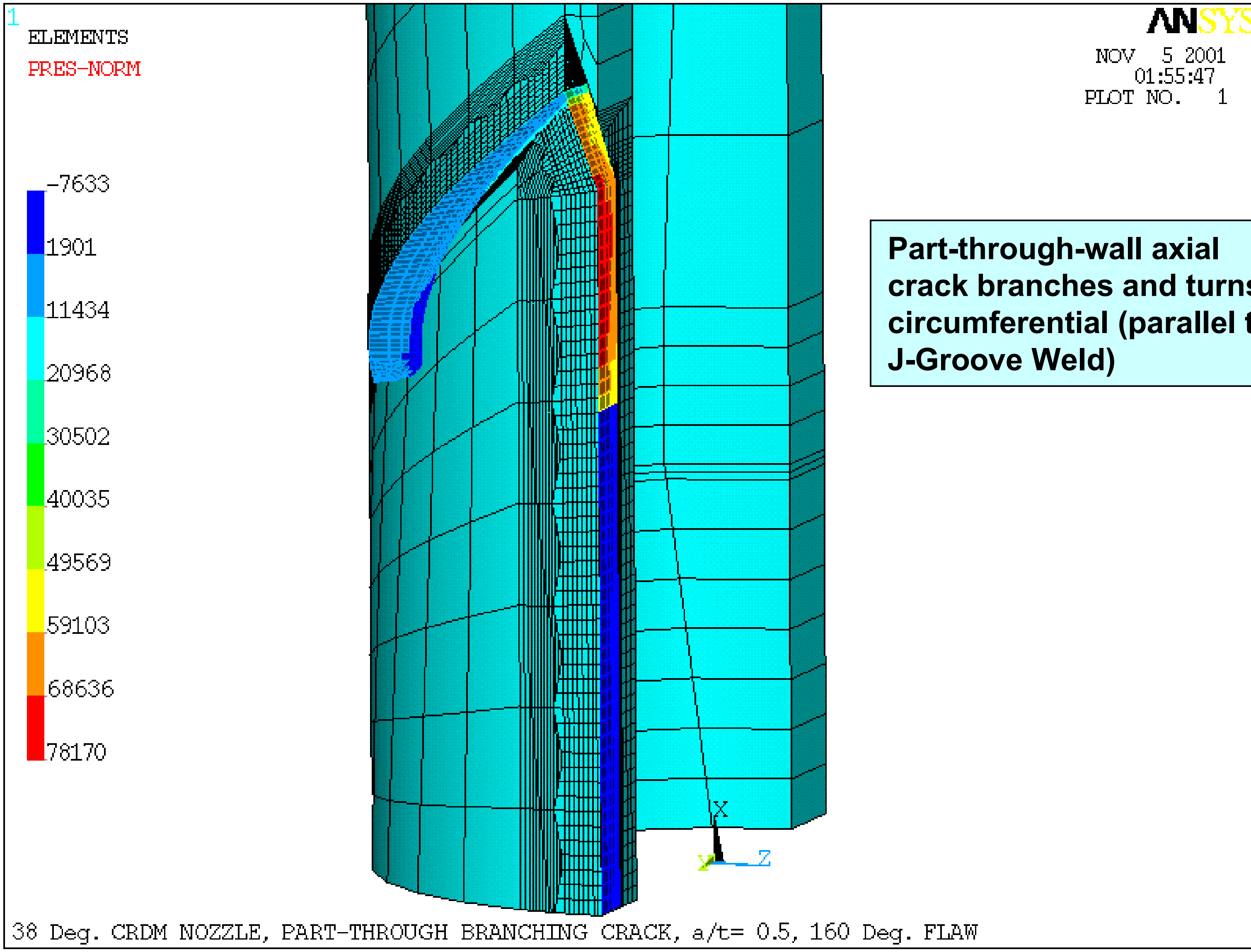
Major Presentation Topics

- Revised Stress Intensity Factor Calculations
- New Weibull Analysis of Time to Leakage / Significant Cracking
- Material Crack Growth Rates
- Effect of Inspections
- Deterministic Analysis
- Sensitivity Studies

Fracture Mechanics Models

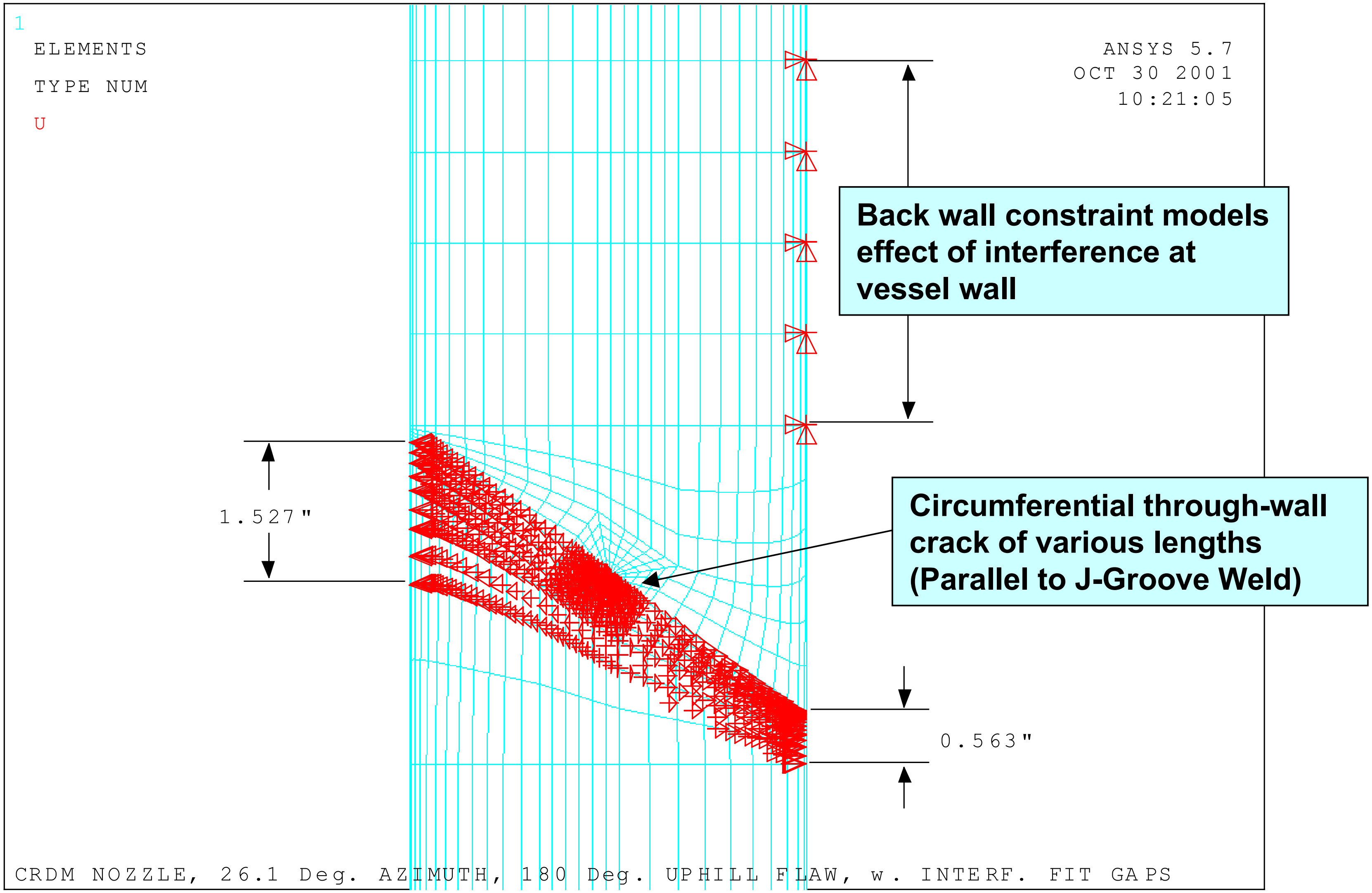
- Original analysis assumed part-through-wall (PTW) cracks (a/t = 0.5, length = 30º) when leakage predicted from Weibull model
- PTW cracks were assumed to propagate from 30º to 160º length, then transition to through-wall cracks for propagation from 180º to 300º
- NRC requested that we investigate effect of assuming through-wall cracks over entire propagation length (30º to 300º)

Fracture Mechanics
Part-Through-Wall Flaw Model



Part-through-wall axial crack branches and turns circumferential (parallel to J-Groove Weld)

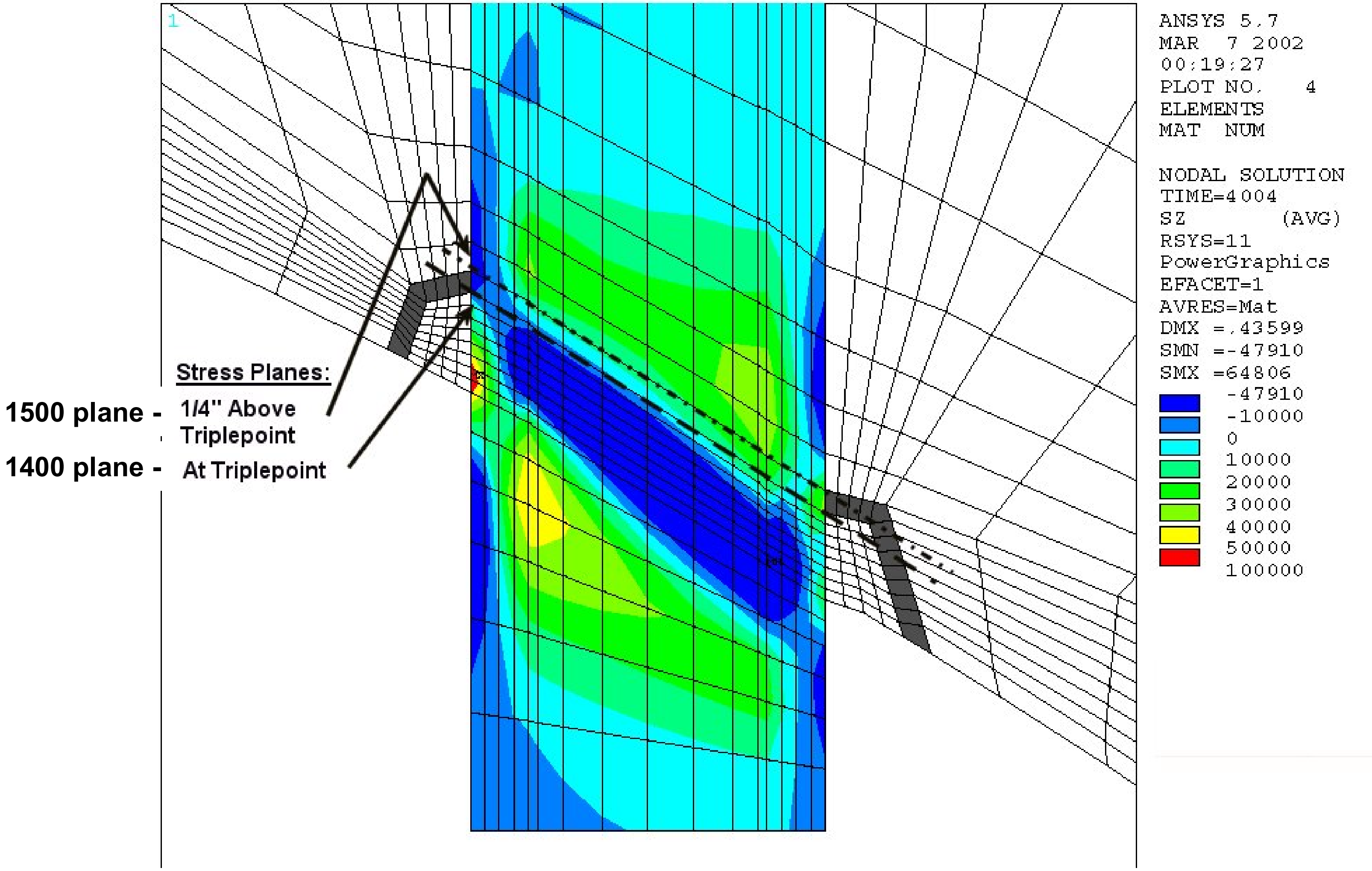
Fracture Mechanics
Through-Wall Crack Model



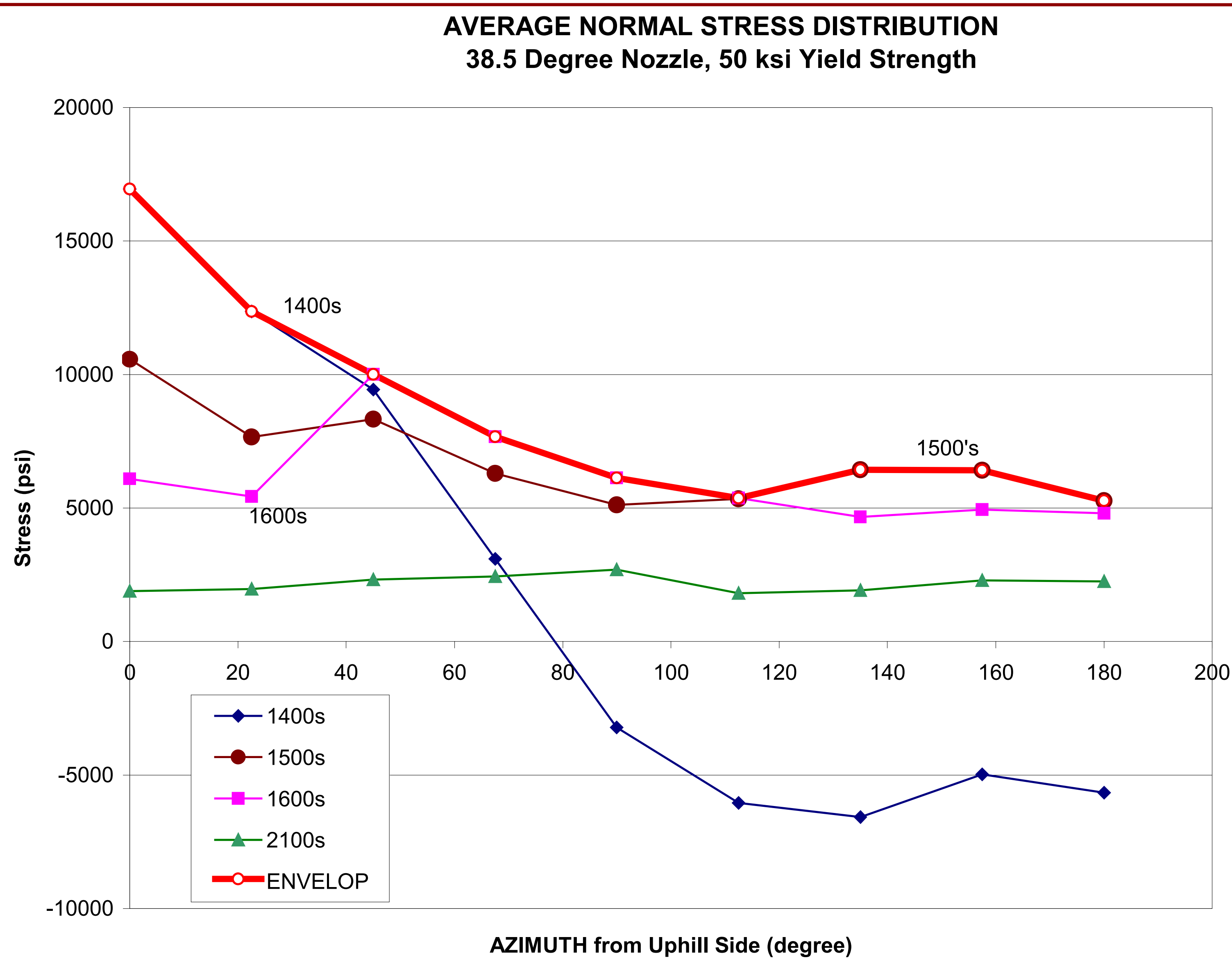
Fracture Mechanics Models (cont’d)

- **Original FM analyses modeled stresses on various planes parallel to J-groove weld root**
  - (I.e. 1400, 1500 planes in next slide)
- **Stresses transition from primarily residual to primarily pressure loading as plane moves upward away from J-groove weld**
- **NRC requested that we investigate effect of assuming crack follows plane of maximum stress**

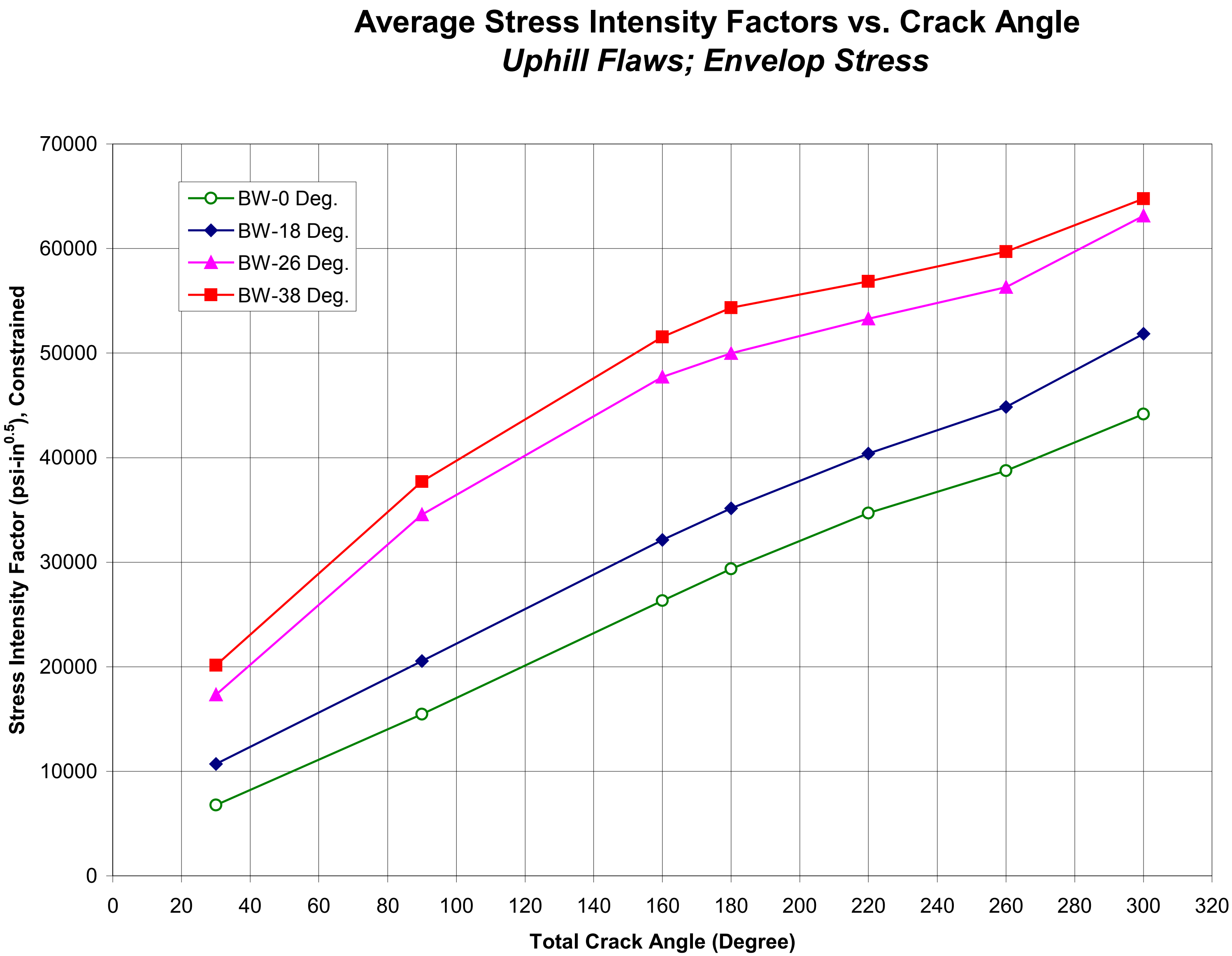
Illustration of Stress Planes



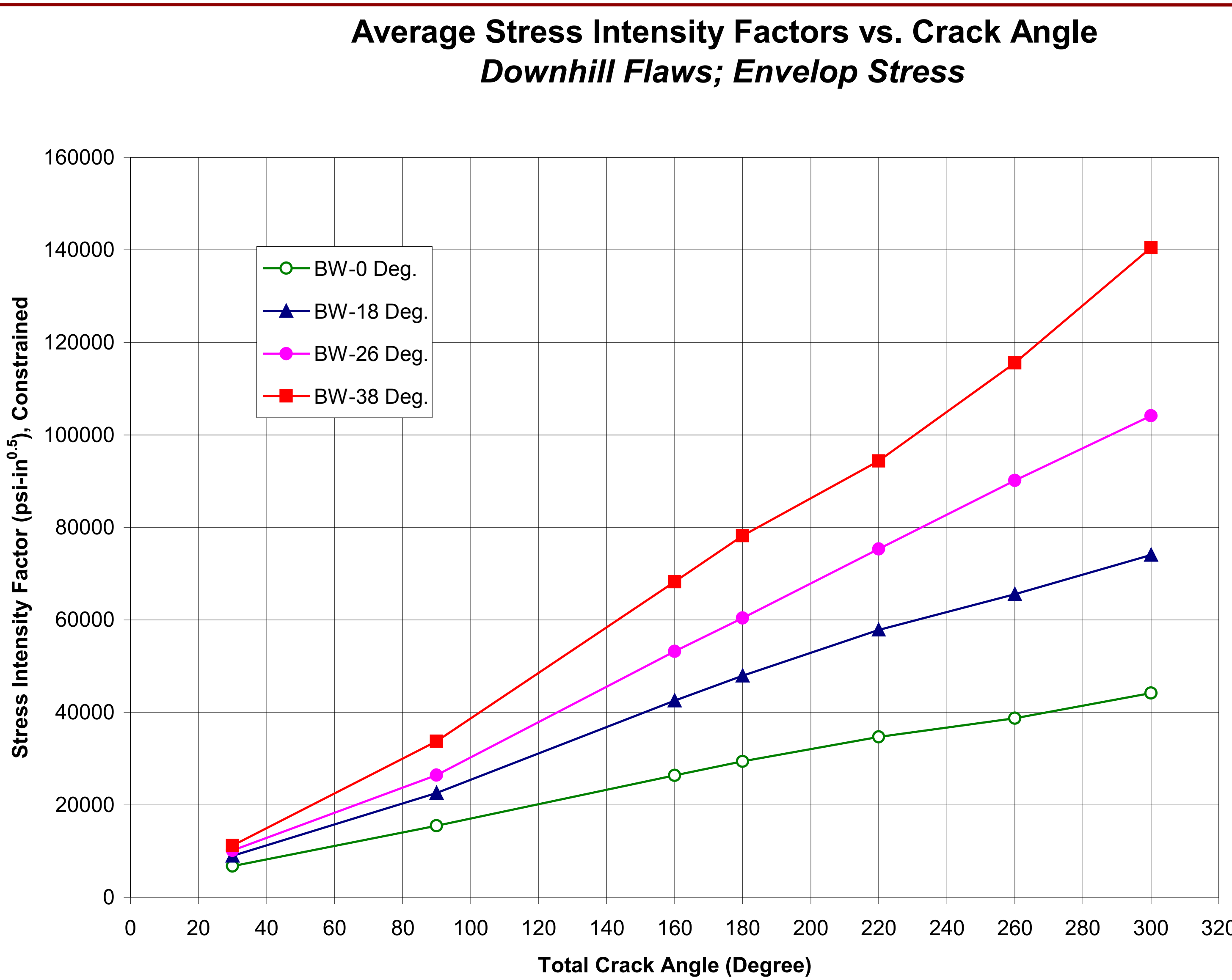
Stresses along Various Stress Planes



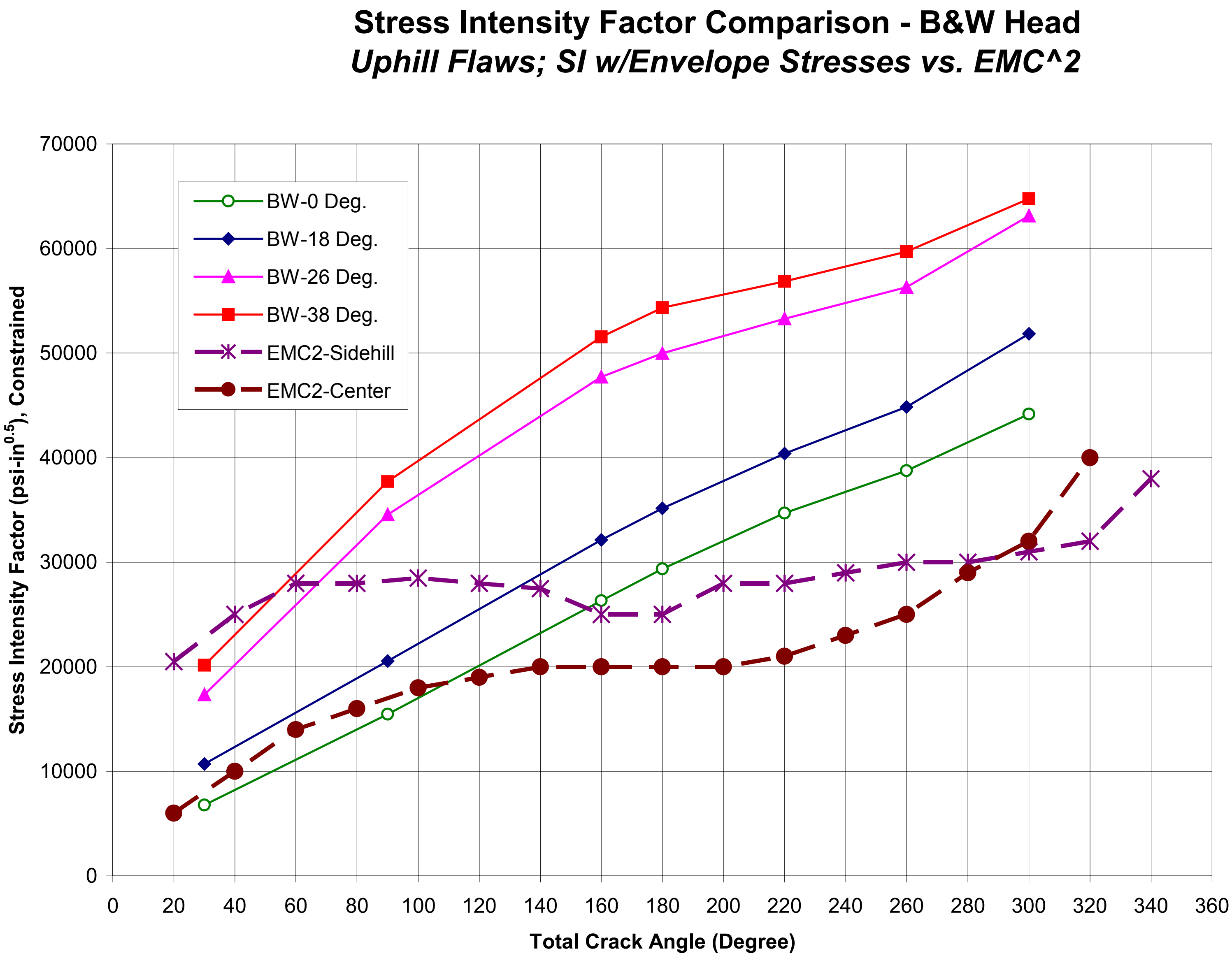
Stress Intensity Factors Uphill Cracking



Stress Intensity Factors Downhill Cracking

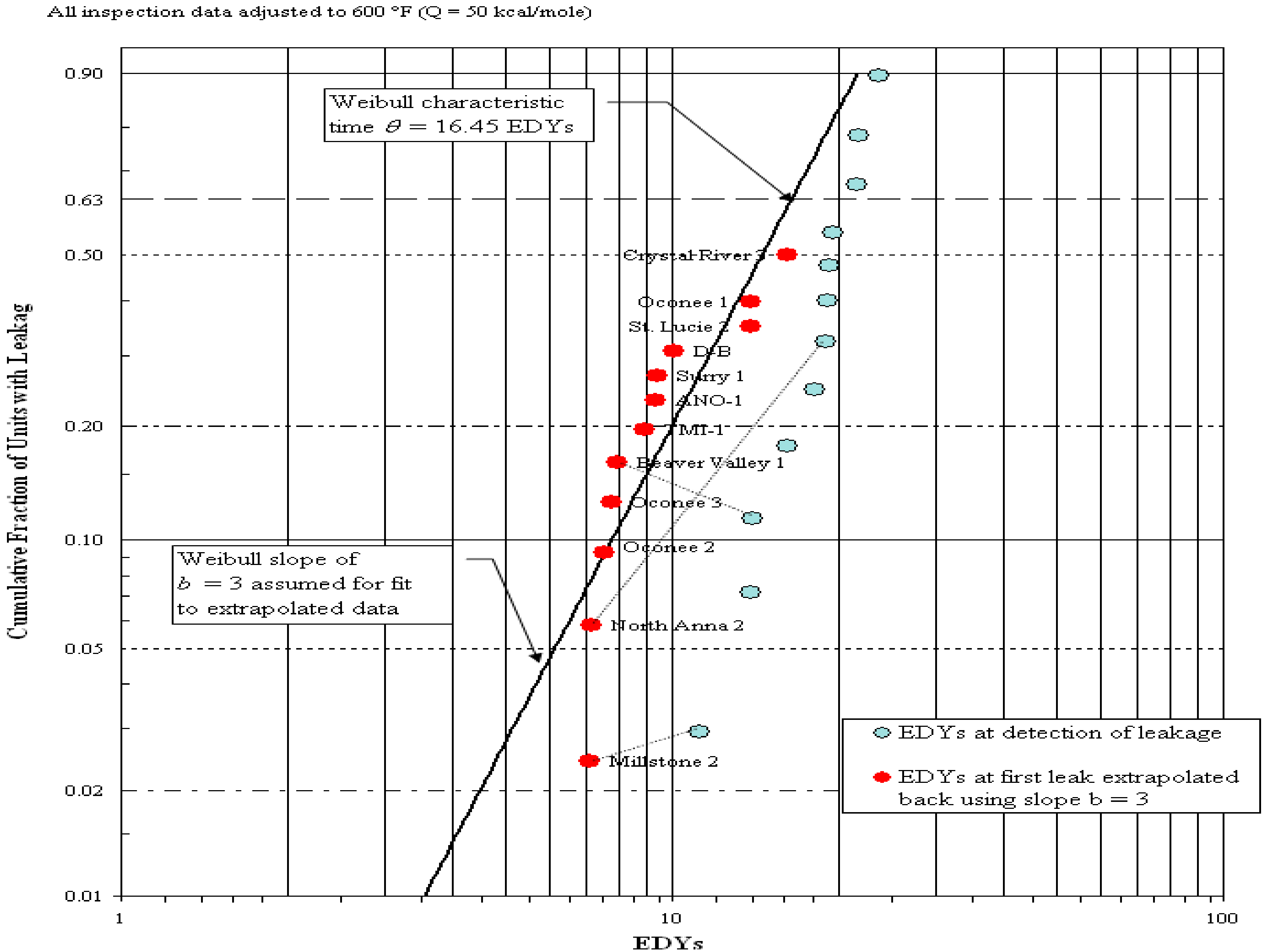


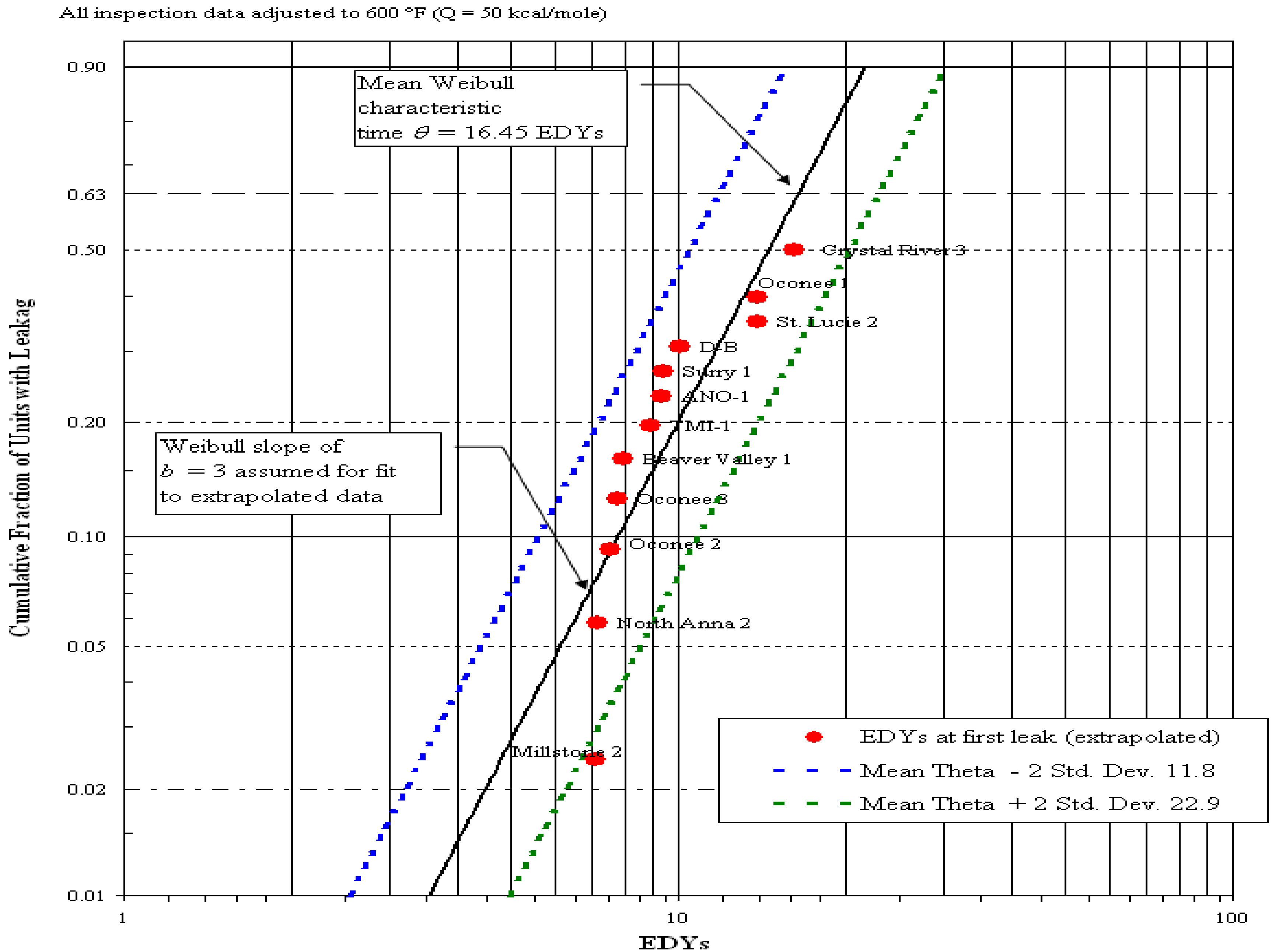
Stress Intensity Factor Comparison



Weibull Model for Time to First Leakage or Cracking

- **Analysis method due to Dominion Engineering**
  - Weibull Slope = 3.0 (assumed)
  - Determine best fit through field inspection results
- **Analysis limited to just those plants that have performed non-visual NDE, plus those in which visual exams have found leakage or cracking**
  - Population = 30 plants
  - 12 had leaks or significant cracking
- **Plants w/ multiple affected nozzles extrapolated back to predict time to first leak or crack**
  - w/ assumed Weibull slope of 3
- **Effects of different Weibull parameters addressed via sensitivity studies**
  - Slope b and characteristic failure time θ


All inspection data adjusted to 600 °F (Q = 50 kcal/mole)
Weibull characteristic time θ = 16.45 EDYs
Weibull slope of b = 3 assumed for fit to extrapolated data
Crystal River 3
Oconee 1
St. Lucie 2
D-B
Surry 1
ANO-1
TMI-1
Beaver Valley 1
Oconee 3
Oconee 2
North Anna 2
Millstone 2
EDYs at detection of leakage
EDYs at first leak extrapolated back using slope b = 3
Cumulative Fraction of Units with Leakag
EDYs
0.90
0.63
0.50
0.20
0.10
0.05
0.02
0.01
1
10
100



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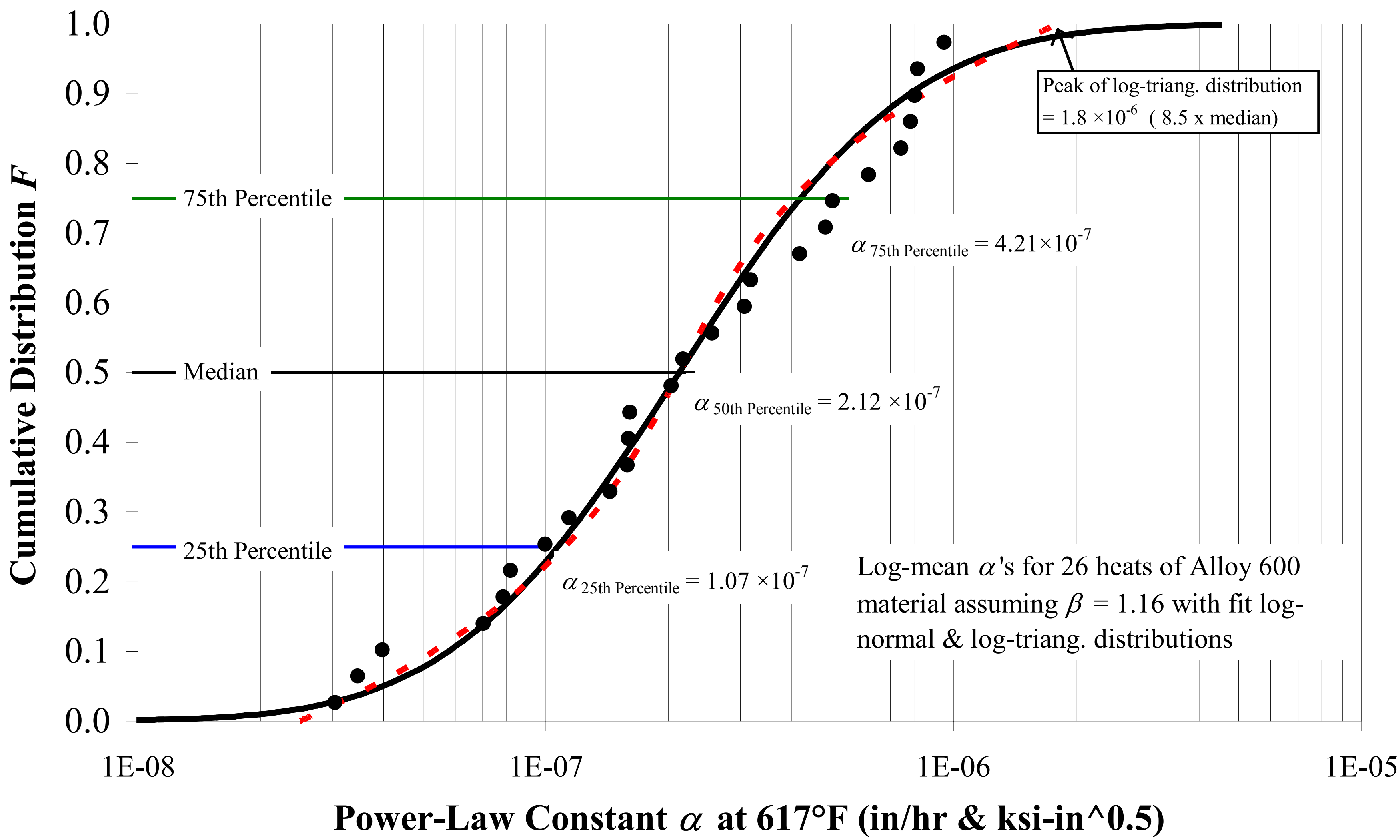
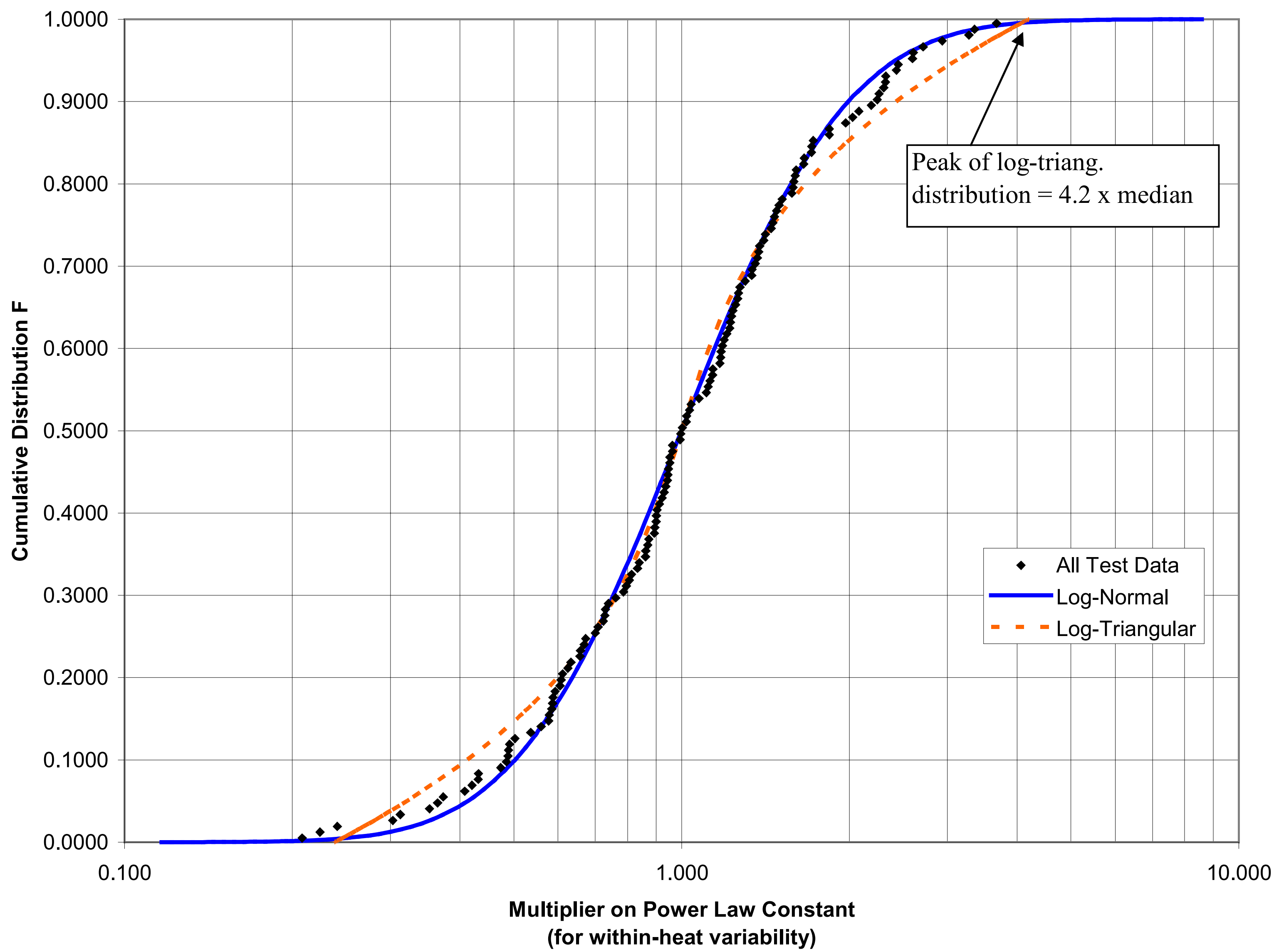
Material Crack Growth Rate Statistics

- **Stress corrosion crack growth data for Alloy 600 taken from MRP-55**
- **Statistical distributions developed for heat-to-heat variation as well as for variability of CGR within a specific heat**
- **Statistical sampling of CGR for PFM analysis assumed to be correlated with Weibull statistics for time to leakage (I.e. nozzles which leak early tend to be sampled from high end of CGR distribution)**
- **Crack growth statistics updated based on latest MRP-55 qualified data set**
  - 26 heats
  - 158 data points

CGR Distributions Based on Heat Data

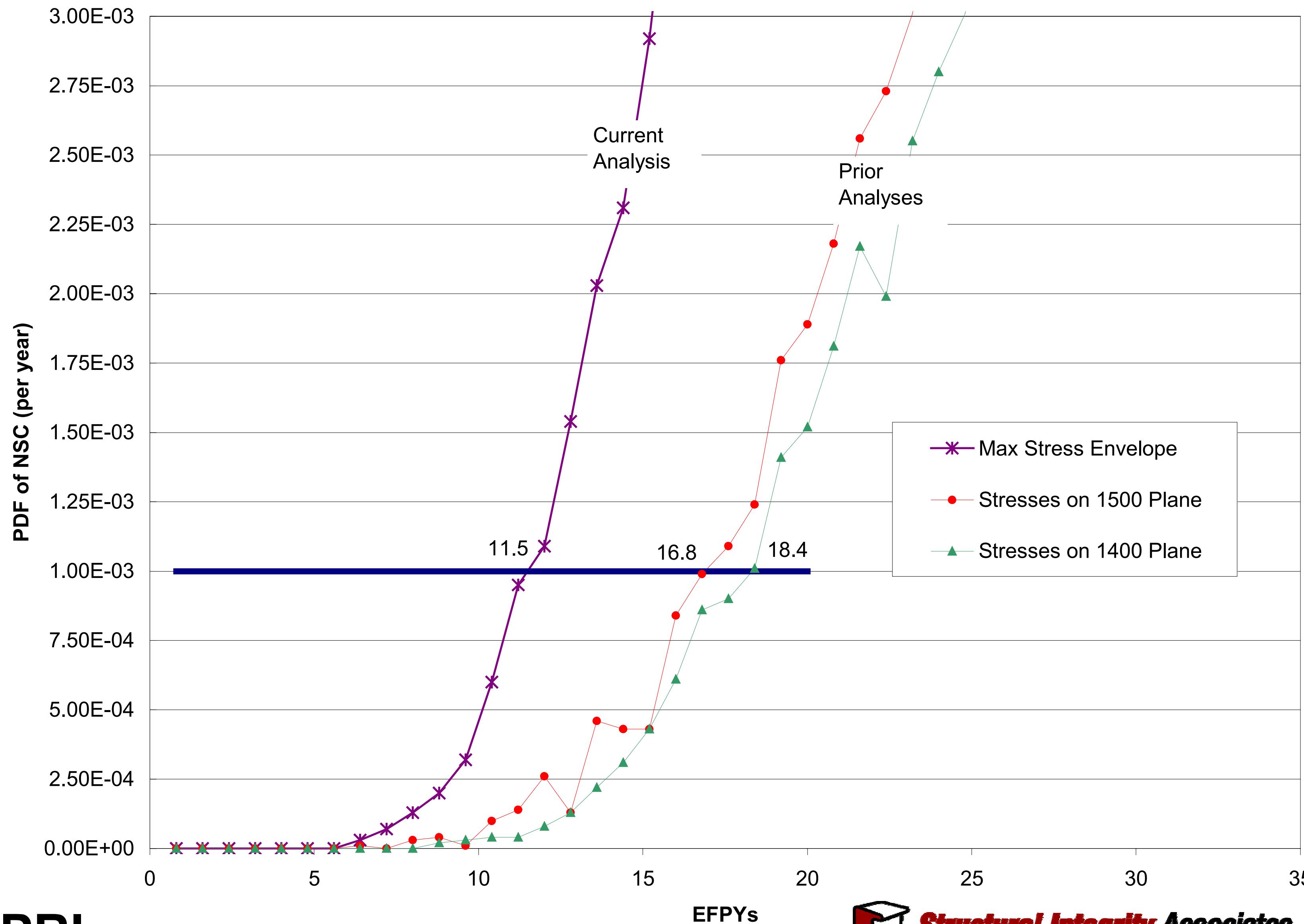


Multiplier on CGR Distribution for Within-Heat Variability



New Base Case Results

600°F No Inspection; New Weibull & CGR Fits



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Inspection Interval Analysis Parameters

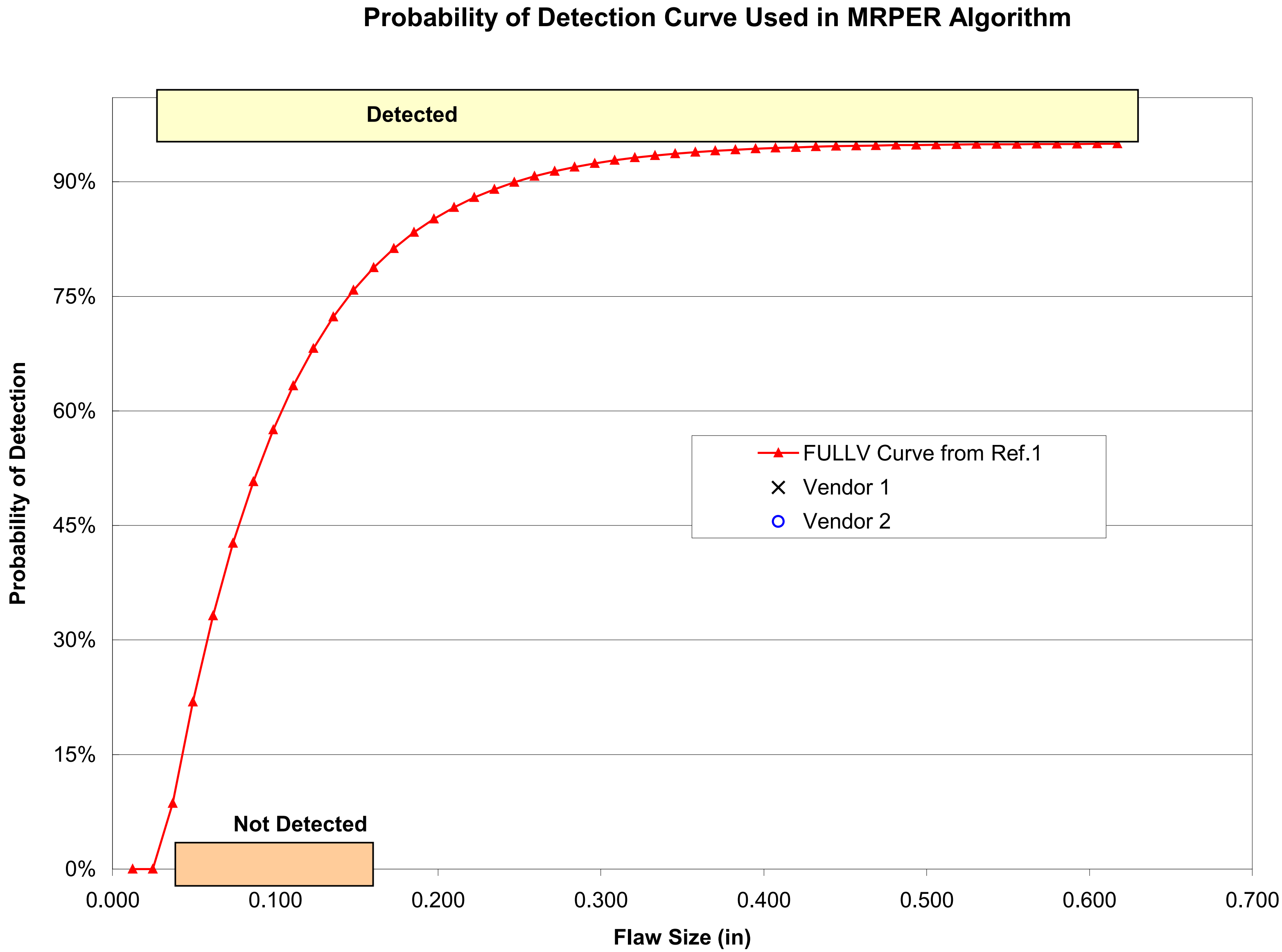
- **Head Temperature: Various from 580°F to 600°F**
- **Weibull Parameters:**
  - Slope = 3
  - Theta = 16.45; +6.5, -4.65 (Triangular)
- **Crack Growth Rate Statistics**
  - Heat-to-Heat - Log-Triangular: -15.365 ± 2.14
  - Within Heat – Log-Triangular: 0 ± 1.4343
- **Crack Growth vs. Leakage Correlation Factors**
  - 0.8 – Heat-to-Heat
  - 0.8 – Within-Heat
- **Probability Targets:**
  - Probability of NSC < 1 x 10^{-3} per plant per year
  - Low Probability of Leak (or significant cracking)

Inspection Interval Analysis Probability of Detection for NDE

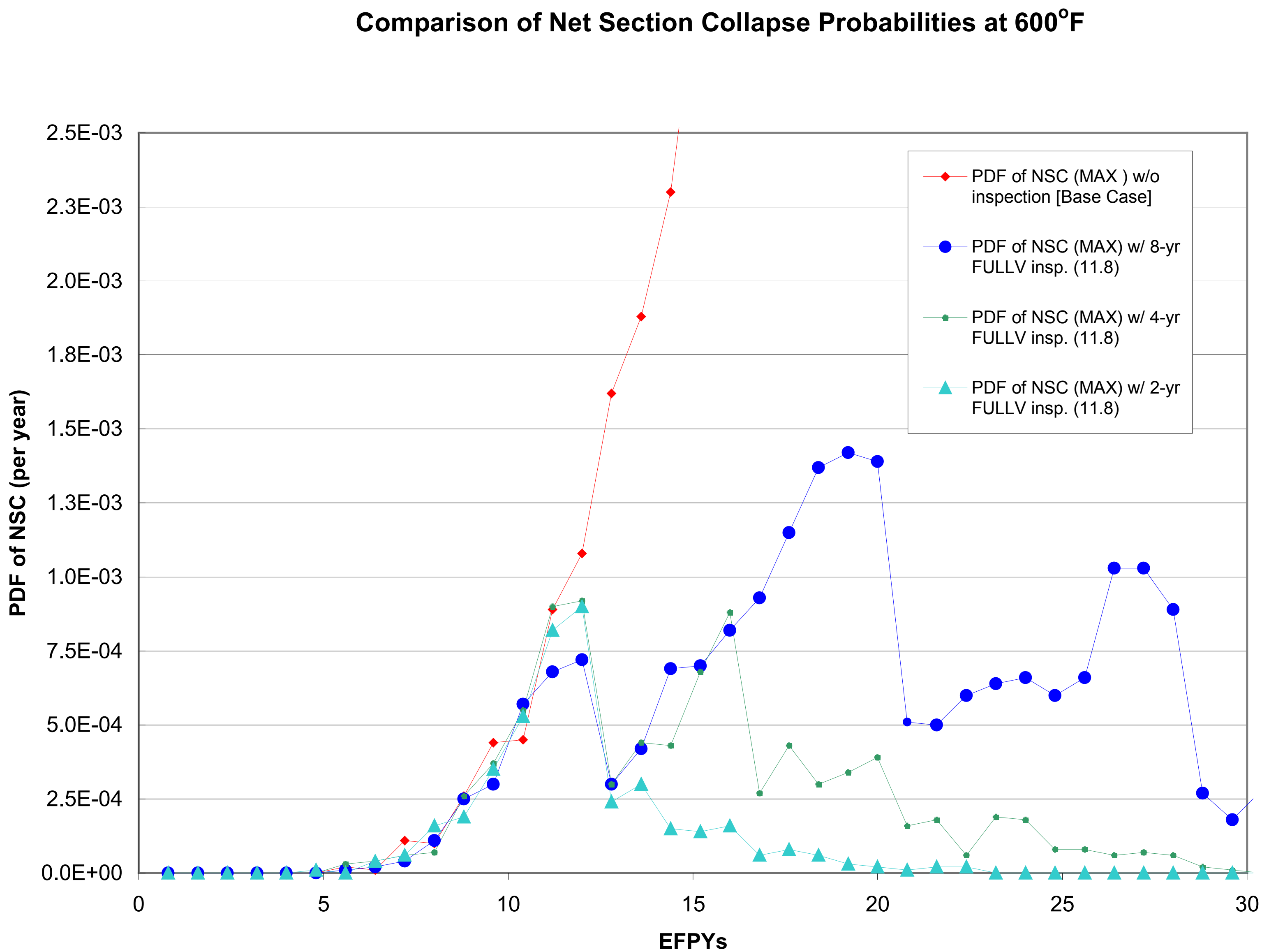
- **Non-Destructive Examinations (NDE)**
  - POD = f(crack depth) per EPRI-TR-102074[1]
  - 80% Coverage Assumed
- **POD Curve Compared to Vendor Inspection Demonstrations**

[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

POD Curve for NDE (Illustrating Comparison to Vendor Demonstrations)



Effect of NDE on NSC (600 F Head, Various Inspection Intervals)



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Deterministic Crack Growth Analyses

- MRP-55 CGR correlations used - 75th percentile $\alpha = 4.21 \times 10^{-7}$, with factor of 2 applied for evaluation of OD connected circumferential flaws
- Stress Intensity Factors for envelope stress plane used to compute crack growth from 30° to ASME Section XI allowable crack length (~ 300°)
- Analyses performed for steepest angle nozzles in typical B&W and Westinghouse Plant
- Analyses run for various head temperatures using standard activation energy temperature adjustment on crack growth law
- Results Indicate that probabilistic-based inspection intervals are conservative

Stress Intensity Factor Summary
B&W Type Plant

Crack Angle (degrees)	K - UPHILL SIDE FLAWS (psi-in^0.5)				K - DOWNHILL SIDE FLAWS (psi-in^0.5)			
	38 DEG.	**26 DEG.**	**18 DEG.**	**0 DEG.**	**38 DEG.**	**26 DEG.**	**18 DEG.**	**0 DEG.**
30	20141	17334	10711	6780	11227	10142	8985	6780
90	37722	34557	20565	15484	33760	26415	22528	15484
160	51559	47718	32124	26336	68230	53181	42552	26336
180	54337	49976	35163	29383	78168	60404	47890	29383
220	56867	53293	40401	34688	94384	75337	57878	34688
260	59702	56314	44839	38758	115569	90144	65578	38758
300	64773	63152	51868	44166	140471	104128	74058	44166

Stress Intensity Factor Summary
Westinghouse Type Plant

Total Flaw Angle (Degrees)	Average K on Crack Front (psi-in^0.5)	
	Downhill	**Uphill**
30	28790	4942
90	59336	14302
160	84080	21782
180	86557	24115
220	89310	30100
260	92769	38017
300	93453	50009

Deterministic Crack Growth Analysis Results

Growth time from 30 degree to 300 degree flaw, B&W 38 degree nozzle

TEMPERATURE DEGREES F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	218000	24.89	205000	23.40
590	168000	19.18	158000	18.04
600	131000	14.95	123000	14.04
602	125000	14.27	117000	13.36
605	116000	13.24	109000	12.44

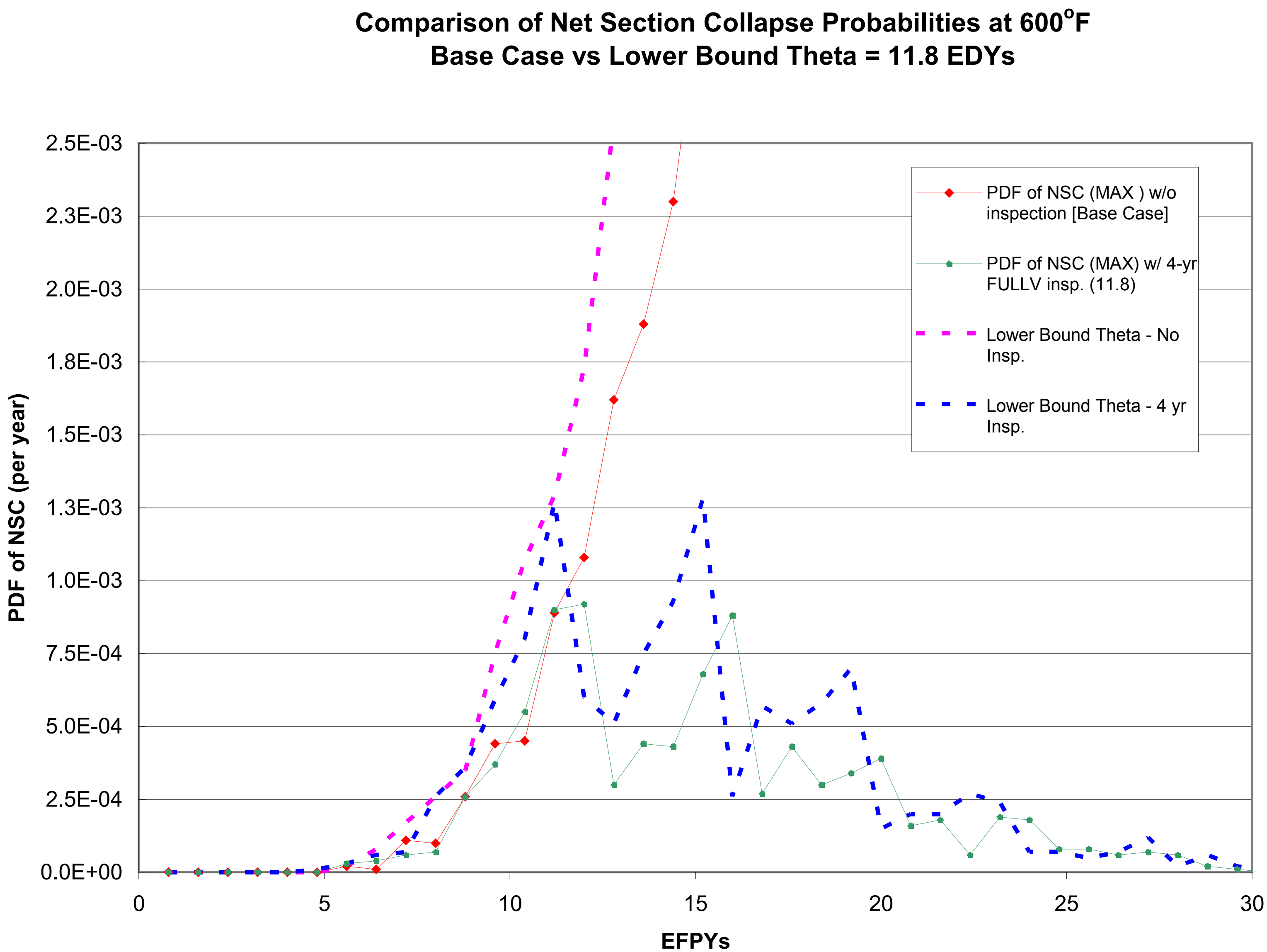
Growth time from 30 degree to 300 degree flaw, Westinghouse 49 degree nozzle

TEMPERATURE DEGREES F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	no growth	no growth	125500	14.33
590	no growth	no growth	97000	11.07
600	no growth	no growth	76000	8.68
602	no growth	no growth	72000	8.22
605	no growth	no growth	67000	7.65

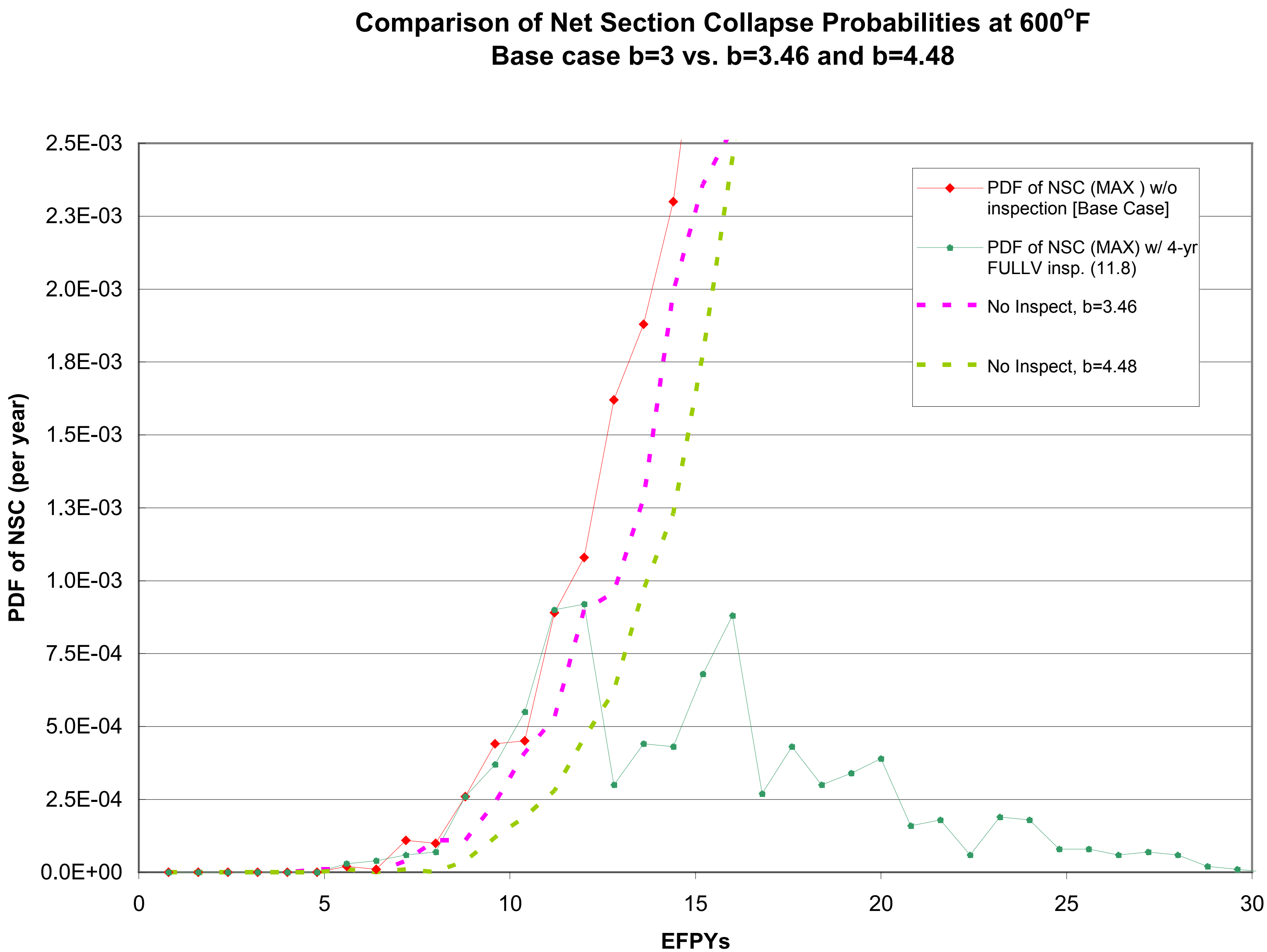
Sensitivity Studies

- Effect of Worst Case θ from Weibull
- Effect of Weibull Slope b
- Effect of Initiation-Growth Correlation Factor
- Typical Plant-Specific Application

Sensitivity to Weibull Characteristic Time to Failure (θ)



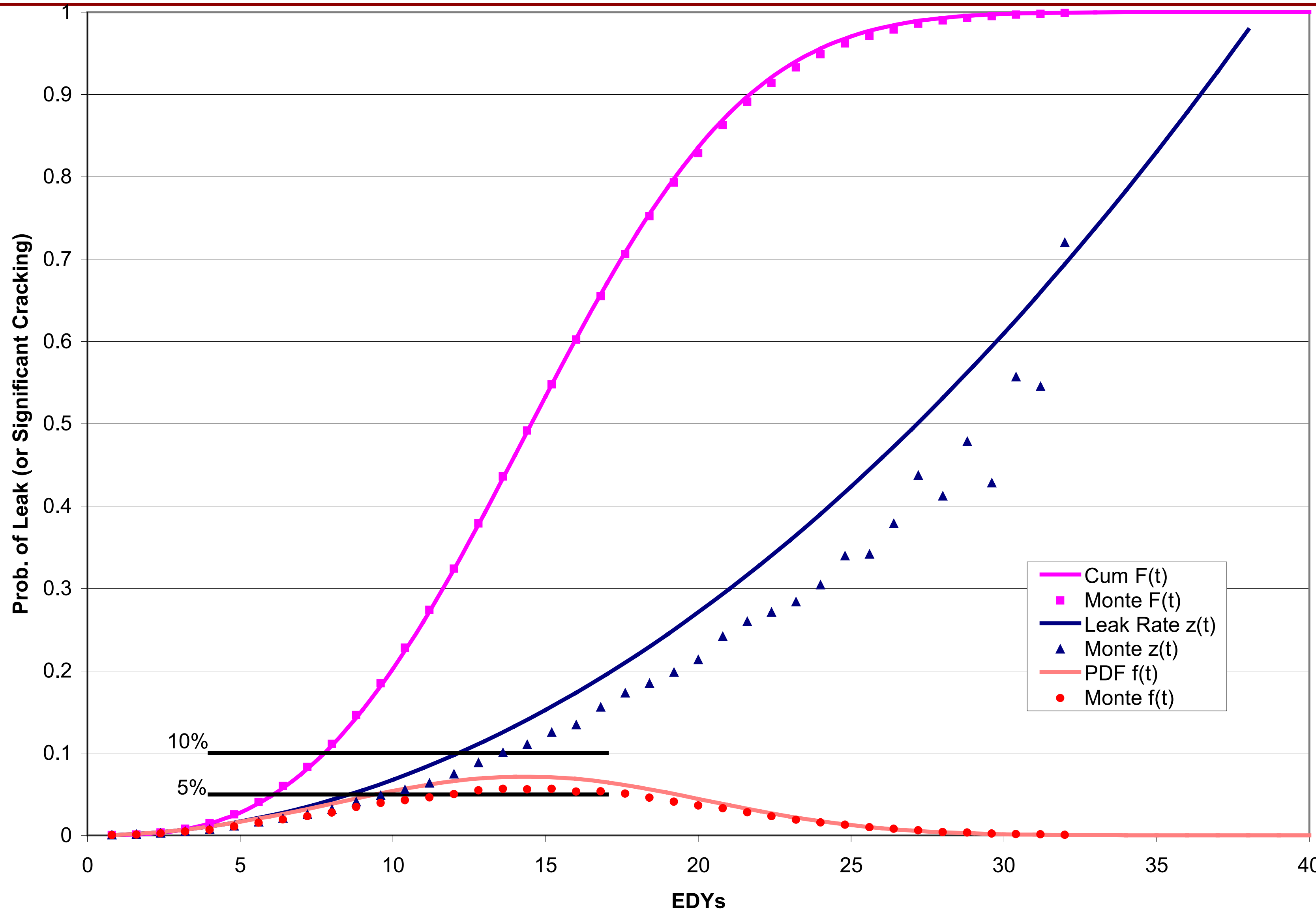
Sensitivity to Weibull Slope (b)



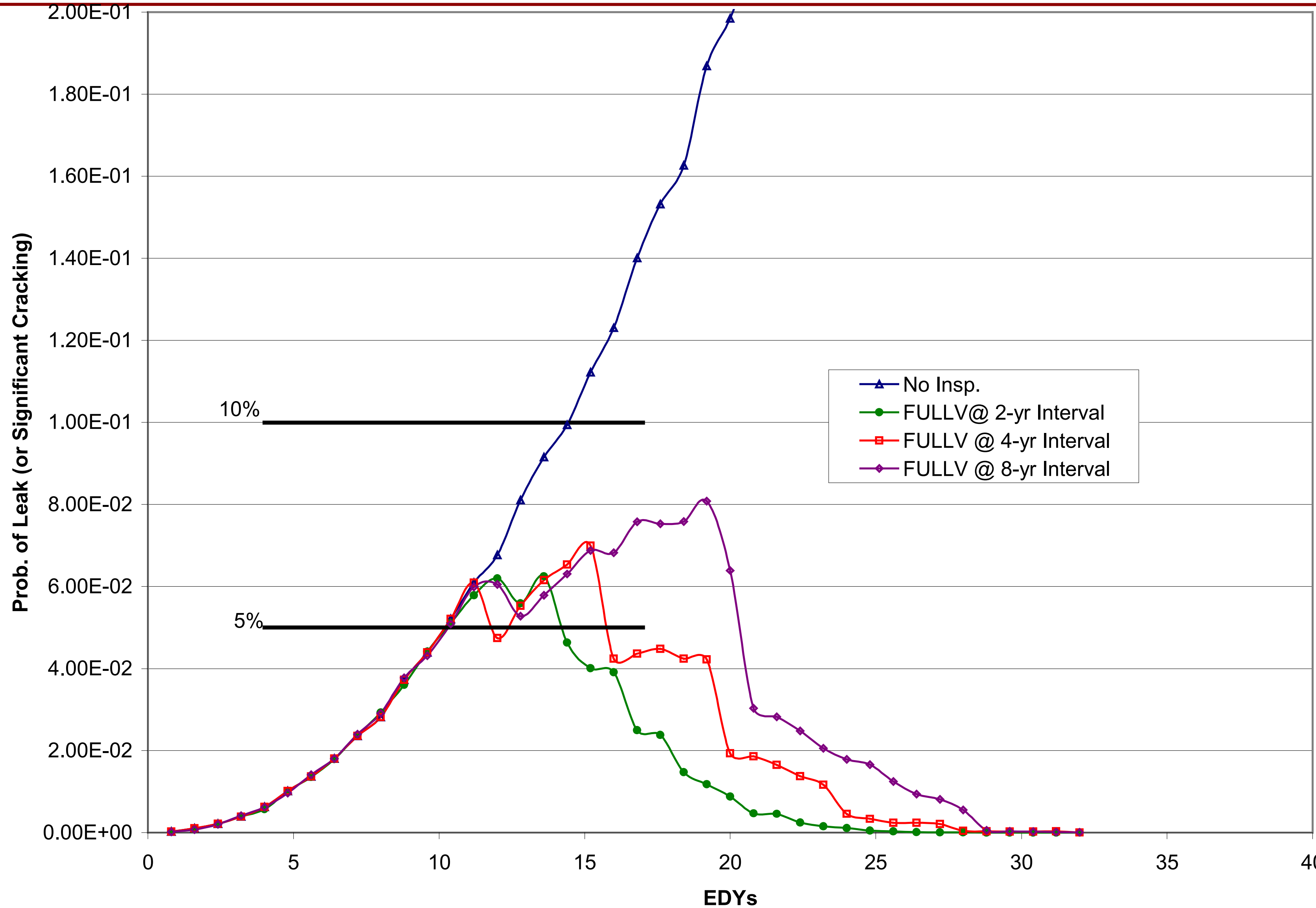
Effect of Inspections on Leakage

- Primary Goal of PFM is to ensure that inspection interval protects against nozzle ejection
- However, effect of inspections on leakage probability (Weibull hazard rate) generated as by-product of analyses
- Results indicate that reasonable assurance against leakage maintained, but this is dependent on inspection coverage (80% assumed)

Leakage Probability (w/o NDE)



Effect of NDE on Leakage Probability



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Conclusions

- **Current PFM Incorporates:**
  - ♦ Updated Weibull model of time to leakage or cracking, including Spring-03 results
  - ♦ Finite Element Fracture Mechanics model updated addressing NRC comments
  - ♦ Crack growth rate statistics based on MRP-55 w/ correlation between time to leakage and CGR
  - ♦ Effect of inspection POD and intervals
- **Important Results**
  - ♦ 4 EDY inspection interval supports safety limit for nozzle ejection and reasonable goals for probability of leakage
  - ♦ Deterministic Fracture Mechanics analysis supports longer inspection intervals
  - ♦ Sensitivity studies indicate results not highly sensitive to reasonable ranges of key variables
- **Remaining Tasks**
  - ♦ Complete analyses for CE and Westinghouse plant types
  - ♦ Documentation