Section 4:
Session 3: Structural Analysis and Fracture Mechanics Issues

This page intentionally left blank.

Probabilistic Fracture Mechanics Analysis of RPV Top Head Nozzles

U.S. Nuclear Regulatory Commission
Argonne National Laboratory

Conference on Vessel Head Penetration Inspection, Cracking, and Repairs

September 29 – October 2, 2003
Gaithersburg, Maryland

Peter Riccardella, Nathaniel Cofie, Angah Miessi
Structural Integrity Associates
Sept. 30, 2003

EPRI

Structural Integrity Associates, Inc.

Project underway since Sept. 2001 under EPRI / MRP sponsorship

Objectives:

- Develop generic methodology to determine probabilities of top head nozzle leakage and failure (ejection)
- Apply to assortment of U.S. PWRs in support of MRP Safety Assessment
- Use to define MRP inspection plan that provides acceptable level of quality and safety

426

Elements of Analysis

- Monte-Carlo PFM model
- Applied stress intensity factors for circumferential cracks
- Weibull analysis of plant inspection data (time to leakage or significant cracking)
- Statistical characterization of laboratory PWSCC crack growth rates
- Effect of inspections (interval and probability of detection)

Monte-Carlo PFM Model

- **A time-dependent Monte Carlo analysis scheme**
- **Predicts probability of leakage and nozzle ejection versus time for a specific set of top head parameters:**
  - Deterministic Parameters
  - Statistical Parameters (Random Variables)
- **Two nested Monte Carlo simulation loops**
  - step through time for each nozzle in a head
  - and then for the total number of head simulations specified

Deterministic Parameters

- Number of top head nozzles
- Angle of each nozzle with respect to the head
- Nozzle diameter and wall thickness
- Number of heats of nozzle material, and number of nozzles from each heat
- K-matrices for each of four nozzle angles into which nozzles are lumped
  - K vs. Crack Length
  - Two Yield Strengths
  - Two Nozzle Interferences

Important Random Variables

- Head operating temperature
- Weibull distribution of time to leakage or cracking (dependent on plant operating time and head temperature)
- Stress corrosion crack growth law distribution
- Correlation factor between time to crack initiation and crack growth law, and
- Critical crack size for each nozzle angle

  Input as distribution type (normal, triangular, log–normal, log-triangular, Poisson, Weibull, etc.) plus mean and variance

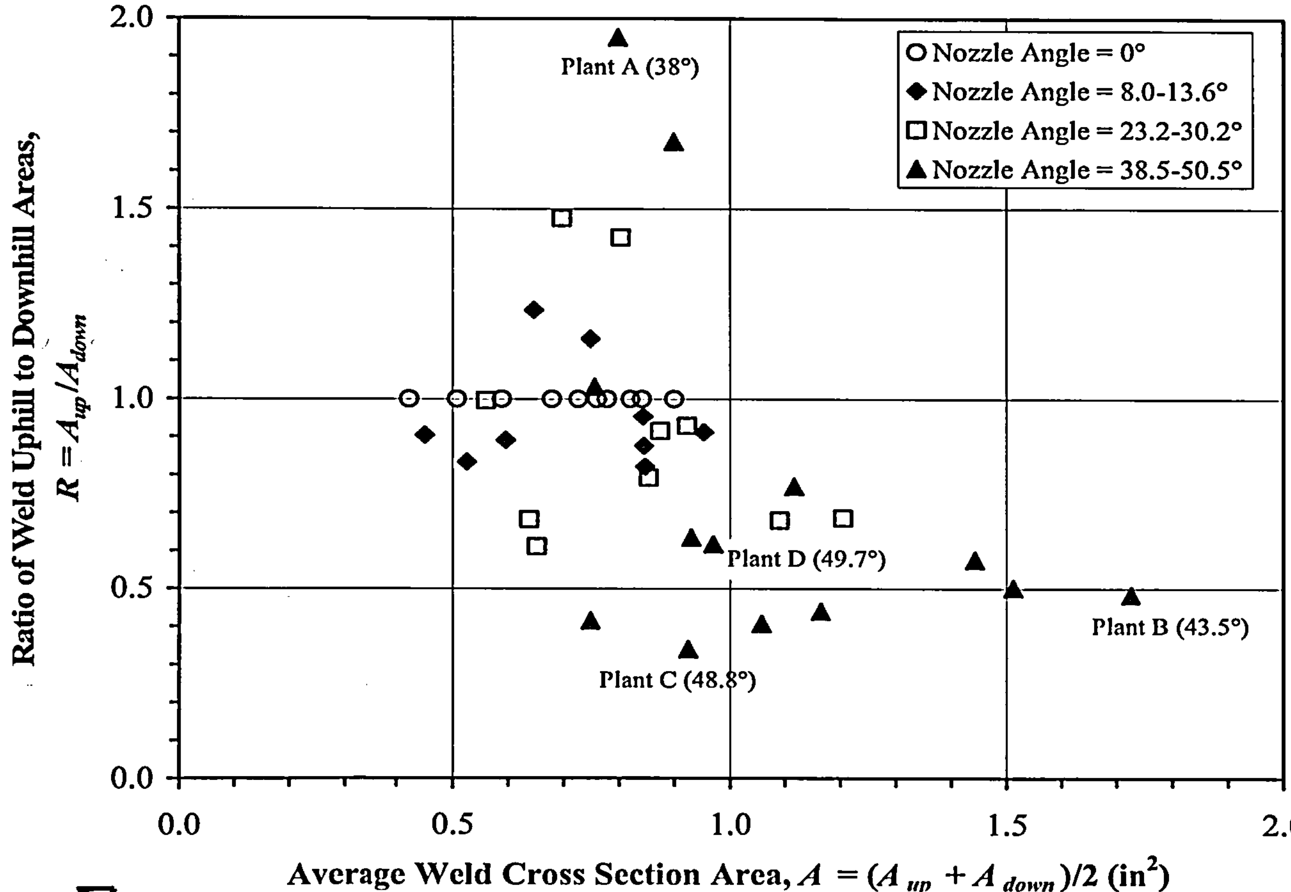
Stress Intensity Factor Calculations

- Analyses performed for four "characteristic plant types"
- Assume that cracking follows planes of maximum stress
- Assume through-wall cracks over entire propagation length (30° to 300°)

	Plant A (B&W)	Plant B (W 2-Loop)	Plant C (W 4-Loop)	Plant D (CE)	
				CEDM	ICI
Top Head: ID (in.) thickness (in)	87.25 6.626	66.3125 5.75	86 7	86 7.6875	
Nozzle: OD (in.) thickness (in)	4.0 0.6175	4.0 0.625	4.0 0.625	4.05 0.661	5.563 0.4065
Total # Nozzles	69	37	96	91	10
Nozzle Angles Analyzed (°)	0, 18, 26, 38.5	0, 13.6, 30, 43.5	48.8	0, 7.8, 49.7	55.3
Nozzle Yield Strengths (ksi)	High:50 Low:37	58	63	High:59 Low:52.5	39.5

431

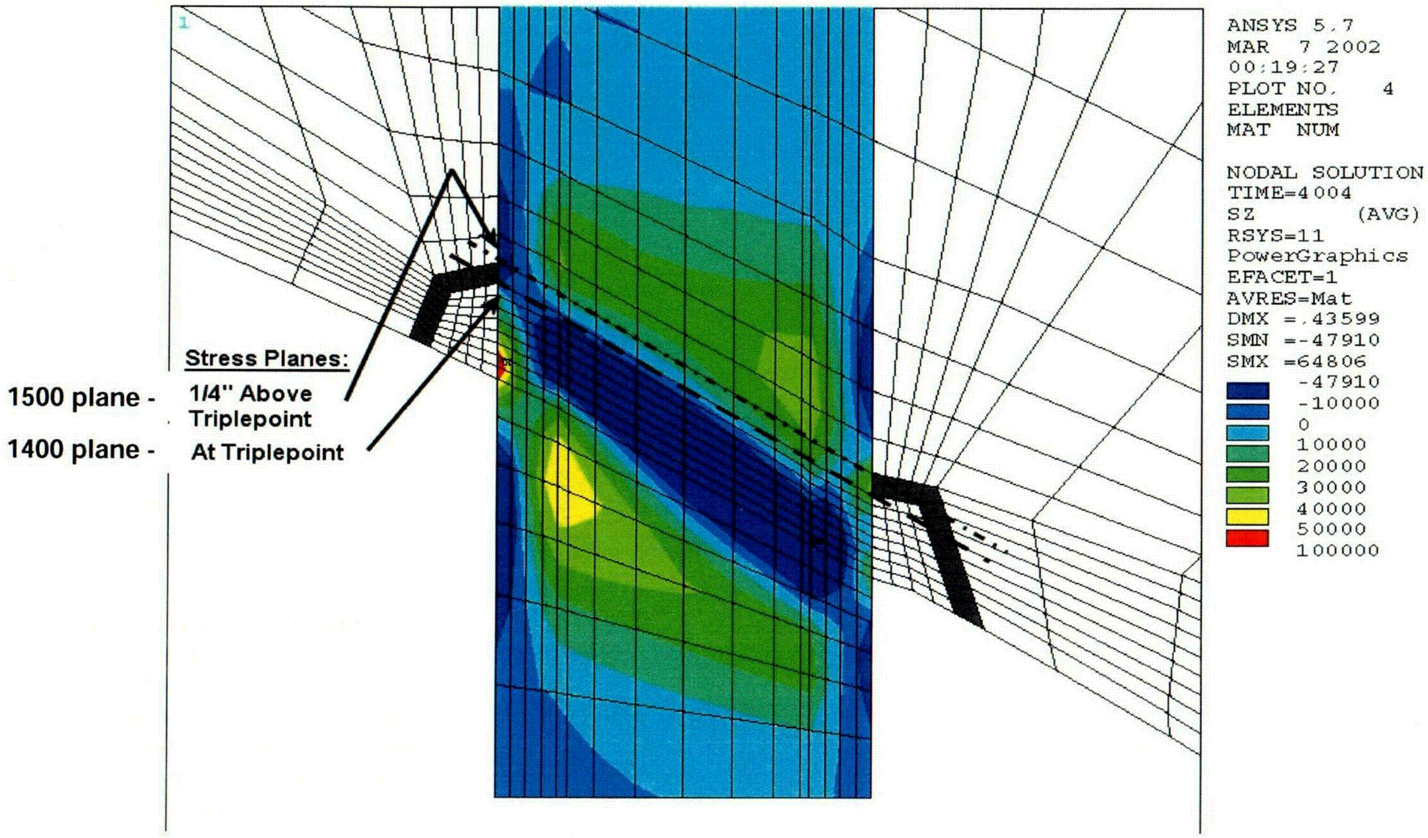
Geometric Comparison of Characteristic Plants



EPRI

Structural Integrity Associates, Inc.

Residual + Operating Stress Analyses of Non-Cracked Nozzles



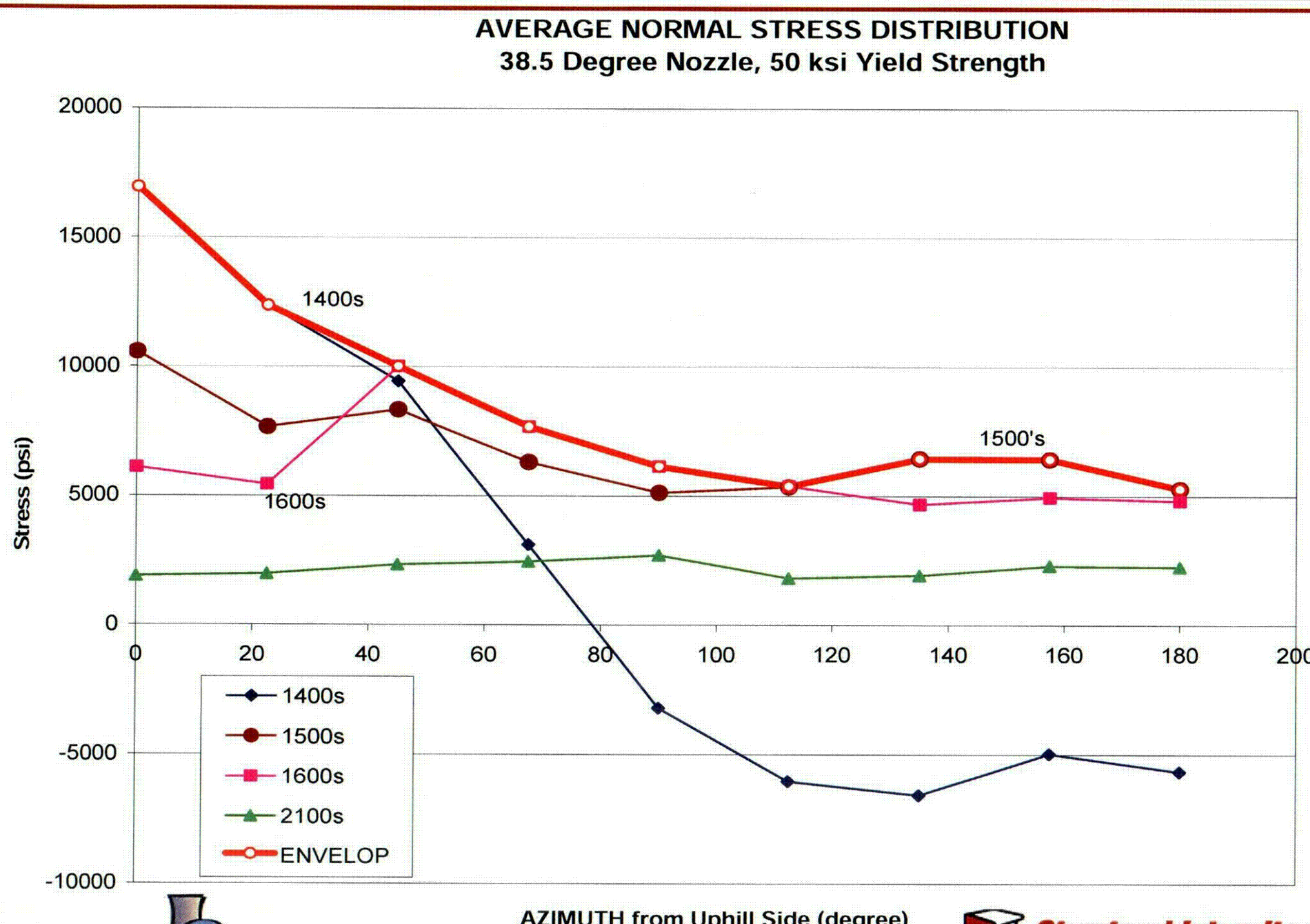
433

EPRI

Structural Integrity Associates, Inc.

C87

Stresses along Various Stress Planes – Plant A

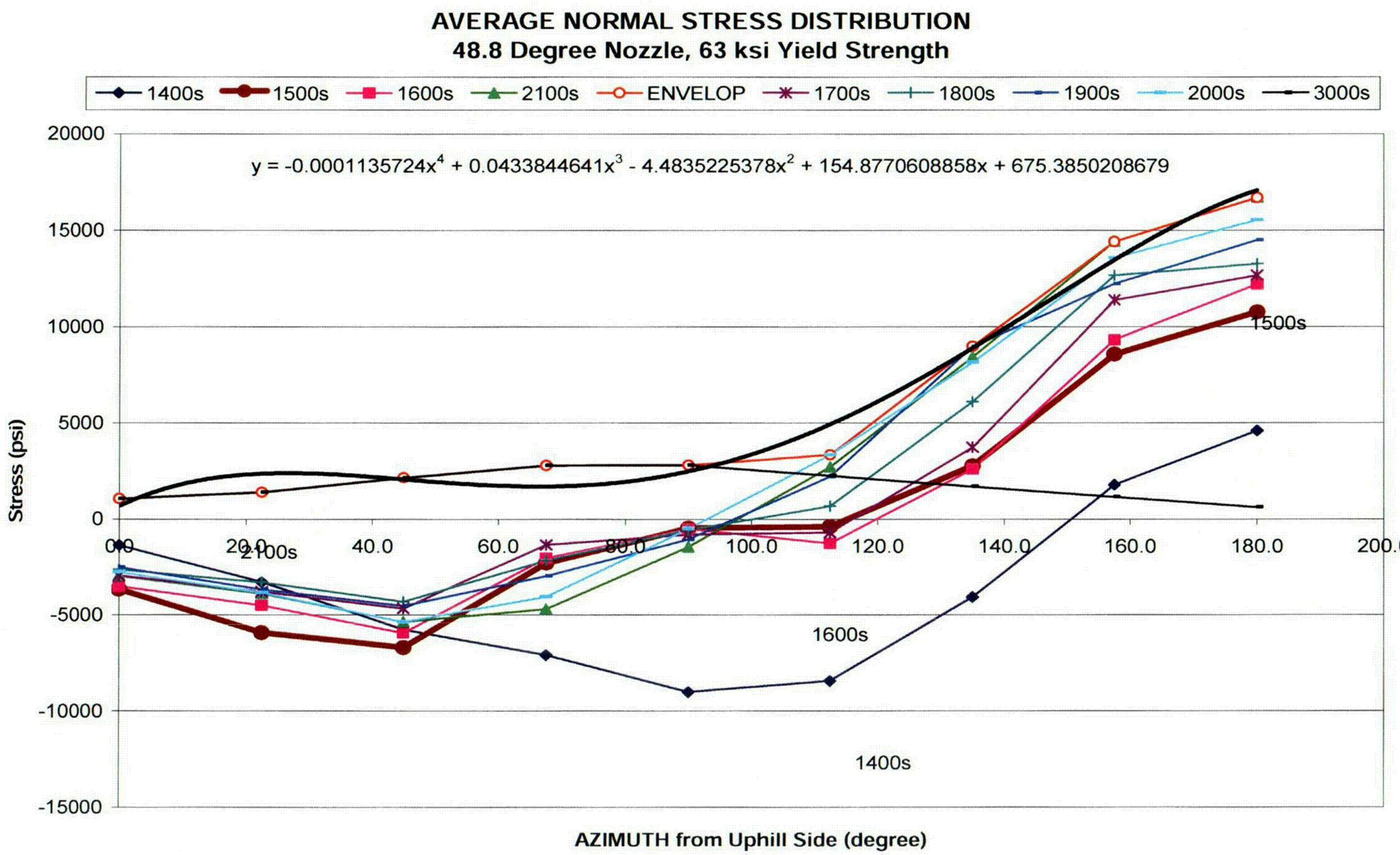


EPRI

Structural Integrity Associates, Inc.

C88

Stresses along Various Stress Planes – Plant C



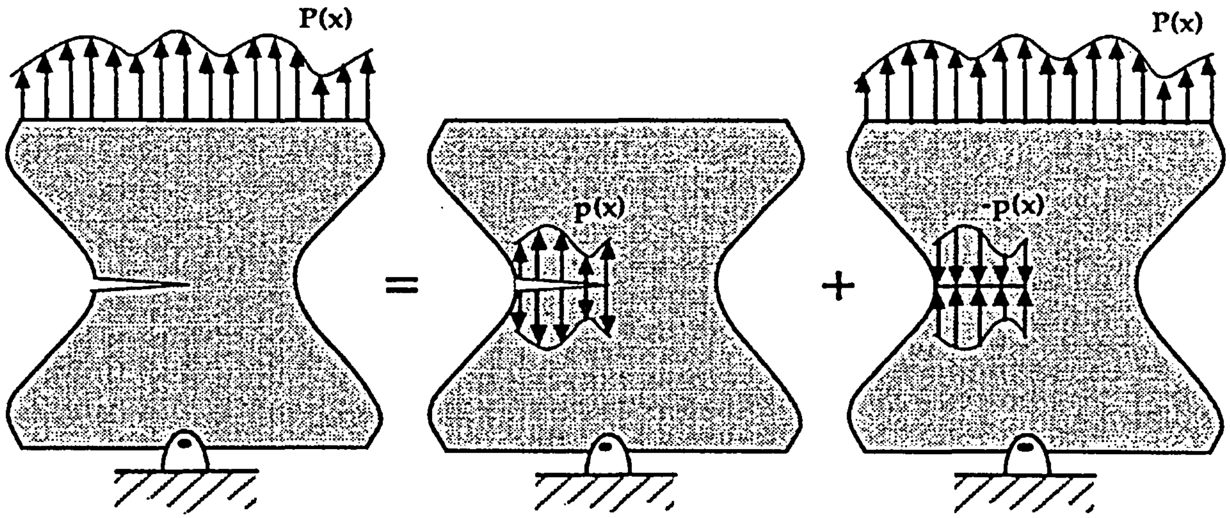
435

EPRI

Structural Integrity Associates, Inc.

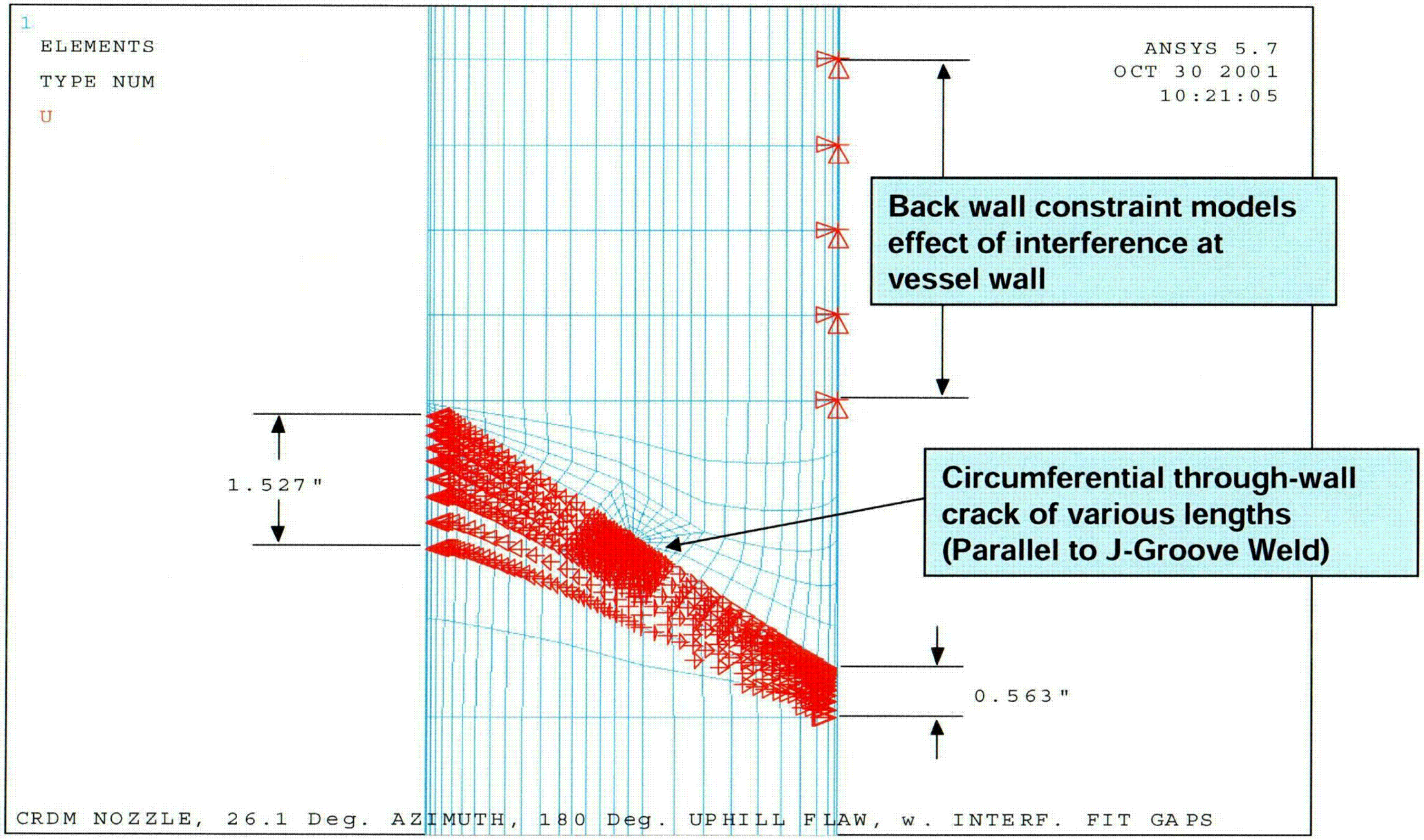
C89

Superposition Approach for K Calculations



Fracture Mechanics

Through Wall Crack Model



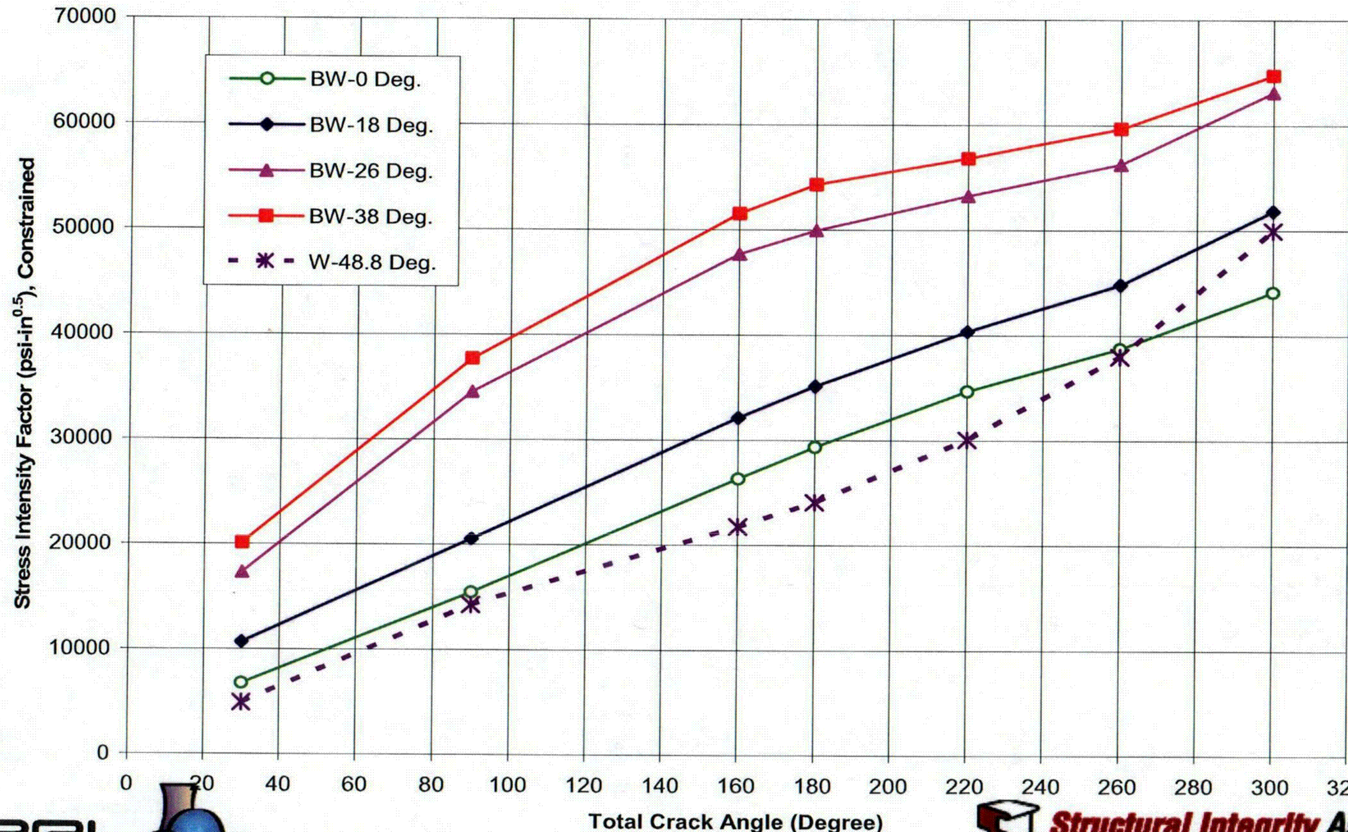
EPRI

Structural Integrity Associates, Inc.

c90

Stress Intensity Factors
Plants A & C - Uphill Cracking

Stress Intensity Factor Comparison - B&W vs. W Heads
Uphill Flaws; Envelop Stress



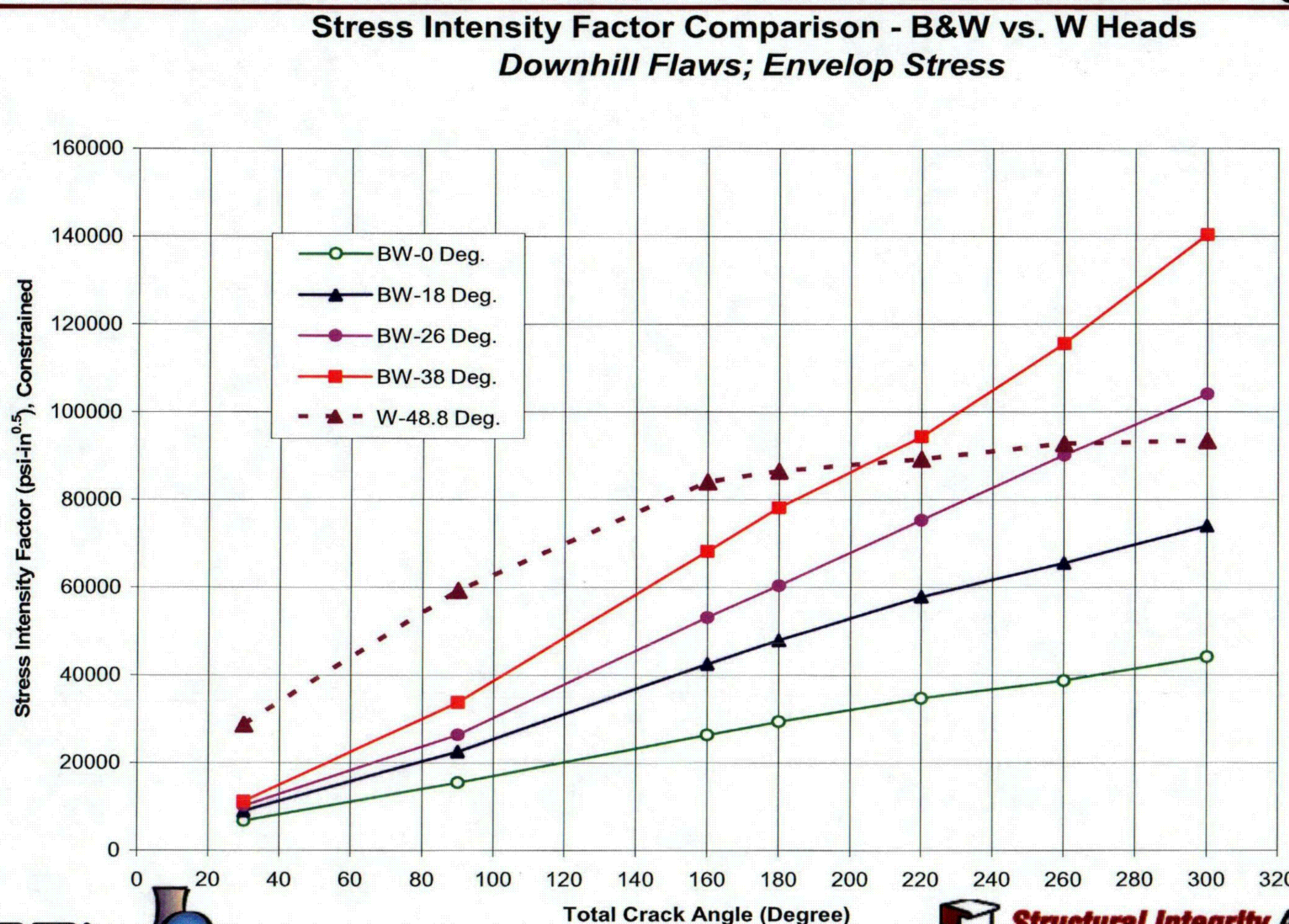
EPRI

Structural Integrity Associates, Inc.

C91

Stress Intensity Factors

Plants A & C - Downhill Cracking



EPRI

Structural Integrity Associates, Inc.

439

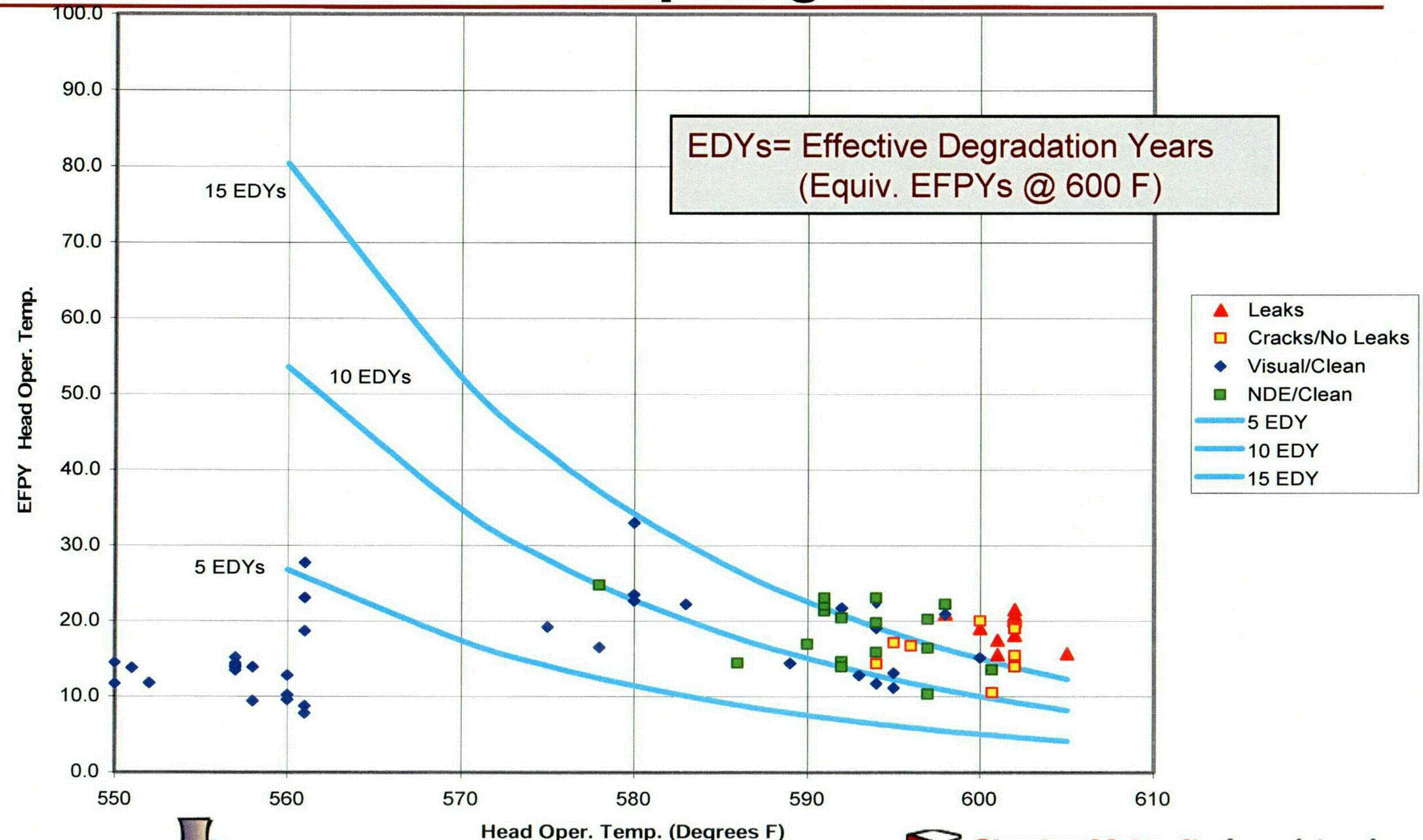
c92

Weibull Model of Time to First Leakage or Cracking

- **"WEI-BAYES" analysis method***
  - ♦ Weibull Slope = 3.0 assumed from prior Alloy 600 experience
  - ♦ Determine best fit through field inspection results
- **Considers only plants that have performed non-visual NDE thru Spring-03**
  - ♦ Population = 30 plants
  - ♦ 12 had leaks or significant cracking
  - ♦ 18 inspected & clean treated as "Suspensions"
  - ♦ Plants that performed only visual examinations excluded
- **Plants w/ multiple cracked or leaking nozzles extrapolated back to time to first leak or crack**
  - ♦ w/ same assumed Weibull slope of 3

**R. B. Abernathy, "The New Weibull Handbook, Reliability and Statistical Analysis for Predicting Life, Safety, Survivability, Risk, Cost and Warranty Claims," Fourth Edition, Sept. 2000*

Summary of Inspections & Results
(Thru Spring-03)

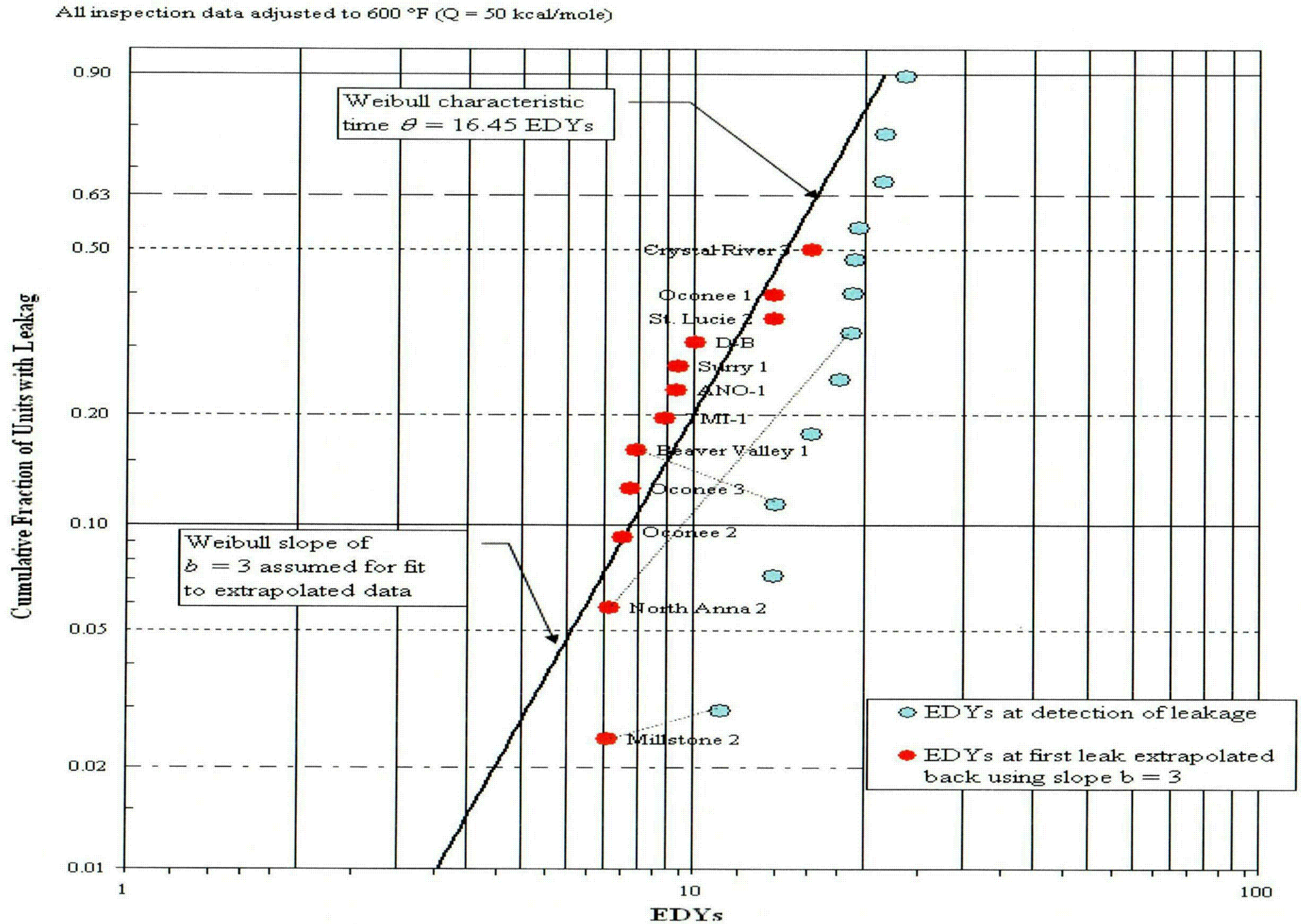


EPRI

Structural Integrity Associates, Inc.

441

C93


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

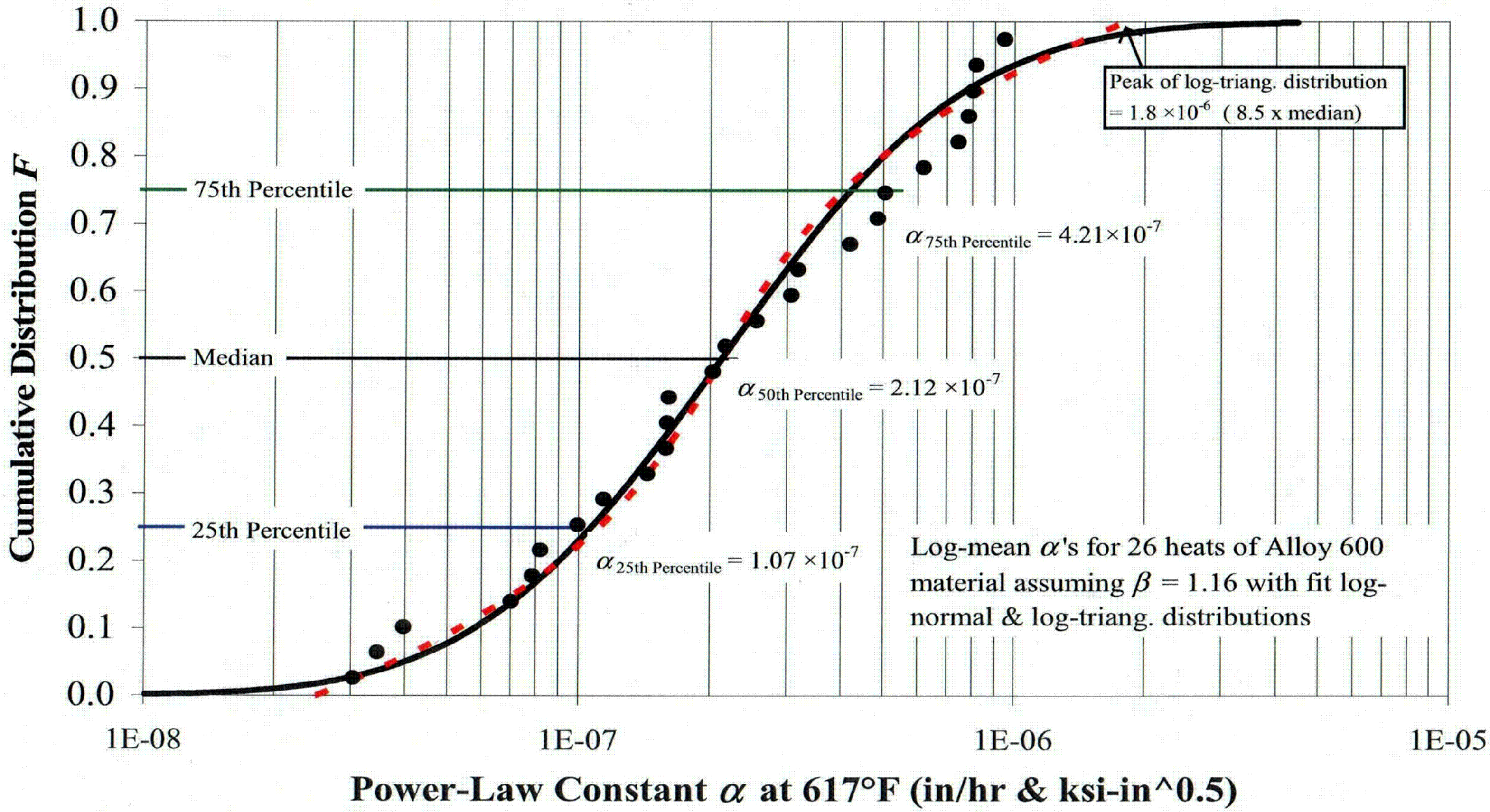
442

C94

Material Crack Growth Rate Statistics

- Crack growth statistics incorporate latest MRP-55 qualified data set
  - 26 heats
  - 158 data points
- 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)

CGR Distributions Based on Heat Data



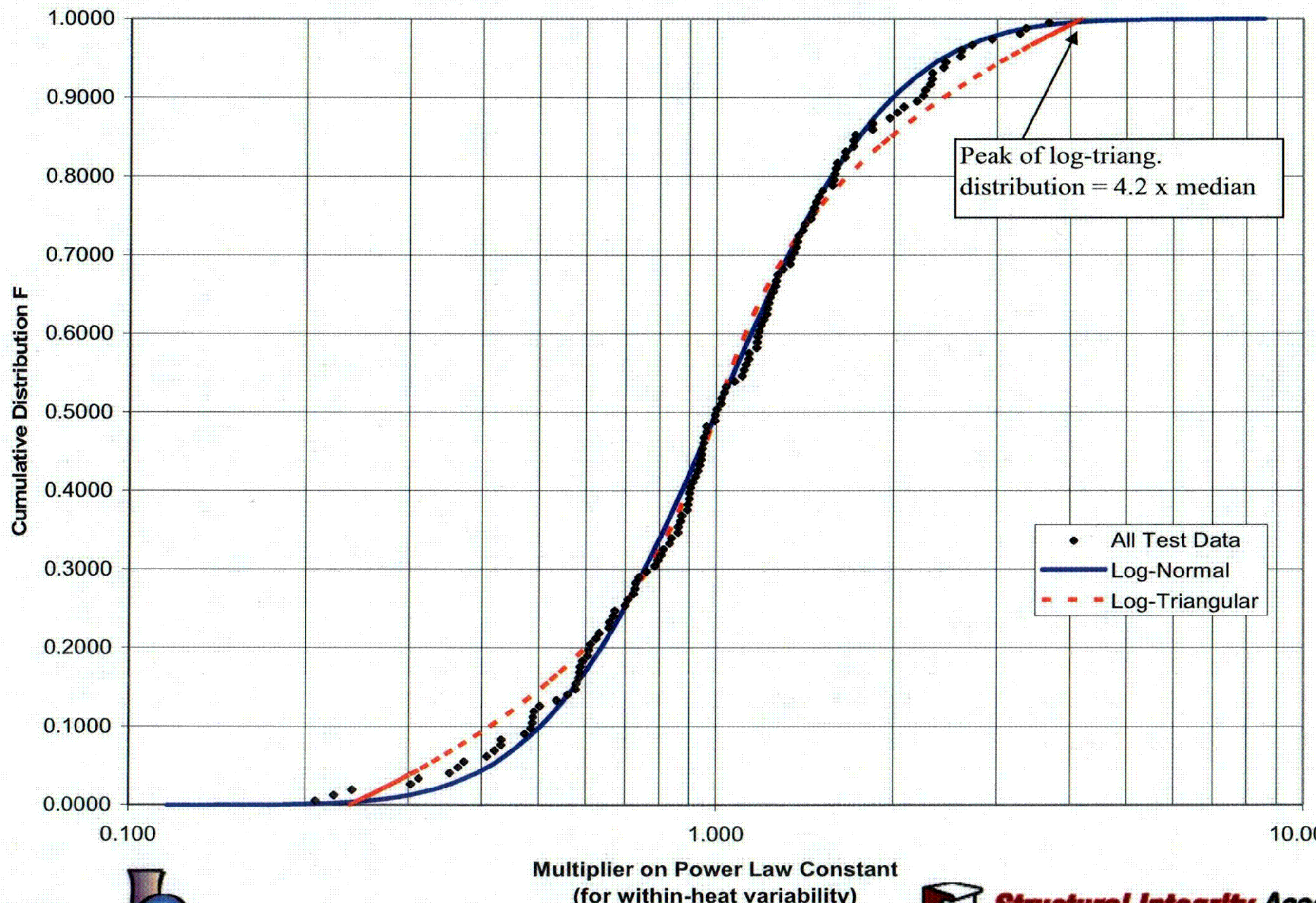
444

EPRI

Structural Integrity Associates, Inc.

C95

Multiplier on CGR Distribution for Within-Heat Variability



EPRI

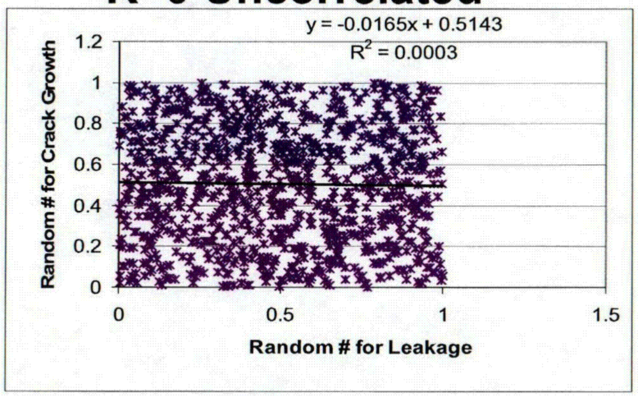
Structural Integrity Associates, Inc.

445

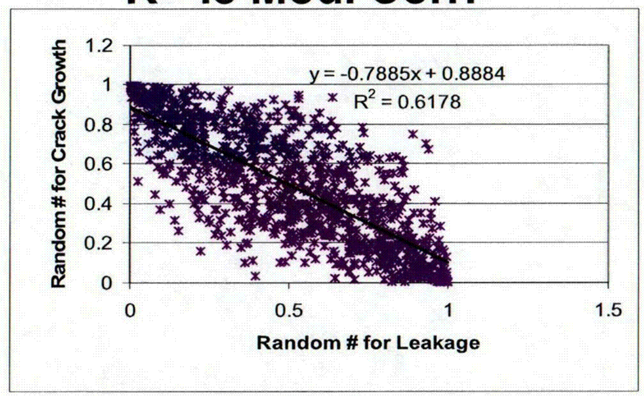
C96

Correlation of CGR with Time-to-Initiation

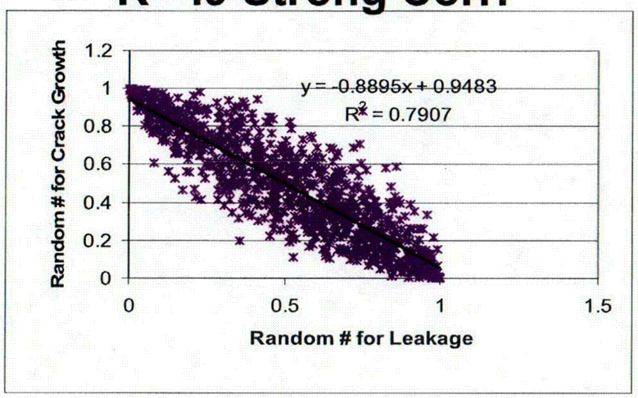
R=0 Uncorrelated



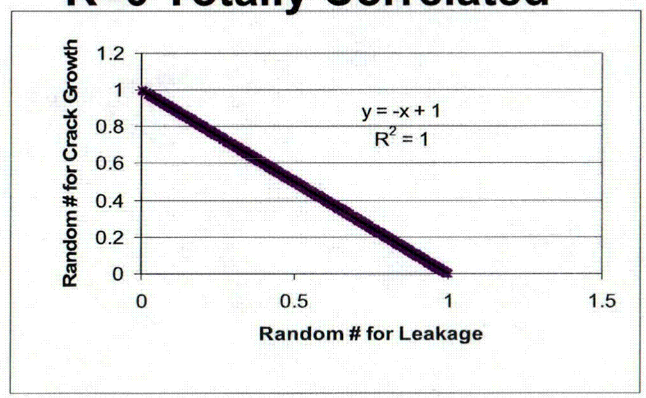
R=-.8 Mod. Corr.



R=-.9 Strong Corr.



R=0 Totally Correlated



EPRI

Structural Integrity Associates, Inc.

446

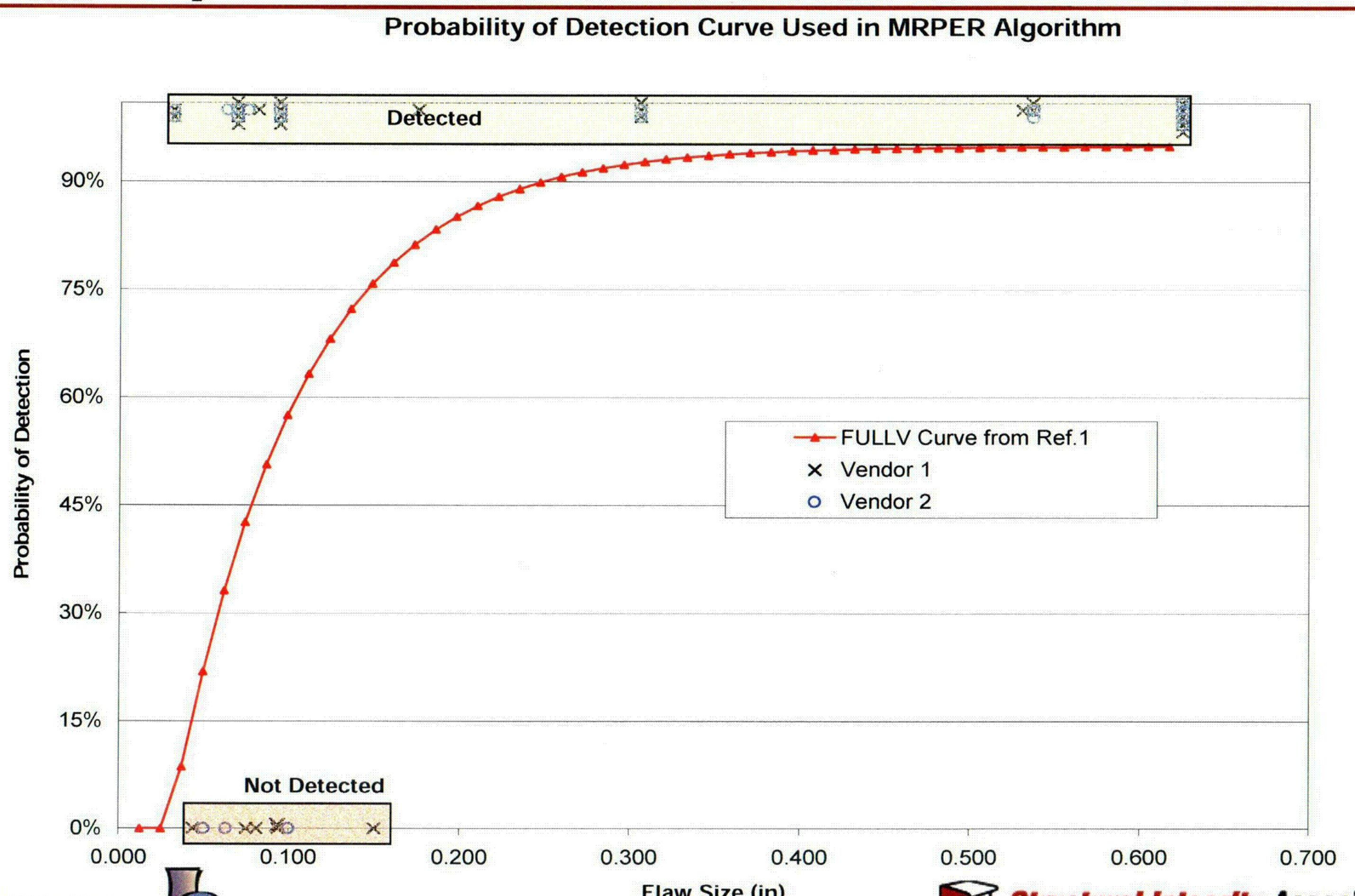
c97

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)



EPRI

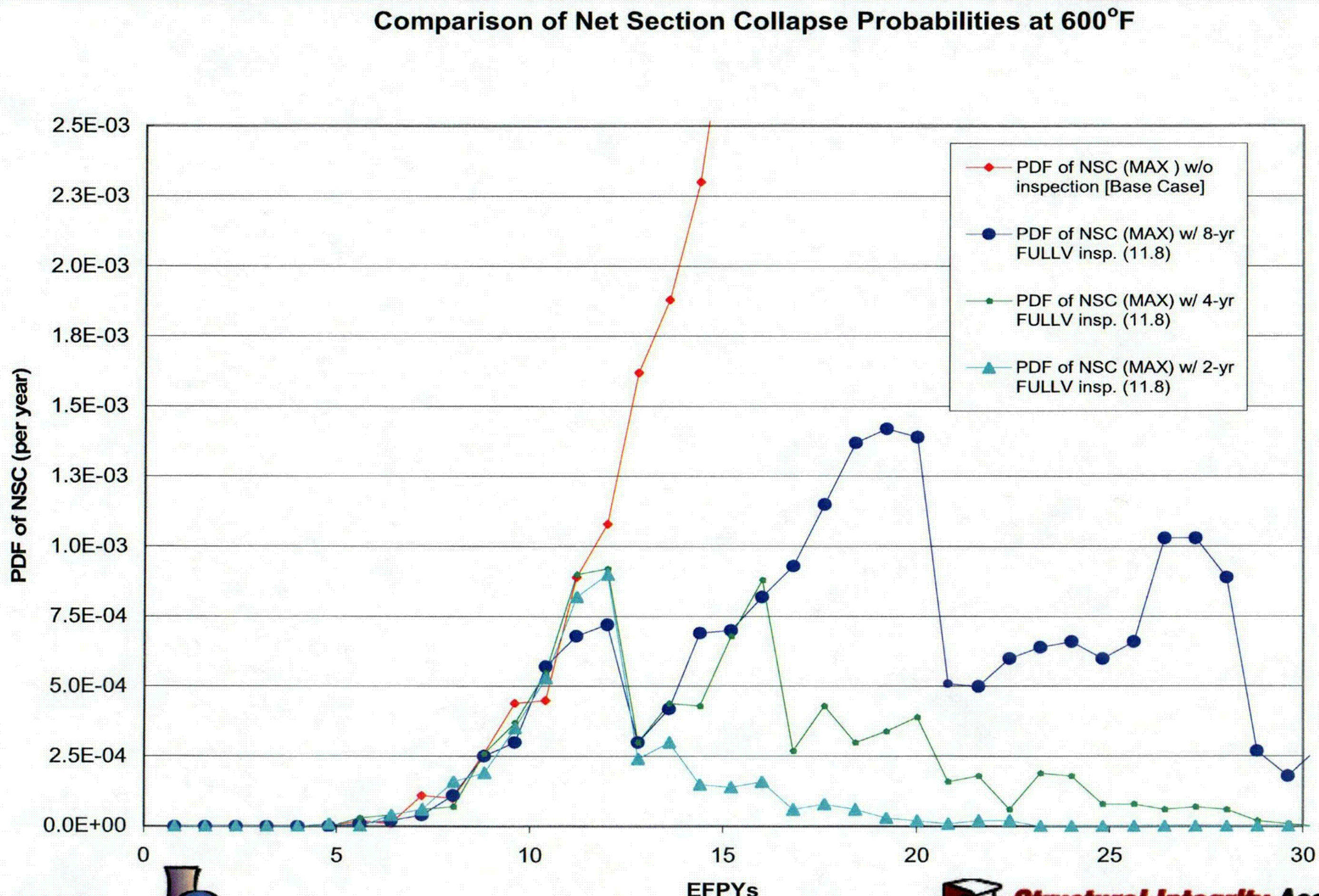
Structural Integrity Associates, Inc.

448

c98

Effect of NDE on Prob. Nozzle Ejection

(Plant A, 600ºF Head, Various Inspection Intervals)



449

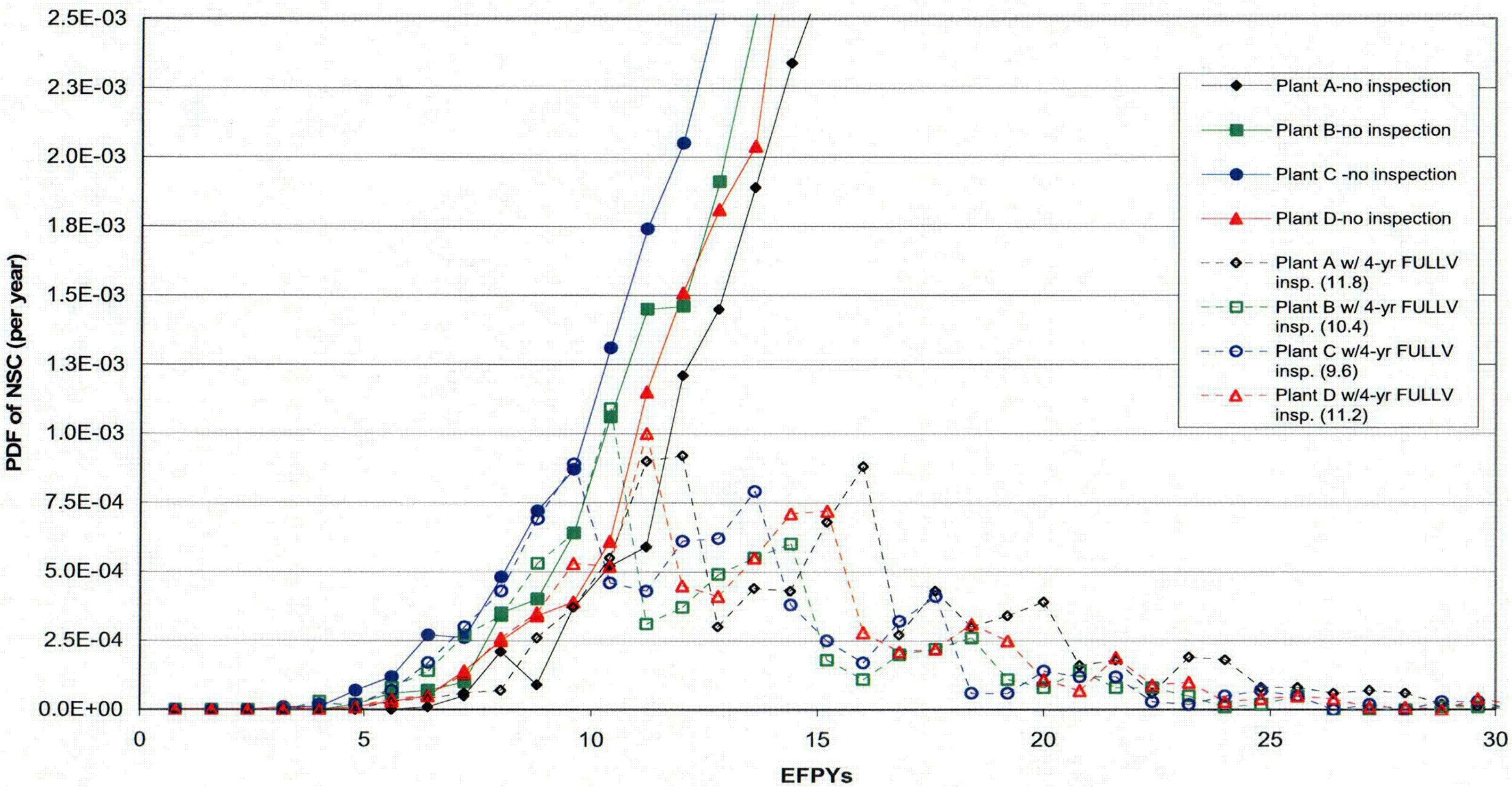
EPRI

Structural Integrity Associates, Inc.

C99

Summary of Results for Characteristic Plants

(Plants A,B,C&D, 600ºF Head, 4-Yr Inspection Intervals)



EPRI

Structural Integrity Associates, Inc.

C100

Deterministic Crack Growth Analyses

- MRP-55 CGR correlations used - 75^{th} percentile, with factor of 2 applied for OD connected circumferential flaws (severe environment effect)
- 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 (worst case) nozzles in Plants A - D
- Analyses run for various head temperatures using standard activation energy (31.05 kcal/mole) temperature adjustment on crack growth law
- Results Indicate that probabilistic-based inspection intervals are conservative

Deterministic Crack Growth Analysis Results (Plants A & B)

TEMPERATURE °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

Plant A – 38.5° Nozzle

TEMPERATURE °F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	468000	53.4	149000	17.0
590	362000	41.3	115000	13.1
600	281000	32.1	90000	10.3
602	267000	30.5	85000	9.7
605	248000	28.3	79000	9.0

Plant B – 43.5° Nozzle

Deterministic Crack Growth Analysis Results (Plants C & D)

TEMPERATURE °F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	no growth	no growth	126000	14.38
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

Plant C – 48.8° Nozzle

TEMPERATURE °F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	215000	24.54	218000	24.89
590	167000	19.06	169000	19.29
600	130000	14.84	131000	14.95
602	123000	14.04	125000	14.27
605	115000	13.13	116000	13.24

Plant D – 49.7° Nozzle

Highlights of Analysis

- Extensive finite element stress intensity factor computations for set of "characteristic plant types"
- Updated Weibull model of field inspection data including Spring-03 results
- Statistical characterization of latest laboratory PWSCC crack growth rate compilation
- Method to correlate CGRs with crack initiation – early crack initiation => more rapid crack growth
- Effects of inspection POD (correlated with inspection demonstrations) and interval evaluated

454

Conclusions

- **PFM demonstrates that RPV top head nozzles meet safety limit for nozzle ejection (< 10^{-3} per plant year) with reasonable inspection intervals**
- **Deterministic fracture mechanics analysis supports longer inspection intervals**
- **Several conservatisms in analysis**
  - Envelope stresses used to compute Ks
  - Entire fleet assumed to be from single Weibull population (even though data indicative of a batch effect, with worst heads being replaced)
  - Crack growth rates assumed correlated with time to crack initiation
  - Conservative POD curve assumed, with 80% coverage

Parametric studies of CRDM Head Failures

W. J. Shack

September 30, 2003

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Introduction

- Discuss three types of calculations
  - Distribution of the probability of failure (ejection) of a nozzle
  - Distribution of the probability of failure (nozzle ejection) of a vessel head
  - Expected numbers of leaks, large cracks, nozzle ejections for a population of plants with the same head temperatures, EFPYs, and numbers of nozzles as the 31 operating plants whose inspection data are used to estimate the statistical parameters describing leakage of the nozzles
- Distributions can be interpreted as describing the range of behavior expected in the whole population of nozzles or heads or as the uncertainty in the prediction of the failure of a specific Alloy 600 nozzle or head assuming that we know only its operating temperature and the number of EFPYs of operation
  - Distributions are broad — about 3 orders of magnitude at any given time
- Results are conservative — e.g., true 95th %tile of probability of failure is lower than the estimates presented here

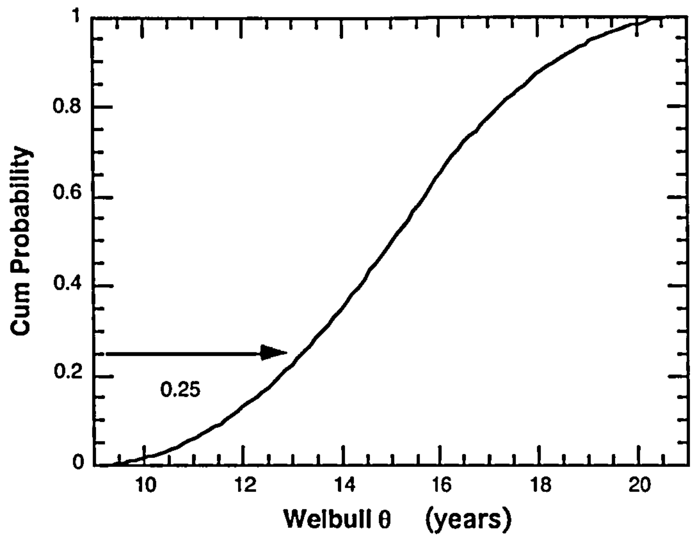
Primary Elements of Model for failure by SCC

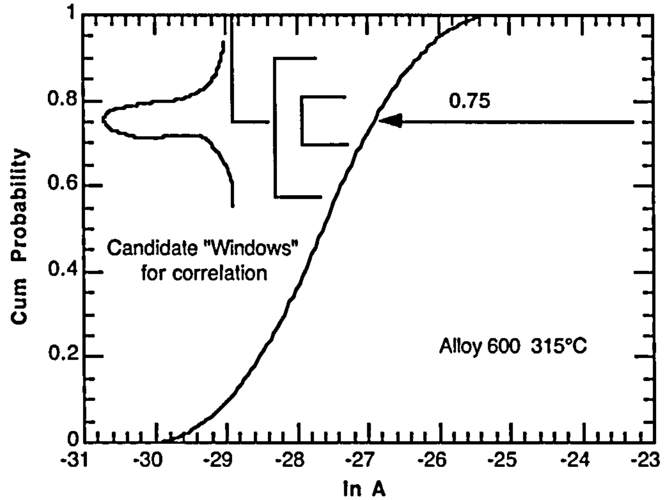
- Weibull model for likelihood and initiation time determined from inspection results
  - Initiation assumed to result in a throughwall circumferential crack
  - More detailed modeling of initiation would have to account for growth by multiple initiation and linking and throughwall growth of part–through cracks. Current models assume growth is dominated by fracture mechanics growth of circ cracks.
- K solutions for circumferential cracks and data on crack growth rates used to predict growth
  - EMC^2 solutions for center and sidehill K
  - MRP-55 distribution for base metal (refit by log triangle) used to describe CGRs
- Time to initiation and CGR assume correlated (short initiation time correlated with high CGR); initiation and K uncorrelated

459

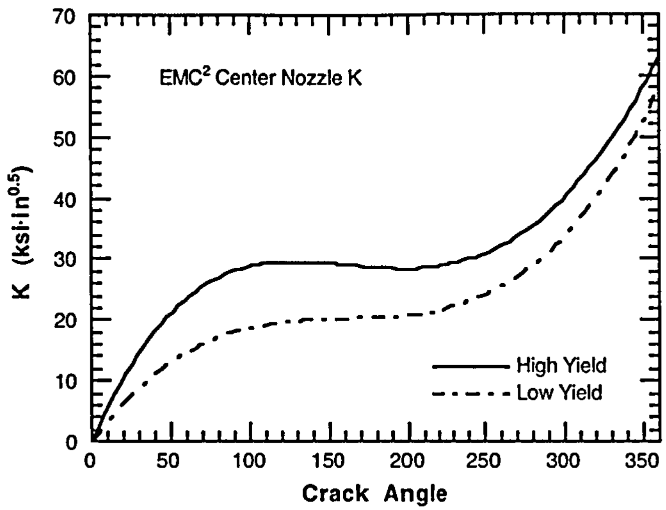
Correlation of Initiation and CGR and K values

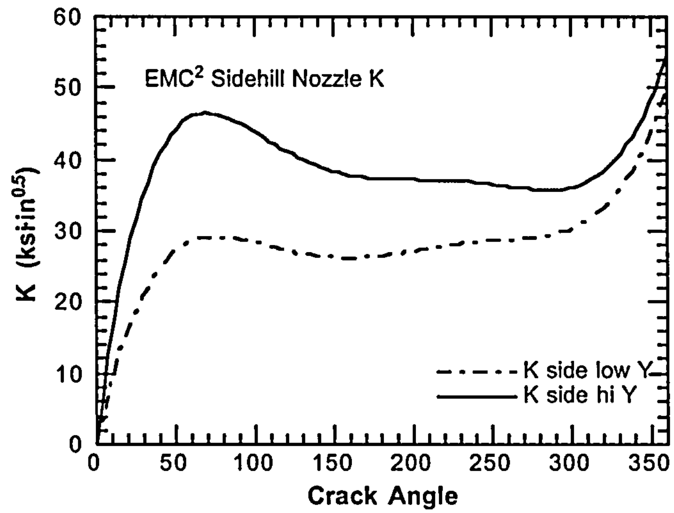
- Correlation between time to initiation and CGR





  - Susceptibility to initiation and CGR growth rate are expected to be correlated. Details of the correlation can have a strong impact on results depending on how much the impact of the "high" CGR tail is affected.
  - For specific cases, a conservative distribution for the scale parameter would lead to nonconservative estimates of the CGR (the 25th %tile value in the conservative distribution could be say the 10th %tile value in the realistic case)





461

- K values are dominated by welding residual stresses until circumferential cracks are very large
- EMC2 solutions show strong dependence on yield stress.
- Random variable α used to sample K solutions $K = (1-\alpha)K_{low} + \alpha K_{high}$

Probabilistic initiation models

- Weibull distribution used to describe probability of initiation
  - Staelhe, Gorman et al. have popularized the use of empirical statistical models to describe initiation. Weibull cumulative probability is

$$F(t) = 1 - \exp\left[-\left(\frac{x}{\theta}\right)^{b}\right]$$

where θ is time until cumulative probability of a leak is 0.63 and b characterizes rate of acceleration with age

  - Typical applications of Weibull statistics assume we have data on failures at several times.

    Plot of lnln [1/(1-F)] vs ln t yields straight line from which slope and scale parameter can be determined

  - For CRDM prior knowledge have been used to select b = 3

    Lab data consistent with b = 3, PWSCC in SG tubes gives values ranging from 1.5 to 6 with a median value about 3

    Analysis of CRDM cracking data seems to suggest higher values, but for purposes of predicting initial failures 3 is a conservative choice

462

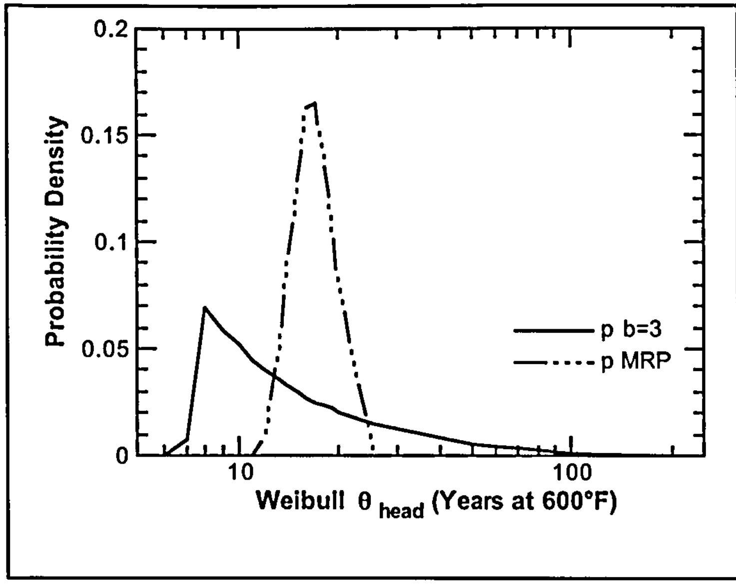
- Estimates of population bounds on Weibull scale factor
  - Consider the likelihood function L:

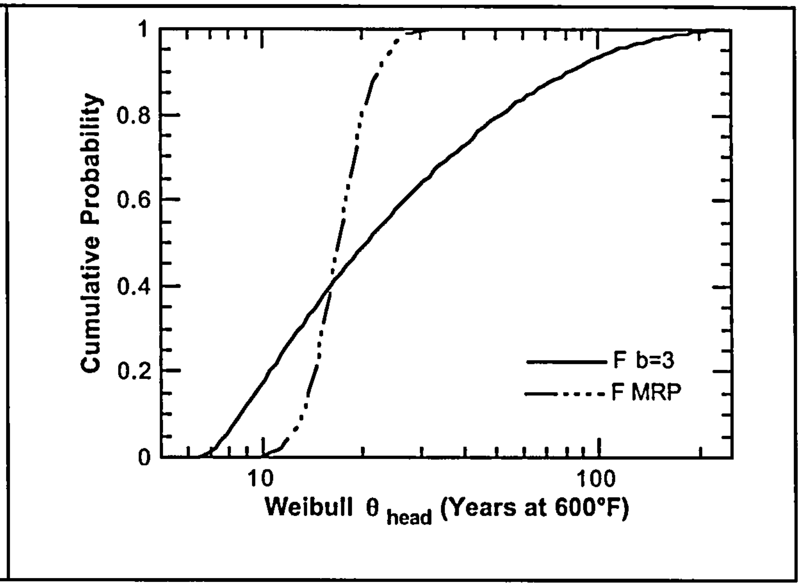
$$L = \prod_{i=1}^{N} \int_0^{\infty} p(\theta) \frac{N_i!}{n_{f_i}!(N_i - n_{f_i})!} \left\{ W(t_i,\theta)^{n_{f_i}} \left(1 - W(t_i,\theta)\right)^{(N_i - n_{f_i})} \right\} d\theta$$

where $p(\theta)$ is the probability distribution function for θ, $W(t_i,\theta)$ is the Weibull cumulative function for time t_i and shape parameter θ, n_{f_i} is the number of leaking nozzles for plant i, N_i is the total number of nozzles for plant i, and N is the total of number of plants considered. The likelihood function is just the usual binomial probability for n_{f_i} items out of a collection of N_i items.

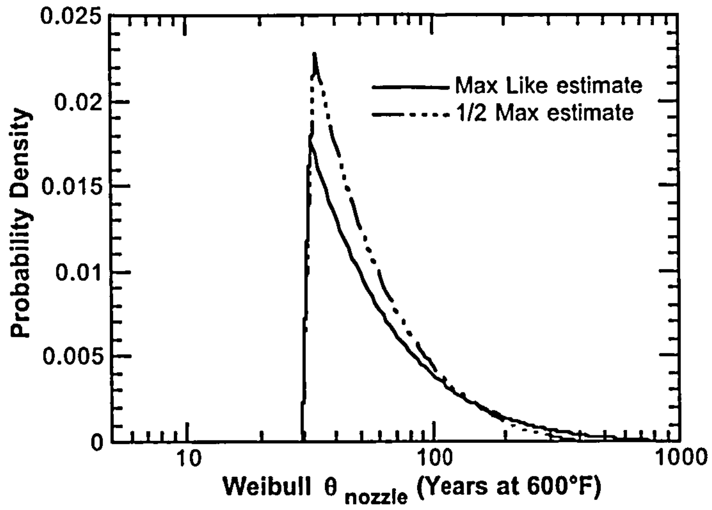
  - Triangular, log-triangular, Weibull, and lognormal distributions for θ were considered. The integrals were evaluated numerically and the distribution parameters varied to find the maximized solution.

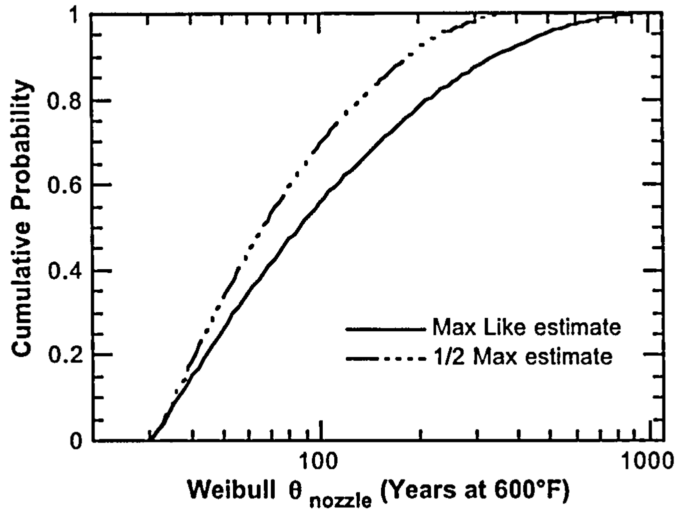
Plant	Head Temp °F	EFPYs	EDYs	Nozzles	Leaks/Cracks
ANO 1	602	19.5	19.6	69	8
ANO-2	590	16.8	11.2	81	0
Beaver Valley 1	595	17.2	14.0	65	4
Calvert Cliffs 2	593.7	20.4	15.8	65	0
Cook 1	580	24.8	10.0	79	0
Cook 2	600.7	13.5	13.9	78	0
Crystal River 3	601	15.5	16.2	69	1
Davis-Besse	605	15.7	19.2	69	5
Farley 1	596.5	20.2	17.5	69	0
Farley 2	596.9	17.9	15.8	69	0
Indian Point 2	585.5	14.4	8.0	97	0
Indian Point 3	593.5	20.5	15.7	78	0
Millstone 2	593.9	14.3	11.2	69	3
North Anna 1	600.1	19.9	20.0	65	0
North Anna 2	600.1	19.9	19.0	65	14
Oconee 1	602	20.2	21.9	69	3
Oconee 2	602	21.9	23.7	69	19
Oconee 3	602	20.0	21.7	69	14
Palo Verde 1	592	14.6	10.6	97	0
Palo Verde 2	591.7	14.0	10.0	97	0
Point Beach 1	591.6	20.4	14.5	49	0
Robinson 2	598	22.0	20.3	69	0
San Onofre 2	590.5	22.5	15.3	91	0
San Onofre 3	590.6	22.4	15.3	91	0
Sequoyah 1	580	5.0	1.5	78	0
St. Lucie 1	590.6	23.1	15.7	77	0
St. Lucie 2	595.6	16.7	13.9	91	1
Surry 1	597.8	20.9	19.1	65	6
TMI 1	601	17.4	18.2	69	6
Turkey Point 3	594.4	23.0	18.3	65	0





- Calculations actually done to find scale factor for probability of leakage of a nozzle. Presented here in terms of scale factor for a head with 69 nozzles from the same heat. For Weibull distributions $\theta_{head} = \theta_{nozzle} / n^{1/b}$
- Maximum Likelihood Estimate is much broader than MRP 6-03 distribution which is essentially an estimate of an “average” value and the uncertainty on that estimate





466

- Maximum is very broad. Value of upper end can be varied significantly with minor effect on the value of likelihood. Physically reasonable. Experience can tell us a lot about the most susceptible nozzles/heads but less susceptible materials involve substantial extrapolation
- Sensitivity calculation was done to determine a distribution where the lower bound value was fixed and the other values adjusted to give a likelihood equal to 1/2 the peak value
- In the 31 plant sample 84 leaks (& large cracks) were observed. For a plant population with the same operating times, temperatures, and number of nozzles as the 31 plant sample, the expected number of leaks are

Weibull scale factor distribution	Expected number of leaks in population
Maximum Likelihood Estimate	55.3 ± 15.3
1/2 Maximum Estimate	69.7 ± 15.7
MRP 6-03	25.6 ± 2.5

467

- Baysian Updates
  - Use generic distributions as prior distributions to get updated distribution

    For a plant that has n_f / no failures at time t:

$$\bar{p}(\theta) = \frac{\left(1 - W(t,\theta)\right)^N p(\theta)}{\int_0^\infty \left(1 - W(t,\theta)\right)^N p(\theta)\, d\theta}$$

$$\bar{p}(\theta) = \frac{\left\{W(t,\theta)^{n_f} \left(1 - W(t,\theta)\right)^{(N-n_f)}\right\} p(\theta)}{\int_0^\infty \left\{W(t,\theta)^{n_f} \left(1 - W(t,\theta)\right)^{(N-n_f)}\right\} p(\theta)\, d\theta}$$

  - One could also develop a "Huntington" or "CE" distribution

$$\bar{p}(\theta) = \frac{\prod_{k=1}^{N} \left\{W(t_k, T_k, \theta)^{n_{f_k}} \left(1 - W(t_k, T_k, \theta)\right)^{(N-n_{f_k})}\right\} p(\theta)}{\int_0^\infty \prod_{k=1}^{N} \left\{W(t_k, T_k, \theta)^{n_{f_k}} \left(1 - W(t_k, T_k, \theta)\right)^{(N-n_{f_k})}\right\} p(\theta)\, d\theta}$$

Probability of leakage for a head

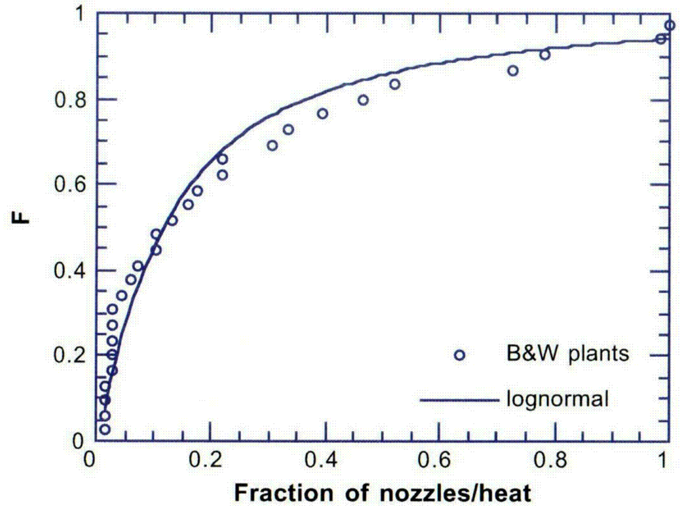
- Probablility of leakage from the head is computed from the probability of leakage for a nozzle. If all nozzles have the same susceptibility to leakage this is just

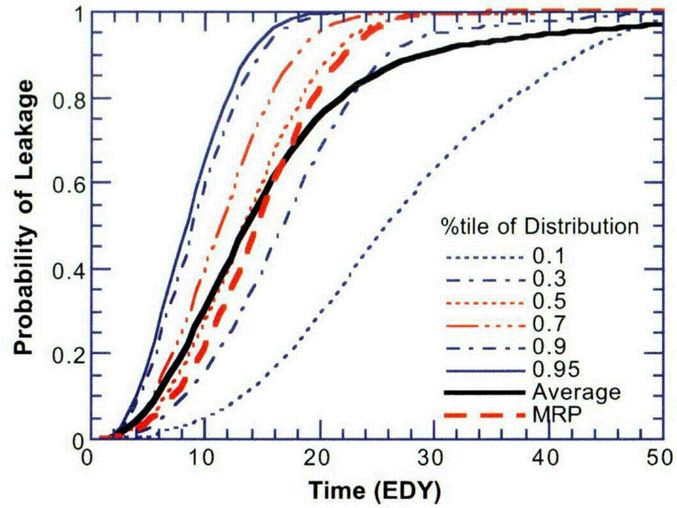
$$P_{leak} = 1 - (1 - P_{nozzle})^N$$

- Most plants appear to have multiple heats of material for nozzles. For the B&W plants the table shows the numbers of nozzles from different heats

ONS–1	ONS–2	ONS–3	ANO–1	Davis Bessie	TMI–1	CR–3
50	2	1	2	32	11	69
1	4	68	21	5	54	
15	27		7	23	1	
	15		36	9	2	
	7		1			
	12		2			
	2					

469





470

- Vessel head calculations are done assuming that the head contains from 1 to 7 heats of material and that the number of nozzles from a specific heat are distributed approximately lognormally.
- Results suggest a high probability of leakage for most plants after 10-15 EDY. MRP 6-03 Weibull scale factor is fairly close to the average value from the distribution.

C101

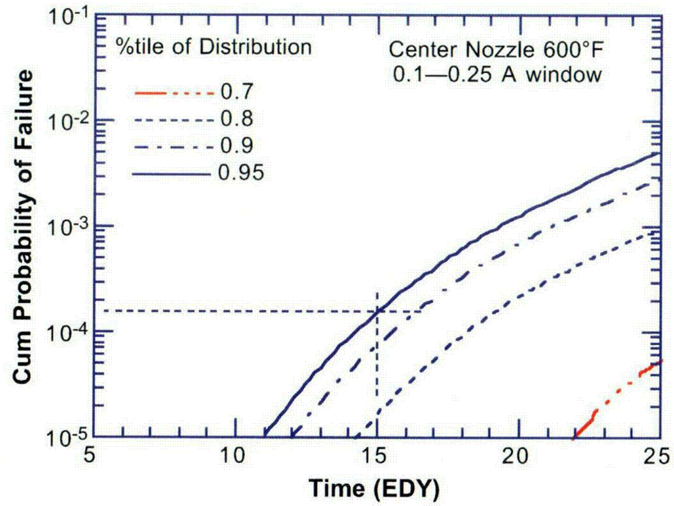
Probability of Failure of CRDM Nozzles

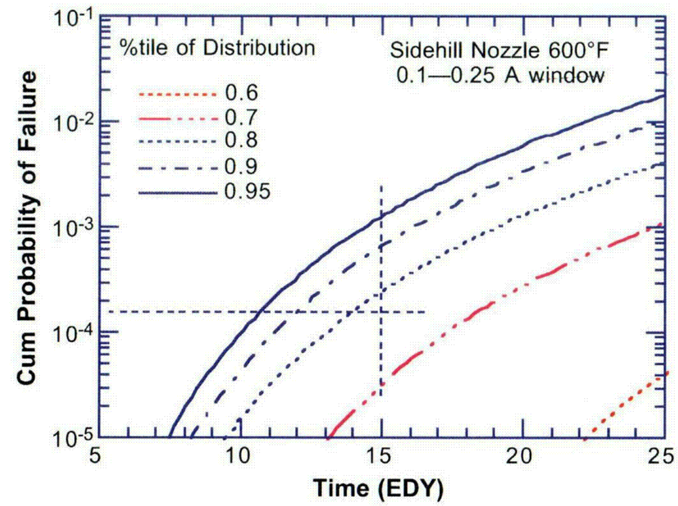
- Probability, $P(t_f < T)$, that a nozzle will fail at a time t_f less than T,

$$P(t_f < T) = \int_0^T p(t)P_c(t_f < T - t)dt$$

  - p(t) is the probability that a crack will initiate at a time t
  - $P_c(t_f < T{-}t)$ conditional probability a crack that initiates at t will fail at a time t_f less than T and is determined by fraction mechanics analysis.

- For a given choice of the Weibull scale factor [which determines p(t)] and stress intensity distribution [which together with the MRP-55 CGR distribution determines $P_c(t_f < T)$], integral gives a probability of failure for a nozzle
- Monte Carlo sampling from the distribution for the scale factor and for the parameter α to determine K gives distributions for the probability of failure of a nozzle





472

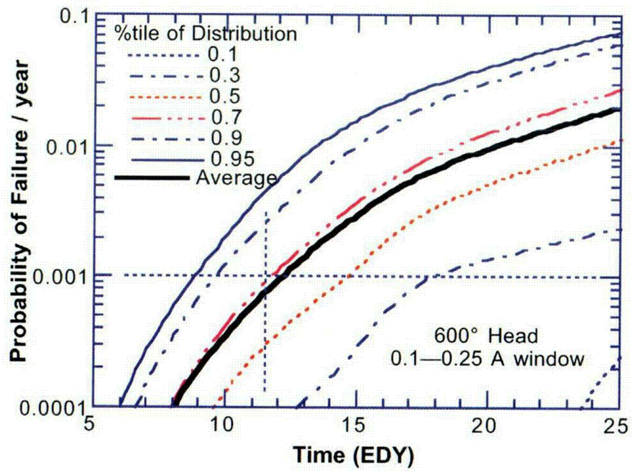
- Probability of failure depends strongly on temperature and choice of correlation window for CGRs
- Sidehill K from EMC^2 is for bounding sidehill angle. POF higher than for center nozzles because of higher K values, but there is overlap in the distributions; interpolation used for head calculations
- If all nozzles are from one heat of material then the POF for the head can be easily calculated from the probability of failure of the nozzles

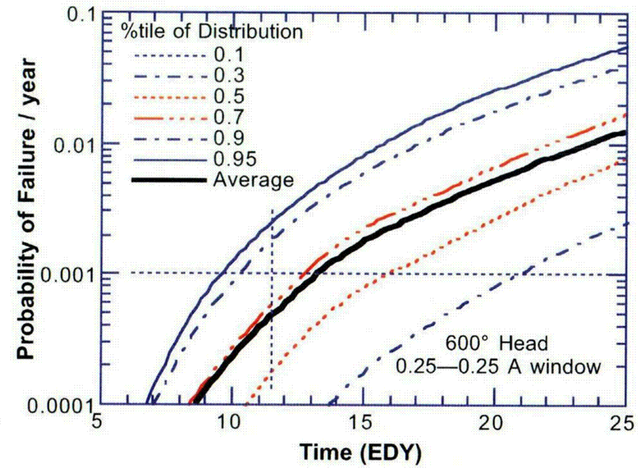
$$P_{head} = 1-(1-P_{nozzle-c})^{N_c}\,(1-P_{nozzle-s})^{N_s}$$

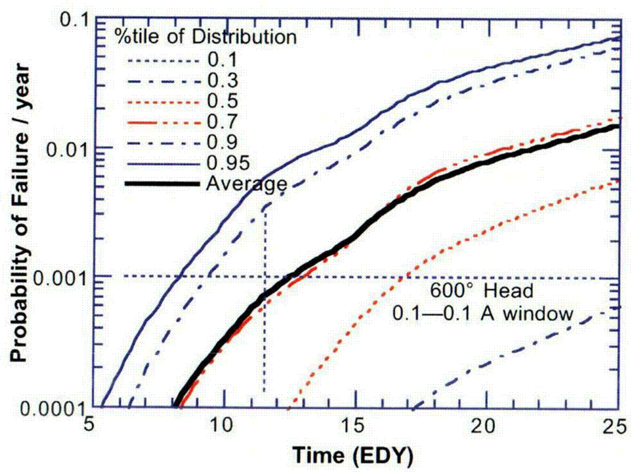
where N_c and N_s are the number of center and sidehill nozzles, respectively

C102

473

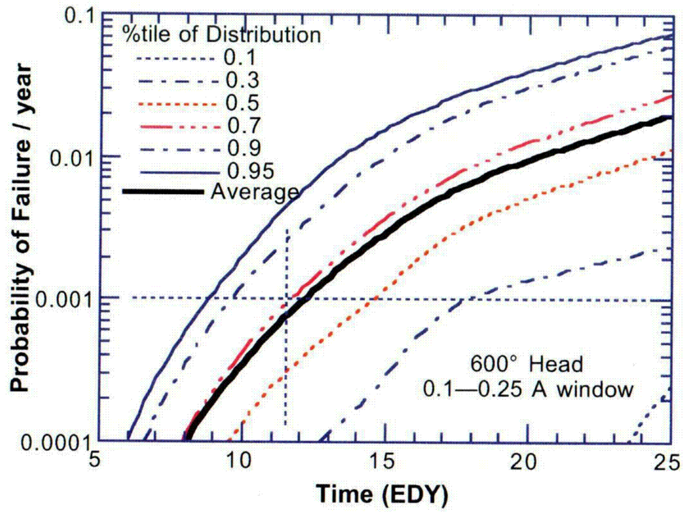


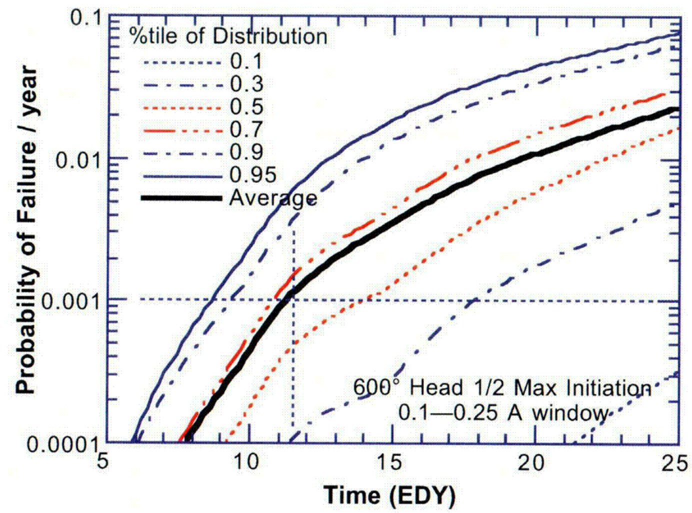




- Calculations for head use multiple heats based on B&W results
- MRP 6-03 POF bounds 70–80% of the population; represents average POF
- $POF_{95th\%tile} \approx 5 \cdot POF_{Average}$

C103



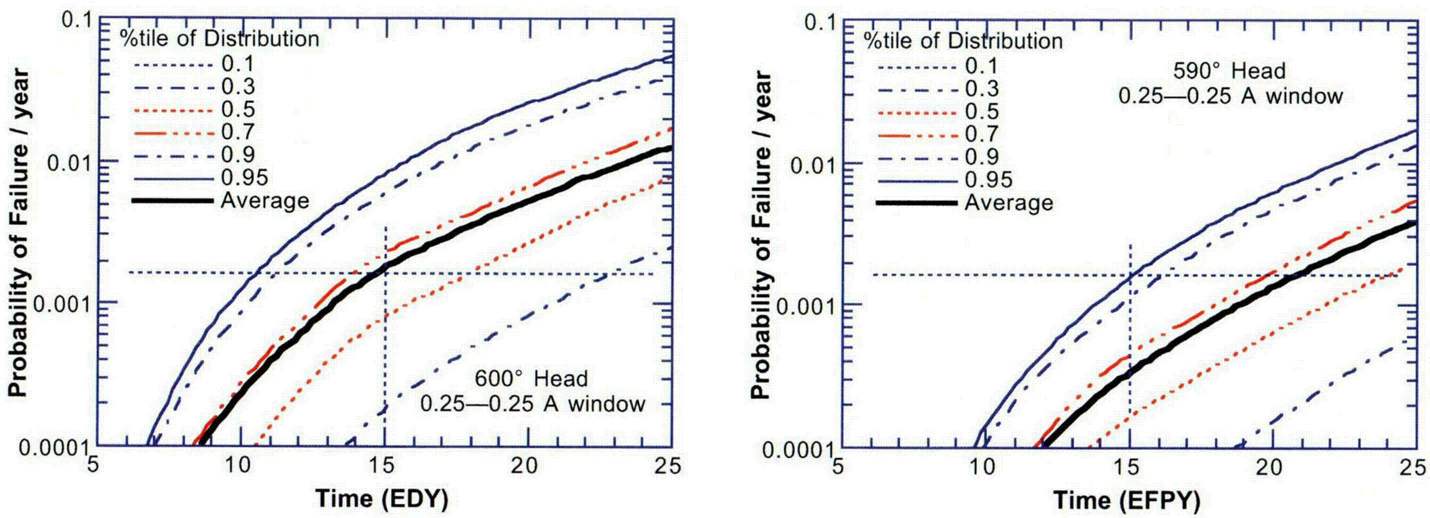


- Using the more conservative 1/2 Maximum Likelihood distribution for the Weibull scale factor shifts the distributions only slightly

474

C104

475



- Decreasing temperature does decrease POF significantly, but there is overlap in the distributions; $POF_{95\%tile}$ at 590°F is comparable to $POF_{average}$ at 600°F

C105

Statistical Checks with operating experience

- For a plant population with the same operating times, temperatures, and number of nozzles as the 31 plant sample, we can compute expected number of large (165°) cracks and nozzle ejections

Model	165°Cracks	Nozzle Ejections
No Interpolation 0.1–0.25 A window	4.1 ± 1.0	1.1 ± 0.53
0.1–0.25 A window	2.8 ± 0.7	0.7 ± 0.33
0.25–0.25 A window	1.8 ± 0.6	< 0.7

- Statistical results suggest all the models are probably conservative. The statistical confidence is higher for the 0.1–0.25 window models.

Analysis of Weld Residual Stresses and Circumferential Through-Wall Crack K-solutions for CRDM Nozzles

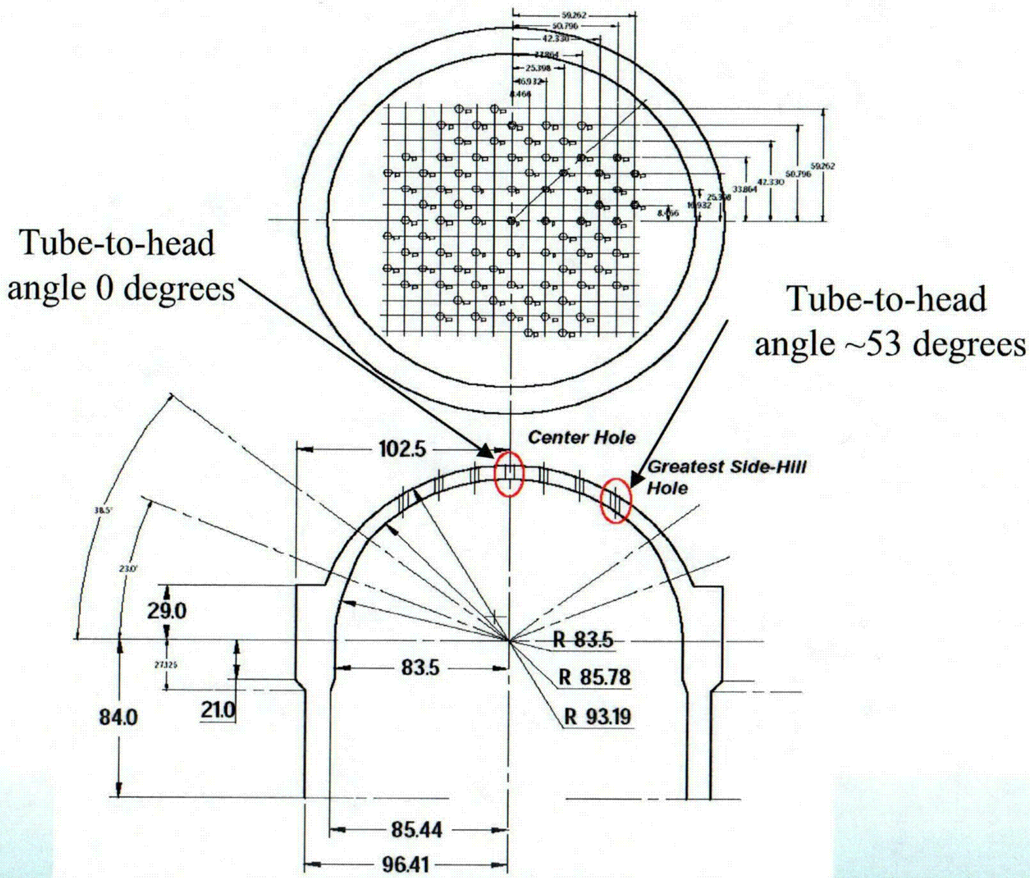
D. Rudland [1], G. Wilkowski [1], Y.-Y. Wang [1], and W. Norris[2]
(1) Engineering Mechanics Corporation of Columbus
(2) U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Research

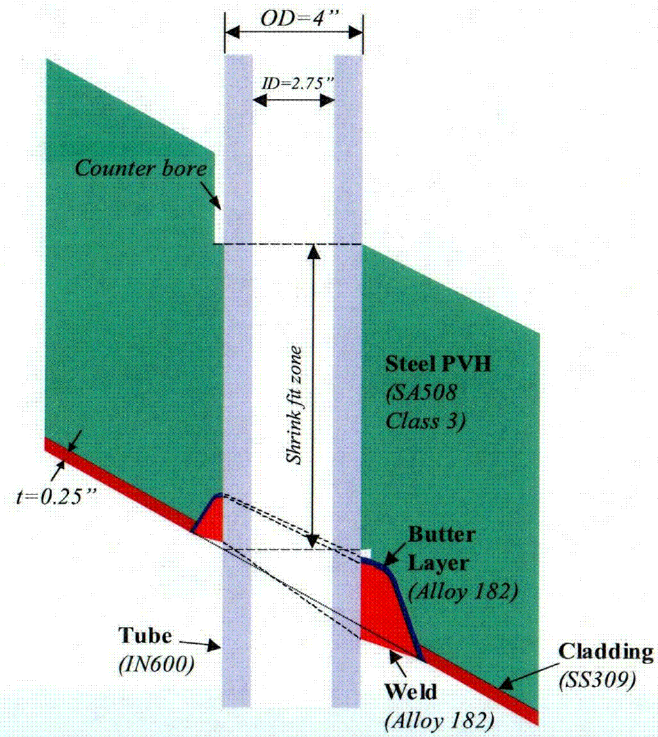
Objective of Program at Emc^2

- *Main objective of the Emc^2 program is to develop a probabilistic computer code to predict the time from detection of leakage to failure for independent assessment of MRP/EPRI analysis.*
  - *Residual stresses calculated and then circumferential through-wall crack inserted to determine crack-driving force.*
  - *Dr. Sharif Rahman and B. N. Rao of Univ. of Iowa assisted Emc^2 in new Visual Fortran probabilistic code.*

- *Numerous meetings with NRC staff and industry (significant amount of proprietary data).*

RPV Head Geometry Used in FE Analyses was a Westinghouse Design (PV-RUF drawings from ORNL)





Overall Modeling Strategy

- *Weld Stress Analysis*
  - *heat treatment for stress relieving*
  - *installing tube into RPV head by shrinkage fit*
  - *welding the J-groove*
  - *hydro-testing*
- *Stress Mapping*
  - *Transferring all solution variables (stress tensor, strain tensors, displacement, BC) from weld stress mesh to a crack mesh*
- *K-Solution Analysis*
  - *Applying the service load (pressure and temperature)*
  - *Unzipping the cracked mesh*
  - *Calculation of K-solution*
  - *Curve-fit for use in probabilistic code structure*

"Generic" CRMD Nozzle Fabrication Steps

- *Rough drill the 4" diameter holes in the RPV head*
- *Arc-gouge the groove area away and grind smooth*
- *Butter the groove area with alloy 182 using SMAW process*
- *Stress relieve the head at 1125F +/-25F*
- *Finish machining the groove area*
- *Finish reaming the main hole (interference area), and finish reaming the counter bore region*
- *Install tube by shrinkage fit (tube submerged in liquid nitrogen)*
- *Welding the J-weld with SMAW process and NDE at each 1/4 depth of weld*
- *Hydro-test*
- *Put into service at elevated temperatures*

The FE analyses followed the highlighted essential fabrication steps

Analyses Included Significant Factors Affecting The Crack-Driving Force Solutions

- *Yield strength level of the tube*
- *Interference fit*
- *Weld bead layout sequence (using generic B&W design)*
- *Weld size and number of weld passes (using generic B&W design)*
- *Operating temperature of the reactor*
- *Location of the nozzle penetrations*

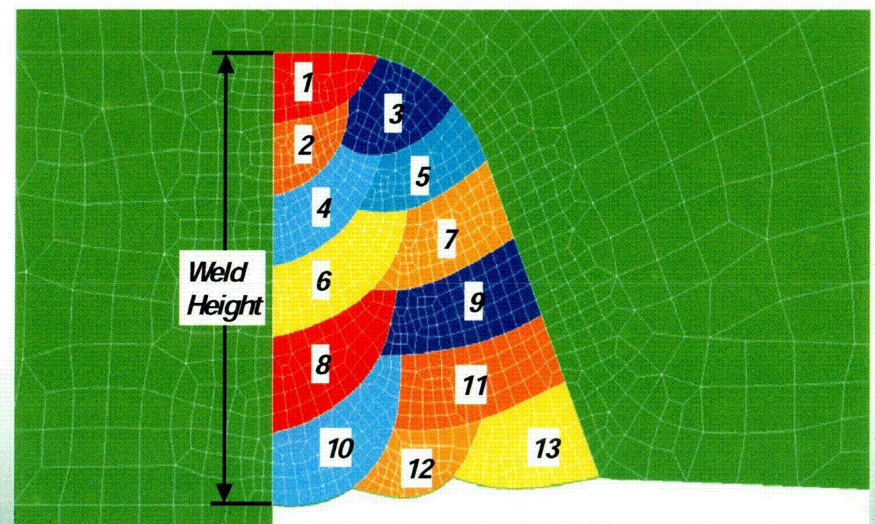
Analyses To Date Focused on Parametric Study of Center Hole and a Detailed 3D Model of The Steepest Side-Hill Nozzle

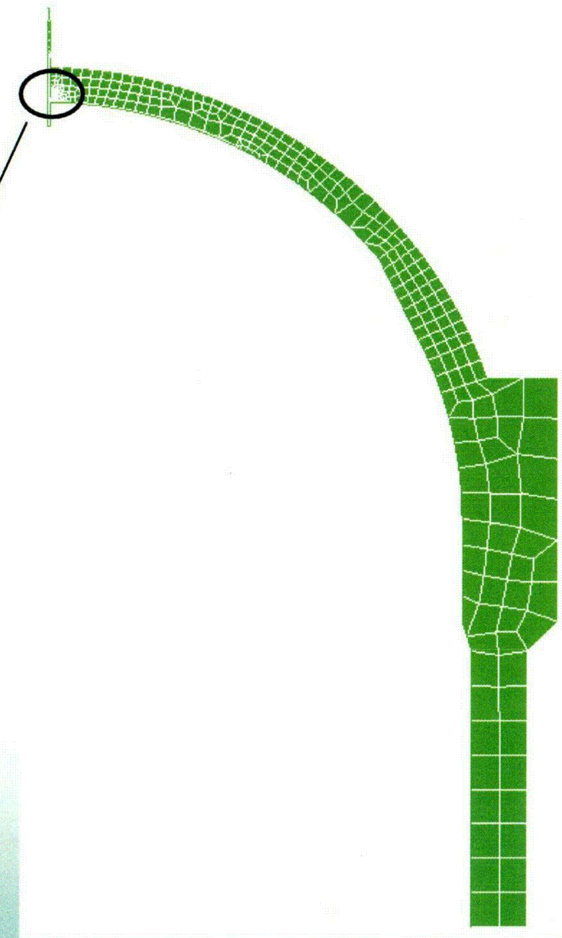
Case #	Interference fit, mm (mils)	Temperature, K (F)	Tube Yield Strength, MPa (ksi)	Weld Bead Layout Sequence	Nozzle Location	Weld Height, mm (in)	Number of Weld Passes
A	0 (0)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
B	0.2286 (9)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
C	0.0508 (2)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
D	0.1143 (4.5)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
E	0 (0)	566.5 (560)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
F	0 (0)	616.3 (605)	259 (37.5)	Head-Tube	Head Center	20 (25/32)	13
G	0 (0)	616.3 (605)	444 (64.5)	Tube-Head	Head Center	20 (25/32)	13
H	0 (0)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	28 (1.10)	20
I	0.2286 (9)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	28 (1.10)	20
J	0.2286 (9)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	36 (1.42)	27
K	0 (0)	616.3 (605)	259 (37.5)	Tube-Head	Greatest Side-hill	Variable	14

Base case analysis

FEM Mesh in Weld Analysis – Center hole

- *Axisymmetric weld analysis*
- *Solution revolved around tube axis for K-solution determination*
- *13 to 20 elements in each weld pass to deal with the temperature and stress gradients in the weld region*





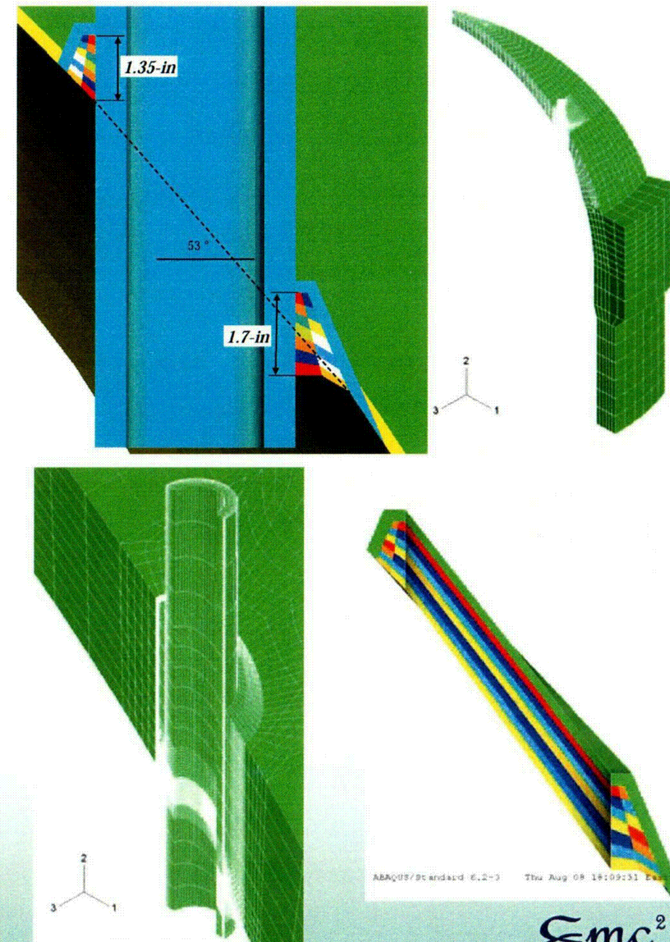
484

NSRC CRDM:8

C107

Side-Hill nozzle - Weld Geometry/Meshing

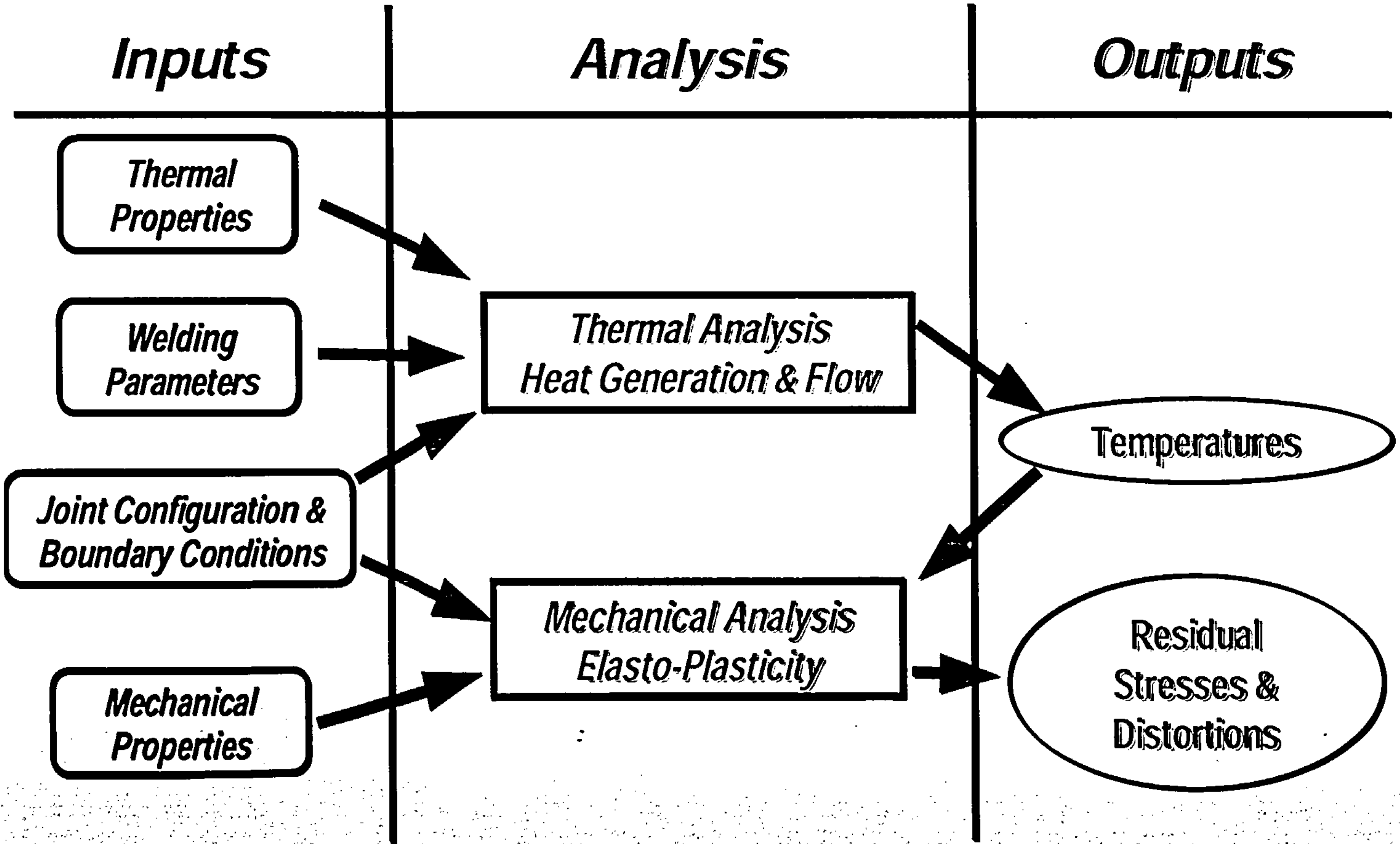
- *As with the centerhole, many factors went into deciding Sidehole geometry*
  - *Used steepest sidehill hole from previous drawing*
  - *Modeled 1/8 of head*
  - *Nozzle/weld details from various trips*
  - *Typical CRDM designs*
  - *Attempted to keep uphill and downhill area similar – Constant volume needed for weld analyses*
  - *Tried to keep some geometry (Bevel angle, etc) same between side-hill and center-hole models*



70,000 nodes and 64,000 8-node linear brick elements in the side-hill model.

C108

Weld Analysis Procedure

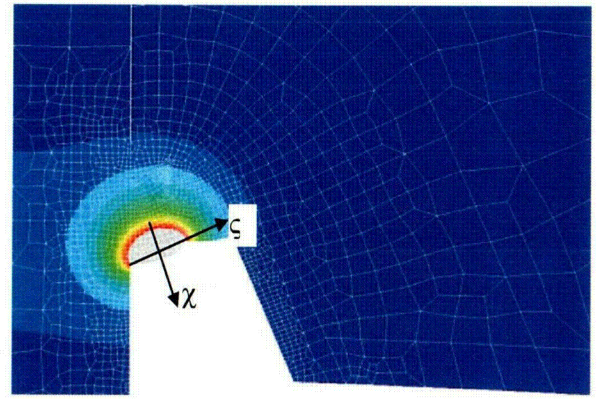


Welding Stress Analysis Procedure (cont.)

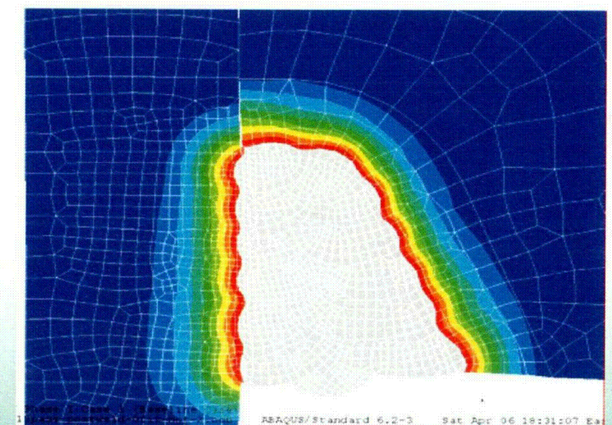
- ***Analysis was done using weld pass-by-pass procedure***
  - ***A weld pass is activated only when it is deposited***
  - ***Pass deposition followed the actual welding sequence***
- ***Heat input from the moving welding arc takes Gaussian distribution***

$$q = \frac{6\sqrt{3}\eta EI}{\pi\sqrt{\pi}\,abc}\, e^{\left[-3\left(\frac{(\chi-\chi_0)^2}{a^2}+\frac{(\varsigma-\varsigma_0)^2}{b^2}+\frac{(V(t-t_o))^2}{c^2}\right)\right]}$$

- ***Effect of weld solidification on materials constitutive behavior are properly treated with proprietary user subroutines***
- ***ABAQUS is the FE solver, enhanced with various user subroutines***



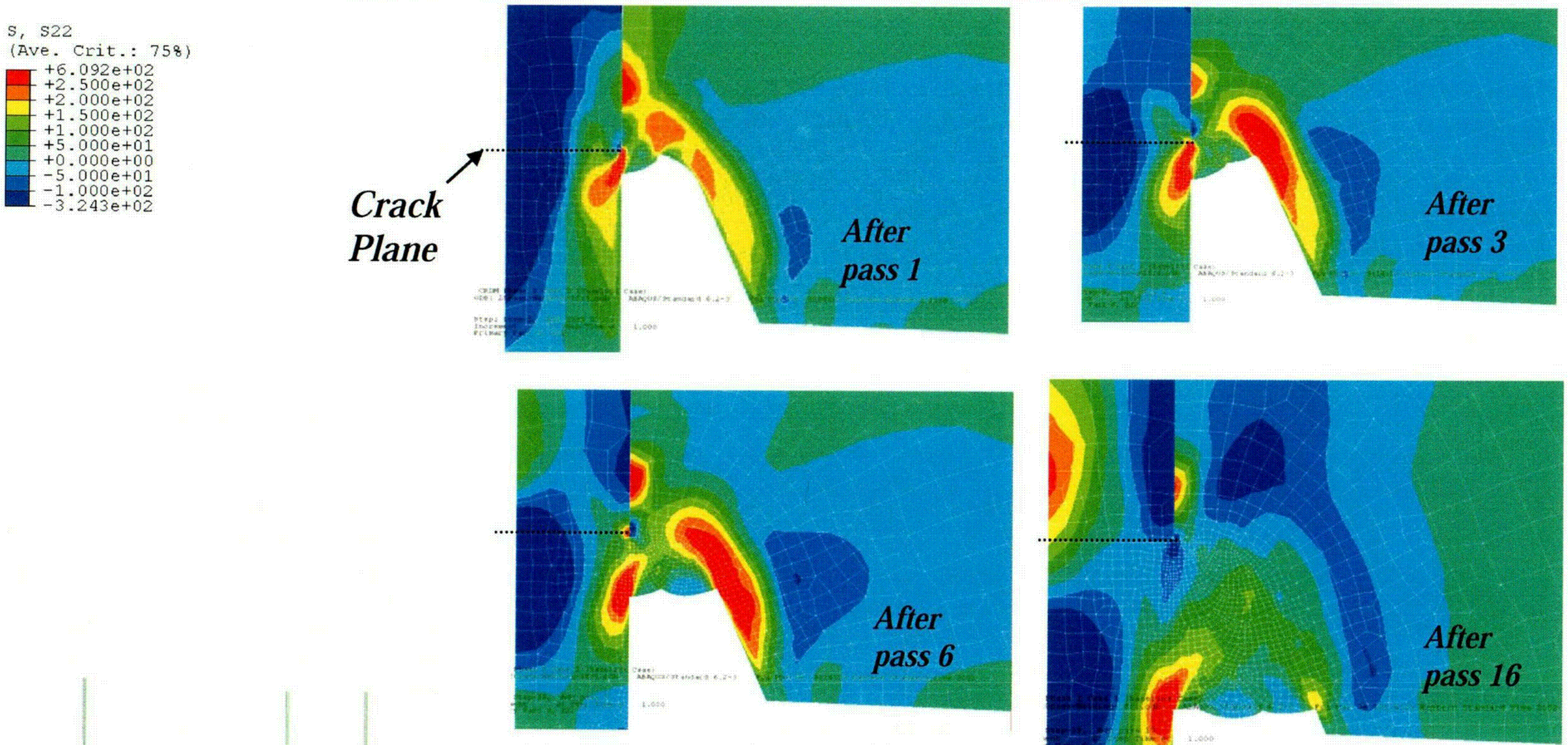
Peak tem erature rofiles



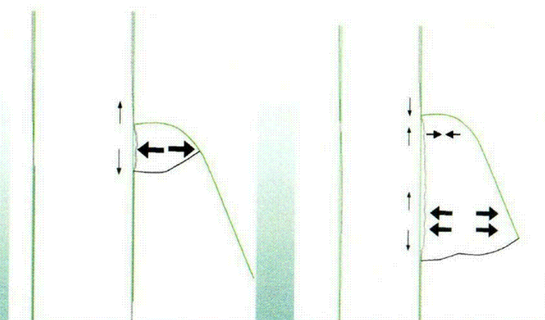
Material Properties

- *Analysis by Emc² involves weld simulation of each weld pass*
- *Base and weld metal stress-strain curves needed from room temperature to 1000C (cooling from molten conditions).*
  - *Since plastic strains for weld calculated in our analysis, the weld metal stress-strain curve should be from annealed weld metal, rather than from as-welded weld metal.*
  - *Speed of welding corresponds to an average strain-rate of 10^{-3}.*
  - *ORNL developed annealed Alloy 182 and A508 stress-strain curves at various temperatures and 10^{-3} strain rate. We used Alloy 600 data from literature (slower loading rate).*

Axial residual stress development in a center-hole case – 20 weld passes max (Crack not present during weld simulation.)



489

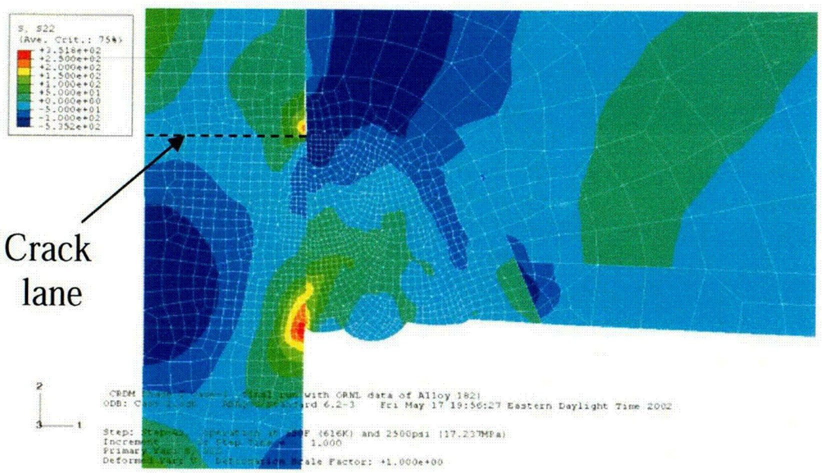


Weld Height Effects on Axial Stress Change is Attributed to "Hinging" Action around Initial Weld Beads

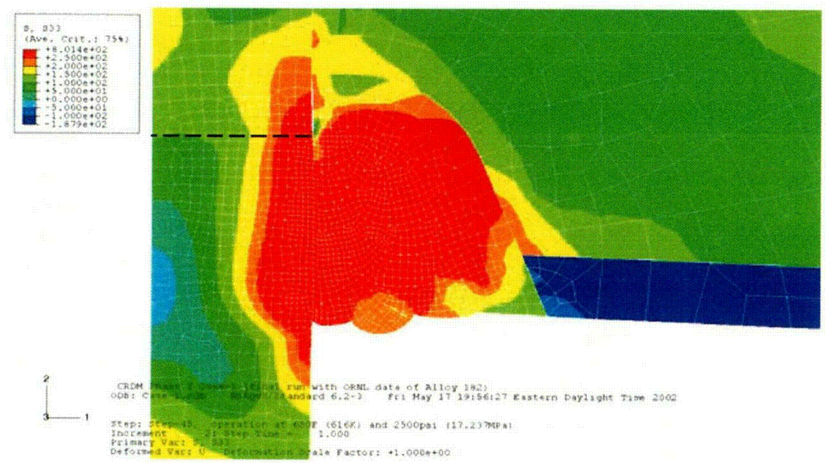
C110

In-Service Stress Distributions of 13-pass J-weld (Design Conditions: 605F and 2,500psi)

490



Axial Stress, MPa



Hoop Stress, MPa

Center-hole model

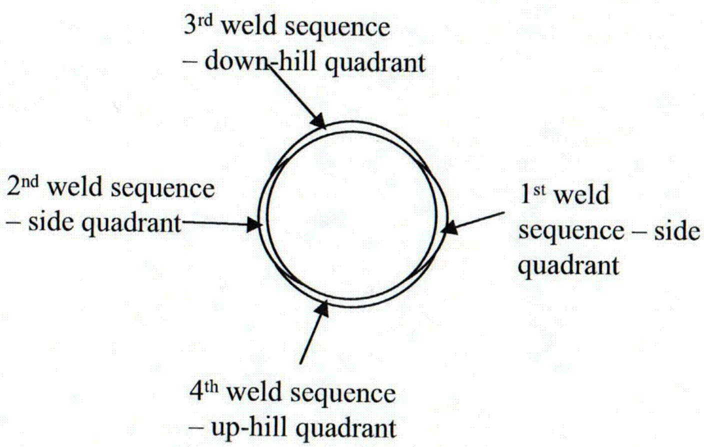
Emc²

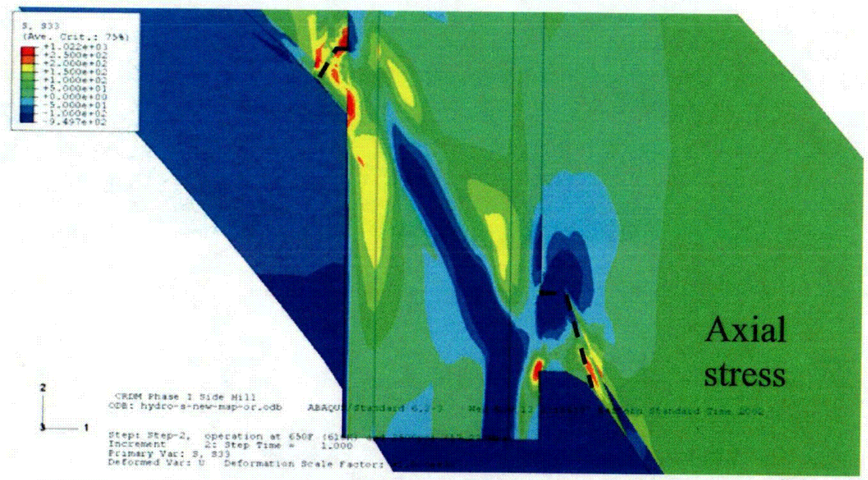
NSRC CRDM:14

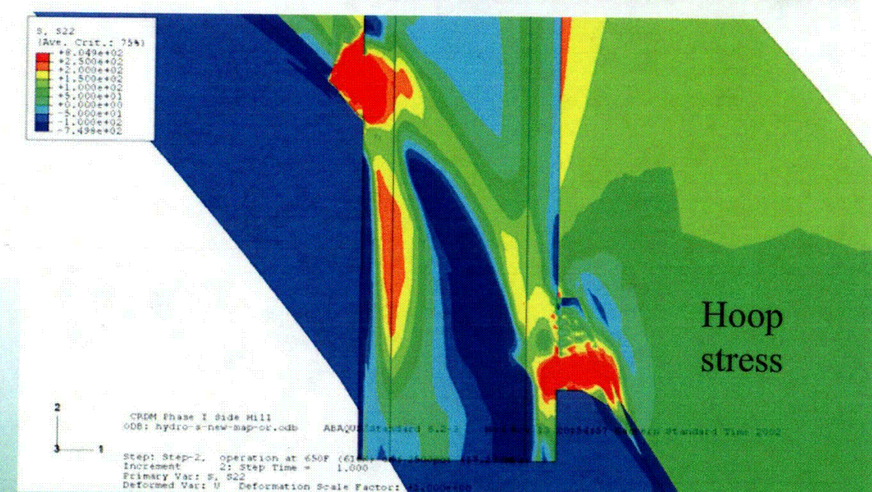
C111

Side-Hill Weld Residual Stress Model
(Design Conditions: 605F and 2,500psi)

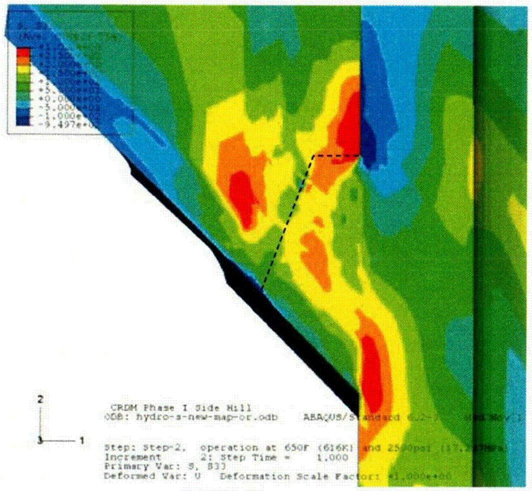
- ***Followed the welding sequence observed in actual fabrication***



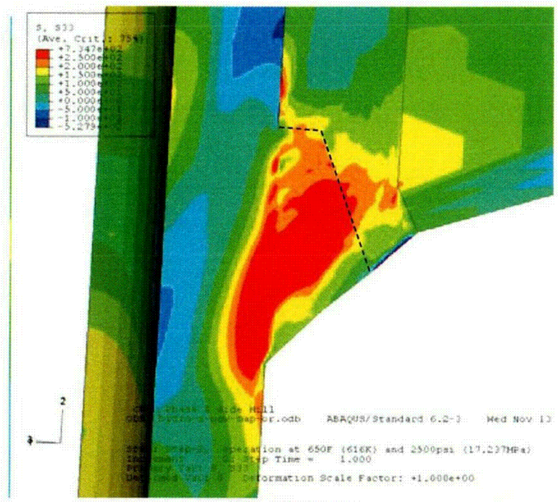




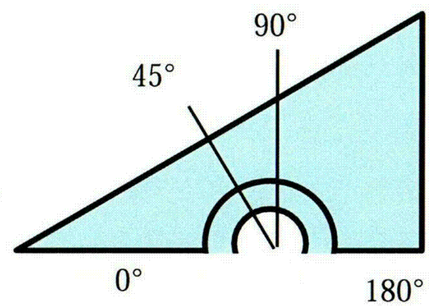
Sectional View of Axial Stresses

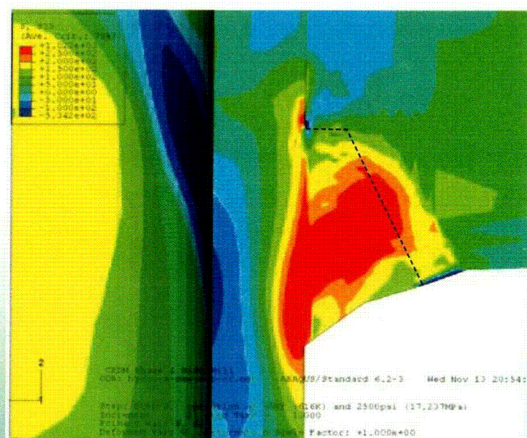


(a) 0-degrees

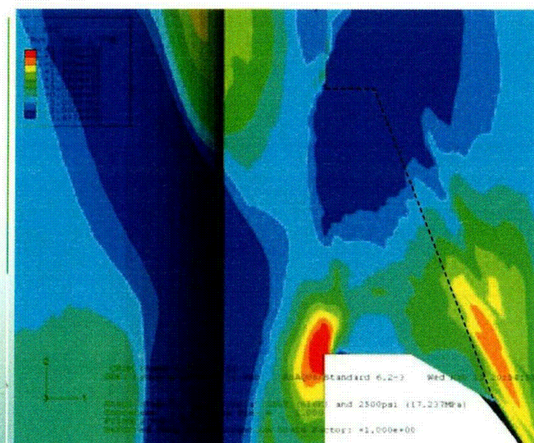


(b) 45-degrees





(c) 90-degrees



(d) 180-degrees

492

C113

Observations of Weld Stresses

- *The as-welded stress states are primarily dependent on the J-weld size, and the tube strength levels.*
  - *(Nozzle angle is expected to be a primary factor as well, but the results are not yet available).*
- *There are appreciable differences between the as-welded stress states and the in-service stress state caused by hydro-test and by the pressure and temperature loading from operation.*
- *The hoop stresses in the tube next to the J-weld are high in tension, generally reaching the yield strength level of the tube on the OD and extending above and below the J-weld region.*

Observations of Weld Stresses

- *The axial stress is highly sensitive to the weld height.*
  - *A large J-weld tends to be beneficial for circumferential crack case as it creates compressive axial stresses at the root of the weld.*

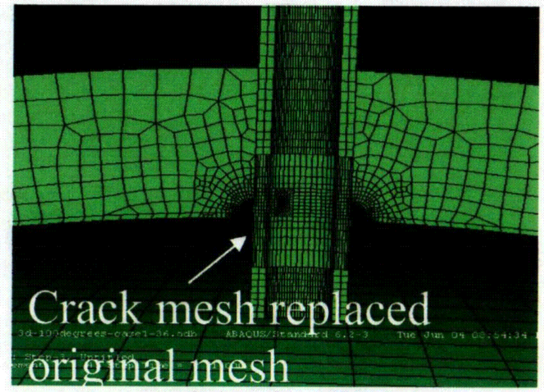
- *As the J-weld height increases, the hoop stresses on the ID surface of the tube increase and the axial stresses at the J-weld root decrease.*
  - *There is probably an optimal weld height to minimize both stress components.*

- *The effects of other fabrication variables such as welding sequence and interference fit are secondary to the stress distribution in the J-weld region.*

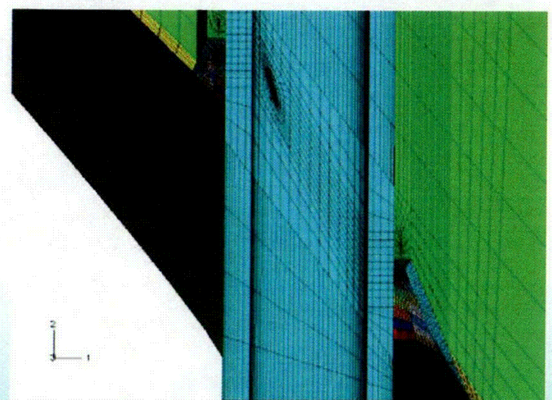
Cracked Mesh

495

- Replaced original mesh at crack location with focused mesh (crack plane zipped)
- Mapped residual stress solution onto "new" mesh
- Added temperature and operating pressure
- Released crack face restraints
- Calculated K/J at crack tip through thickness



Center hole



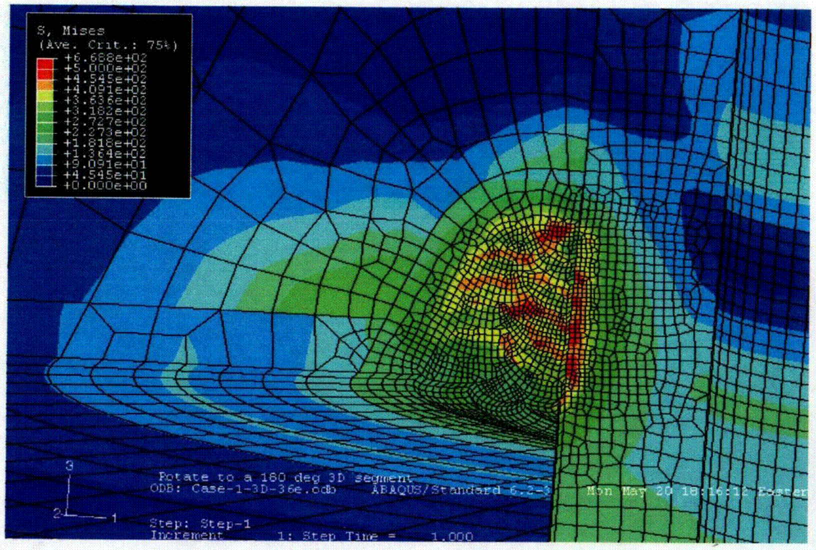
Steepest sidehill

C114

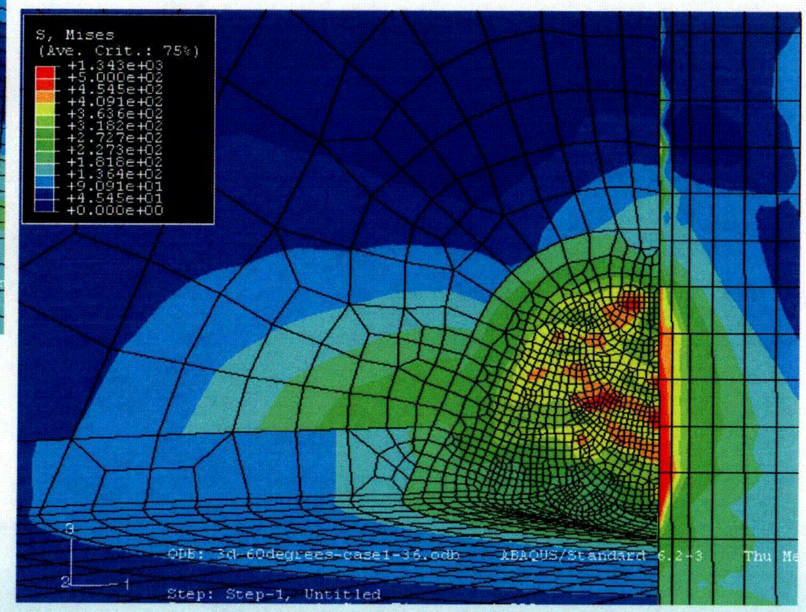
Parametric Analyses

- *10 circumferential through-wall-crack lengths: 40 to 320 degrees*
- *2 tube yield strengths: 37.5 ksi (258.6 MPa) for base case, and 64.4ksi (444 MPa)*
- *3 interference fits: 0, 2 (base case), and 4.5 mils (radial interference at room temperature and P = 0)*
- *Two operating temperatures: 605 F (base case) and 560 F*
- *One operating pressure: 2,500 psi*
- *Center-hole and largest side-hill angle*
  - *Most parametric work completed on center hole – Only baseline case run for largest side-hill angle*
- *Friction between tube and RPV hole included using friction factor of 0.1 (solid lubrication of boric acid crystals)*
  - *With circumferential crack, the tube tips in the hole and contacts the RPV head.*

Mapped Solution for Center-Hole Case

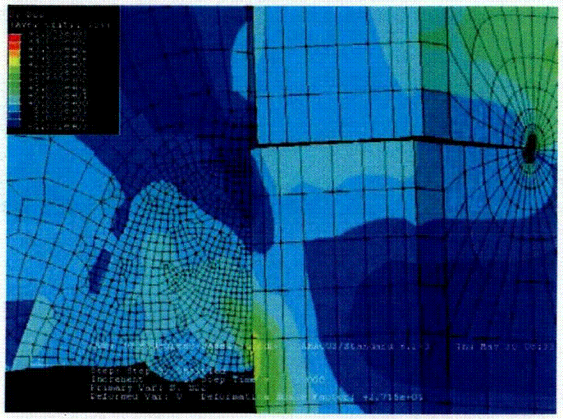


Original

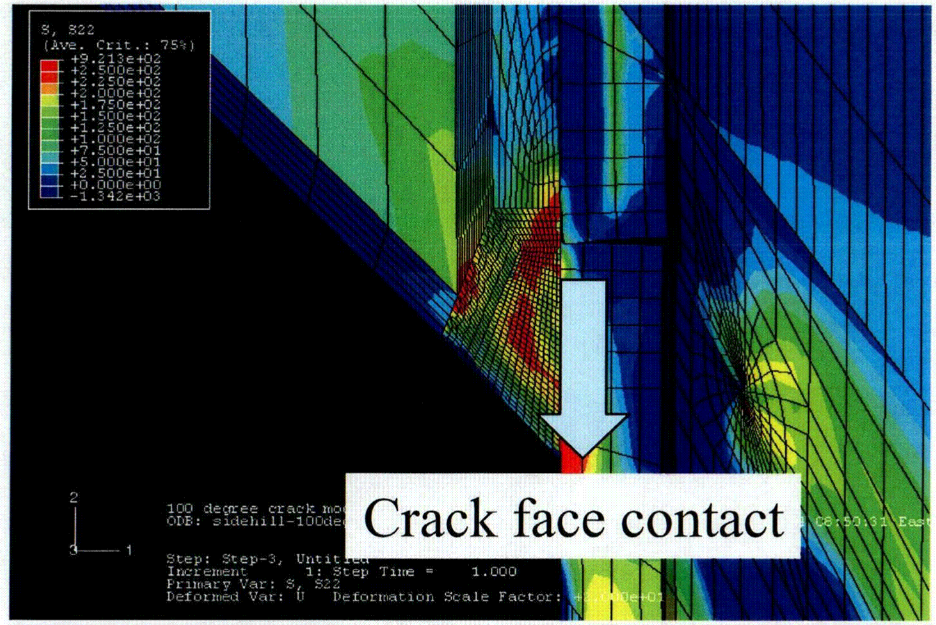


Mapped

Center-hole Cracked Case at Design Conditions



Mode III loading



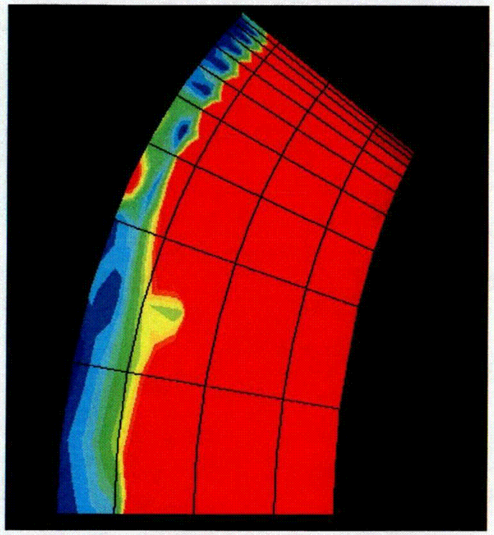
Trend suggests crack will not grow perpendicular to wall thickness – Angled crack growth through the thickness will be investigated in current program

Emc²

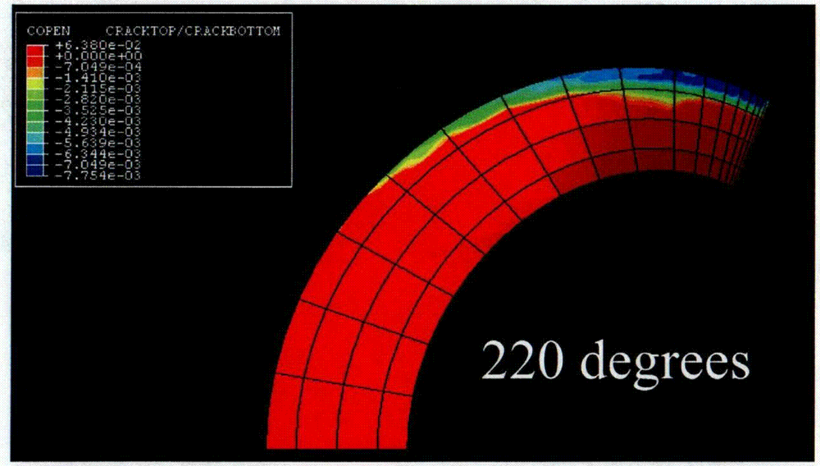
498

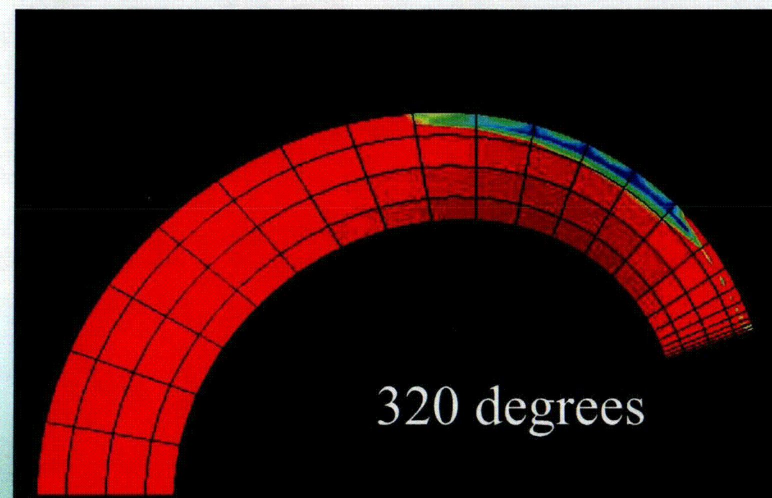
C116

Side-Hill nozzle – Crack face opening



60 degrees





Crack closure exists at all crack lengths

Red – crack open
Other – crack closed

C117

K-solutions from Center hole TWC Analyses

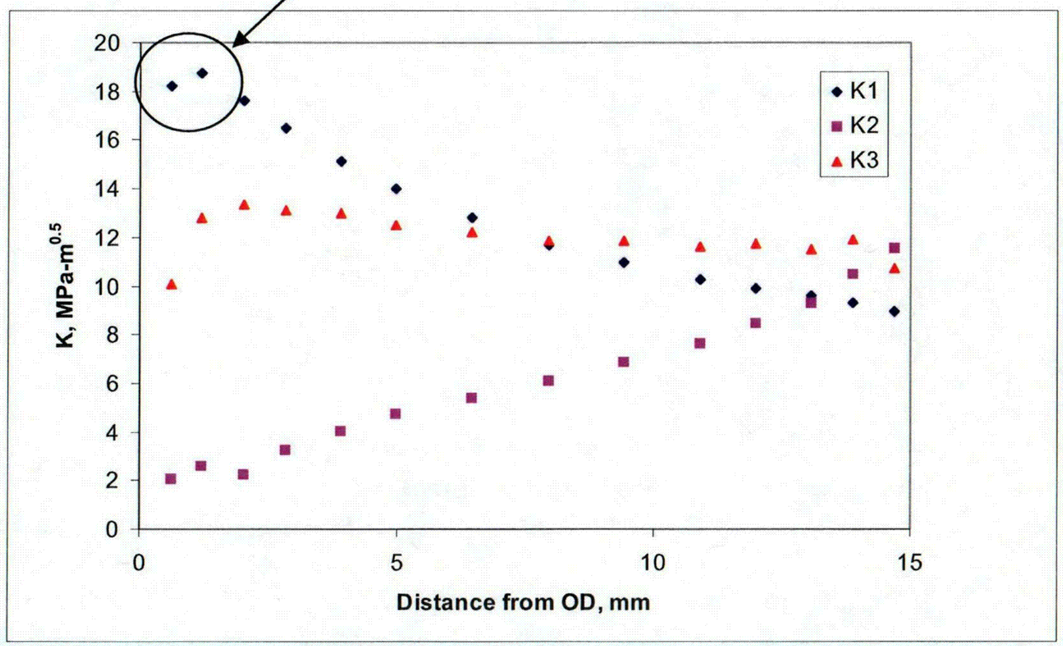
- ***With crack perpendicular to tube surface, large K_{III} and K_{II} component exists.***
  - ***Mode I = opening***
  - ***Mode II = in-plane sliding***
  - ***Mode III = out-of-plane sliding***

500

- ***Since subcritical cracks grow in maximum Mode I direction, crack angle through the thickness should not be perpendicular to tube surface.***

- ***K_{eq} was calculated from total J.***

Extrapolation technique used for path dependent J/K values

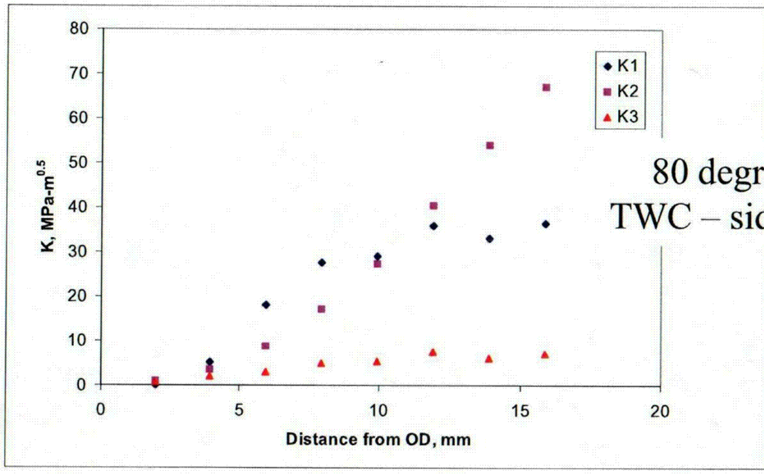


100-degree circumferential through-wall crack case

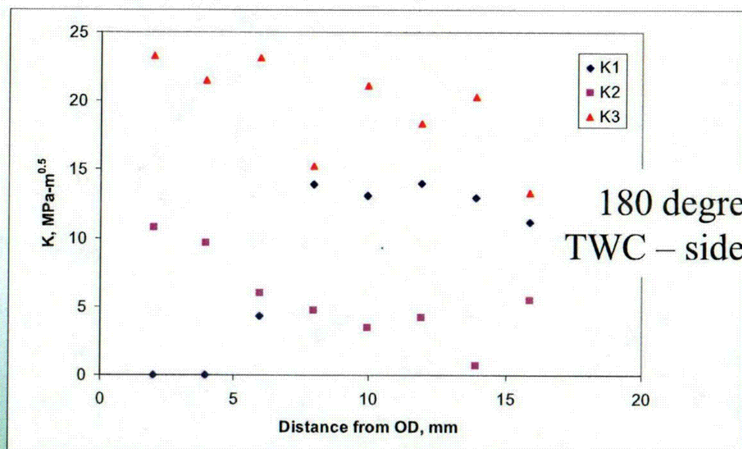
Emc²

C118

Side-Hill nozzle – J/K-solutions

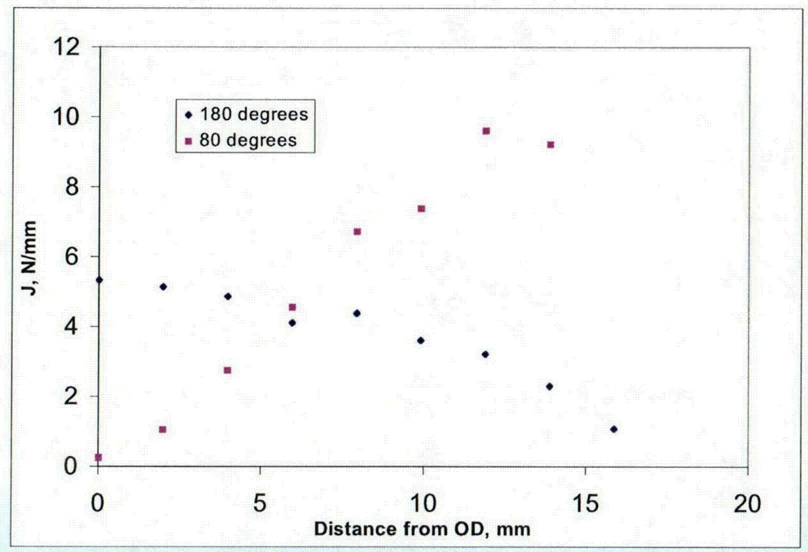


80 degree
TWC – side hill



180 degree
TWC – side hill

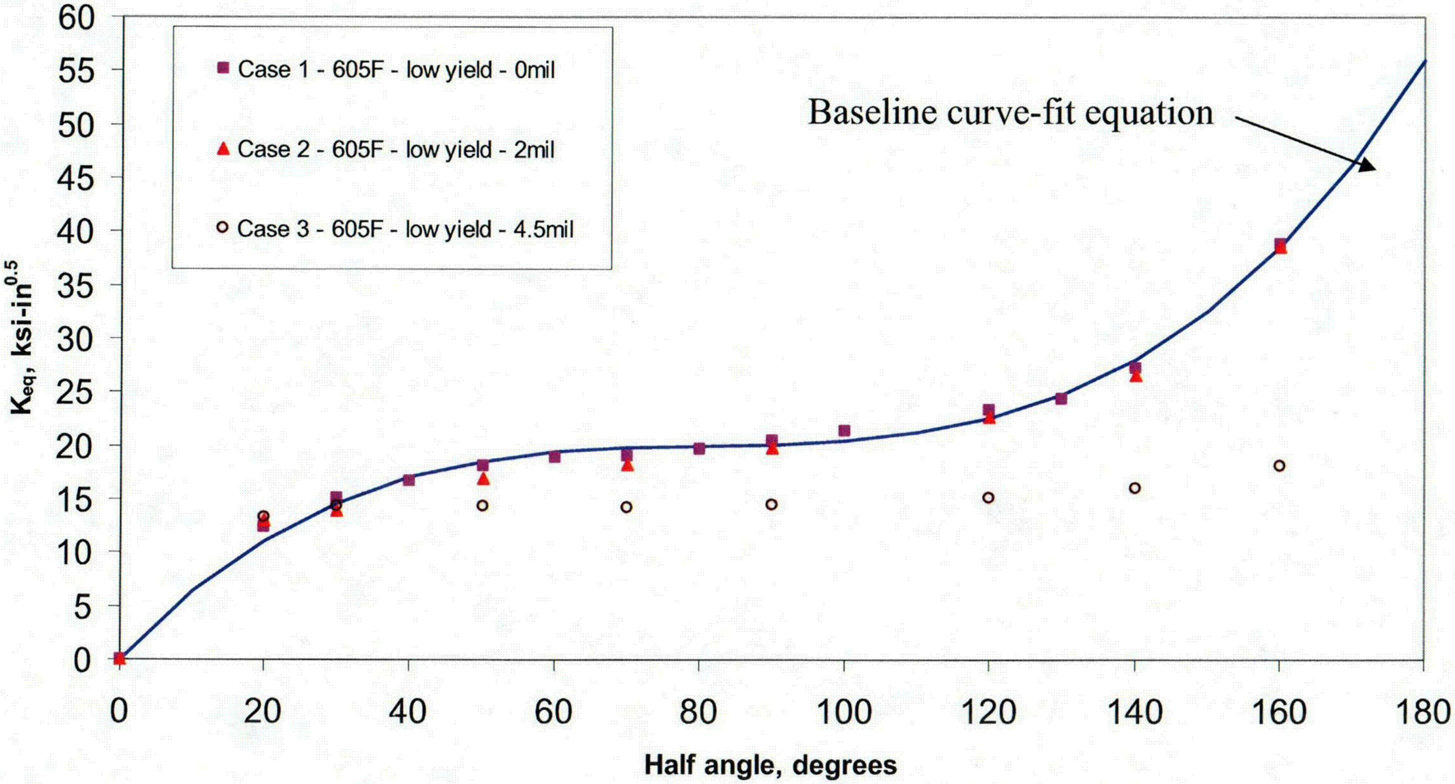
Huge gradient due
to crack closure



501

C119

Center Hole $K_{J(average)}$ -solution Comparison

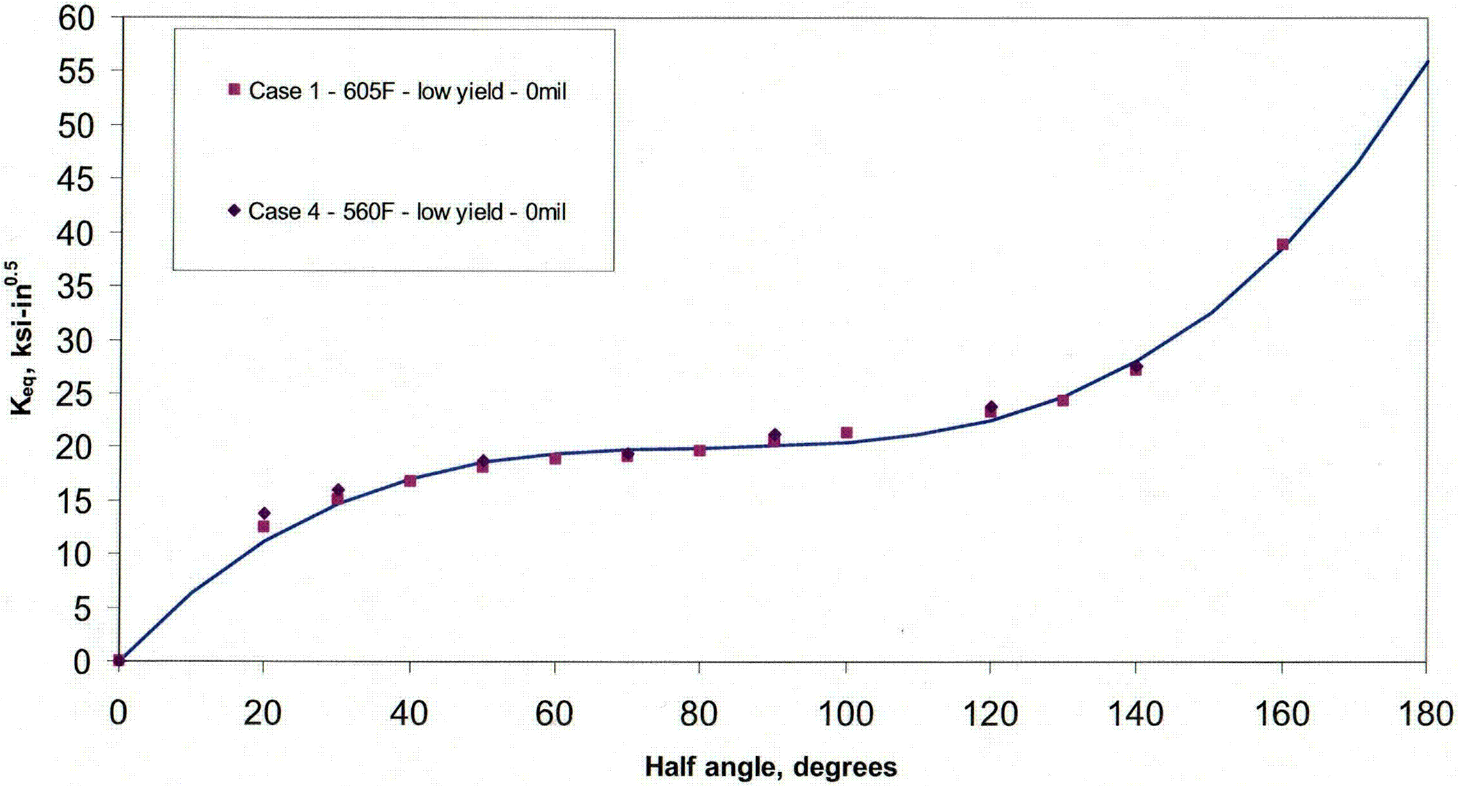


Center-hole circumferential though-wall cracks
(Effect of room temperature interference fit)

$\mathcal{E}mc^2$

C120

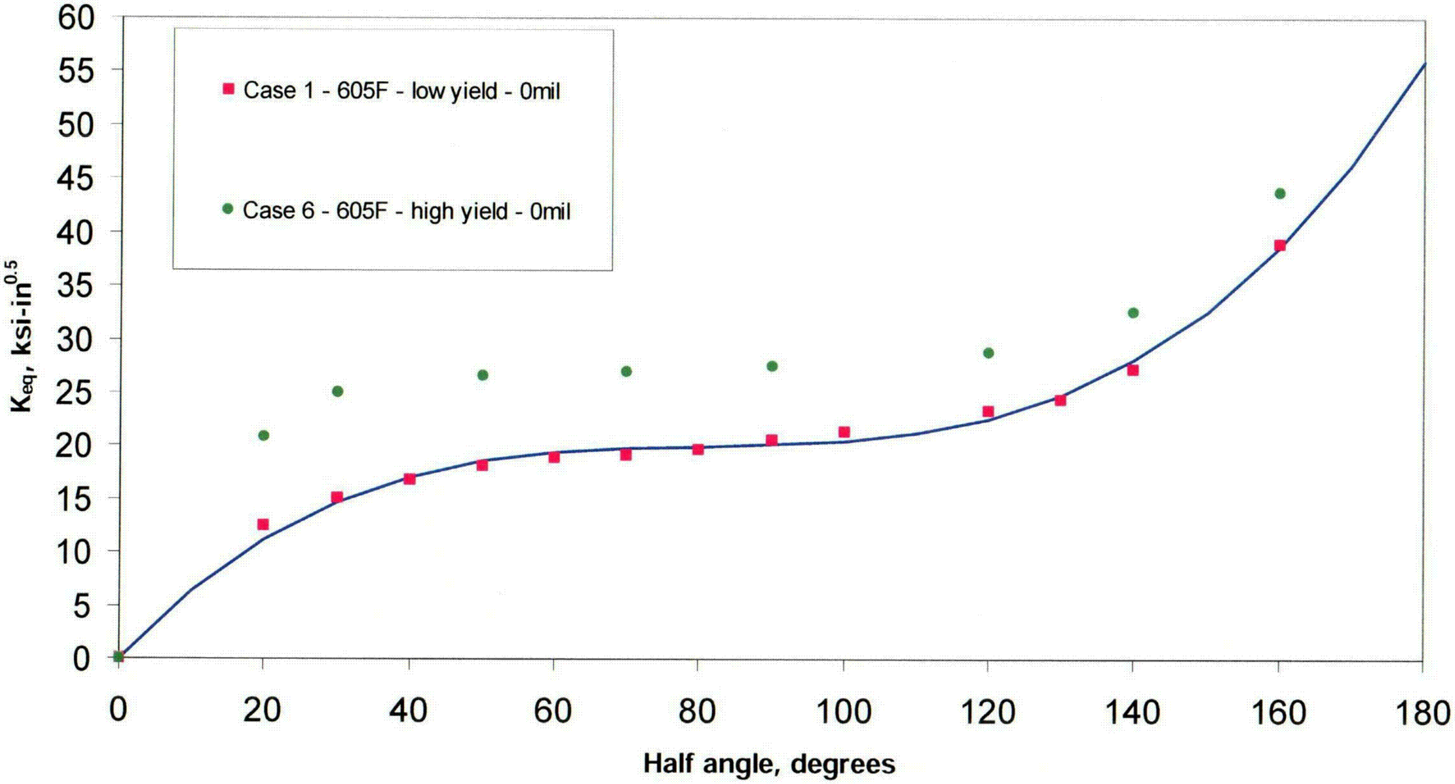
Center Hole $K_{J(average)}$ -solution Comparison



Center-hole circumferential though-wall cracks
(Effect of operating temperature)

504

Center Hole $K_{J(average)}$ -solution Comparison

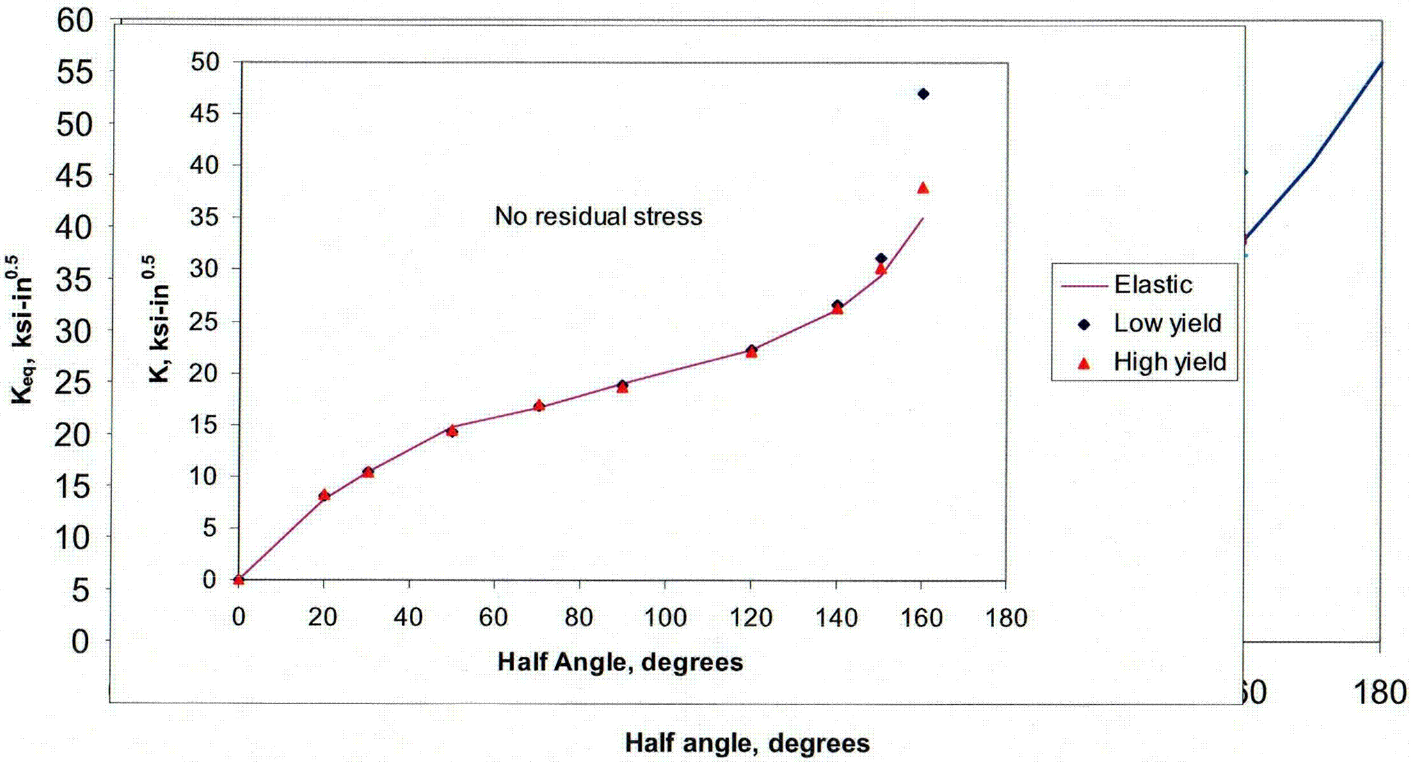


Center-hole circumferential though-wall cracks
(Effect of tube yield strength)

Emc²

C122

Center Hole $K_{J(average)}$ -solution Comparison



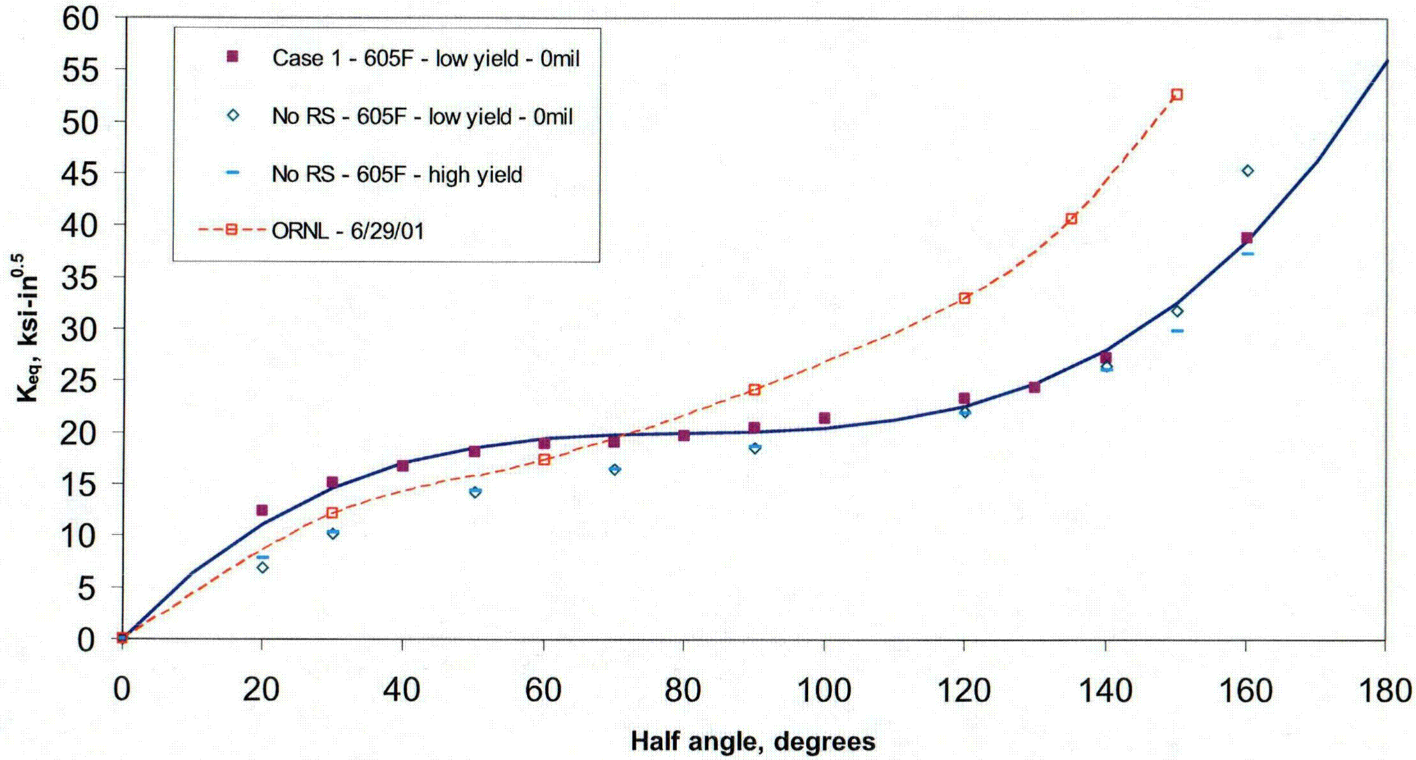
Center-hole circumferential though-wall cracks
(Comparison without residual stresses)

$\mathcal{E}mc^2$

505

C123

Center Hole $K_{J(average)}$ -solution Comparison



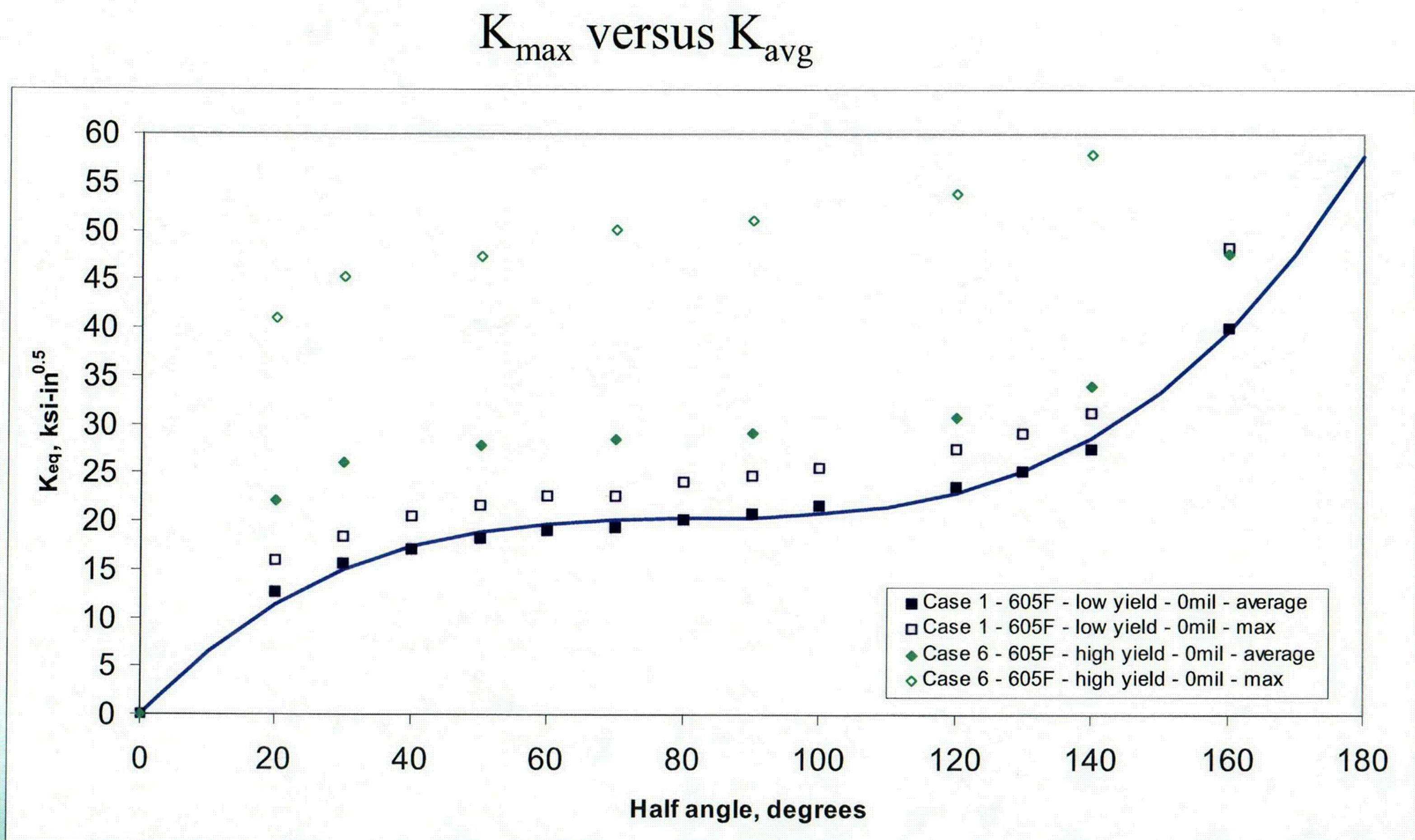
Center-hole circumferential though-wall cracks
(Comparison without residual stresses)

Emc²

506

C124

Center Hole $K_{J(average)}$ -solution

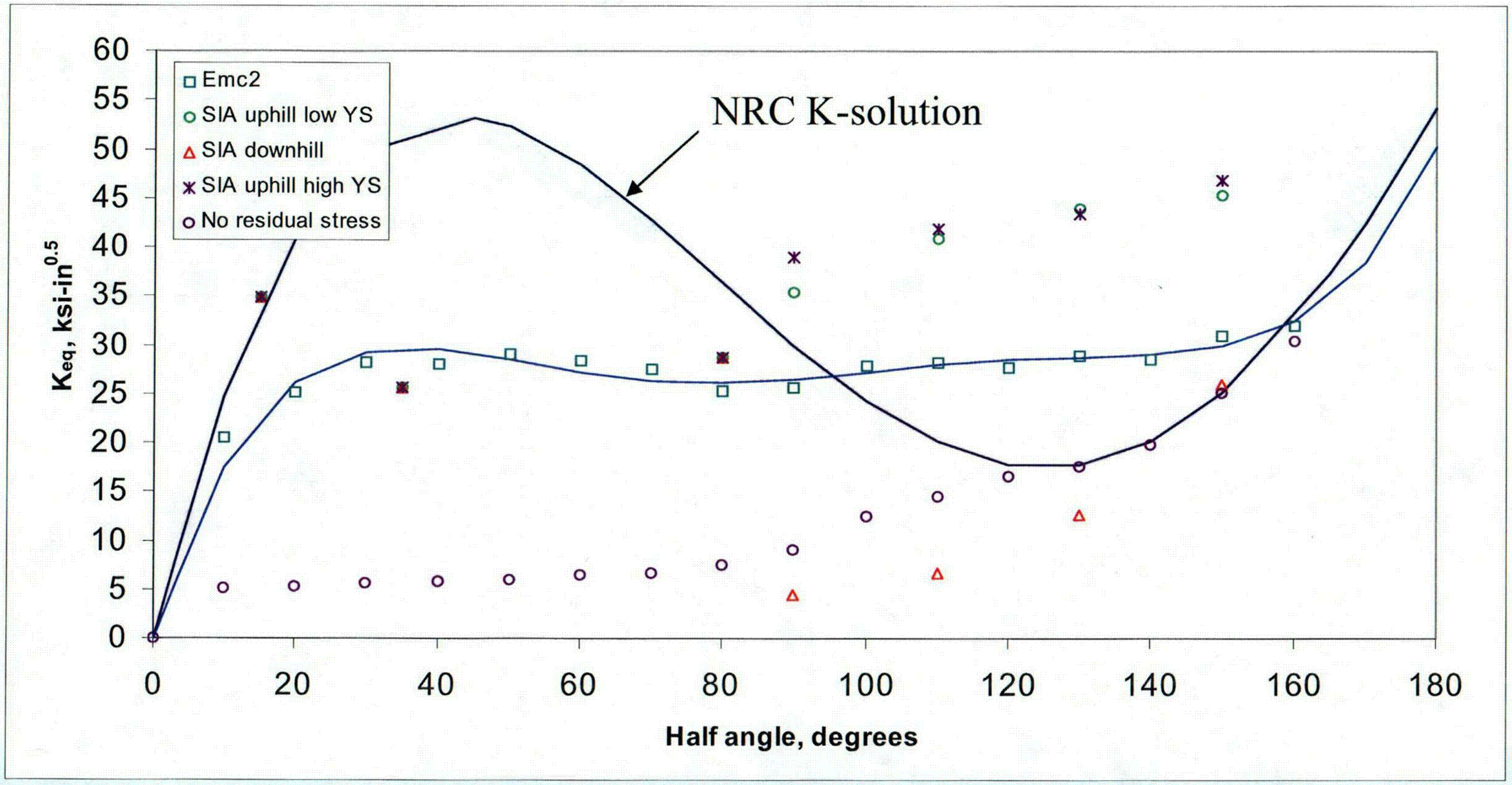


NSRC CRDM:31

507

C/25

Side-Hill nozzle – $K_{J(average)}$ -solutions



Due to change in J-gradient through the thickness as a function of crack length, the K_{eq} is almost independent of crack length

Emc²

508

C126

K-solution Observations

- *Tube yield strength had large effect of K solution – high yield gave large J gradient through thickness.*
- *For low yield, residual stress made no difference in K for cracks greater than 180 degrees.*
- *Large interference fit decreased the K solutions, but intermediate interference fit (2 mil on radius) had no effect on K.*
- *The range of operating temperature considered (560F versus 605F) did not significantly affect the K-solution.*
  - *(Temperature affects the PWSCC crack growth rate, but not the crack driving force.)*
- *The overall results are consistent with past ORNL tube-only K values.*

General Significant Observations

- *Residual stresses in hoop direction increase with increasing weld size, and stresses in longitudinal direction at J-weld root decrease with increasing weld size.*
  - *There should be optimum design.*

- *By mapping entire stress field, it can be seen that there are Mode I, II, and III components when keeping the crack perpendicular to the tube surface.*
  - *PWSCC crack will probably grow in Mode I direction that would be angled through the thickness.*
  - *Future work concentrating on optimal crack angle though thickness for maximum K_I contribution!!*

United States Nuclear Regulatory Commission

International Cooperative Project: PWSCC and NDE in Ni-Base Alloys and Dissimilar Metal Welds

Conference On Vessel Head Penetration Inspection, Cracking and Repairs

October 1, 2003

Carol E. Moyer, Materials Engineer
Office of Nuclear Regulatory Research
301-415-6764 cem3@nrc.gov

United States Nuclear Regulatory Commission

Objectives for Research Cooperative

- Document the range of locations and crack morphologies associated with PWSCC. Distinguish PWSCC cracks from similar-appearing features, such as weld hot tears.
- Identify, develop and assess NDE methods for accurately detecting, sizing and characterizing tight cracks such as PWSCC.
- Develop representative NDE mock-ups with cracks to simulate tight PWSCC cracks.

United States Nuclear Regulatory Commission

Project Organization

- Task 1 – Atlas of crack morphology for PWSCC
  - Compile existing work
  - Perform new fractography, metallography
- Task 2 – Round Robin of NDE techniques on PWSCC and simulated cracks
  - Assess techniques to detect and size cracks
  - Assess techniques to manufacture test blocks
- Other suggested topics: modeling, effects of surface condition, validation of structural integrity assessment, effects of weld repairs

513

United States Nuclear Regulatory Commission

What is Needed Next

- People with common interests, resources
- Crack morphology information (reports, etc.)
- Set of relevant specimens
  - Cracks removed from plant components
  - Components from cancelled plants
  - Simulated or manufactured cracks
- Discussions to define project tasks

515

United States Nuclear Regulatory Commission