NRC FORM 658
(9-1999)

U.S. NUCLEAR REGULATORY COMMISSION

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Do not include proprietary materials.

DATE OF MEETING
08/14/2003

The attached document(s), which was/were handed out in this meeting, is/are to be placed in the public domain as soon as possible. The minutes of the meeting will be issued in the near future. Following are administrative details regarding this meeting:

Docket Number(s)	50-368 and 50-382
Plant/Facility Name	Arkansas Nuclear One, Unit 2 and Waterford 3
TAC Number(s) (if available)	MB8927, MB9542, MB9644, MB9882, MB9883
Reference Meeting Notice	08/08/03 (ML032200089)
Purpose of Meeting (copy from meeting notice)	EOI will discuss its May 8, June 11, and July 1, 2003, relaxation requests from NRC's vessel head inspection Order.

NAME OF PERSON WHO ISSUED MEETING NOTICE	TITLE
Tom Alexion	Project Manager

OFFICE
Nuclear Reactor Regulation

DIVISION
Division of Licensing Project Management

BRANCH
Project Directorate IV

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Docket File/Central File
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DF01

ANO-2 and W3 NDE Order Relaxations

Entergy Operations, Inc.

Date – August 14, 2003

Introduction

Bill James

Purpose of Meeting

- Comprehensively review Entergy's RVH issues
- Review Entergy's current relaxation approach and basis for compliance with the Order
- Provide technical review of supporting analysis for relaxation options
- Reach mutual agreement on our deliverables and timing

Overview

William Sims

Challenges for Order Compliance

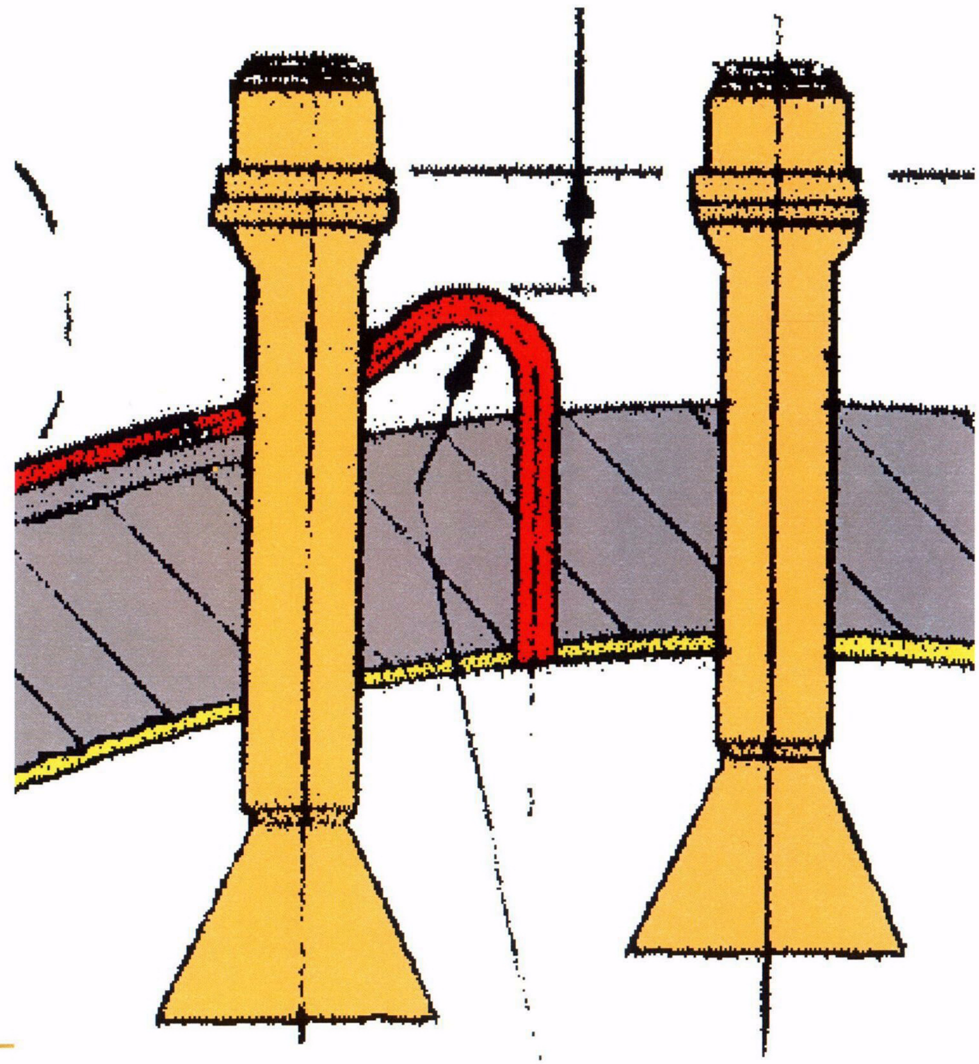
- ANO-2 BMV hardship
- Vent Line – Volumetric examination will not provide leakage assessment
- CEDM/ICI – Cannot perform full volumetric examination due to nozzle configurations.

Approach for Order Compliance

- **Vent Line**
  - ANO-2 – LFECT & wetted surface ECT
  - W3 – BMV & wetted surface ECT
- **CEDM**
  - ANO-2 – LFECT & supplemental visual
  - W3 – BMV
  - Volumetric examination of accessible areas
  - Deterministic analysis of flaw growth from unexamined area
  - Probabilistic analysis for areas not examined
- **ICI**
  - BMV
  - Volumetric examination of accessible areas
  - Deterministic analysis of flaw growth from unexamined area
  - Probabilistic analysis for areas not examined

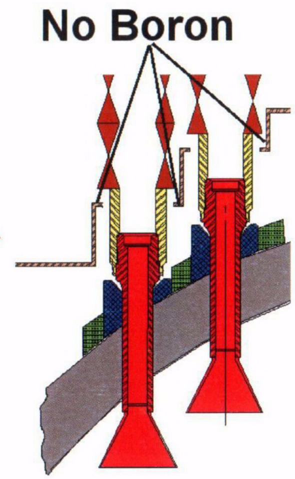
Vent Line Configuration & Examination

- Cannot do leakage assessment with ultrasonics
- Manual ECT Wetted surface of J-weld and automated exam of nozzle.
- ANO-2 only – Low frequency ECT of the vessel OD
- Relaxation: ANO2 – BMV, Combination UT and ETC

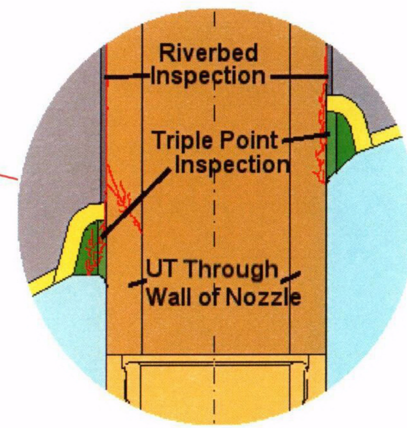


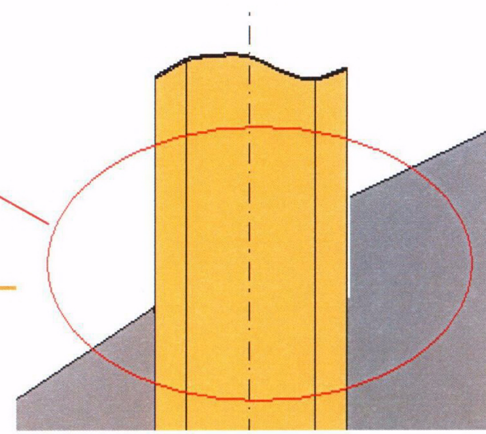
C01

CEDM Inspection Approach



- ANO-2 Combination of Supplementary and BMV inspection
- W3 Bare Metal Inspection
- Volumetric Insp. of nozzle/J-weld
  - UT through wall of nozzle
  - Weld fusion line and Triple Point
  - Riverbed
- Low Freq ECT Vessel Inspection
  - Leakage/degradation assessment on vessel OD and annulus region
- Relaxation: ANO2 – BMV, Threaded blind zone

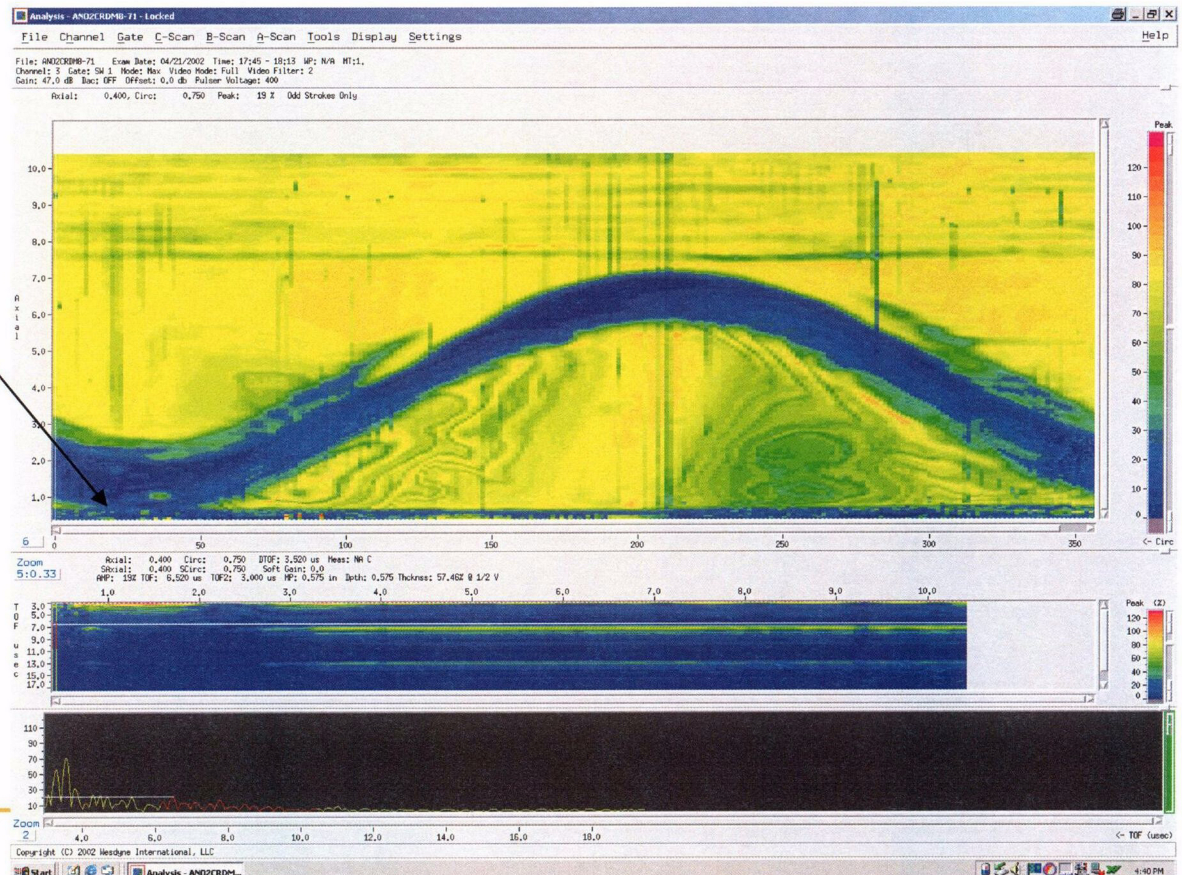




C02

ANO-2 CEDM Refuel Outage 15 - Ultrasonic Results

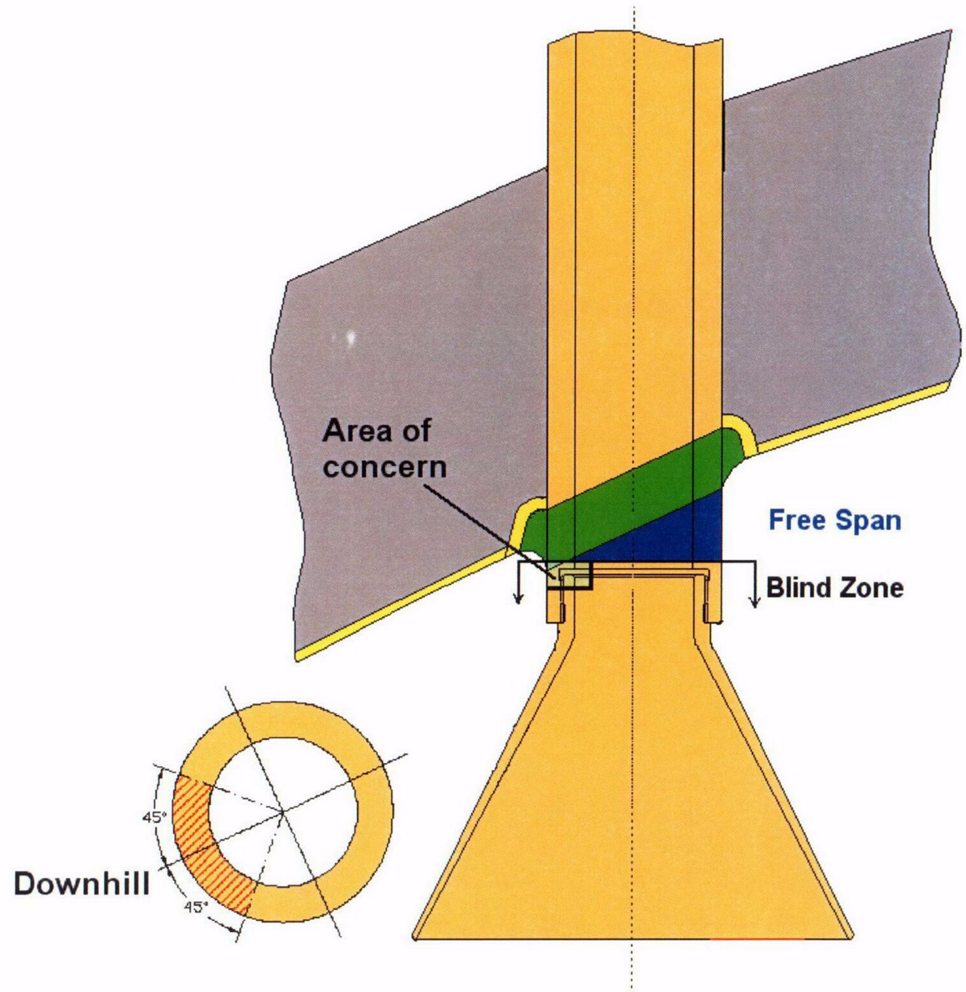
- Weld Extends into blind zone



C03

CEDM Ultrasonic Free Span Results

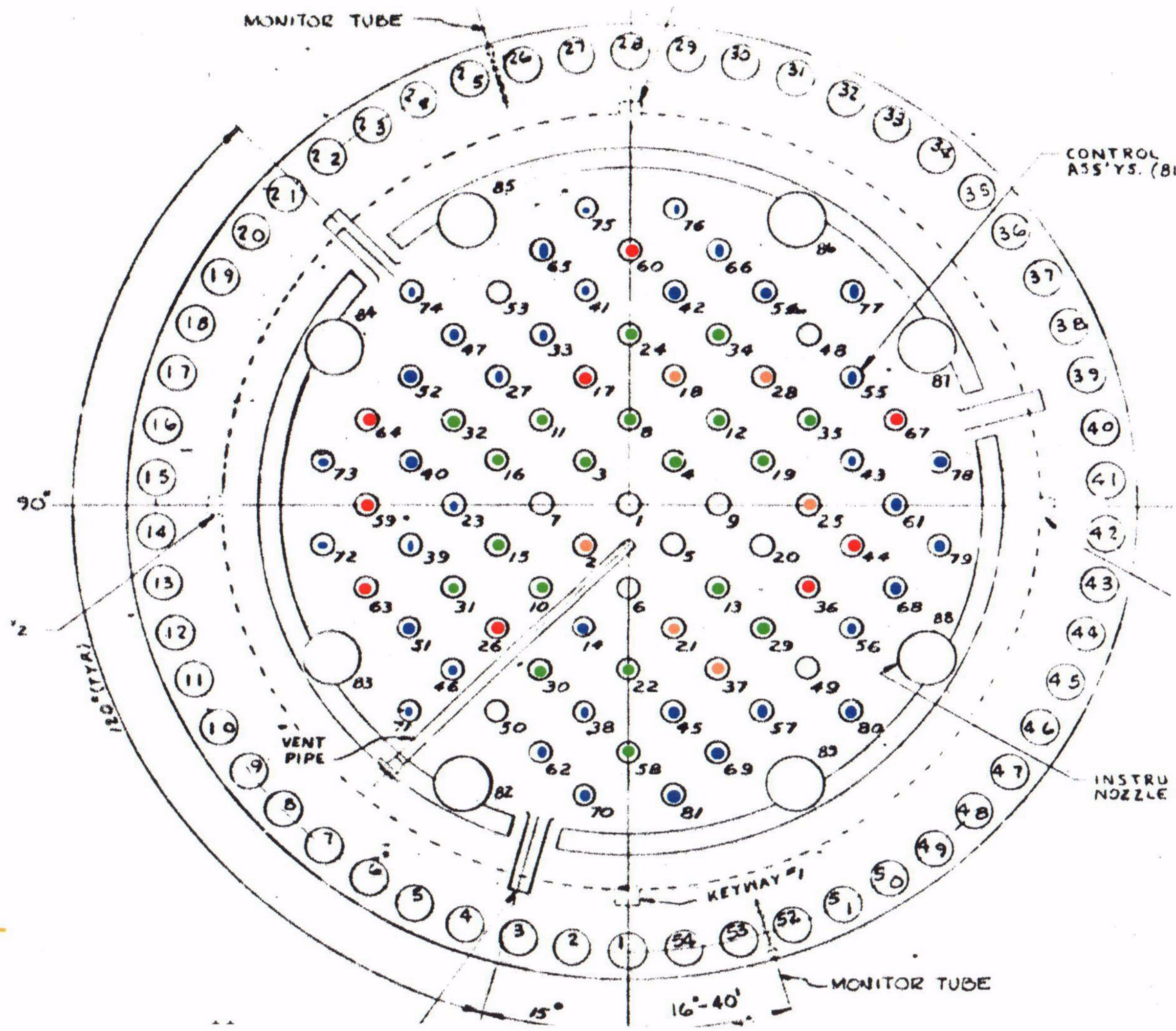
- ANO-2 UT data reveals many nozzles have no free span on down hill side
  - 46% CEDMs with no free span
  - 11% CEDMs with 0 - .10" free span
  - 23% CEDMs with 0.11 - 0.20"
  - 7% CEDMs with 0.21-0.30"
  - Remaining greater than 0.30" or no data



C04

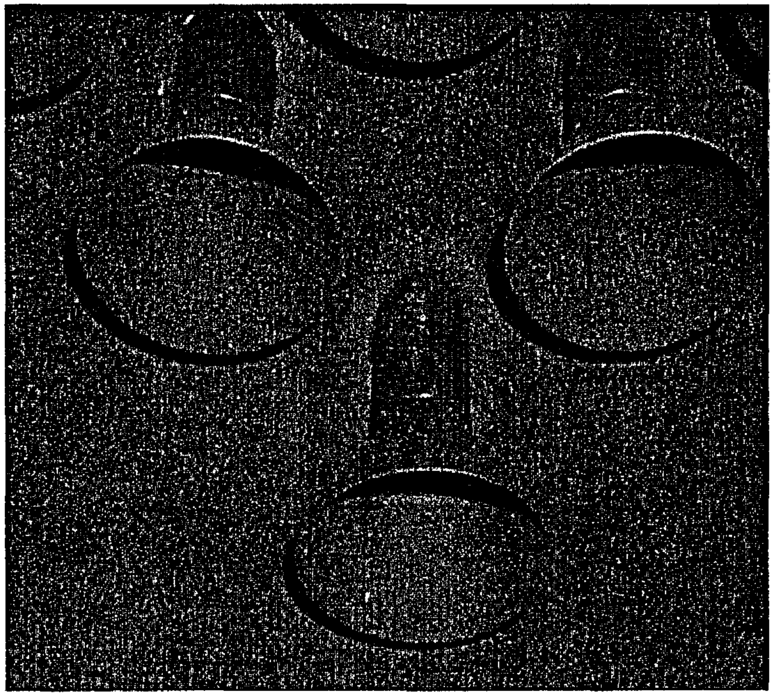
Plot of Free Span Length

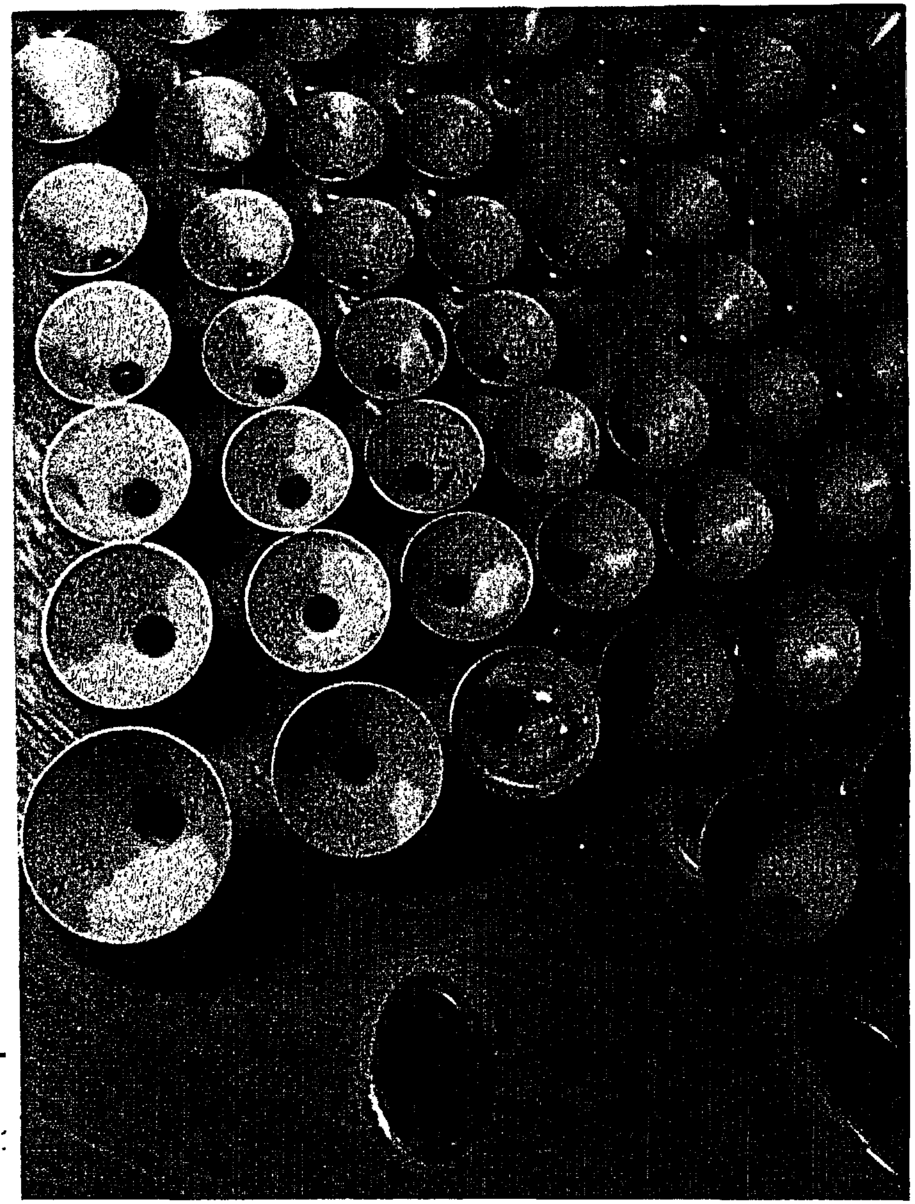
- Free Span Length
  - Blue = 0.0
  - Red = 0.01 thru 0.10
  - Green = 0.11 thru 0.20
  - Orange = -.21 thru 0.30
  - No color indicates either greater than 0.30, or no data available.



C05

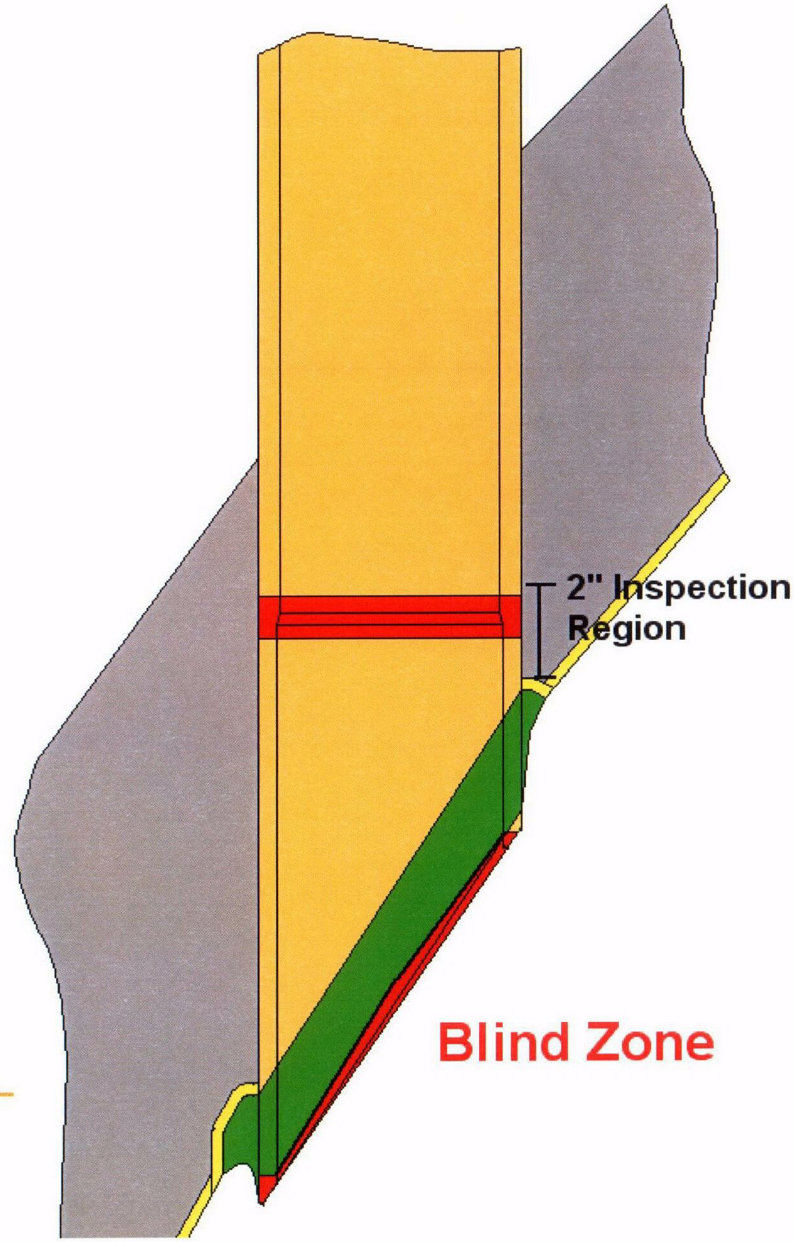
W3 CEDM and ICI Pictures





ICI Inspection Approach

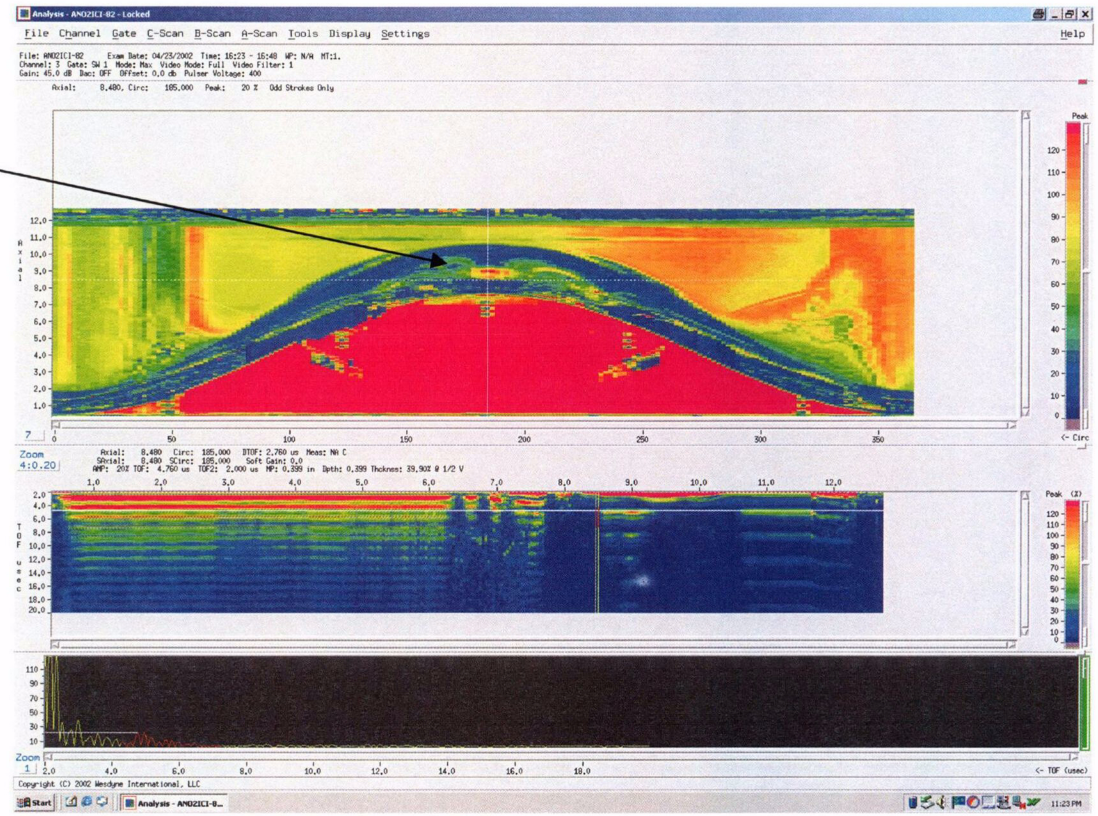
- ANO-2/W3 Bare Metal Inspection
- Volumetric Insp. of nozzle/J-weld
  - UT through wall of nozzle
  - Triple Point
  - Riverbed (Leakage)
- Relaxation: Counterbore and nozzle end blind zone,



C06

ANO-2 ICI Refuel Outage 15 - Ultrasonic Results

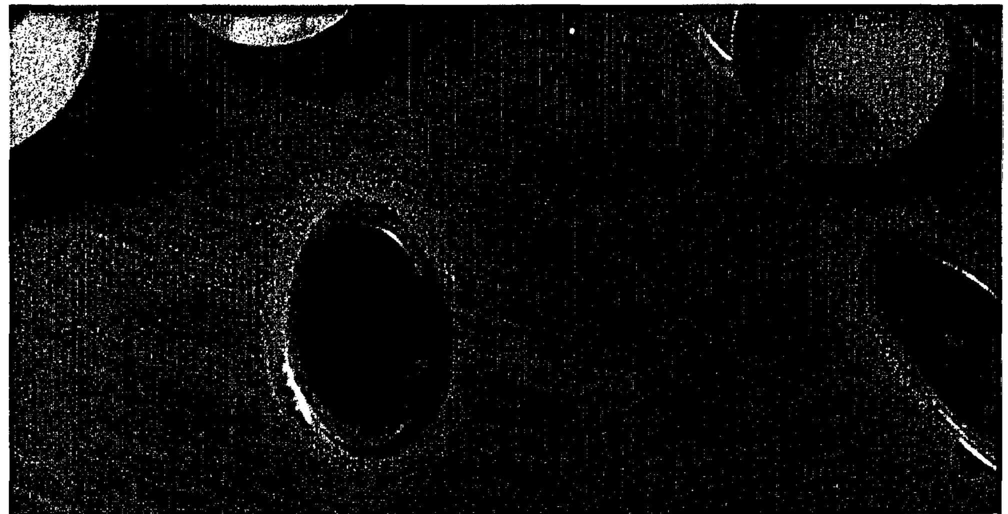
- Minimal free length detectable

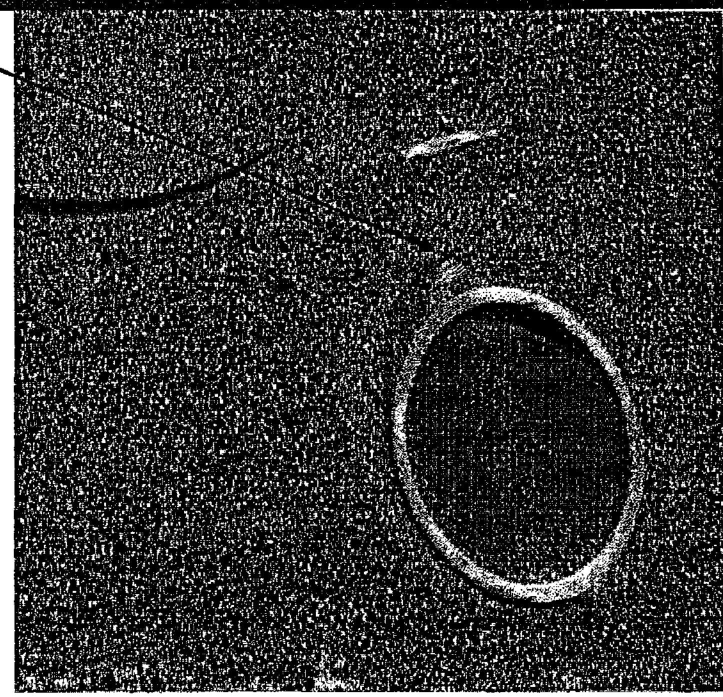


C07

W3 ICI Pictures

- Free length on upper hillside

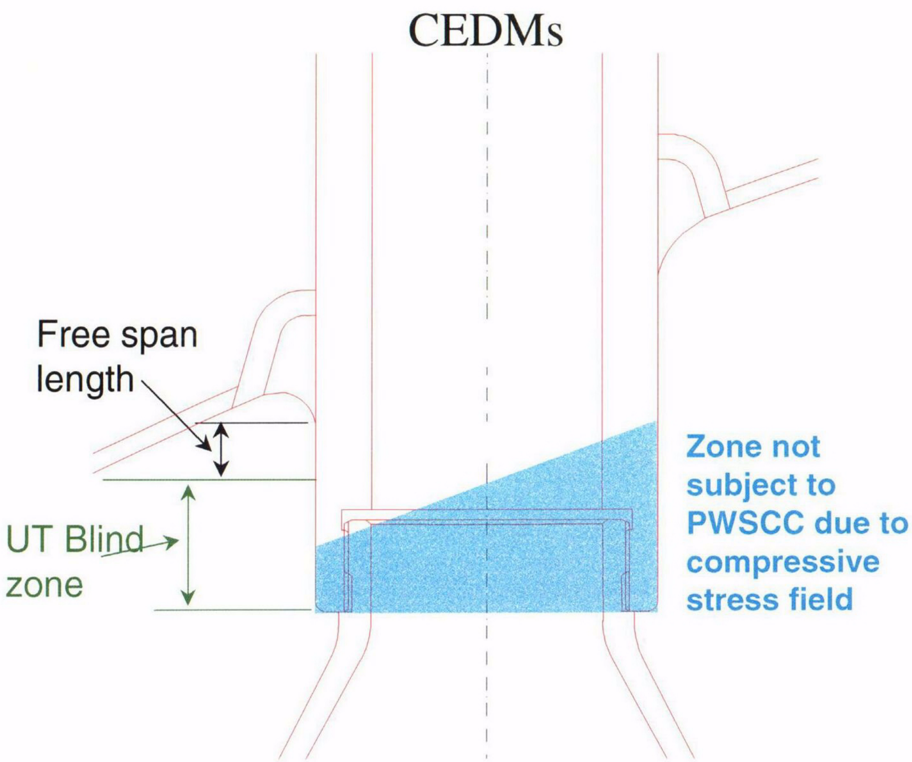


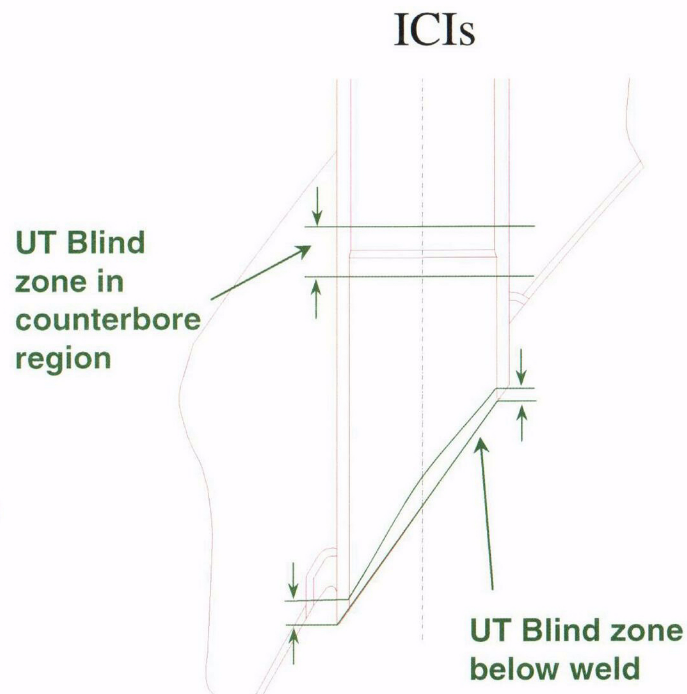


Deterministic Analysis

Jai Brihmadesam

Purpose of Deterministic Fracture Mechanics





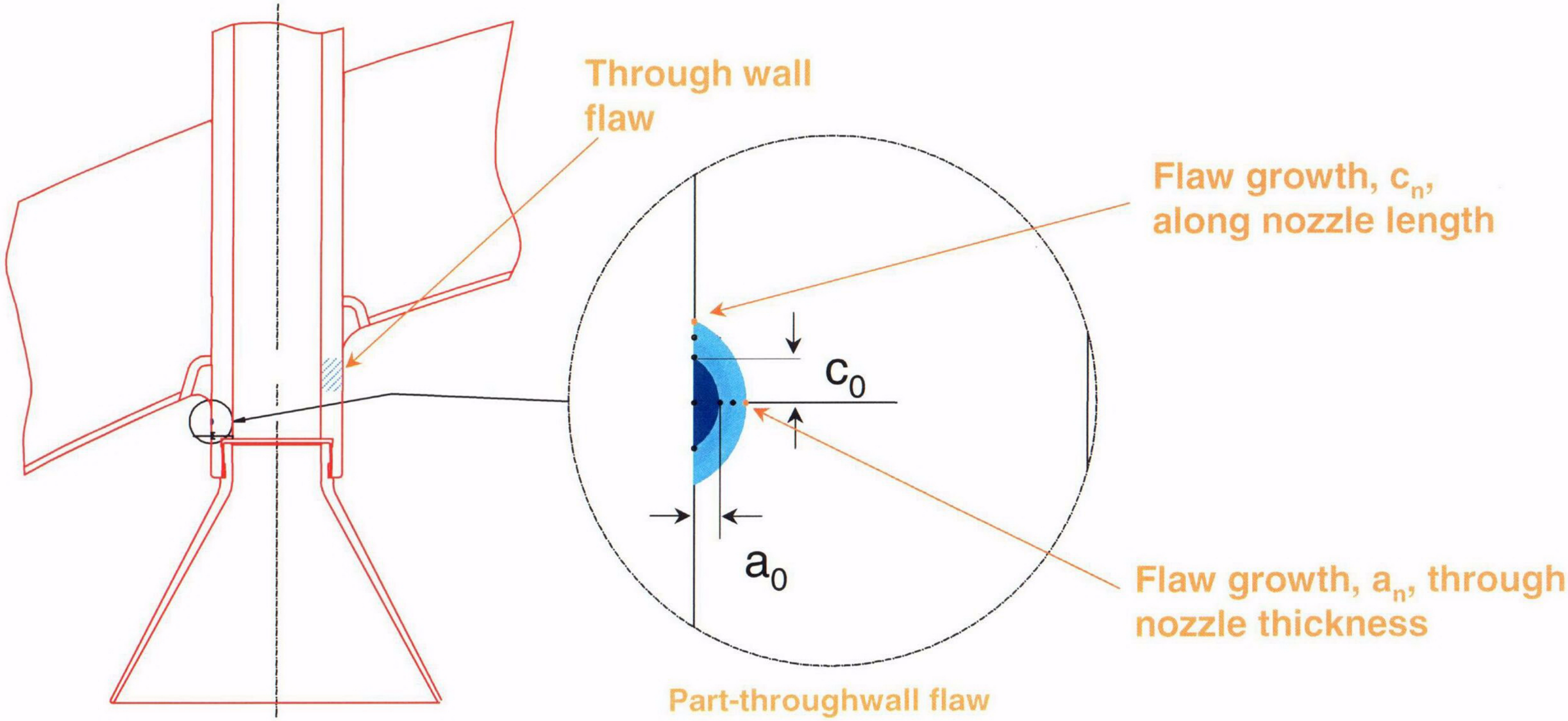
- Define minimum free span length for at least 1 cycle of flaw growth for I.D. and O.D. part-through wall flaws and through wall flaws.
- Define portion of the CEDM nozzle end not susceptible to PWSCC

- Define minimum free span length for at least 1 cycle of flaw growth for I.D. part-through wall flaws.
- Define area of counterbore for at least 1 cycle of flaw growth for I.D. part-through wall flaws.

C08

Postulated Flaws-CEDMs

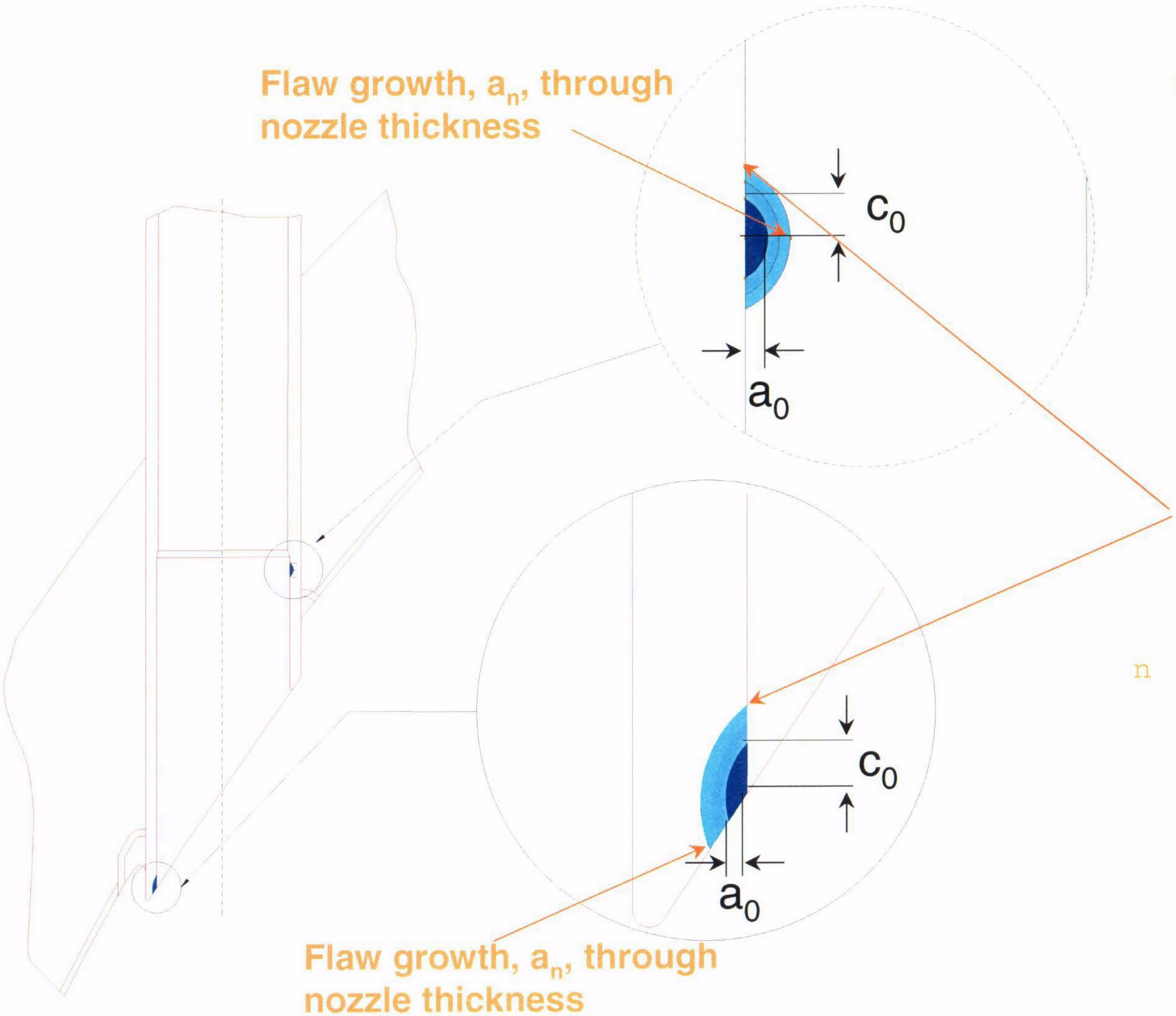
- Flaws configurations considered: through wall, I.D. part through wall, and O.D. part through wall (as shown below)



- Flaws evaluated at uphill, downhill, and mid-plane locations
- Initial flaw depth (a_0)—for part through wall flaws—and length ($2c_0$)—for all flaws—based on NDE detection limits

C09

Postulated Flaws-ICIs



- **I.D. part-through wall flaws considered at downhill nozzle end and uphill just below the counterbore.**
- **Initial edge flaw length (c_0), counterbore flaw length ($2c_0$), and depth (a_0) based on NDE detection limits**

c10

Deterministic Fracture Mechanics Analyses

- **Finite Element Model:**

  Model geometry based on evaluation of both NDE (UT) data and design drawings/ Waterford under evaluation

  Highest yield strength nozzle in each nozzle group (for example, 0°, 8.8°, 28.8°, 49.6°) was evaluated.

  Temperature-dependent stress-strain curve for wrought tube material, and elastic-perfectly-plastic stress strain curve for weld material

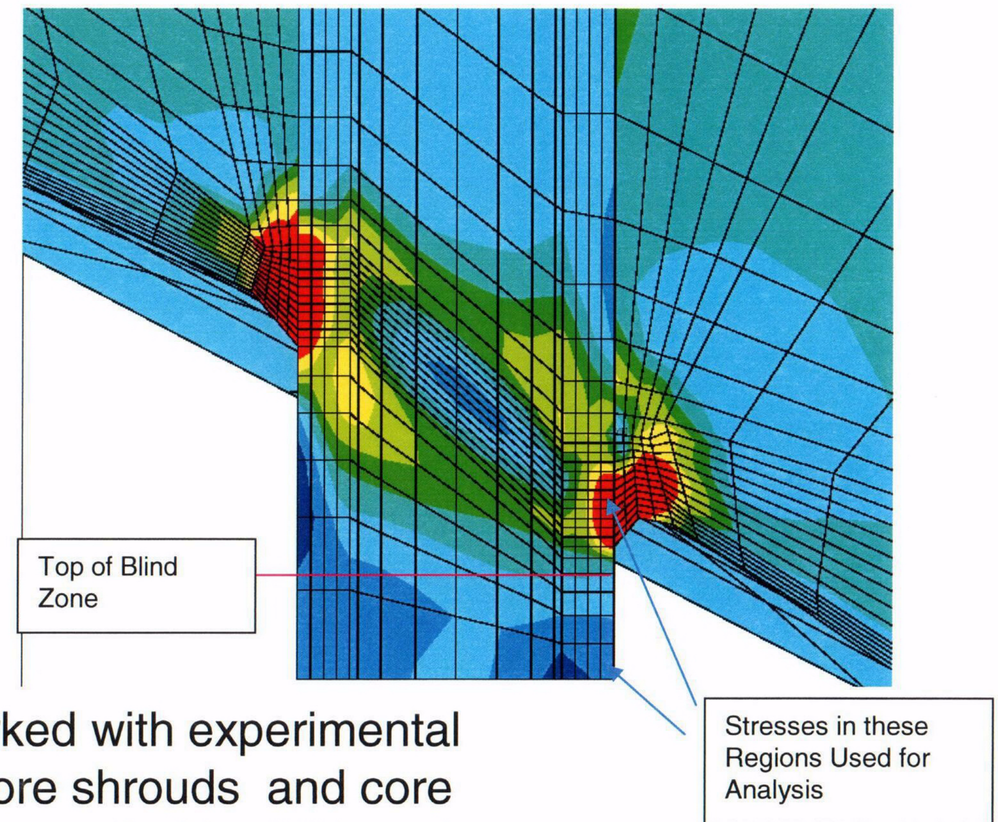
  Model uses a 3-D solid (brick) mesh with four elements representing the tube thickness and approximately 0.125-inch spacing along the tube height on the downhill side.

Deterministic Fracture Mechanics Analyses

- **Finite Element Stress Analysis:**

Model combines stresses obtained from analyses covering Fabrication + Hydro + Normal Operating

Residual Stresses (through wall distribution) at all nodal points from the bottom of the nozzle to the top of the attaching J-weld.



Method to quantify residual stresses similar to model used for BWRVIP-14 and 59, benchmarked with experimental residual stress determination on core shrouds and core shroud supports and independently verified by BCL under contract with the NRC.

C11

Deterministic Fracture Mechanics Analyses

n Fracture Mechanics (General Approach)

Through wall stress distribution along the tube length determined by averaging the stress on the flaw as the flaw grows in depth and length.

Choice of flaw location based on definition of a reference line (e.g., the location of the UT blind zone) with particular location of flaw defined as user input. (Flaw tips or flaw center based on location.)

Stress profile for initial flaw based on an average profile at three (3) locations on the flaw—the lower tip, center of the flaw, and the upper tip.

The distance between the upper flaw tip and the weld bottom is divided into twenty (20) equal segments to establish stress profiles

Deterministic Fracture Mechanics Analyses

▪ Fracture Mechanics (General Approach)-continued

As the flaw grows, the stress profile imposed on the flaw is re-averaged to account for the new flaw position. This averaging method was determined to be more conservative than a force-averaging technique.

Flaw growth based on EPRI MRP curve at the 75th percentile

Flaw growth in the depth and length dimensions computed independently using the different flaw influence coefficients (at the "a-tip" and "c-tip" of the flaw)

Time increment for flaw growth is approximately 20-24 hours of operating time. At the end of each increment, the flaw size is updated. Based on the new flaw size, the flaw influence coefficients and stress coefficients are determined.

Deterministic Fracture Mechanics Analyses

n **Fracture Mechanics Models**

Surface Flaws:

- Based on NASA model (SC04) covering a range from a very thick-wall cylinder (R/t = 1.0) to a flat plate (R/t = 300).
- Depth-to-half length aspect ratio (a/c) of the flaw is variable from 0.2 to 1.0
- Flaw depth-to-thickness ratio (a/t) is variable from 0.0 to 1.0

Through wall Flaws:

- Based on ASME Pressure Vessels and Piping (PVP) paper for through wall axial cracks in pipes and cylinders (thick-wall solution)

Deterministic Fracture Mechanics Analyses

Comparison of Conventional & Entergy Approaches for Flaw Evaluation

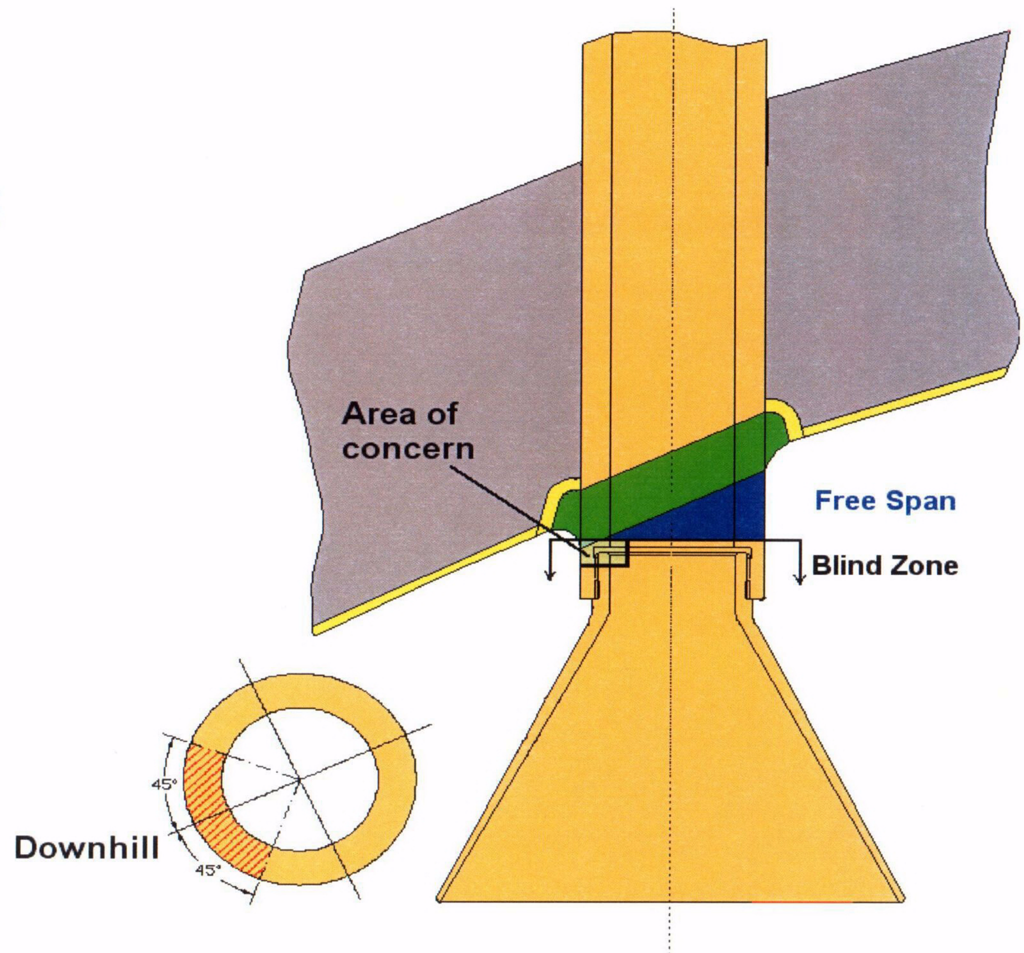
Flaw Type	Feature	Conventional Approach	Entergy Approach
Surface Flaws (ID & OD) Part Through wall	Stress	Distribution fixed at initial flaw location	Variable distribution along length of tube & flaw face pressurized
	Cylinder Geometry	Fixed "R/t" ratio of 4.0	Variable "R/t" ratio from 1 to 300
	Flaw Geometry	Fixed aspect ratio; "a/c" = 0.33	Variable aspect ratio; "a/c" from 0.2 to 1.0
	Flaw Growth	Only growth in depth direction evaluated	Growth both in the depth and length directions evaluated independently
Through wall Axial Flaws	Stress	Uniform tension @ initial flaw location	Variable along length; both membrane and bending components considered; flaw face pressurized
	Model	Center cracked panel without correction factors	Thick cylinder with correction for flaw/tube geometry

CEDM Summary Results for ANO-2

- ID flaws do not grow significantly for all nozzle groups
- OD and Through-wall flaws uphill and mid-plane locations for all nozzle groups do not grow significantly
- Only concern is for downhill locations
  - Small angle nozzles flaw grow within one cycle
  - Large angle nozzles weld extends into blind zone

CEDM Summary Results for ANO-2

- Only area of concern is the lower hillside (+/- 45° Circumference



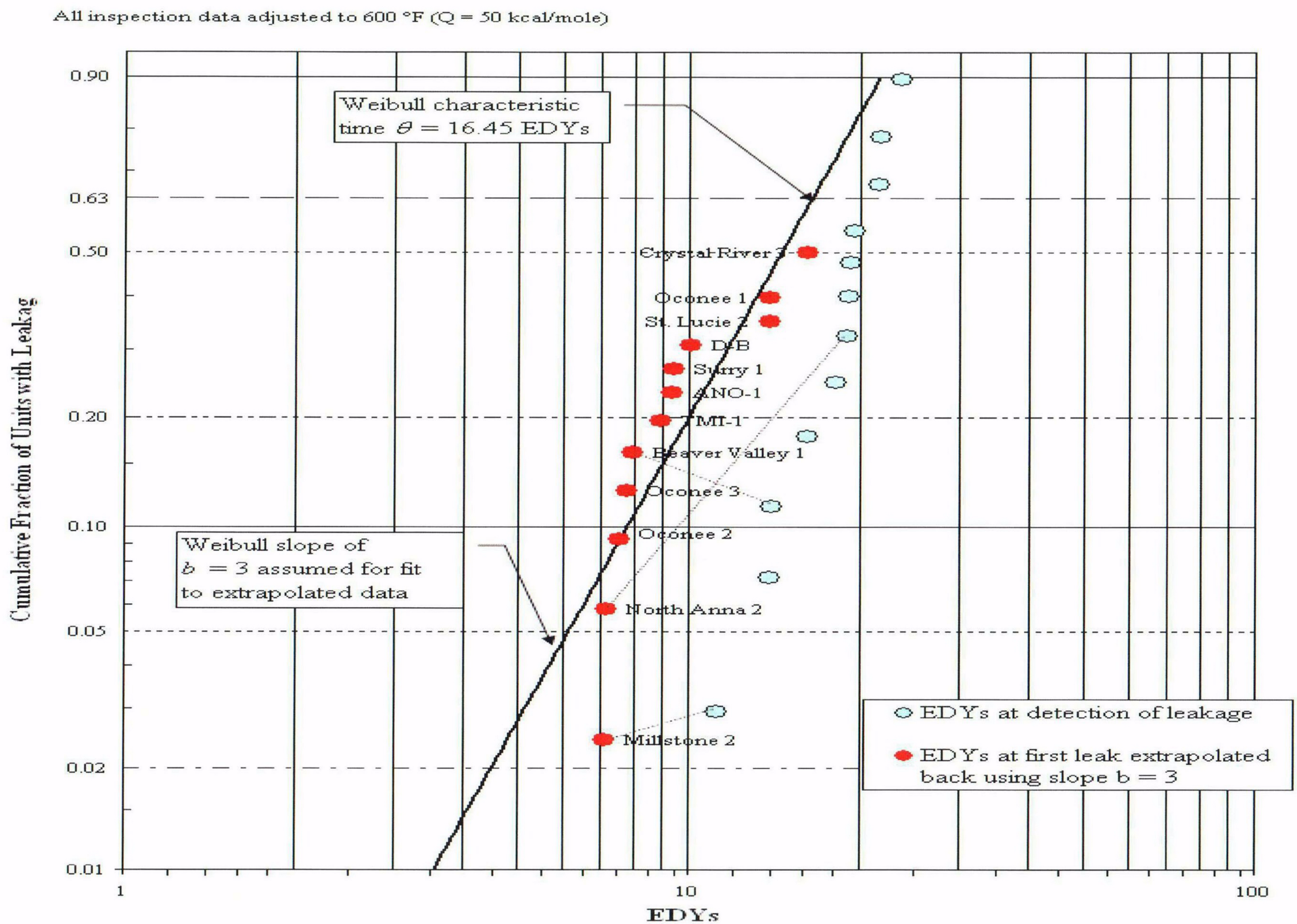
C12

Probabilistic Analysis

Pete Riccardella

Probability of Leakage

- Analysis based on prior MRP developed technology
- Weibull analysis of plant inspection data
  - Population = 30 plants that have performed non-visual NDE or visual exams that have found leakage or cracking
  - 12 had leaks or significant cracking
  - Includes both Nozzle and Weld Metal Cracking
- Plants w/ multiple affected nozzles extrapolated back to predict time to first leak or crack

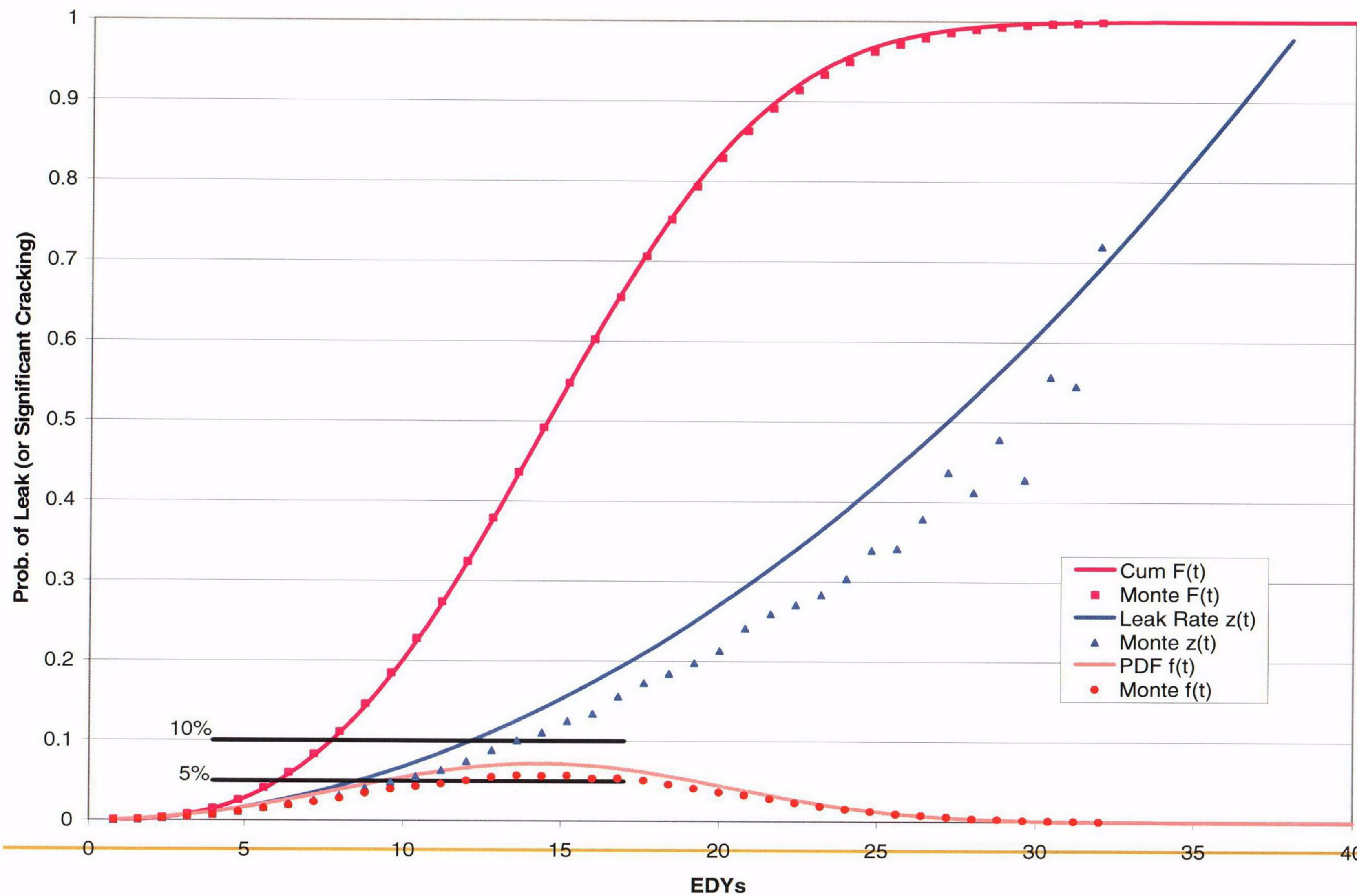

All inspection data adjusted to 600 °F (Q = 50 kcal/mole)
Weibull characteristic time θ = 16.45 EDYs
Weibull slope of b = 3 assumed for fit to extrapolated data
Crystal River 3
Oconee 1
St. Lucie 2
D-B
Surry 1
ANO-1
TMI-1
Beaver Valley 1
Oconee 3
Oconee 2
North Anna 2
Millstone 2
EDYs at detection of 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

C13

Effect of Inspections on Leakage

- Primary Goal of MRP PFM is to ensure that inspections protect 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, dependent on inspection coverage (80% assumed)

Leakage Probability (w/o NDE)



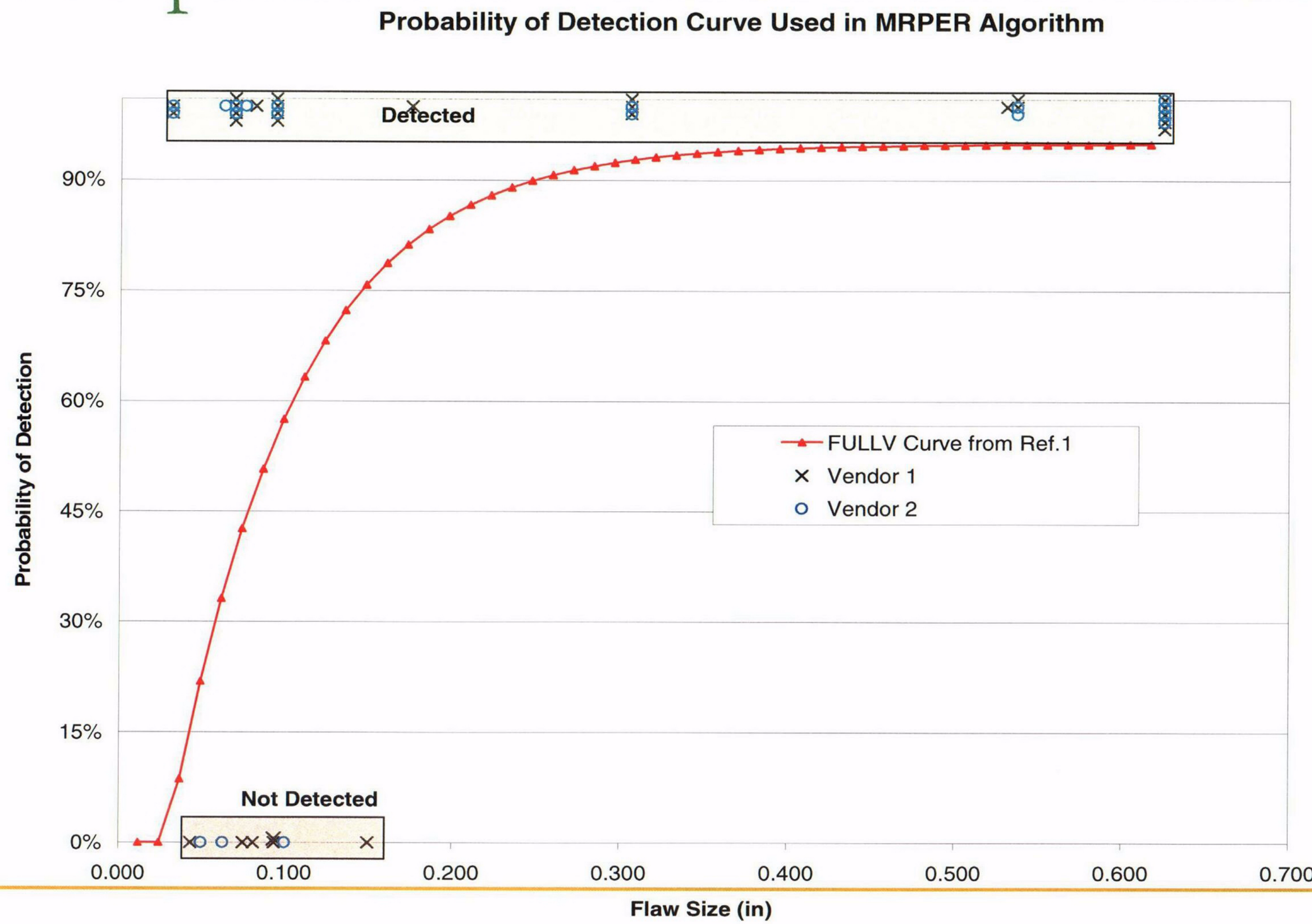
C14

Probability of Detection Assumptions 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

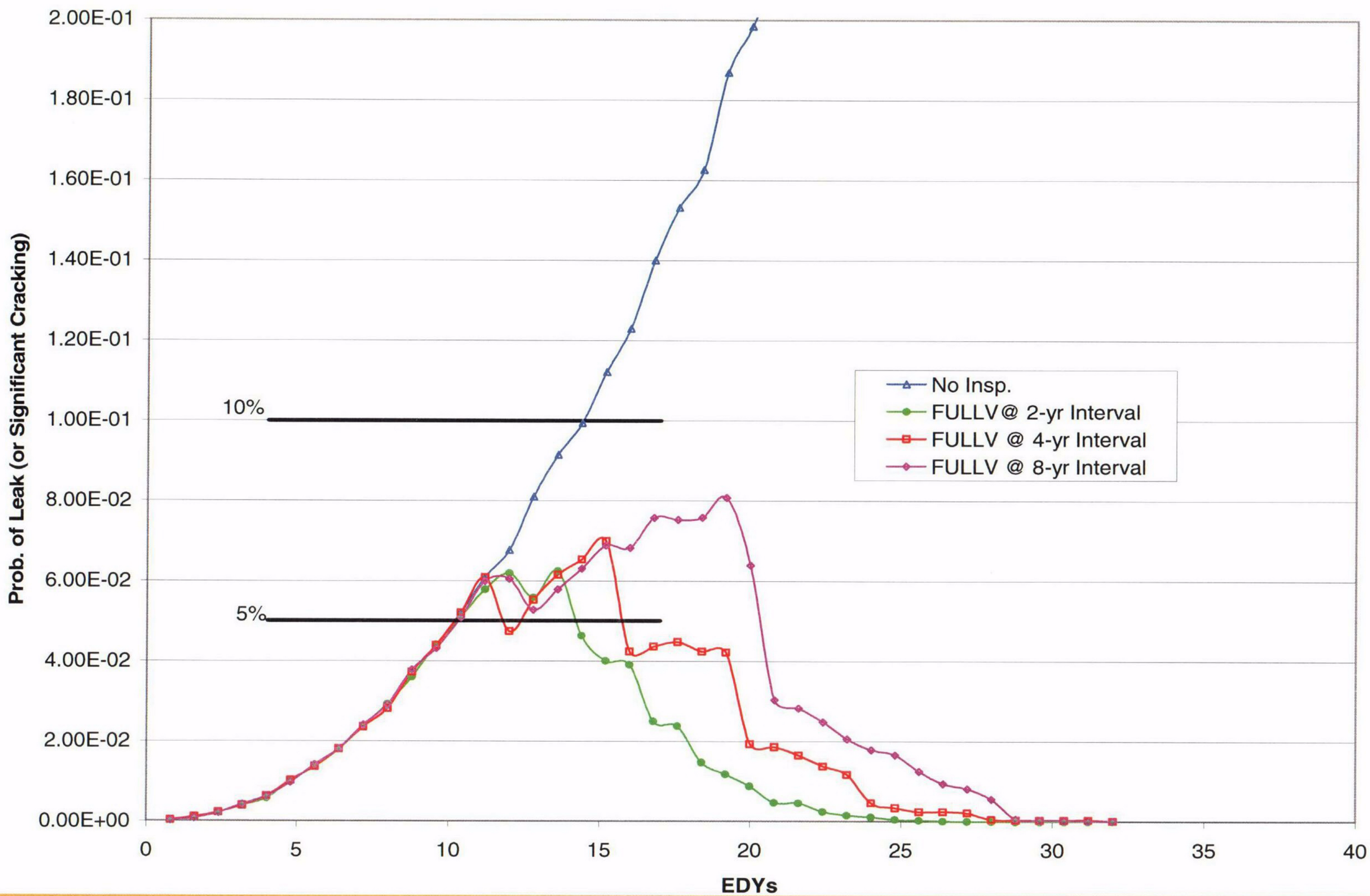
[1]Dimitrijevic, V. and Ammirato, F., "Use of Nondestructive Evaluation Data to Improve Analysis of Reactor Pressure Vessel Integrity, " EPRI Report TR-102074, Yankee Atomic Electric Co. March 1993

POD Curve for NDE (Illustrating Comparison to Vendor Demonstrations)



C15

Effect of NDE on Leakage Probability



C16

Proposed Probabilistic Approach for ANO-2 and W-3 Order Relaxation

- Conduct Plant Specific Probability of Leakage Analysis
- Include effect of proposed inspection
- Evaluate inspection zone limitations in terms of reduced examination coverage
- Being performed on CEDMs/ Expected to be conservative for ICIs
- Expect only minor effect on probability of leakage due to limited inspections

Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc
Developedby: J. S. Brihmadesam **Verified by: B. C. Gray**

Note : Only for use when $R_{outside}/t$ is between 2.0 and 5.0 (Thickwall Cylinder)

Refrences :

1) ASME PVP paper PVP-350, Page 143; 1997 {Fracture Mechanics Model}
2) Crack Growth of Alloy 600 Base Metal in PWR Environments; EPRI MRP Report MRP 55 Rev. 1, 2002

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8.8"degree Nozzle, "0" Degree Azimuth 1.294 inch above Nozzle Bottom

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

Note : ***Used the Metric form of the equation from EPRI MRP 55-Rev. 1.***
The correction is applied in the determination of the crack extension to obtain the value in inch/hr.

Through Wall Axial Flaw

The first Input is to locate the Reference Line (eg. top of the Blind Zone). The throughwall flaw "Upper Tip" is located at the Reference Line.

Enter the elevation of the Reference Line (eg.Blind Zone) above the nozzle bottom in inches.

$BZ := 1.544$ Location of Blind Zone above nozzle bottom (inch)

The Second Input is the Upper Limit for the evaluation, which is the bottom of the fillet weld leg. This is shown on the Excel spread sheet as weld bottom. Enter this dimension (measured from nozzle bottom) below.

$UL_{Strs.Dist} := 1.786$ Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

Input Data :-

$L := .794$	Initial Flaw Length TW axial
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\nu := 0.307$	Poissons ratio @ 600 F
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

$$C_0 := e^{\left[\frac{-Q_g}{1.103 \cdot 10^{-3}} \cdot \left(\frac{1}{T+459.67} - \frac{1}{T_{ref}+459.67}\right)\right]} \cdot \alpha_{0c}$$

$$Tim_{opr} := Years \cdot 365 \cdot 24$$

$$R_o := \frac{od}{2} \qquad R_i := \frac{id}{2} \qquad t := R_o - R_i \qquad R_m := R_i + \frac{t}{2} \qquad CF_{inhr} := 1.417 \cdot 10^5$$

$$C_{blk} := \frac{Tim_{opr}}{I_{lim}} \qquad Prnt_{blk} := \left|\frac{I_{lim}}{50}\right| \qquad l := \frac{L}{2}$$

Stress Distribution in the tube. The outside surface is the reference surface for all analysis in accordance with the reference.

Stress Input Data

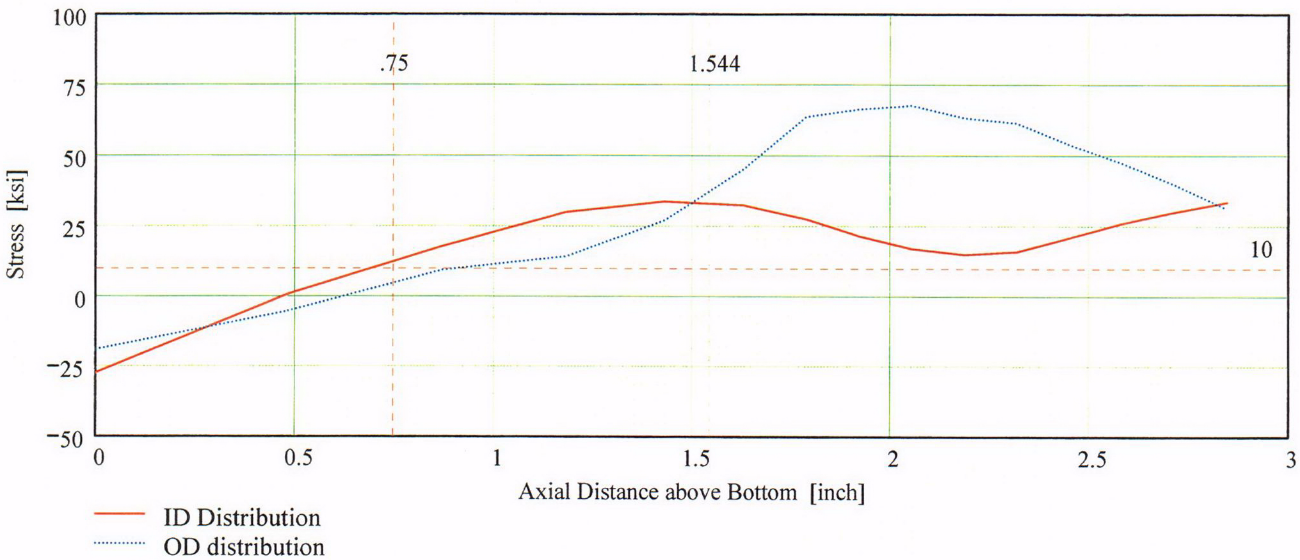
Import the Required data from applicable Excel spread Sheet. The column designations are as follows:
Cloumn "0" = Axial distance from Minimum to Maximum recorded on the data sheet (inches)
Column "1" = ID Stress data at each Elevation (ksi)
Column "5" = OD Stress data at each Elevation (ksi)

$Data_{All}$:=

	0	1	2	3	4	5
0	0	-27.4	-24.36	-22.21	-20.41	-18.98
1	0.48	0.63	-1.49	-3.6	-4.44	-5.27
2	0.87	17.66	16.42	14.61	12.41	9.38
3	1.18	29.8	26.05	22.72	18.95	14.2
4	1.43	33.62	27.79	24.8	24.32	26.99
5	1.63	32.36	28.47	27.59	34.28	45.1
6	1.79	27.39	28.92	31.39	43.88	63.72
7	1.92	21.5	25.56	33.55	48.09	66.36
8	2.05	16.94	23.79	34.06	49.47	67.67
9	2.18	14.83	22.26	34.78	49.05	63.38

DATA FROM EXCEL SPREAD SHEET

$AllAxl := Data_{All}^{\langle 0 \rangle}$ $AllID := Data_{All}^{\langle 1 \rangle}$ $AllOD := Data_{All}^{\langle 5 \rangle}$



Observing the stress distribution select the region in the table above labeled $Data_{All}$ that represents the region of interest. This needs to be done especially for distributions that have a large compressive stress at the nozzle bottom and high tensile stresses at the J-weld location. Copy the selection in the above table , click on the "Data" statement below and delete it from the edit menu. Type "Data and the Mathcad "equal" sign (Shift-Colon) then insert the same to the right of the Mathcad Equals sign below (paste symbol).

Data :=

0	−27.404	−24.356	−22.209	−20.407	−18.978
0.483	0.633	−1.486	−3.599	−4.44	−5.268
0.87	17.665	16.422	14.61	12.415	9.376
1.18	29.798	26.049	22.723	18.95	14.201
1.428	33.623	27.792	24.8	24.321	26.989
1.627	32.364	28.469	27.591	34.284	45.104
1.786	27.394	28.918	31.388	43.882	63.718

DATA SELECTED FOR ANALYSIS

$Axl := Data^{\langle 0 \rangle}$ $ID := Data^{\langle 1 \rangle}$ $OD := Data^{\langle 5 \rangle}$ ← only ID & OD Data used.

$R_{ID} := regress(Axl, ID, 3)$ $R_{OD} := regress(Axl, OD, 3)$

$FL_{Cntr} := BZ - 1$ Flaw Center above Nozzle Bottom

$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - BZ}{20}$$

No User Input required beyond this Point

Calculation to develop Stress Profiles for Analysis

Hoop Stress Profile in the axial direction of the tube for ID and OD locations

$N := 20$ Number of locations for stress profiles

$Loc_0 := FL_{Cntr} - L$

$i := 1..N + 3$

$$Incr_i := \begin{cases} 1 & \text{if } i < 4 \\ Inc_{Strs.avg} & \text{otherwise} \end{cases}$$

$Loc_i := Loc_{i-1} + Incr_i$

$SID_i := R_{ID_3} + R_{ID_4} \cdot Loc_i + R_{ID_5} \cdot (Loc_i)^2 + R_{ID_6} \cdot (Loc_i)^3$

$SOD_i := R_{OD_3} + R_{OD_4} \cdot Loc_i + R_{OD_5} \cdot (Loc_i)^2 + R_{OD_6} \cdot (Loc_i)^3$

Development of Elevation-Averaged stresses at 20 elevations along the tube for use in Fracture Mechanics Model

$j := 1..N$

$$S_{id_j} := \begin{cases} \dfrac{SID_j + SID_{j+1} + SID_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{id_{j-1}} \cdot (j+1) + SID_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{od_j} := \begin{cases} \dfrac{SOD_j + SOD_{j+1} + SOD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{od_{j-1}} \cdot (j+1) + SOD_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$\sigma_{m_j} := \frac{S_{od_j} + S_{id_j}}{2} + P_{Int}$$

$$\sigma_{b_j} := \frac{S_{od_j} - S_{id_j}}{2}$$

Stress Distributions for use in Fracture Mechanics Analysis

	Membrane Stress σ_m	Bending Stress σ_b	OD Stress S_{od}	ID Stress S_{id}
0	0	0	0	0
1	23.795	-3.536	18.023	25.096
2	27.339	-1.932	23.172	27.036
3	29.561	-0.851	26.475	28.176
4	31.121	-0.028	28.858	28.914
5	32.304	0.649	30.719	29.42
6	33.253	1.238	32.256	29.779
7	34.044	1.771	33.58	30.039
8	34.727	2.266	34.757	30.226
9	35.33	2.735	35.83	30.361
10	35.875	3.186	36.826	30.453
11	36.374	3.626	37.766	30.513
12	36.839	4.058	38.662	30.546
13	37.276	4.485	39.526	30.555
14	37.69	4.91	40.365	30.545
15	38.086	5.333	41.185	30.518

$Prop_{Length} := UL_{Strs.Dist} - (FL_{Cntr} + l)$ $\qquad Prop_{Length} = 0.242$

Calculations : Recursive calculations to estimate flaw growth

Recursive loop for Entergy Model

$TWC_{pwscc} :=$

$i \leftarrow 0$

$l_0 \leftarrow l$

$NCB_0 \leftarrow C_{blk}$

while $i \le I_{lim}$

$\sigma_{m.appld} \leftarrow$
- σ_{m_1} if $l_i \le l_0$
- σ_{m_2} if $l_0 < l_i \le l_0 + Inc_{Strs.avg}$
- σ_{m_3} if $l_0 + Inc_{Strs.avg} < l_i \le l_0 + 2 \cdot Inc_{Strs.avg}$
- σ_{m_4} if $l_0 + 2 \cdot Inc_{Strs.avg} < l_i \le l_0 + 3 \cdot Inc_{Strs.avg}$
- σ_{m_5} if $l_0 + 3 \cdot Inc_{Strs.avg} < l_i \le l_0 + 4 \cdot Inc_{Strs.avg}$
- σ_{m_6} if $l_0 + 4 \cdot Inc_{Strs.avg} < l_i \le l_0 + 5 \cdot Inc_{Strs.avg}$
- σ_{m_7} if $l_0 + 5 \cdot Inc_{Strs.avg} < l_i \le l_0 + 6 \cdot Inc_{Strs.avg}$
- σ_{m_8} if $l_0 + 6 \cdot Inc_{Strs.avg} < l_i \le l_0 + 7 \cdot Inc_{Strs.avg}$
- σ_{m_9} if $l_0 + 7 \cdot Inc_{Strs.avg} < l_i \le l_0 + 8 \cdot Inc_{Strs.avg}$
- $\sigma_{m_{10}}$ if $l_0 + 8 \cdot Inc_{Strs.avg} < l_i \le l_0 + 9 \cdot Inc_{Strs.avg}$
- $\sigma_{m_{11}}$ if $l_0 + 9 \cdot Inc_{Strs.avg} < l_i \le l_0 + 10 \cdot Inc_{Strs.avg}$
- σ_{m} if $l_0 + 10 \cdot Inc_{Strs.avg} < l_i \le l_0 + 11 \cdot Inc_{Strs.avg}$

$\sigma_{m_{12}}$ if $l_0 + 10 \cdot Inc_{Strs.avg} < l_i \le l_0 + 11 \cdot Inc_{Strs.avg}$

$\sigma_{m_{13}}$ if $l_0 + 11 \cdot Inc_{Strs.avg} < l_i \le l_0 + 12 \cdot Inc_{Strs.avg}$

$\sigma_{m_{14}}$ if $l_0 + 12 \cdot Inc_{Strs.avg} < l_i \le l_0 + 13 \cdot Inc_{Strs.avg}$

$\sigma_{m_{15}}$ if $l_0 + 13 \cdot Inc_{Strs.avg} < l_i \le l_0 + 14 \cdot Inc_{Strs.avg}$

$\sigma_{m_{16}}$ if $l_0 + 14 \cdot Inc_{Strs.avg} < l_i \le l_0 + 15 \cdot Inc_{Strs.avg}$

$\sigma_{m_{17}}$ if $l_0 + 15 \cdot Inc_{Strs.avg} < l_i \le l_0 + 16 \cdot Inc_{Strs.avg}$

$\sigma_{m_{18}}$ if $l_0 + 16 \cdot Inc_{Strs.avg} < l_i \le l_0 + 17 \cdot Inc_{Strs.avg}$

$\sigma_{m_{19}}$ if $l_0 + 17 \cdot Inc_{Strs.avg} < l_i \le l_0 + 18 \cdot Inc_{Strs.avg}$

$\sigma_{m_{20}}$ otherwise

$\sigma_{b.appld} \leftarrow$

σ_{b_1} if $l_i \le l_0$

σ_{b_2} if $l_0 < l_i \le l_0 + Inc_{Strs.avg}$

σ_{b_3} if $l_0 + Inc_{Strs.avg} < l_i \le l_0 + 2 \cdot Inc_{Strs.avg}$

σ_{b_4} if $l_0 + 2 \cdot Inc_{Strs.avg} < l_i \le l_0 + 3 \cdot Inc_{Strs.avg}$

σ_{b_5} if $l_0 + 3 \cdot Inc_{Strs.avg} < l_i \le l_0 + 4 \cdot Inc_{Strs.avg}$

σ_{b_6} if $l_0 + 4 \cdot Inc_{Strs.avg} < l_i \le l_0 + 5 \cdot Inc_{Strs.avg}$

σ_{b_7} if $l_0 + 5 \cdot Inc_{Strs.avg} < l_i \le l_0 + 6 \cdot Inc_{Strs.avg}$

σ_{b_8} if $l_0 + 6 \cdot Inc_{Strs.avg} < l_i \le l_0 + 7 \cdot Inc_{Strs.avg}$

σ_{b_9} if $l_0 + 7 \cdot Inc_{Strs.avg} < l_i \le l_0 + 8 \cdot Inc_{Strs.avg}$

$\sigma_{b_{10}}$ if $l_0 + 8 \cdot Inc_{Strs.avg} < l_i \le l_0 + 9 \cdot Inc_{Strs.avg}$

$\sigma_{b_{11}}$ if $l_0 + 9 \cdot Inc_{Strs.avg} < l_i \le l_0 + 10 \cdot Inc_{Strs.avg}$

$\sigma_{b_{12}}$ if $l_0 + 10 \cdot Inc_{Strs.avg} < l_i \le l_0 + 11 \cdot Inc_{Strs.avg}$

$\sigma_{b_{13}}$ if $l_0 + 11 \cdot Inc_{Strs.avg} < l_i \le l_0 + 12 \cdot Inc_{Strs.avg}$

$\sigma_{b_{14}}$ if $l_0 + 12 \cdot Inc_{Strs.avg} < l_i \le l_0 + 13 \cdot Inc_{Strs.avg}$

$\sigma_{b_{15}}$ if $l_0 + 13 \cdot Inc_{Strs.avg} < l_i \le l_0 + 14 \cdot Inc_{Strs.avg}$

$\sigma_{b_{16}}$ if $l_0 + 14 \cdot Inc_{Strs.avg} < l_i \le l_0 + 15 \cdot Inc_{Strs.avg}$

$\sigma_{b_{17}}$ if $l_0 + 15 \cdot Inc_{Strs.avg} < l_i \le l_0 + 16 \cdot Inc_{Strs.avg}$

$\sigma_{b_{18}}$ if $l_0 + 16 \cdot Inc_{Strs.avg} < l_i \le l_0 + 17 \cdot Inc_{Strs.avg}$

$\sigma_{b_{19}}$ if $l_0 + 17 \cdot Inc_{Strs.avg} < l_i \le l_0 + 18 \cdot Inc_{Strs.avg}$

$\sigma_{b_{20}}$ otherwise

$\lambda_i \leftarrow \left[12\cdot\left(1-\nu^2\right)\right]^{0.25}\cdot\frac{l_i}{\left(R_m\cdot t\right)^{0.5}}$ Geometry Influence Coefficients

$A_{em_i} \leftarrow 1.0090 + 0.3621\cdot\lambda_i + 0.0565\cdot(\lambda_i)^2 - 0.0082\cdot(\lambda_i)^3 + 0.0004\cdot(\lambda_i)^4 - 8.326\cdot10^{-6}\cdot(\lambda_i)^5$

$A_{bm_i} \leftarrow -0.0063 + 0.0919\cdot\lambda_i - 0.0168\cdot(\lambda_i)^2 - 0.0052\cdot(\lambda_i)^3 + 0.0008\cdot(\lambda_i)^4 - 2.9701\cdot10^{-5}\cdot(\lambda_i)^5$

$A_{eb_i} \leftarrow 0.0029 + 0.0707\cdot\lambda_i - 0.0197\cdot(\lambda_i)^2 + 0.0034\cdot(\lambda_i)^3 - 0.0003\cdot(\lambda_i)^4 + 8.8052\cdot10^{-6}\cdot(\lambda_i)^5$

$A_{bb_i} \leftarrow 0.9961 - 0.3806\cdot\lambda_i + 0.1239\cdot(\lambda_i)^2 - 0.0211\cdot(\lambda_i)^3 + 0.0017\cdot(\lambda_i)^4 - 4.9939\cdot10^{-5}\cdot(\lambda_i)^5$

$K_{pm_i} \leftarrow \sigma_{m.appld}\cdot\left(\pi\cdot l_i\right)^{0.5}$

$K_{pb_i} \leftarrow \sigma_{b.appld}\cdot\left(\pi\cdot l_i\right)^{0.5}$ Equivalent Flat Plate Solutions

$K_{membrnOD_i} \leftarrow \left(A_{em_i} + A_{bm_i}\right)\cdot K_{pm_i}$

$K_{membrnID_i} \leftarrow \left(A_{em_i} - A_{bm_i}\right)\cdot K_{pm_i}$

$K_{bendOD_i} \leftarrow \left(A_{eb_i} + A_{bb_i}\right)\cdot K_{pb_i}$

$K_{bendID_i} \leftarrow \left(A_{eb_i} - A_{bb_i}\right)\cdot K_{pb_i}$

← Flat Plate Solutions Corrected for Thick wall Cylinder geometry

$K_{AppOD_i} \leftarrow K_{membrnOD_i} + K_{bendOD_i}$

$K_{AppID_i} \leftarrow K_{membrnID_i} + K_{bendID_i}$

$K_{App_i} \leftarrow \frac{K_{AppOD_i} + K_{AppID_i}}{2}$ SIF Used for Crack Growth

$K_{\alpha_i} \leftarrow K_{App_i}\cdot 1.099$

$K_{\alpha_i} \leftarrow \begin{cases} 9.0 & \text{if } K_{\alpha_i} \le 9.0 \\ K_{\alpha_i} & \text{otherwise} \end{cases}$

$D_{len_i} \leftarrow C_0\cdot\left(K_{\alpha_i} - 9.0\right)^{1.16}$

$D_{lengrth_i} \leftarrow \begin{cases} D_{len_i}\cdot CF_{inhr}\cdot C_{blk} & \text{if } K_{\alpha_i} \le 80.0 \\ 4\cdot10^{-10}\cdot CF_{inhr}\cdot C_{blk} & \text{otherwise} \end{cases}$

$output_{(i,0)} \leftarrow i$

$output_{(i,1)} \leftarrow \frac{NCB_i}{365\cdot 24}$

$output_{(i,2)} \leftarrow \lambda_i$

$output_{(i,2)} \leftarrow ...$

$output_{(i,3)} \leftarrow l_i - l_0$

$output_{(i,4)} \leftarrow l_i$

$output_{(i,5)} \leftarrow K_{App_i}$

$output_{(i,6)} \leftarrow K_{AppOD_i}$

$output_{(i,7)} \leftarrow K_{AppID_i}$

$output_{(i,8)} \leftarrow K_{membrnOD_i}$

$output_{(i,9)} \leftarrow K_{membrnID_i}$

$output_{(i,10)} \leftarrow K_{bendOD_i}$

$output_{(i,11)} \leftarrow K_{bendID_i}$

$i \leftarrow i + 1$

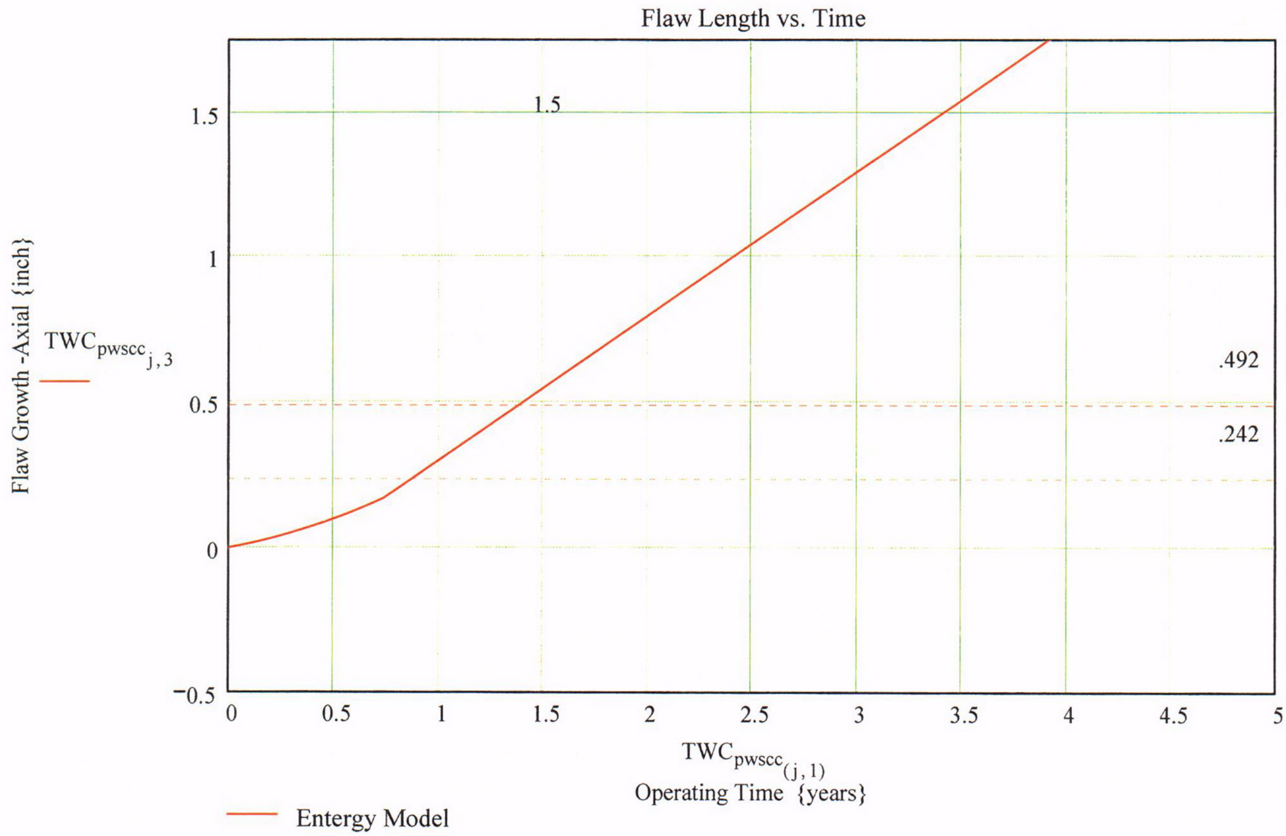
$l_i \leftarrow l_{i-1} + D_{lengrth_{i-1}}$

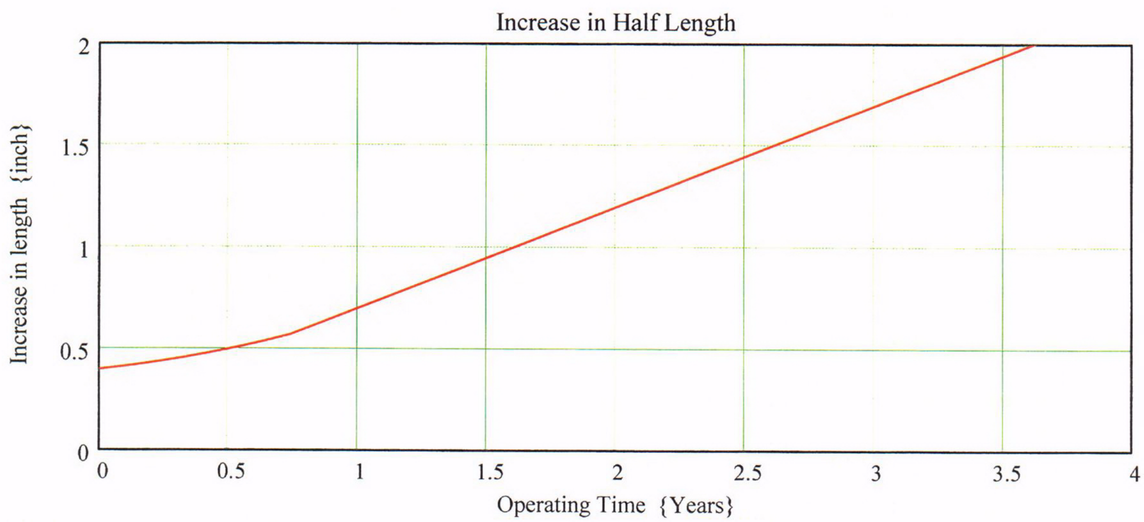
$NCB_i \leftarrow NCB_{i-1} + C_{blk}$

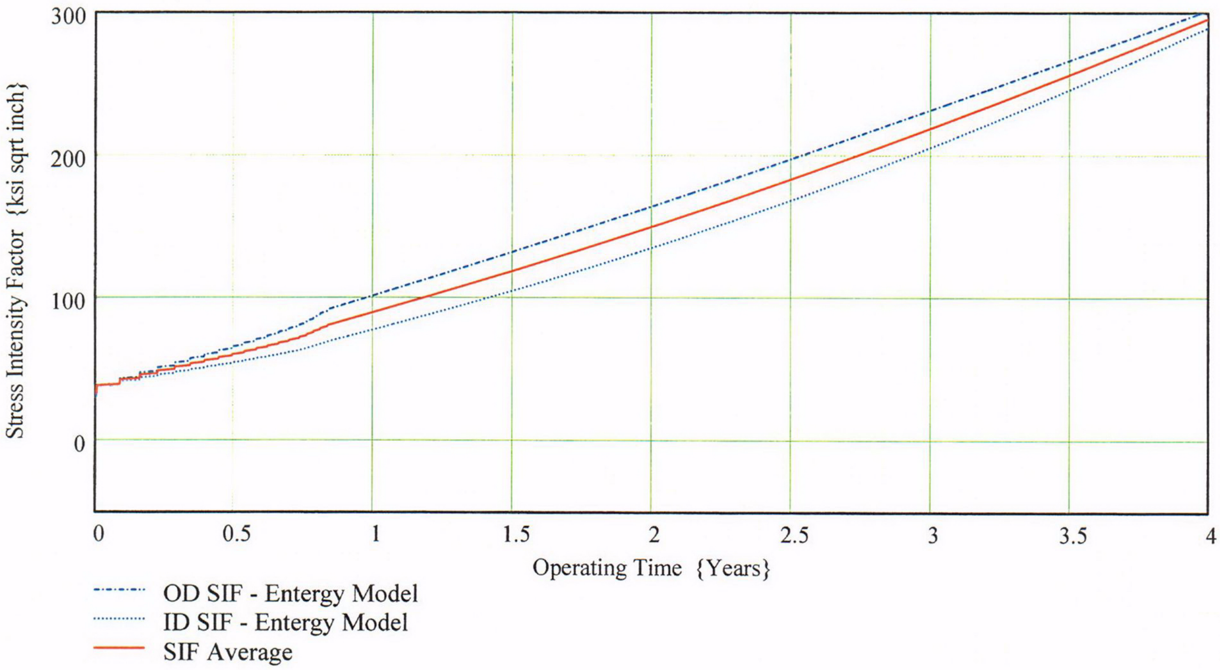
output

$j := 0 .. I_{lim}$

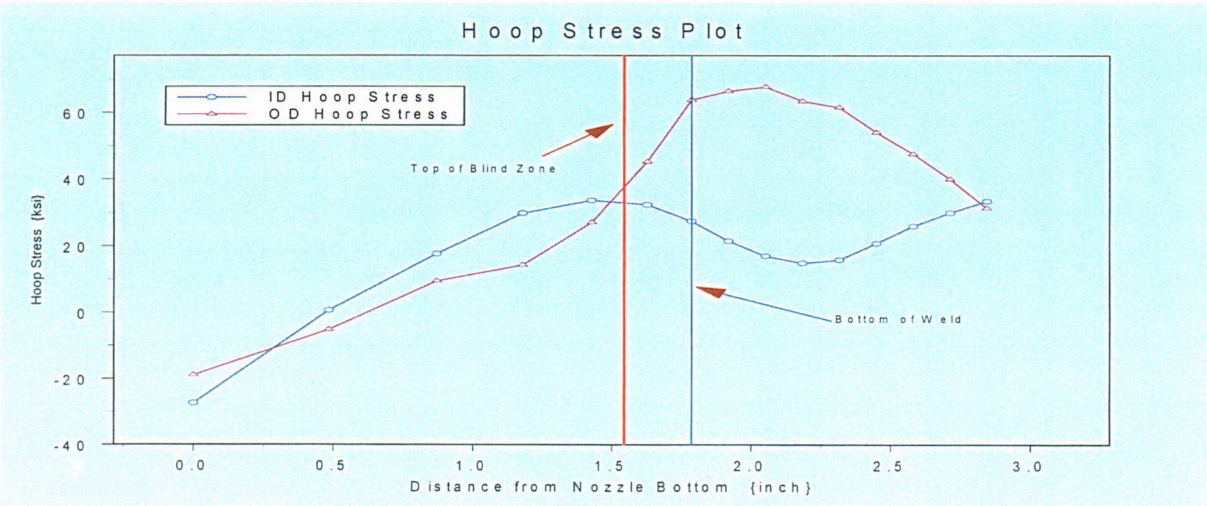
$Prop_{Length} = 0.242$

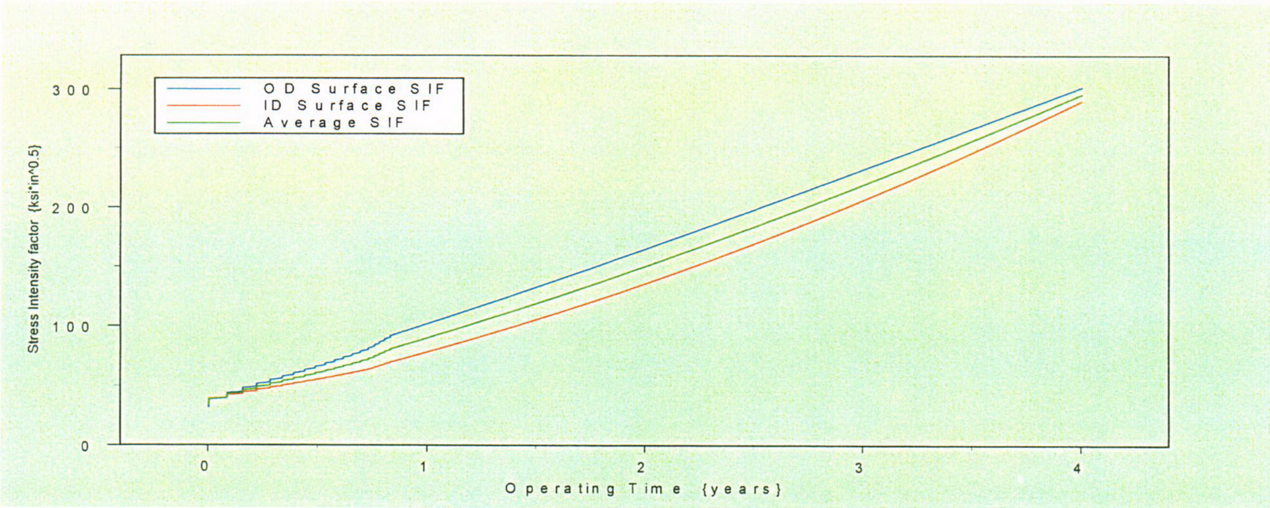


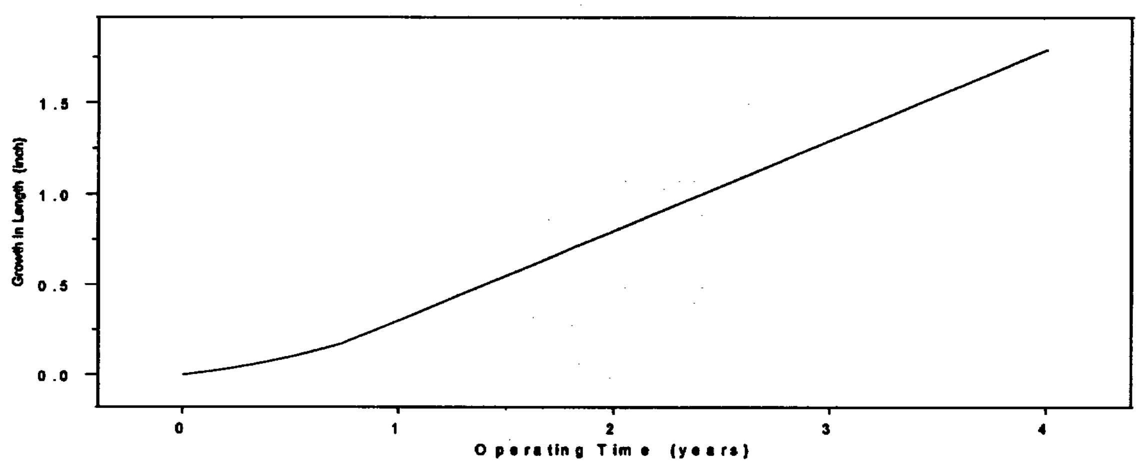



300
200
100
0
Stress Intensity Factor {ksi sqrt inch}
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {Years}
OD SIF - Entergy Model
ID SIF - Entergy Model
SIF Average

$TWC_{pwscc_{(j,6)}} =$	$TWC_{pwscc_{(j,7)}} =$	$TWC_{pwscc_{(j,8)}} =$
31.965	35.69	35.246
38.727	39.253	40.52
38.756	39.279	40.549
38.784	39.305	40.579
38.813	39.331	40.608
38.842	39.357	40.638
38.871	39.382	40.667
38.9	39.408	40.697
38.929	39.434	40.726
38.958	39.46	40.756
38.987	39.486	40.785
39.016	39.512	40.815
39.045	39.538	40.844
39.074	39.564	40.874
39.103	39.59	40.904
39.132	39.617	40.933


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Bottom of Weld
Hoop Stress (ksi)
60
40
20
0
-20
-40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Distance from Nozzle Bottom (inch)


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor (ksi*in^0.5)
300
200
100
0
0
1
2
3
4
Operating Time (years)


1.5
1.0
0.5
0.0
Growth in Length (inch)
0
1
2
3
4
Operating Time (years)

Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc
Developedby: J. S. Brihmadesam Verified by: B. C. Gray

Note : Only for use when $R_{outside}/t$ is between 2.0 and 5.0 (Thickwall Cylinder)

Refrences :

1) ASME PVP paper PVP-350, Page 143; 1997 {Fracture Mechanics Model}
2) Crack Growth of Alloy 600 Base Metal in PWR Environments; EPRI MRP Report MRP 55 Rev. 1, 2002

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8.8"degree Nozzle, "0" Degree Azimuth 1.3 inch above Nozzle Bottom

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

Note : ***Used the Metric form of the equation from EPRI MRP 55-Rev. 1.***
The correction is applied in the determination of the crack extension to obtain the value in inch/hr.

Through Wall Axial Flaw

The first Input is to locate the Reference Line (eg. top of the Blind Zone). The throughwall flaw "Upper Tip" is located at the Reference Line.

Enter the elevation of the Reference Line (eg.Blind Zone) above the nozzle bottom in inches.

$BZ := 1.3$ Location of Blind Zone above nozzle bottom (inch)

The Second Input is the Upper Limit for the evaluation, which is the bottom of the fillet weld leg. This is shown on the Excel spread sheet as weld bottom. Enter this dimension (measured from nozzle bottom) below.

$UL_{Strs.Dist} := 1.786$ Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

Input Data :-

$L := .794$	Initial Flaw Length TW axial
$OD := 4.05$	Tube OD
$ID := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$v := 0.307$	Poissons ratio @ 600 F
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

$$C_0 := e^{\left[\frac{-Q_g}{1.103 \cdot 10^{-3}} \cdot \left(\frac{1}{T+459.67} - \frac{1}{T_{ref}+459.67}\right)\right]} \cdot \alpha_{0c} \qquad Tim_{opr} := Years \cdot 365 \cdot 24$$

$$R_o := \frac{OD}{2}$$

$$R_i := \frac{ID}{2} \qquad t := R_o - R_i \qquad R_m := R_i + \frac{t}{2} \qquad CF_{inhr} := 1.417 \cdot 10^5$$

$$C_{blk} := \frac{Tim_{opr}}{I_{lim}} \qquad Prnt_{blk} := \left|\frac{I_{lim}}{50}\right| \qquad l := \frac{L}{2} \qquad L_1 := BZ$$

Stress Distribution in the tube. The outside surface is the reference surface for all analysis in accordance with the reference.

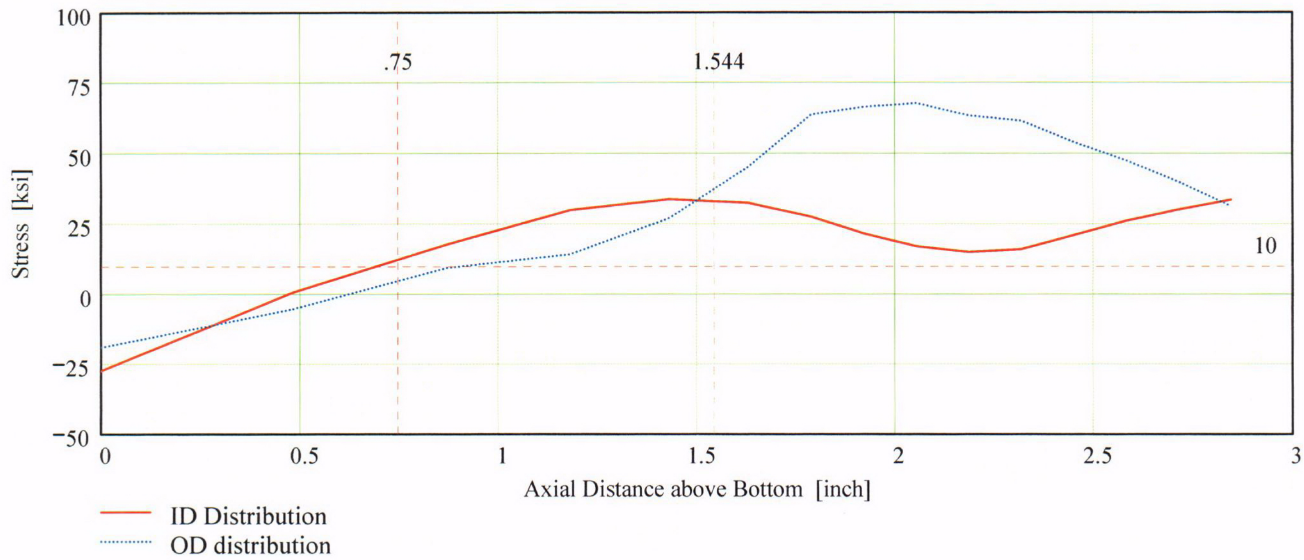
Stress Input Data

Import the Required data from applicable Excel spread Sheet. The column designations are as follows:
Cloumn "0" = Axial distance from Minimum to Maximum recorded on the data sheet (inches)
Column "1" = ID Stress data at each Elevation (ksi)
Column "5" = OD Stress data at each Elevation (ksi)

$Data_{All} :=$

	0	1	2	3	4	5
0	0	-27.4	-24.36	-22.21	-20.41	-18.98
1	0.48	0.63	-1.49	-3.6	-4.44	-5.27
2	0.87	17.66	16.42	14.61	12.41	9.38
3	1.18	29.8	26.05	22.72	18.95	14.2
4	1.43	33.62	27.79	24.8	24.32	26.99
5	1.63	32.36	28.47	27.59	34.28	45.1
6	1.79	27.39	28.92	31.39	43.88	63.72
7	1.92	21.5	25.56	33.55	48.09	66.36
8	2.05	16.94	23.79	34.06	49.47	67.67
9	2.18	14.83	22.26	34.78	49.05	63.38

$AllAxl := Data_{All}^{\langle 0 \rangle}$ $AllID := Data_{All}^{\langle 1 \rangle}$ $AllOD := Data_{All}^{\langle 5 \rangle}$



Observing the stress distribution select the region in the table above labeled $Data_{All}$ that represents the region of interest. This needs to be done especially for distributions that have a large compressive stress at the nozzle bottom and high tensile stresses at the J-weld location. Copy the selection in the above table , click on the "Data" statement below and delete it from the edit menu. Type "Data and the Mathcad "equal" sign (Shift-Colon) then insert the same to the right of the Mathcad Equals sign below (paste symbol).

$$Data := \begin{pmatrix} 0 & -27.404 & -24.356 & -22.209 & -20.407 & -18.978 \\ 0.483 & 0.633 & -1.486 & -3.599 & -4.44 & -5.268 \\ 0.87 & 17.665 & 16.422 & 14.61 & 12.415 & 9.376 \\ 1.18 & 29.798 & 26.049 & 22.723 & 18.95 & 14.201 \\ 1.428 & 33.623 & 27.792 & 24.8 & 24.321 & 26.989 \\ 1.627 & 32.364 & 28.469 & 27.591 & 34.284 & 45.104 \\ 1.786 & 27.394 & 28.918 & 31.388 & 43.882 & 63.718 \end{pmatrix}$$

$Axl := Data^{\langle 0 \rangle}$ $ID := Data^{\langle 1 \rangle}$ $OD := Data^{\langle 5 \rangle}$

$R_{ID} := regress(Axl, ID, 3)$ $R_{OD} := regress(Axl, OD, 3)$

C21

$FL_{Cntr} := BZ - 1$ Flaw Center above Nozzle Bottom

$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - BZ}{20}$$

$$Incr_{Edg} := \frac{UL_{Strs.Dist} - BZ}{20}$$

$RID_{All} := regress(AllAxl, AllID, 3)$

$ROD_{All} := regress(AllAxl, AllOD, 3)$

No User Input required beyond this Point

Calculation to develop Stress Profiles for Analysis

Hoop Stress Profile in the axial direction of the tube for ID and OD locations

$N := 20$ Number of locations for stress profiles

$Loc_0 := FL_{Cntr} - L$

$i := 1 .. N + 3$

$$Incr_i := \begin{cases} 1 & \text{if } i < 4 \\ Inc_{Strs.avg} & \text{otherwise} \end{cases}$$

$$Incr_{edg_i} := \begin{cases} \frac{L_1}{2} & \text{if } i < 4 \\ Incr_{Edg} & \text{otherwise} \end{cases}$$

$$Loc_i := Loc_{i-1} + Incr_i$$

$$Loc1_i := \begin{cases} 0 & \text{if } i = 1 \\ Loc1_{i-1} + Incr_{edg_i} & \text{otherwise} \end{cases}$$

$$SID_i := R_{ID_3} + R_{ID_4} \cdot Loc_i + R_{ID_5} \cdot (Loc_i)^2 + R_{ID_6} \cdot (Loc_i)^3$$

$$SOD_i := R_{OD_3} + R_{OD_4} \cdot Loc_i + R_{OD_5} \cdot (Loc_i)^2 + R_{OD_6} \cdot (Loc_i)^3$$

$$SID_{All_i} := RID_{All_3} + RID_{All_4} \cdot Loc1_i + RID_{All_5} \cdot (Loc1_i)^2 + RID_{All_6} \cdot (Loc1_i)^3$$

$$SOD_{All_i} := ROD_{All_3} + ROD_{All_4} \cdot Loc1_i + ROD_{All_5} \cdot (Loc1_i)^2 + ROD_{All_6} \cdot (Loc1_i)^3$$

Development of Elevation-Averaged stresses at 20 elevations along the tube for use in Fracture Mechanics Model

$$j := 1..N$$

$$S_{id_j} := \begin{cases} \dfrac{SID_j + SID_{j+1} + SID_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{id_{j-1}} \cdot (j+1) + SID_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{od_j} := \begin{cases} \dfrac{SOD_j + SOD_{j+1} + SOD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{od_{j-1}} \cdot (j+1) + SOD_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{id.all_j} := \begin{cases} \dfrac{SID_{All_j} + SID_{All_{j+1}} + SID_{All_{j+2}}}{3} & \text{if } j = 1 \\ \dfrac{S_{id.all_{j-1}} \cdot (j+1) + SID_{All_{j+2}}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{od.all_j} := \begin{cases} \dfrac{SOD_{All_j} + SOD_{All_{j+1}} + SOD_{All_{j+2}}}{3} & \text{if } j = 1 \\ \dfrac{S_{od.all_{j-1}} \cdot (j+1) + SOD_{All_{j+2}}}{j+2} & \text{otherwise} \end{cases}$$

$$\sigma_{m_j} := \frac{S_{od_j} + S_{id_j}}{2} + P_{Int} \qquad \sigma_{b_j} := \frac{S_{od_j} - S_{id_j}}{2} \qquad \sigma_{m.all_j} := \frac{S_{od.all_j} + S_{id.all_j}}{2} + P_{Int}$$

Stress Distributions for use in Fracture Mechanics Analysis

Membrane Stress: $\sigma_m =$

	0
0	0
1	15.27
2	18.819
3	21.119
4	22.794
5	24.115
6	25.215
7	26.169
8	27.022
9	27.802
10	28.53
11	29.217
12	29.874
13	30.507
14	31.122
15	31.723

Bending Stress: $\sigma_b =$

	0
0	0
1	-4.731
2	-4.823
3	-4.766
4	-4.625
5	-4.426
6	-4.184
7	-3.905
8	-3.594
9	-3.254
10	-2.885
11	-2.489
12	-2.066
13	-1.617
14	-1.142
15	-0.64

OD Stress: $S_{od} =$

	0
0	0
1	8.303
2	11.761
3	14.117
4	15.934
5	17.454
6	18.796
7	20.029
8	21.193
9	22.314
10	23.41
11	24.493
12	25.572
13	26.655
14	27.745
15	28.848

ID Stress: $S_{id} =$

	0
0	0
1	17.766
2	21.408
3	23.65
4	25.184
5	26.306
6	27.164
7	27.839
8	28.381
9	28.821
10	29.18
11	29.471
12	29.705
13	29.889
14	30.029
15	30.128

Membrane stress (Edge Crack): $\sigma_{m.all} =$

	0
0	0
1	5.53
2	12.037
3	16.08
4	18.889
5	20.99
6	22.646
7	24.005
8	25.153
9	26.146
10	27.022
11	27.807
12	28.518
13	29.169
14	29.77
15	30.329

$Prop_{Length} := UL_{Strs.Dist} - (FL_{Cntr} + 1)$ $\qquad$ $Prop_{Length} = 0.486$

Calculations : Recursive calculations to estimate flaw growth

Recursive loop for Entergy Model and Industry Model

$TWC_{pwscc} :=$

$i \leftarrow 0$

$l_0 \leftarrow 1$

$NCB_0 \leftarrow C_{blk}$

while $i \le I_{lim}$

$\sigma_{m.appld} \leftarrow$

σ_{m_1} if $l_i \le l_0$

σ_{m_2} if $l_0 < l_i \le l_0 + Inc_{Strs.avg}$

σ_{m_3} if $l_0 + Inc_{Strs.avg} < l_i \le l_0 + 2 \cdot Inc_{Strs.avg}$

σ_{m_4} if $l_0 + 2 \cdot Inc_{Strs.avg} < l_i \le l_0 + 3 \cdot Inc_{Strs.avg}$

σ_{m_5} if $l_0 + 3 \cdot Inc_{Strs.avg} < l_i \le l_0 + 4 \cdot Inc_{Strs.avg}$

σ_{m_6} if $l_0 + 4 \cdot Inc_{Strs.avg} < l_i \le l_0 + 5 \cdot Inc_{Strs.avg}$

σ_{m_7} if $l_0 + 5 \cdot Inc_{Strs.avg} < l_i \le l_0 + 6 \cdot Inc_{Strs.avg}$

σ_{m_8} if $l_0 + 6 \cdot Inc_{Strs.avg} < l_i \le l_0 + 7 \cdot Inc_{Strs.avg}$

σ_{m_9} if $l_0 + 7 \cdot Inc_{Strs.avg} < l_i \le l_0 + 8 \cdot Inc_{Strs.avg}$

$\sigma_{m_{10}}$ if $l_0 + 8 \cdot Inc_{Strs.avg} < l_i \le l_0 + 9 \cdot Inc_{Strs.avg}$

$\sigma_{m_{11}}$ if $l_0 + 9 \cdot Inc_{Strs.avg} < l_i \le l_0 + 10 \cdot Inc_{Strs.avg}$

$\sigma_{m_{12}}$ if $l_0 + 10 \cdot Inc_{Strs.avg} < l_i \le l_0 + 11 \cdot Inc_{Strs.avg}$

$\sigma_{m_{13}}$ if $l_0 + 11 \cdot Inc_{Strs.avg} < l_i \le l_0 + 12 \cdot Inc_{Strs.avg}$

$\sigma_{m_{14}}$ if $l_0 + 12 \cdot Inc_{Strs.avg} < l_i \le l_0 + 13 \cdot Inc_{Strs.avg}$

$\sigma_{m_{15}}$ if $l_0 + 13 \cdot Inc_{Strs.avg} < l_i \le l_0 + 14 \cdot Inc_{Strs.avg}$

$\sigma_{m_{16}}$ if $l_0 + 14 \cdot Inc_{Strs.avg} < l_i \le l_0 + 15 \cdot Inc_{Strs.avg}$

$\sigma_{m_{17}}$ if $l_0 + 15 \cdot Inc_{Strs.avg} < l_i \le l_0 + 16 \cdot Inc_{Strs.avg}$

$\sigma_{m_{18}}$ if $l_0 + 16 \cdot Inc_{Strs.avg} < l_i \le l_0 + 17 \cdot Inc_{Strs.avg}$

$\sigma_{m_{19}}$ if $l_0 + 17 \cdot Inc_{Strs.avg} < l_i \le l_0 + 18 \cdot Inc_{Strs.avg}$

$\sigma_{m_{20}}$ otherwise

$$\sigma_{b.appld} \leftarrow \begin{cases} \sigma_{b_1} & \text{if } l_i \le l_0 \\ \sigma_{b_2} & \text{if } l_0 < l_i \le l_0 + Inc_{Strs.avg} \\ \sigma_{b_3} & \text{if } l_0 + Inc_{Strs.avg} < l_i \le l_0 + 2\cdot Inc_{Strs.avg} \\ \sigma_{b_4} & \text{if } l_0 + 2\cdot Inc_{Strs.avg} < l_i \le l_0 + 3\cdot Inc_{Strs.avg} \\ \sigma_{b_5} & \text{if } l_0 + 3\cdot Inc_{Strs.avg} < l_i \le l_0 + 4\cdot Inc_{Strs.avg} \\ \sigma_{b_6} & \text{if } l_0 + 4\cdot Inc_{Strs.avg} < l_i \le l_0 + 5\cdot Inc_{Strs.avg} \\ \sigma_{b_7} & \text{if } l_0 + 5\cdot Inc_{Strs.avg} < l_i \le l_0 + 6\cdot Inc_{Strs.avg} \\ \sigma_{b_8} & \text{if } l_0 + 6\cdot Inc_{Strs.avg} < l_i \le l_0 + 7\cdot Inc_{Strs.avg} \\ \sigma_{b_9} & \text{if } l_0 + 7\cdot Inc_{Strs.avg} < l_i \le l_0 + 8\cdot Inc_{Strs.avg} \\ \sigma_{b_{10}} & \text{if } l_0 + 8\cdot Inc_{Strs.avg} < l_i \le l_0 + 9\cdot Inc_{Strs.avg} \\ \sigma_{b_{11}} & \text{if } l_0 + 9\cdot Inc_{Strs.avg} < l_i \le l_0 + 10\cdot Inc_{Strs.avg} \\ \sigma_{b_{12}} & \text{if } l_0 + 10\cdot Inc_{Strs.avg} < l_i \le l_0 + 11\cdot Inc_{Strs.avg} \\ \sigma_{b_{13}} & \text{if } l_0 + 11\cdot Inc_{Strs.avg} < l_i \le l_0 + 12\cdot Inc_{Strs.avg} \\ \sigma_{b_{14}} & \text{if } l_0 + 12\cdot Inc_{Strs.avg} < l_i \le l_0 + 13\cdot Inc_{Strs.avg} \\ \sigma_{b_{15}} & \text{if } l_0 + 13\cdot Inc_{Strs.avg} < l_i \le l_0 + 14\cdot Inc_{Strs.avg} \\ \sigma_{b_{16}} & \text{if } l_0 + 14\cdot Inc_{Strs.avg} < l_i \le l_0 + 15\cdot Inc_{Strs.avg} \\ \sigma_{b_{17}} & \text{if } l_0 + 15\cdot Inc_{Strs.avg} < l_i \le l_0 + 16\cdot Inc_{Strs.avg} \\ \sigma_{b_{18}} & \text{if } l_0 + 16\cdot Inc_{Strs.avg} < l_i \le l_0 + 17\cdot Inc_{Strs.avg} \\ \sigma_{b_{19}} & \text{if } l_0 + 17\cdot Inc_{Strs.avg} < l_i \le l_0 + 18\cdot Inc_{Strs.avg} \\ \sigma_{b_{20}} & \text{otherwise} \end{cases}$$

$$\lambda_i \leftarrow \left[12\cdot\left(1 - v^2\right)\right]^{0.25} \cdot \frac{l_i}{(R_m \cdot t)^{0.5}}$$

$$A_{em_i} \leftarrow 1.0090 + 0.3621\cdot\lambda_i + 0.0565\cdot(\lambda_i)^2 - 0.0082\cdot(\lambda_i)^3 + 0.0004\cdot(\lambda_i)^4 - 8.326\cdot 10^{-6}\cdot(\lambda_i)^5$$

$$A_{bm_i} \leftarrow -0.0063 + 0.0919\cdot\lambda_i - 0.0168\cdot(\lambda_i)^2 - 0.0052\cdot(\lambda_i)^3 + 0.0008\cdot(\lambda_i)^4 - 2.9701\cdot 10^{-5}\cdot(\lambda_i)^5$$

$$A_{eb_i} \leftarrow 0.0029 + 0.0707\cdot\lambda_i - 0.0197\cdot(\lambda_i)^2 + 0.0034\cdot(\lambda_i)^3 - 0.0003\cdot(\lambda_i)^4 + 8.8052\cdot 10^{-6}\cdot(\lambda_i)^5$$

$$A_{bb_i} \leftarrow 0.9961 - 0.3806\cdot\lambda_i + 0.1239\cdot(\lambda_i)^2 - 0.0211\cdot(\lambda_i)^3 + 0.0017\cdot(\lambda_i)^4 - 4.9939\cdot 10^{-5}\cdot(\lambda_i)^5$$

$$K_{pm_i} \leftarrow \sigma_{m.appld} \cdot \left(\pi \cdot l_i\right)^{0.5}$$

$$K_{pb_i} \leftarrow \sigma_{b.appld} \cdot \left(\pi \cdot l_i\right)^{0.5}$$

$$K_{membrnOD_i} \leftarrow \left(A_{em_i} + A_{bm_i}\right) \cdot K_{pm_i}$$

$$K_{membrnID_i} \leftarrow \left(A_{em_i} - A_{bm_i}\right) \cdot K_{pm_i}$$

$$K_{bendOD_i} \leftarrow \left(A_{eb_i} + A_{bb_i}\right) \cdot K_{pb_i}$$

$$K_{bendID_i} \leftarrow \left(A_{eb_i} - A_{bb_i}\right) \cdot K_{pb_i}$$

$$K_{AppOD_i} \leftarrow K_{membrnOD_i} + K_{bendOD_i}$$

$$K_{AppID_i} \leftarrow K_{membrnID_i} + K_{bendID_i}$$

$$K_{WH_i} \leftarrow \sigma_{m_i} \cdot \left(\pi \cdot l_i\right)^{0.5}$$

$$K_{App_i} \leftarrow \frac{K_{AppOD_i} + K_{AppID_i}}{2}$$

$$K_{WH.Icnr.Strs_i} \leftarrow \sigma_{m.appld} \cdot \left(\pi \cdot l_i\right)^{0.5}$$

$$K_{\alpha_i} \leftarrow K_{App_i} \cdot 1.099$$

$$K_{\alpha_i} \leftarrow \begin{cases} 9.0 & \text{if } K_{\alpha_i} \le 9.0 \\ K_{\alpha_i} & \text{otherwise} \end{cases}$$

$$D_{len_i} \leftarrow C_0 \cdot \left(K_{\alpha_i} - 9.0\right)^{1.16}$$

$$D_{lengrth_i} \leftarrow \begin{cases} D_{len_i} \cdot CF_{inhr} \cdot C_{blk} & \text{if } K_{\alpha_i} \le 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} & \text{otherwise} \end{cases}$$

$$output_{(i,0)} \leftarrow i$$

$$output_{(i,1)} \leftarrow \frac{NCB_i}{365 \cdot 24}$$

$$output_{(i,2)} \leftarrow \lambda_i$$

$$output_{(i,3)} \leftarrow l_i - l_0$$

$$output_{(i,4)} \leftarrow l_i$$

$$output_{(i,5)} \leftarrow K_{App_i}$$

$$output_{(i,6)} \leftarrow K_{AppOD_i}$$

$$output_{(i,7)} \leftarrow K_{AppID_i}$$

$output_{(i,8)} \leftarrow K_{membrnOD_i}$

$output_{(i,9)} \leftarrow K_{membrnID_i}$

$output_{(i,10)} \leftarrow K_{bendOD_i}$

$output_{(i,11)} \leftarrow K_{bendID_i}$

$output_{(i,12)} \leftarrow K_{WH_i}$

$output_{(i,13)} \leftarrow K_{WH.Icnr.Strs_i}$

$i \leftarrow i + 1$

$l_i \leftarrow l_{i-1} + D_{lengrth_{i-1}}$

$NCB_i \leftarrow NCB_{i-1} + C_{blk}$

output

Recursive Loop For Edge Crack Model

$TWCEDG_{pwscc} :=$

$i \leftarrow 0$

$L1_0 \leftarrow |L1|$

$NCB_0 \leftarrow C_{blk}$

while $i \le I_{lim}$

$$\sigma_{m.appld} \leftarrow \begin{array}{ll}
\sigma_{m.all_1} & \text{if } L1_i \le L1_0 \\
\sigma_{m.all_2} & \text{if } L1_0 < L1_i \le L1_0 + Incr_{Edg} \\
\sigma_{m.all_3} & \text{if } L1_0 + Incr_{Edg} < L1_i \le L1_i + 2 \cdot Incr_{Edg} \\
\sigma_{m.all_4} & \text{if } L1_0 + 2 \cdot Incr_{Edg} < L1_i \le L1_0 + 3 \cdot Incr_{Edg} \\
\sigma_{m.all_5} & \text{if } L1_0 + 3 \cdot Incr_{Edg} < L1_i \le L1_0 + 4 \cdot Incr_{Edg} \\
\sigma_{m.all_6} & \text{if } L1_0 + 4 \cdot Incr_{Edg} < L1_i \le L1_0 + 5 \cdot Incr_{Edg} \\
\sigma_{m.all_7} & \text{if } L1_0 + 5 \cdot Incr_{Edg} < L1_i \le L1_0 + 6 \cdot Incr_{Edg} \\
\sigma_{m.all_8} & \text{if } L1_0 + 6 \cdot Incr_{Edg} < L1_i \le L1_0 + 7 \cdot Incr_{Edg} \\
\sigma_{m.all_9} & \text{if } L1_0 + 7 \cdot Incr_{Edg} < L1_i \le L1_0 + 8 \cdot Incr_{Edg} \\
\sigma_{m.all_{10}} & \text{if } L1_0 + 8 \cdot Incr_{Edg} < L1_i \le L1_0 + 9 \cdot Incr_{Edg} \\
\sigma_{m.all_{11}} & \text{if } L1_0 + 9 \cdot Incr_{Edg} < L1_i \le L1_0 + 10 \cdot Incr_{Edg} \\
\sigma_{m.all_{12}} & \text{if } L1_0 + 10 \cdot Incr_{Edg} < L1_i \le L1_0 + 11 \cdot Incr_{Edg} \\
\sigma_{m.all_{13}} & \text{if } L1_0 + 11 \cdot Incr_{Edg} < L1_i \le L1_0 + 12 \cdot Incr_{Edg} \\
\sigma_{m.all_{14}} & \text{if } L1_0 + 12 \cdot Incr_{Edg} < L1_i \le L1_0 + 13 \cdot Incr_{Edg} \\
\sigma_{m.all_{15}} & \text{if } L1_0 + 13 \cdot Incr_{Edg} < L1_i \le L1_0 + 14 \cdot Incr_{Edg} \\
\sigma_{m.all_{16}} & \text{if } L1_0 + 14 \cdot Incr_{Edg} < L1_i \le L1_0 + 15 \cdot Incr_{Edg} \\
\sigma_{m.all_{17}} & \text{if } L1_0 + 15 \cdot Incr_{Edg} < L1_i \le L1_0 + 16 \cdot Incr_{Edg} \\
\sigma_{m.all_{18}} & \text{if } L1_0 + 16 \cdot Incr_{Edg} < L1_i \le L1_0 + 17 \cdot Incr_{Edg} \\
\sigma_{m.all_{19}} & \text{if } L1_0 + 17 \cdot Incr_{Edg} < L1_i \le L1_0 + 18 \cdot Incr_{Edg} \\
\sigma_{m.all_{20}} & \text{otherwise}
\end{array}$$

$b \leftarrow UL_{Strs.Dist}$

$$Z_i \leftarrow \begin{cases} 0.99 & \text{if } \frac{L1_i}{b} \geq 1.0 \\ \frac{L1_i}{b} & \text{otherwise} \end{cases}$$

$$F_{a.b_i} \leftarrow 1.12 - 0.231\cdot(Z_i) + 10.55\cdot(Z_i)^2 - 21.72\cdot(Z_i)^3 + 30.39\cdot(Z_i)^4$$

$$K_{edg.Crk_i} \leftarrow \begin{cases} \sigma_{m.appld}\cdot\sqrt{\pi\cdot L1_i} & \text{if } \left(\sigma_{m.appld}\cdot\sqrt{\pi\cdot L1_i}\right) \leq 0 \\ \sigma_{m.appld}\cdot(\pi\cdot L1_i)^{0.5}\cdot F_{a.b_i} & \text{otherwise} \end{cases}$$

$$K_{A_i} \leftarrow K_{edg.Crk_i}\cdot 1.099$$

$$K_{\alpha_i} \leftarrow \begin{cases} 9.0 & \text{if } K_{A_i} \leq 9.0 \\ K_{A_i} & \text{otherwise} \end{cases}$$

$$D_{len_i} \leftarrow C_0\cdot(K_{\alpha_i} - 9.0)^{1.16}$$

$$D_{lengrth_i} \leftarrow \begin{cases} D_{len_i}\cdot CF_{inhr}\cdot C_{blk} & \text{if } K_{\alpha_i} \leq 80.0 \\ 4\cdot 10^{-10}\cdot CF_{inhr}\cdot C_{blk} & \text{otherwise} \end{cases}$$

$$output_{(i,0)} \leftarrow i$$

$$output_{(i,1)} \leftarrow \frac{NCB_i}{365\cdot 24}$$

$$output_{(i,2)} \leftarrow L1_i - L1_0$$

$$output_{(i,3)} \leftarrow D_{lengrth_i}$$

$$output_{(i,4)} \leftarrow K_{edg.Crk_i}$$

$$output_{(i,5)} \leftarrow F_{a.b_i}$$

$$i \leftarrow i + 1$$

$$L1_i \leftarrow L1_{i-1} + D_{lengrth_{i-1}}$$

$$NCB_i \leftarrow NCB_{i-1} + C_{blk}$$

output

Pressurized Cylindrical Shell with a Fixed End Containing an axial throughwall Crack: Yashi & Erdogan; Murakami Problem set 9.38

$MF_{mura} :=$

	0	1	2
0	1	1	2.933
1	1	1.1	0.151
2	1	1.5	0.346
3	1	2	0.572
4	1	10	1.286
5	2	1	5.754
6	2	1.1	0.284
7	2	1.5	0.839
8	2	2	1.34
9	2	10	1.645
10	3	1	9.164
11	3	1.1	0.49
12	3	1.5	1.5
13	3	2	2.015
14	3	10	2.067
15	10	1	43.555
16	10	1.1	2.853
17	10	1.5	4.703
18	10	2	4.912
19	10	10	4.923

$A := MF_{mura}^{\langle 0 \rangle}$ $C := MF_{mura}^{\langle 1 \rangle}$ $F_m := MF_{mura}^{\langle 2 \rangle}$

$M_{mem} := \text{augment}(A, C)$

$R_{MF} := \text{regress}(M_{mem}, F_m, 3)$

$F(A, C) := \text{interp}\left[R_{MF}, M_{mem}, F_m, \begin{pmatrix} A \\ C \end{pmatrix}\right]$ $F(10, 10) = 4.928$

$$
\begin{aligned}
TWC_{Mura} :=\; & i \leftarrow 0 \\
& L1_0 \leftarrow \frac{L}{2} \\
& NCB_0 \leftarrow C_{blk} \\
& \text{while } i \le I_{lim} \\
& \quad \sigma_{m.appld} \leftarrow \begin{cases}
\sigma_{m.all_1} & \text{if } L1_i \le L1_0 \\
\sigma_{m.all_2} & \text{if } L1_0 < L1_i \le L1_0 + Incr_{Edg} \\
\sigma_{m.all_3} & \text{if } L1_0 + Incr_{Edg} < L1_i \le L1_i + 2 \cdot Incr_{Edg} \\
\sigma_{m.all_4} & \text{if } L1_0 + 2 \cdot Incr_{Edg} < L1_i \le L1_0 + 3 \cdot Incr_{Edg} \\
\sigma_{m.all_5} & \text{if } L1_0 + 3 \cdot Incr_{Edg} < L1_i \le L1_0 + 4 \cdot Incr_{Edg} \\
\sigma_{m.all_6} & \text{if } L1_0 + 4 \cdot Incr_{Edg} < L1_i \le L1_0 + 5 \cdot Incr_{Edg} \\
\sigma_{m.all_7} & \text{if } L1_0 + 5 \cdot Incr_{Edg} < L1_i \le L1_0 + 6 \cdot Incr_{Edg} \\
\sigma_{m.all_8} & \text{if } L1_0 + 6 \cdot Incr_{Edg} < L1_i \le L1_0 + 7 \cdot Incr_{Edg} \\
\sigma_{m.all_9} & \text{if } L1_0 + 7 \cdot Incr_{Edg} < L1_i \le L1_0 + 8 \cdot Incr_{Edg} \\
\sigma_{m.all_{10}} & \text{if } L1_0 + 8 \cdot Incr_{Edg} < L1_i \le L1_0 + 9 \cdot Incr_{Edg} \\
\sigma_{m.all_{11}} & \text{if } L1_0 + 9 \cdot Incr_{Edg} < L1_i \le L1_0 + 10 \cdot Incr_{Edg} \\
\sigma_{m.all_{12}} & \text{if } L1_0 + 10 \cdot Incr_{Edg} < L1_i \le L1_0 + 11 \cdot Incr_{Edg} \\
\sigma_{m.all_{13}} & \text{if } L1_0 + 11 \cdot Incr_{Edg} < L1_i \le L1_0 + 12 \cdot Incr_{Edg} \\
\sigma_{m.all_{14}} & \text{if } L1_0 + 12 \cdot Incr_{Edg} < L1_i \le L1_0 + 13 \cdot Incr_{Edg} \\
\sigma_{m.all_{15}} & \text{if } L1_0 + 13 \cdot Incr_{Edg} < L1_i \le L1_0 + 14 \cdot Incr_{Edg} \\
\sigma_{m.all_{16}} & \text{if } L1_0 + 14 \cdot Incr_{Edg} < L1_i \le L1_0 + 15 \cdot Incr_{Edg} \\
\sigma_{m.all_{17}} & \text{if } L1_0 + 15 \cdot Incr_{Edg} < L1_i \le L1_0 + 16 \cdot Incr_{Edg} \\
\sigma_{m.all_{18}} & \text{if } L1_0 + 16 \cdot Incr_{Edg} < L1_i \le L1_0 + 17 \cdot Incr_{Edg} \\
\sigma_{m.all_{19}} & \text{if } L1_0 + 17 \cdot Incr_{Edg} < L1_i \le L1_0 + 18 \cdot Incr_{Edg} \\
\sigma_{m.all_{20}} & \text{otherwise}
\end{cases} \\
& \quad C \leftarrow 2.087 - FL_{Cntr} \\
& \quad Z \leftarrow \frac{C}{\;}
\end{aligned}
$$

$\quad L1_i$

$A_{T_i} \leftarrow \frac{L1_i}{t}$

$F_{M_i} \leftarrow F(Z_i, A_{T_i})$

$K_{Mura_i} \leftarrow \sigma_{m.appld} \cdot (\pi \cdot L1_i)^{0.5} \cdot F_{M_i}$

$K_{A_i} \leftarrow K_{Mura_i} \cdot 1.099$

$K_{\alpha_i} \leftarrow \begin{cases} 9.0 & \text{if } K_{A_i} \le 9.0 \\ K_{A_i} & \text{otherwise} \end{cases}$

$D_{len_i} \leftarrow C_0 \cdot (K_{\alpha_i} - 9.0)^{1.16}$

$D_{lengrth_i} \leftarrow \begin{cases} D_{len_i} \cdot CF_{inhr} \cdot C_{blk} & \text{if } K_{\alpha_i} \le 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} & \text{otherwise} \end{cases}$

$output_{(i,0)} \leftarrow i$

$output_{(i,1)} \leftarrow \frac{NCB_i}{365 \cdot 24}$

$output_{(i,2)} \leftarrow L1_i - L1_0$

$output_{(i,3)} \leftarrow D_{lengrth_i}$

$output_{(i,4)} \leftarrow K_{Mura_i}$

$output_{(i,5)} \leftarrow F_{M_i}$

$i \leftarrow i + 1$

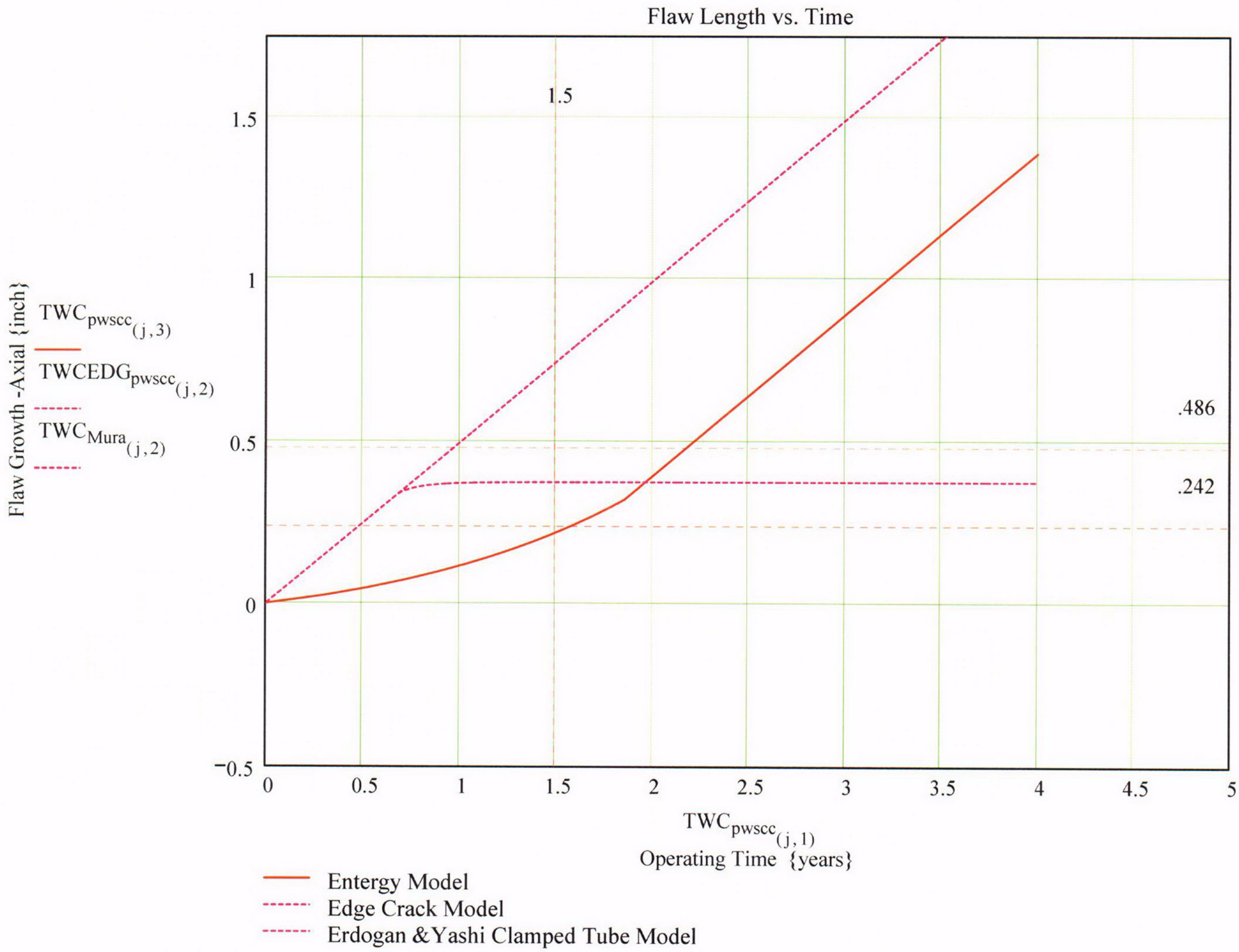
$L1_i \leftarrow L1_{i-1} + D_{lengrth_{i-1}}$

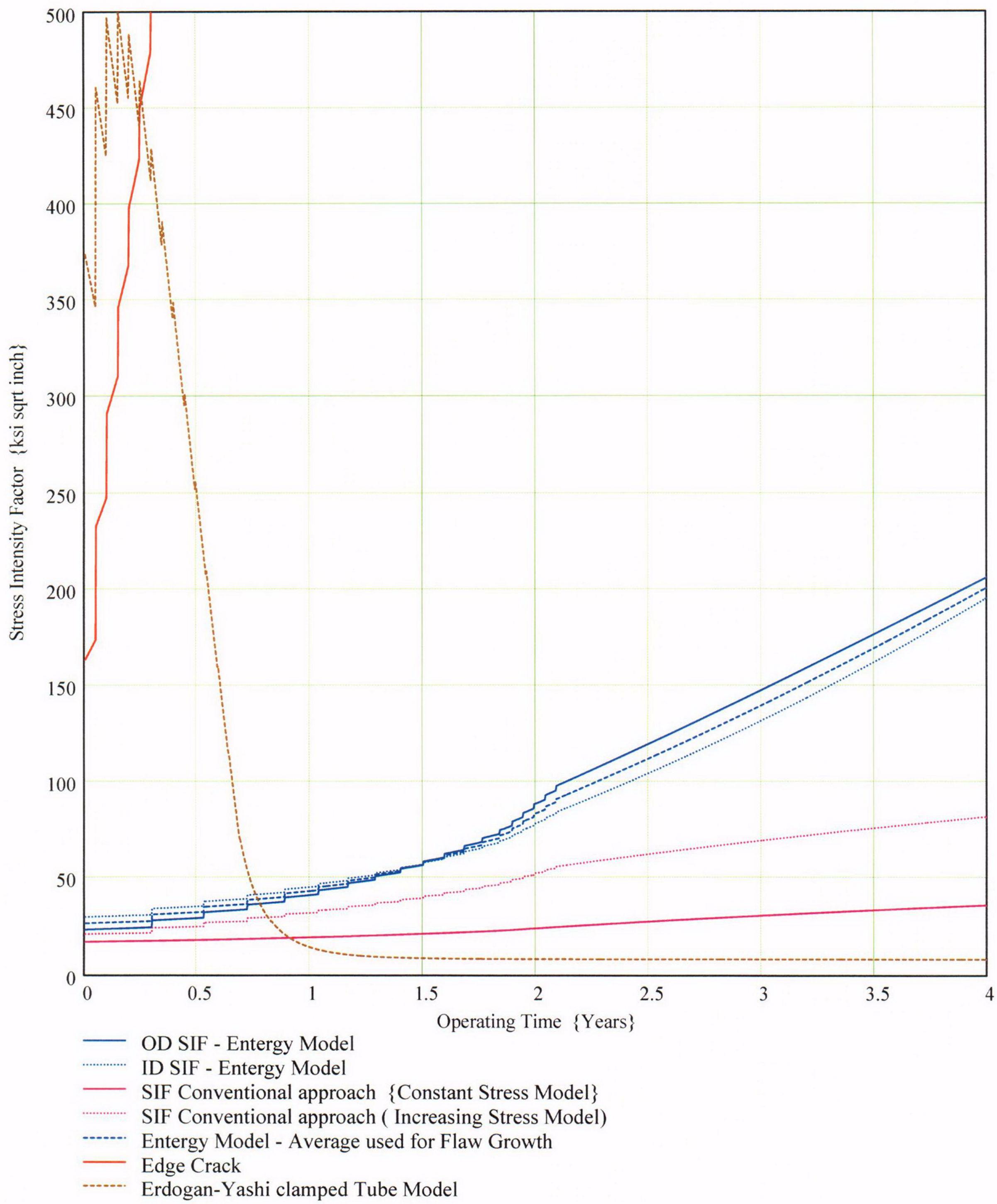
$NCB_i \leftarrow NCB_{i-1} + C_{blk}$

output

$j := 1 .. I_{lim}$

$Prop_{Length} = 0.486$

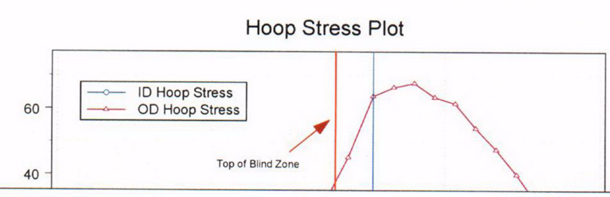



Stress Intensity Factor {ksi sqrt inch}
500
450
400
350
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {Years}
OD SIF - Entergy Model
ID SIF - Entergy Model
SIF Conventional approach {Constant Stress Model}
SIF Conventional approach (Increasing Stress Model)
Entergy Model - Average used for Flaw Growth
Edge Crack
Erdogan-Yashi clamped Tube Model

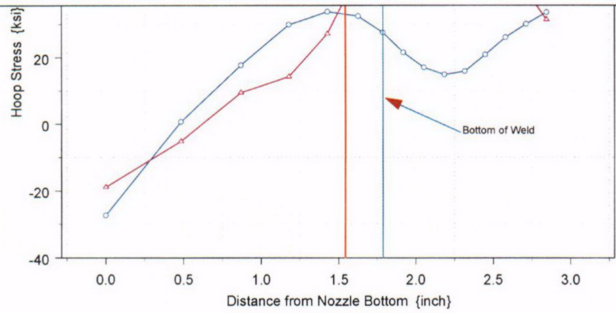
C23

$TWC_{pwscc_{(j,6)}} =$	$TWCEDG_{pwscc_{(j,2)}} =$	$TWC_{pwscc_{(j,7)}} =$	$TWC_{pwscc_{(j,8)}} =$
23.407	$1.324 \cdot 10^{-3}$	29.92	27.884
23.417	$2.648 \cdot 10^{-3}$	29.93	27.895
23.428	$3.972 \cdot 10^{-3}$	29.941	27.906
23.438	$5.296 \cdot 10^{-3}$	29.951	27.917
23.448	$6.62 \cdot 10^{-3}$	29.961	27.928
23.459	$7.944 \cdot 10^{-3}$	29.971	27.94
23.469	$9.268 \cdot 10^{-3}$	29.981	27.951

23.48	0.011	29.992	27.962
23.49	0.012	30.002	27.973
23.5	0.013	30.012	27.984
23.511	0.015	30.022	27.996
23.521	0.016	30.032	28.007
23.532	0.017	30.043	28.018
23.542	0.019	30.053	28.029
23.552	0.02	30.063	28.041
23.563	0.021	30.073	28.052


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
60
40
Top of Blind Zone

C24


Hoop Stress {ksi}
20
0
-20
-40
Bottom of Weld
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Distance from Nozzle Bottom {inch}

SOD =

	0
0	0
1	-2.009
2	6.13
3	20.789
4	22.133
5	23.542
6	25.021
7	26.57
8	28.192
9	29.891
10	31.667
11	33.525
12	35.465
13	37.491
14	39.605
15	41.809

Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw

Developed by Central Engineering Programs, Entergy Operations Inc
Developedby: J. S. Brihmadesam **Verified by: B. C. Gray**

Refrences :
1) "Stress Intensity factors for Part-through Surface cracks"; NASA TM-11707; July 1992.
2) Crack Growth of Alloy 600 Base Metal in PWR Environments; EPRI MRP Report MRP 55 Rev. 1, 2002

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8.8" Degree Nozzle, "0" Degree Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

Mean Radius -to- Thickness Ratio:- "R_m/t" -- between 1.0 and 300.0

Note : ***Used the Metric form of the equation from EPRI MRP 55-Rev. 1.***
The correction is applied in the determination of the crack extension to obtain the value in inch/hr .

OD Surface Flaw

The first Required input is a location for a point on the tube elevation to define the point of interest (e.g. The top of the Blind Zone, or bottom of fillet weld etc.). This reference point is necessar to evaluate the stress distribution on the flaw both for the initial flaw and for a growing flaw. This is defined as the reference point. Enter a number (inch) that represnets the reference point elevation measured upward from the nozzle end.

$$Ref_{Point} := 1.544$$

To place the flaw with repsect to the reference point, the flaw tips and center can be located as follows:

1) ***The Upper "c- tip" located at the reference point (Enter 1)***
2) ***The Center of the flaw at the reference point (Enter 2)***
3) ***The lower "c- tip" located at the reference point (Enter 3).***

$$Val := 2$$

Input Data :-

$L := 0.3966$	Initial Flaw Length
$a_0 := 0.0661$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

$$R_o := \frac{od}{2} \qquad R_{id} := \frac{id}{2} \qquad t := R_o - R_{id} \qquad R_m := R_{id} + \frac{t}{2} \qquad Tim_{opr} := Years \cdot 365 \cdot 24$$

$$CF_{inhr} := 1.417 \cdot 10^5 \qquad C_{blk} := \frac{Tim_{opr}}{I_{lim}} \qquad Prnt_{blk} := \left| \frac{I_{lim}}{50} \right| \qquad c_0 := \frac{L}{2} \qquad R_t := \frac{R_m}{t}$$

$$C_{01} := e^{\left[\frac{-Q_g}{1.103 \cdot 10^{-3}} \cdot \left(\frac{1}{T+459.67} - \frac{1}{T_{ref}+459.67} \right) \right]} \cdot \alpha_{0c}$$

Temperature Correction for Coefficient Alpha

$$C_0 := C_{01}$$

75 th percentile MRP-55 Revision 1

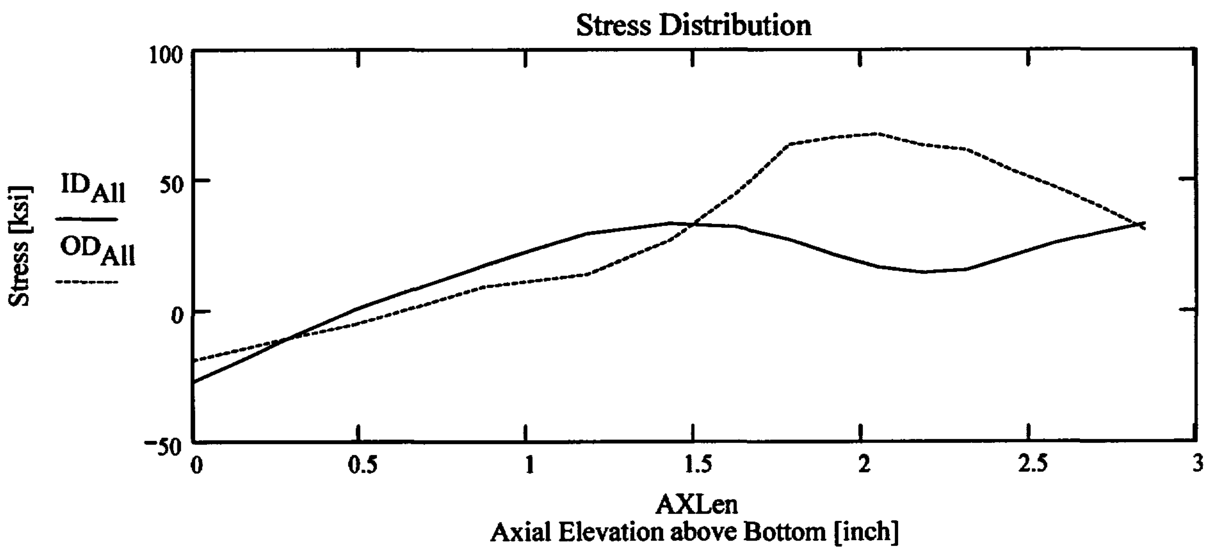
Stress Input Data

Input all available Nodal stress data in the table below. The column designations are as follows:
Column "0" = Axial distance from minumum to maximum recorded on data sheet(inches)
Column "1" = ID Stress data at each Elevation (ksi)
Column "2" = Quarter Thickness Stress data at each Elevation (ksi)
Column "3" = Mid Thickness Stress data at each Elevation (ksi)
Column "4" = Three Quarter Thickness Stress data at each Elevation (ksi)
Column "5" = OD Stress data at each Elevation (ksi)

AllData :=

	0	1	2	3	4	5
0	0	-27.4	-24.36	-22.21	-20.41	-18.98
1	0.48	0.63	-1.49	-3.6	-4.44	-5.27
2	0.87	17.66	16.42	14.61	12.41	9.38
3	1.18	29.8	26.05	22.72	18.95	14.2
4	1.43	33.62	27.79	24.8	24.32	26.99
5	1.63	32.36	28.47	27.59	34.28	45.1
6	1.79	27.39	28.92	31.39	43.88	63.72
7	1.92	21.5	25.56	33.55	48.09	66.36
8	2.05	16.94	23.79	34.06	49.47	67.67
9	2.18	14.83	22.26	34.78	49.05	63.38

$AXLen := AllData^{\langle 0 \rangle}$ $\quad ID_{All} := AllData^{\langle 1 \rangle}$ $\quad OD_{All} := AllData^{\langle 5 \rangle}$



Observing the stress distribution select the region in the table above labeled $Data_{All}$ that represents the region of interest. This needs to be done especially for distributions that have a large compressive stress at the nozzle bottom and high tensile stresses at the J-weld location. Copy the selection in the above table , click on the "Data" statement below and delete it from the edit menu. Type "Data and the Mathcad "equal" sign (Shift-Colon) then insert the same to the right of the Mathcad Equals sign below (paste symbol).

$$Data := \begin{pmatrix} 0 & -27.404 & -24.356 & -22.209 & -20.407 & -18.978 \\ 0.483 & 0.633 & -1.486 & -3.599 & -4.44 & -5.268 \\ 0.87 & 17.665 & 16.422 & 14.61 & 12.415 & 9.376 \\ 1.18 & 29.798 & 26.049 & 22.723 & 18.95 & 14.201 \\ 1.428 & 33.623 & 27.792 & 24.8 & 24.321 & 26.989 \\ 1.627 & 32.364 & 28.469 & 27.591 & 34.284 & 45.104 \\ 1.786 & 27.394 & 28.918 & 31.388 & 43.882 & 63.718 \\ 1.919 & 21.498 & 25.556 & 33.55 & 48.089 & 66.365 \\ 2.051 & 16.944 & 23.793 & 34.064 & 49.472 & 67.672 \end{pmatrix}$$

$Axl := Data^{\langle 0 \rangle}$ $MD := Data^{\langle 3 \rangle}$ $ID := Data^{\langle 1 \rangle}$ $TQ := Data^{\langle 4 \rangle}$ $QT := Data^{\langle 2 \rangle}$ $OD := Data^{\langle 5 \rangle}$

$R_{ID} := regress(Axl, ID, 3)$ $R_{QT} := regress(Axl, QT, 3)$

$R_{OD} := regress(Axl, OD, 3)$

$R_{MD} := regress(Axl, MD, 3)$ $R_{TQ} := regress(Axl, TQ, 3)$

$UL_{Strs.Dist} := 1.786$ Upper Axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom)

$$FL_{Cntr} := \begin{vmatrix} Ref_{Point} - c_0 \ \text{if } Val = 1 \\ Ref_{Point} \ \text{if } Val = 2 \\ Ref_{Point} + c_0 \ \text{otherwise} \end{vmatrix}$$

Flaw center Location Location above Nozzle Bottom

$U_{Tip} := FL_{Cntr} + c_0$

$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

No User Input is required beyond this Point

Calculation to Develop Hoop Stress Profiles in the Axial Direction for Fracture Mechanics Analysis

$N := 20$ *Number of locations for stress profiles*

$Loc_0 := FL_{Cntr} - L$

$i := 1..N+3$

$$Incr_i := \begin{cases} c_0 & \text{if } i < 4 \\ Inc_{Strs.avg} & \text{otherwise} \end{cases}$$

$Loc_i := Loc_{i-1} + Incr_i$

$$SID_i := R_{ID_3} + R_{ID_4} \cdot Loc_i + R_{ID_5} \cdot (Loc_i)^2 + R_{ID_6} \cdot (Loc_i)^3$$

$$SQT_i := R_{QT_3} + R_{QT_4} \cdot Loc_i + R_{QT_5} \cdot (Loc_i)^2 + R_{QT_6} \cdot (Loc_i)^3$$

$$SMD_i := R_{MD_3} + R_{MD_4} \cdot Loc_i + R_{MD_5} \cdot (Loc_i)^2 + \left[R_{MD_6} \cdot (Loc_i)^3 \right]$$

$$STQ_i := R_{TQ_3} + R_{TQ_4} \cdot Loc_i + R_{TQ_5} \cdot (Loc_i)^2 + R_{TQ_6} \cdot (Loc_i)^3$$

$$SOD_i := R_{OD_3} + R_{OD_4} \cdot Loc_i + R_{OD_5} \cdot (Loc_i)^2 + R_{OD_6} \cdot (Loc_i)^3$$

Development of Elevation-Averaged stresses at 20 elevations along the tube for use in Fracture Mechanics Model

$j := 1..N$

$$S_{id_j} := \begin{cases} \dfrac{SID_j + SID_{j+1} + SID_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{id_{j-1}} \cdot (j+1) + SID_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{qt_j} := \begin{cases} \dfrac{SQT_j + SQT_{j+1} + SQT_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{qt_{(j-1)}} \cdot (j+1) + SQT_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{md_j} := \begin{cases} \dfrac{SMD_j + SMD_{j+1} + SMD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{md_{j-1}} \cdot (j+1) + SMD_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{tq_j} := \begin{cases} \dfrac{STQ_j + STQ_{j+1} + STQ_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{tq_{j-1}} \cdot (j+1) + STQ_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{od_j} := \begin{cases} \dfrac{SOD_j + SOD_{j+1} + SOD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{od_{j-1}} \cdot (j+1) + SOD_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

Elevation-Averaged Hoop Stress Distribution for OD Flaws (i.e. OD to ID Stress distribution)

$u_0 := 0.000$ $\quad u_1 := 0.25$ $\quad u_2 := 0.50$ $\quad u_3 := 0.75$ $\quad u_4 := 1.00$

$$Y := \text{stack}(u_0, u_1, u_2, u_3, u_4)$$

$SIG_1 := \text{stack}(S_{od_{,}}, S_{tq_{,}}, S_{md_{,}}, S_{qt_{,}}, S_{id_{,}})$ $\qquad SIG_2 := \text{stack}(S_{od_{\frown}}, S_{tq_{\frown}}, S_{md_{\frown}}, S_{qt_{\frown}}, S_{id_{\frown}})$

$SIG_3 := stack\left(S_{od_3}, S_{tq_3}, S_{md_3}, S_{qt_3}, S_{id_3}\right)$ $SIG_4 := stack\left(S_{od_4}, S_{tq_4}, S_{md_4}, S_{qt_4}, S_{id_4}\right)$

$SIG_5 := stack\left(S_{od_5}, S_{tq_5}, S_{md_5}, S_{qt_5}, S_{id_5}\right)$ $SIG_6 := stack\left(S_{od_6}, S_{tq_6}, S_{md_6}, S_{qt_6}, S_{id_6}\right)$

$SIG_7 := stack\left(S_{od_7}, S_{tq_7}, S_{md_7}, S_{qt_7}, S_{id_7}\right)$ $SIG_8 := stack\left(S_{od_8}, S_{tq_8}, S_{md_8}, S_{qt_8}, S_{id_8}\right)$

$SIG_9 := stack\left(S_{od_9}, S_{tq_9}, S_{md_9}, S_{qt_9}, S_{id_9}\right)$ $SIG_{10} := stack\left(S_{od_{10}}, S_{tq_{10}}, S_{md_{10}}, S_{qt_{10}}, S_{id_{10}}\right)$

$SIG_{11} := stack\left(S_{od_{11}}, S_{tq_{11}}, S_{md_{11}}, S_{qt_{11}}, S_{id_{11}}\right)$ $SIG_{12} := stack\left(S_{od_{12}}, S_{tq_{12}}, S_{md_{12}}, S_{qt_{12}}, S_{id_{12}}\right)$

$SIG_{13} := stack\left(S_{od_{13}}, S_{tq_{13}}, S_{md_{13}}, S_{qt_{13}}, S_{id_{13}}\right)$ $SIG_{14} := stack\left(S_{od_{14}}, S_{tq_{14}}, S_{md_{14}}, S_{qt_{14}}, S_{id_{14}}\right)$

$SIG_{15} := stack\left(S_{od_{15}}, S_{tq_{15}}, S_{md_{15}}, S_{qt_{15}}, S_{id_{15}}\right)$ $SIG_{16} := stack\left(S_{od_{16}}, S_{tq_{16}}, S_{md_{16}}, S_{qt_{16}}, S_{id_{16}}\right)$

$SIG_{17} := stack\left(S_{od_{17}}, S_{tq_{17}}, S_{md_{17}}, S_{qt_{17}}, S_{id_{17}}\right)$ $SIG_{18} := stack\left(S_{od_{18}}, S_{tq_{18}}, S_{md_{18}}, S_{qt_{18}}, S_{id_{18}}\right)$

$SIG_{19} := stack\left(S_{od_{19}}, S_{tq_{19}}, S_{md_{19}}, S_{qt_{19}}, S_{id_{19}}\right)$ $SIG_{20} := stack\left(S_{od_{20}}, S_{tq_{20}}, S_{md_{20}}, S_{qt_{20}}, S_{id_{20}}\right)$

Regression of Throughwall Stress distribution to obtain Stress Coefficients throughwall using a Third Order polynomial

$ODRG_1 := regress\left(Y, SIG_1, 3\right)$ $ODRG_2 := regress\left(Y, SIG_2, 3\right)$

$ODRG_3 := \text{regress}(Y, SIG_3, 3)$

$ODRG_4 := \text{regress}(Y, SIG_4, 3)$

$ODRG_5 := \text{regress}(Y, SIG_5, 3)$

$ODRG_6 := \text{regress}(Y, SIG_6, 3)$

$ODRG_7 := \text{regress}(Y, SIG_7, 3)$

$ODRG_8 := \text{regress}(Y, SIG_8, 3)$

$ODRG_9 := \text{regress}(Y, SIG_9, 3)$

$ODRG_{10} := \text{regress}(Y, SIG_{10}, 3)$

$ODRG_{11} := \text{regress}(Y, SIG_{11}, 3)$

$ODRG_{12} := \text{regress}(Y, SIG_{12}, 3)$

$ODRG_{13} := \text{regress}(Y, SIG_{13}, 3)$

$ODRG_{14} := \text{regress}(Y, SIG_{14}, 3)$

$ODRG_{15} := \text{regress}(Y, SIG_{15}, 3)$

$ODRG_{16} := \text{regress}(Y, SIG_{16}, 3)$

$ODRG_{17} := \text{regress}(Y, SIG_{17}, 3)$

$ODRG_{18} := \text{regress}(Y, SIG_{18}, 3)$

$ODRG_{19} := \text{regress}(Y, SIG_{19}, 3)$

$ODRG_{20} := \text{regress}(Y, SIG_{20}, 3)$

Stress Distribution in the tube. ***Stress Influence coefficients obtained from thrid order polynomial curve fit to the throughwall stress distribution***

$Prop_{Length} := UL_{Strs.Dist} - FL_{Cntr} - c_0$

$Prop_{Length} = 0.044$

Data Files for Flaw Shape Factors from NASA (NASA-TM-111707-SC04 Model) {NO INPUT Required}

Mettu Raju Newman Sivakumar Forman Solution of ID Part throughwall Flaw in Cyinder

Jsb :=

	0	1	2
0	1.000	0.200	0.000
1	1.000	0.200	0.200
2	1.000	0.200	0.500
3	1.000	0.200	0.800
4	1.000	0.200	1.000
5	1.000	0.400	0.000
6	1.000	0.400	0.200
7	1.000	0.400	0.500
8	1.000	0.400	0.800
9	1.000	0.400	1.000
10	1.000	1.000	0.000
11	1.000	1.000	0.200
12	1.000	1.000	0.500
13	1.000	1.000	0.800
14	1.000	1.000	1.000
15	2.000	0.200	0.000
16	2.000	0.200	0.200
17	2.000	0.200	0.500
18	2.000	0.200	0.800
19	2.000	0.200	1.000
20	2.000	0.400	0.000
21	2.000	0.400	0.200
22	2.000	0.400	0.500
23	2.000	0.400	0.800
24	2.000	0.400	1.000
25	2.000	1.000	0.000
26	2.000	1.000	0.200
27	2.000	1.000	0.500
28	2.000	1.000	0.800
29	2.000	1.000	1.000
30	4.000	0.200	0.000
31	4.000	0.200	0.200
32	4.000	0.200	0.500
33	4.000	0.200	0.800
34	4.000	0.200	1.000

35	4.000	0.400	0.000
36	4.000	0.400	0.200
37	4.000	0.400	0.500
38	4.000	0.400	0.800
39	4.000	0.400	1.000
40	4.000	1.000	0.000
41	4.000	1.000	0.200
42	4.000	1.000	0.500
43	4.000	1.000	0.800
44	4.000	1.000	1.000
45	10.000	0.200	0.000
46	10.000	0.200	0.200
47	10.000	0.200	0.500
48	10.000	0.200	0.800
49	10.000	0.200	1.000
50	10.000	0.400	0.000
51	10.000	0.400	0.200
52	10.000	0.400	0.500
53	10.000	0.400	0.800
54	10.000	0.400	1.000
55	10.000	1.000	0.000
56	10.000	1.000	0.200
57	10.000	1.000	0.500
58	10.000	1.000	0.800
59	10.000	1.000	1.000
60	300.000	0.200	0.000
61	300.000	0.200	0.200
62	300.000	0.200	0.500
63	300.000	0.200	0.800
64	300.000	0.200	1.000
65	300.000	0.400	0.000
66	300.000	0.400	0.200
67	300.000	0.400	0.500
68	300.000	0.400	0.800
69	300.000	0.400	1.000
70	300.000	1.000	0.000
71	300.000	1.000	0.200
72	300.000	1.000	0.500
73	300.000	1.000	0.800
74	300.000	1.000	1.000

Sambi :=

	0	1	2	3	4	5	6	7
0	1.244	0.754	0.564	0.454	0.755	0.153	0.06	0.032
1	1.237	0.719	0.536	0.435	0.594	0.076	0.021	0.009
2	1.641	0.867	0.615	0.486	0.648	0.089	0.026	0.011
3	2.965	1.336	0.858	0.635	1.293	0.271	0.109	0.058
4	4.498	1.839	1.107	0.783	2.129	0.481	0.202	0.11
5	1.146	0.716	0.546	0.448	0.889	0.17	0.064	0.032
6	1.175	0.709	0.539	0.444	0.809	0.132	0.046	0.023
7	1.452	0.806	0.589	0.474	0.934	0.17	0.064	0.033
8	2.119	1.046	0.714	0.55	1.492	0.329	0.136	0.073
9	2.8	1.279	0.833	0.621	2.143	0.497	0.21	0.114
10	1.03	0.715	0.577	0.49	1.148	0.202	0.076	0.039
11	1.054	0.725	0.586	0.499	1.202	0.214	0.081	0.042
12	1.146	0.76	0.606	0.513	1.354	0.256	0.1	0.053
13	1.305	0.817	0.634	0.527	1.594	0.327	0.133	0.071
14	1.412	0.866	0.657	0.537	1.796	0.387	0.161	0.087
15	1.111	0.688	0.522	0.426	0.72	0.121	0.041	0.02
16	1.193	0.7	0.524	0.427	0.611	0.079	0.022	0.01
17	1.655	0.868	0.614	0.484	0.693	0.105	0.035	0.017
18	2.732	1.255	0.817	0.609	1.207	0.245	0.097	0.051
19	3.842	1.634	1.009	0.726	1.826	0.395	0.162	0.086
20	1.077	0.685	0.528	0.436	0.817	0.14	0.049	0.023
21	1.136	0.692	0.528	0.436	0.796	0.13	0.046	0.022
22	1.403	0.785	0.576	0.465	0.959	0.182	0.071	0.037
23	1.942	0.984	0.682	0.53	1.425	0.315	0.131	0.071
24	2.454	1.168	0.78	0.591	1.915	0.443	0.188	0.102
25	1.02	0.72	0.585	0.498	1.152	0.196	0.072	0.036
26	1.044	0.722	0.584	0.498	1.185	0.209	0.079	0.041
27	1.117	0.746	0.597	0.505	1.318	0.25	0.098	0.052
28	1.236	0.797	0.625	0.523	1.56	0.315	0.127	0.068
29	1.335	0.844	0.652	0.538	1.775	0.37	0.151	0.08
30	1.009	0.65	0.507	0.427	0.589	0.073	0.018	0.006
31	1.162	0.691	0.524	0.434	0.612	0.08	0.023	0.01
32	1.64	0.861	0.613	0.488	0.786	0.134	0.049	0.025
33	2.51	1.178	0.782	0.596	1.16	0.242	0.097	0.051
34	3.313	1.464	0.932	0.693	1.517	0.339	0.139	0.073
35	1	0.655	0.518	0.44	0.754	0.118	0.036	0.017
36	1.109	0.685	0.53	0.445	0.793	0.13	0.045	0.022
37	1.36	0.773	0.575	0.472	0.994	0.195	0.078	0.041
38	1.727	0.914	0.653	0.523	1.4	0.318	0.134	0.073
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

39	2.025	1.032	0.72	0.566	1.761	0.427	0.161	0.1
40	0.986	0.711	0.589	0.513	1.127	0.189	0.068	0.034
41	1.03	0.72	0.591	0.513	1.163	0.204	0.077	0.04
42	1.094	0.743	0.603	0.52	1.286	0.243	0.096	0.051
43	1.156	0.777	0.625	0.536	1.498	0.302	0.122	0.064
44	1.194	0.804	0.644	0.551	1.681	0.35	0.142	0.073
45	0.981	0.636	0.501	0.422	0.598	0.078	0.02	0.007
46	1.147	0.685	0.521	0.432	0.612	0.08	0.023	0.01
47	1.584	0.839	0.6	0.48	0.806	0.142	0.053	0.028
48	2.298	1.099	0.739	0.568	1.262	0.277	0.114	0.062
49	2.921	1.323	0.859	0.645	1.715	0.402	0.169	0.092
50	0.975	0.645	0.516	0.439	0.75	0.114	0.036	0.017
51	1.096	0.68	0.528	0.444	0.788	0.128	0.045	0.022
52	1.31	0.755	0.565	0.466	0.984	0.192	0.076	0.04
53	1.565	0.858	0.625	0.505	1.378	0.309	0.129	0.07
54	1.749	0.938	0.675	0.539	1.747	0.411	0.174	0.095
55	0.982	0.709	0.588	0.515	1.123	0.188	0.068	0.034
56	1.025	0.718	0.59	0.513	1.156	0.202	0.076	0.039
57	1.078	0.738	0.6	0.518	1.266	0.236	0.092	0.048
58	1.118	0.765	0.619	0.533	1.453	0.286	0.113	0.059
59	1.137	0.786	0.636	0.548	1.613	0.326	0.129	0.067
60	0.936	0.62	0.486	0.405	0.582	0.068	0.015	0.005
61	1.145	0.681	0.514	0.42	0.613	0.081	0.024	0.011
62	1.459	0.79	0.569	0.454	0.79	0.138	0.051	0.026
63	1.774	0.917	0.641	0.501	1.148	0.239	0.096	0.051
64	1.974	1.008	0.696	0.537	1.482	0.328	0.134	0.07
65	0.982	0.651	0.512	0.427	0.721	0.103	0.031	0.013
66	1.095	0.677	0.52	0.431	0.782	0.127	0.045	0.022
67	1.244	0.727	0.546	0.446	0.946	0.18	0.071	0.037
68	1.37	0.791	0.585	0.473	1.201	0.253	0.102	0.054
69	1.438	0.838	0.618	0.496	1.413	0.31	0.126	0.066

$W := Jsb^{\langle 0\rangle}$ $X := Jsb^{\langle 1\rangle}$ $Y := Jsb^{\langle 2\rangle}$

$a_U := Sambi^{\langle 0\rangle}$ $a_L := Sambi^{\langle 1\rangle}$ $a_Q := Sambi^{\langle 2\rangle}$ $a_C := Sambi^{\langle 3\rangle}$

$c_U := Sambi^{\langle 4\rangle}$ $c_L := Sambi^{\langle 5\rangle}$ $c_Q := Sambi^{\langle 6\rangle}$ $c_C := Sambi^{\langle 7\rangle}$

$$n := \begin{cases} 3 & \text{if } R_t \le 4.0 \\ 2 & \text{otherwise} \end{cases}$$

"a-Tip" Uniform Term

$M_{aU} := \text{augment}(W, X, Y)$ $\quad V_{aU} := a_U$ $\quad R_{aU} := \text{regress}(M_{aU}, V_{aU}, n)$

$$f_{aU}(W, X, Y) := \text{interp}\left[R_{aU}, M_{aU}, V_{aU}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aU}(4, .4, .8) = 1.741$ *Check Calculation*

Linear Term

$M_{aL} := \text{augment}(W, X, Y)$ $\quad V_{aL} := a_L$ $\quad R_{aL} := \text{regress}(M_{aL}, V_{aL}, n)$

$$f_{aL}(W, X, Y) := \text{interp}\left[R_{aL}, M_{aL}, V_{aL}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aL}(4, .4, .8) = 0.919$ *Check Calculation*

Quadratic Term

$M_{aQ} := \text{augment}(W, X, Y)$ $\quad V_{aQ} := a_Q$ $\quad R_{aQ} := \text{regress}(M_{aQ}, V_{aQ}, n)$

$$f_{aQ}(W,X,Y) := \text{interp}\left[R_{aQ}, M_{aQ}, V_{aQ}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aQ}(4, .4, .8) = 0.656$ *Check Calculation*

Cubic Term

$M_{aC} := \text{augment}(W, X, Y)$ $\quad V_{aC} := a_C$ $\quad R_{aC} := \text{regress}(M_{aC}, V_{aC}, n)$

$$f_{aC}(W,X,Y) := \text{interp}\left[R_{aC}, M_{aC}, V_{aC}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aC}(4, .4, .8) = 0.524$ *Check Calculation*

"C" Tip Coefficients

Uniform Term

$M_{cU} := \text{augment}(W, X, Y) \qquad V_{cU} := c_U \qquad R_{cU} := \text{regress}(M_{cU}, V_{cU}, n)$

$$f_{cU}(W, X, Y) := \text{interp}\left[R_{cU}, M_{cU}, V_{cU}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cU}(4, .4, .8) = 1.371$ *Check Calculation*

Linear Term

$M_{cL} := \text{augment}(W, X, Y) \qquad V_{cL} := c_L \qquad R_{cL} := \text{regress}(M_{cL}, V_{cL}, n)$

$$f_{cL}(W, X, Y) := \text{interp}\left[R_{cL}, M_{cL}, V_{cL}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cL}(2, .4, .8) = 0.319$ *Check Calculation*

Quadratic Term

$M_{cQ} := \text{augment}(W,X,Y)$ $\quad V_{cQ} := c_Q$ $\quad R_{cQ} := \text{regress}(M_{cQ}, V_{cQ}, n)$

$$f_{cQ}(W,X,Y) := \text{interp}\left[R_{cQ}, M_{cQ}, V_{cQ}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cQ}(4,.4,.8) = 0.126$ *Check Calculation*

Cubic Term

$M_{cC} := \text{augment}(W,X,Y)$ $\quad V_{cC} := c_C$ $\quad R_{cC} := \text{regress}(M_{cC}, V_{cC}, n)$

$$f_{cC}(W,X,Y) := \text{interp}\left[R_{cC}, M_{cC}, V_{cC}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cC}(4,.4,.8) = 0.068$ *Check Calculation*

Calculations : Recursive calculations to estimate flaw growth.

Recursive Loop for Calculation of PWSCC Crack Growth Entergy Model

$CGR_{sambi} :=$

$j \leftarrow 0$

$a_0 \leftarrow a_0$

$c_0 \leftarrow c_0$

$NCB_0 \leftarrow C_{blk}$

while $j \leq I_{lim}$

$\sigma_0 \leftarrow$

$ODRG1_3$ if $c_j \leq c_0$

$ODRG2_3$ if $c_0 < c_j \leq c_0 + Inc_{Strs.avg}$

$ODRG3_3$ if $c_0 + Inc_{Strs.avg} < c_j \leq c_0 + 2 \cdot Inc_{Strs.avg}$

$ODRG4_3$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 3 \cdot Inc_{Strs.avg}$

$ODRG5_3$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 4 \cdot Inc_{Strs.avg}$

$ODRG6_3$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 5 \cdot Inc_{Strs.avg}$

$ODRG7_3$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 6 \cdot Inc_{Strs.avg}$

$ODRG8_3$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 7 \cdot Inc_{Strs.avg}$

$ODRG9_3$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 8 \cdot Inc_{Strs.avg}$

$ODRG10_3$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 9 \cdot Inc_{Strs.avg}$

$ODRG11_3$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 10 \cdot Inc_{Strs.avg}$

$ODRG12_3$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 11 \cdot Inc_{Strs.avg}$

$ODRG13_3$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 12 \cdot Inc_{Strs.avg}$

$ODRG14_3$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 13 \cdot Inc_{Strs.avg}$

$$ODRG_{15_3} \text{ if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$$

$$ODRG_{16_3} \text{ if } c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$$

$$ODRG_{17_3} \text{ if } c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$$

$$ODRG_{18_3} \text{ if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$

$$ODRG_{19_3} \text{ if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$$

$$ODRG_{20_3} \text{ otherwise}$$

$$\sigma_1 \leftarrow ODRG_{1_4} \text{ if } c_j \le c_0$$

$$ODRG_{2_4} \text{ if } c_0 < c_j \le c_0 + Inc_{Strs.avg}$$

$$ODRG_{3_4} \text{ if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$$

$$ODRG_{4_4} \text{ if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$$

$$ODRG_{5_4} \text{ if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$$

$$ODRG_{6_4} \text{ if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$$

$$ODRG_{7_4} \text{ if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$$

$$ODRG_{8_4} \text{ if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$$

$$ODRG_{9_4} \text{ if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$$

$$ODRG_{10_4} \text{ if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$$

$$ODRG_{11_4} \text{ if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$$

$$ODRG_{12_4} \text{ if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$$

$$ODRG_{13_4} \text{ if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$$

$$ODRG_{14_4} \text{ if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$$

$$ODRG_{15_4} \text{ if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$$

$$ODRG16_4 \quad \text{if } c_0 + 14\cdot Inc_{Strs.avg} < c_j \le c_0 + 15\cdot Inc_{Strs.avg}$$
$$ODRG17_4 \quad \text{if } c_0 + 15\cdot Inc_{Strs.avg} < c_j \le c_0 + 16\cdot Inc_{Strs.avg}$$
$$ODRG18_4 \quad \text{if } c_0 + 16\cdot Inc_{Strs.avg} < c_j \le c_0 + 17\cdot Inc_{Strs.avg}$$
$$ODRG19_4 \quad \text{if } c_0 + 17\cdot Inc_{Strs.avg} < c_j \le c_0 + 18\cdot Inc_{Strs.avg}$$
$$ODRG20_4 \quad \text{otherwise}$$

$$\sigma_2 \leftarrow \begin{array}{ll} ODRG1_5 & \text{if } c_j \le c_0 \\ ODRG2_5 & \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\ ODRG3_5 & \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2\cdot Inc_{Strs.avg} \\ ODRG4_5 & \text{if } c_0 + 2\cdot Inc_{Strs.avg} < c_j \le c_0 + 3\cdot Inc_{Strs.avg} \\ ODRG5_5 & \text{if } c_0 + 3\cdot Inc_{Strs.avg} < c_j \le c_0 + 4\cdot Inc_{Strs.avg} \\ ODRG6_5 & \text{if } c_0 + 4\cdot Inc_{Strs.avg} < c_j \le c_0 + 5\cdot Inc_{Strs.avg} \\ ODRG7_5 & \text{if } c_0 + 5\cdot Inc_{Strs.avg} < c_j \le c_0 + 6\cdot Inc_{Strs.avg} \\ ODRG8_5 & \text{if } c_0 + 6\cdot Inc_{Strs.avg} < c_j \le c_0 + 7\cdot Inc_{Strs.avg} \\ ODRG9_5 & \text{if } c_0 + 7\cdot Inc_{Strs.avg} < c_j \le c_0 + 8\cdot Inc_{Strs.avg} \\ ODRG10_5 & \text{if } c_0 + 8\cdot Inc_{Strs.avg} < c_j \le c_0 + 9\cdot Inc_{Strs.avg} \\ ODRG11_5 & \text{if } c_0 + 9\cdot Inc_{Strs.avg} < c_j \le c_0 + 10\cdot Inc_{Strs.avg} \\ ODRG12_5 & \text{if } c_0 + 10\cdot Inc_{Strs.avg} < c_j \le c_0 + 11\cdot Inc_{Strs.avg} \\ ODRG13_5 & \text{if } c_0 + 11\cdot Inc_{Strs.avg} < c_j \le c_0 + 12\cdot Inc_{Strs.avg} \\ ODRG14_5 & \text{if } c_0 + 12\cdot Inc_{Strs.avg} < c_j \le c_0 + 13\cdot Inc_{Strs.avg} \\ ODRG15_5 & \text{if } c_0 + 13\cdot Inc_{Strs.avg} < c_j \le c_0 + 14\cdot Inc_{Strs.avg} \\ ODRG16_5 & \text{if } c_0 + 14\cdot Inc_{Strs.avg} < c_j \le c_0 + 15\cdot Inc_{Strs.avg} \\ ODRG17_5 & \text{if } c_0 + 15\cdot Inc_{Strs.avg} < c_j \le c_0 + 16\cdot Inc_{Strs.avg} \end{array}$$

$$ODRG_{18_5} \quad \text{if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$
$$ODRG_{19_5} \quad \text{if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$$
$$ODRG_{20_5} \quad \text{otherwise}$$

$$\sigma_3 \leftarrow \; ODRG_{1_6} \quad \text{if } c_j \le c_0$$
$$ODRG_{2_6} \quad \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg}$$
$$ODRG_{3_6} \quad \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$$
$$ODRG_{4_6} \quad \text{if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$$
$$ODRG_{5_6} \quad \text{if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$$
$$ODRG_{6_6} \quad \text{if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$$
$$ODRG_{7_6} \quad \text{if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$$
$$ODRG_{8_6} \quad \text{if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$$
$$ODRG_{9_6} \quad \text{if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$$
$$ODRG_{10_6} \quad \text{if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$$
$$ODRG_{11_6} \quad \text{if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$$
$$ODRG_{12_6} \quad \text{if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$$
$$ODRG_{13_6} \quad \text{if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$$
$$ODRG_{14_6} \quad \text{if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$$
$$ODRG_{15_6} \quad \text{if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$$
$$ODRG_{16_6} \quad \text{if } c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$$
$$ODRG_{17_6} \quad \text{if } c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$$
$$ODRG_{18_6} \quad \text{if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$
$$ODRG_{19} \quad \text{if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$$

[illegible]

$ODRG20_6$ otherwise

$\xi_0 \leftarrow \sigma_0$

$\xi_1 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.25 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^3$

$\xi_2 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.5 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^3$

$\xi_3 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.75 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^3$

$\xi_4 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{1.0 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^3$

$x_0 \leftarrow 0.0$

$x_1 \leftarrow 0.25$

$x_2 \leftarrow 0.5$

$x_3 \leftarrow 0.75$

$x_4 \leftarrow 1.0$

$X \leftarrow stack(x_0, x_1, x_2, x_3, x_4)$

$ST \leftarrow stack(\xi_0, \xi_1, \xi_2, \xi_3, \xi_4)$

$RG \leftarrow regress(X, ST, 3)$

$\sigma_{00} \leftarrow RG_3 + P_{Int}$

$\sigma_{10} \leftarrow RG_4$

$\sigma_{20} \leftarrow RG_5$

$\sigma_{30} \leftarrow RG_6$

$AR_j \leftarrow \frac{a_j}{c_j}$

$AT_j \leftarrow \frac{a_j}{t}$

$$G_{au_j} \leftarrow f_{aU}(R_t, AR_j, AT_j)$$

$$G_{al_j} \leftarrow f_{aL}(R_t, AR_j, AT_j)$$

$$G_{aq_j} \leftarrow f_{aQ}(R_t, AR_j, AT_j)$$

$$G_{ac_j} \leftarrow f_{aC}(R_t, AR_j, AT_j)$$

$$G_{cu_j} \leftarrow f_{cU}(R_t, AR_j, AT_j)$$

$$G_{cl_j} \leftarrow f_{cL}(R_t, AR_j, AT_j)$$

$$G_{cq_j} \leftarrow f_{cQ}(R_t, AR_j, AT_j)$$

$$G_{cc_j} \leftarrow f_{cC}(R_t, AR_j, AT_j)$$

$$Q_j \leftarrow \begin{cases} 1 + 1.464\cdot\left(\dfrac{a_j}{c_j}\right)^{1.65} & \text{if } c_j \ge a_j \\ 1 + 1.464\cdot\left(\dfrac{c_j}{a_j}\right)^{1.65} & \text{otherwise} \end{cases}$$

$$K_{a_j} \leftarrow \left(\frac{\pi\cdot a_j}{Q_j}\right)^{0.5}\cdot\left(\sigma_{00}\cdot G_{au_j} + \sigma_{10}\cdot G_{al_j} + \sigma_{20}\cdot G_{aq_j} + \sigma_{30}\cdot G_{ac_j}\right)$$

$$K_{c_j} \leftarrow \left(\frac{\pi\cdot c_j}{Q_j}\right)^{0.5}\cdot\left(\sigma_{00}\cdot G_{cu_j} + \sigma_{10}\cdot G_{cl_j} + \sigma_{20}\cdot G_{cq_j} + \sigma_{30}\cdot G_{cc_j}\right)$$

$$K_{\alpha_j} \leftarrow K_{a_j}\cdot 1.099$$

$$K_{\gamma_j} \leftarrow K_{c_j}\cdot 1.099$$

$$K_{\alpha_j} \leftarrow \begin{cases} 9.0 & \text{if } K_{\alpha_j} \le 9.0 \\ K_{\alpha_j} & \text{otherwise} \end{cases}$$

$$K_{\gamma_j} \leftarrow \begin{cases} 9.0 & \text{if } K_{\gamma_j} \le 9.0 \\ K_{\gamma_j} & \text{otherwise} \end{cases}$$

$$D_{a_j} \leftarrow C_0\cdot\left(K_{\alpha_j} - 9.0\right)^{1.16}$$

$D_{[illegible]} \leftarrow$ | $D_{[illegible]}\cdot CF_{[illegible]}\cdot C_{[illegible]}$ if $K_{[illegible]} < 80.0$

$D_{ag_j} \leftarrow \left| \begin{array}{l} D_{a_j} \cdot CF_{inhr} \cdot C_{blk} \ \text{if}\ K_{\alpha_j} < 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} \ \text{otherwise} \end{array} \right.$

$D_{c_j} \leftarrow C_0 \cdot \left(K_{\gamma_j} - 9.0\right)^{1.16}$

$D_{cg_j} \leftarrow \left| \begin{array}{l} D_{c_j} \cdot CF_{inhr} \cdot C_{blk} \ \text{if}\ K_{\gamma_j} < 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} \ \text{otherwise} \end{array} \right.$

$output_{(j,0)} \leftarrow j$

$output_{(j,1)} \leftarrow a_j$

$output_{(j,2)} \leftarrow c_j - c_0$

$output_{(j,3)} \leftarrow D_{ag_j}$

$output_{(j,4)} \leftarrow D_{cg_j}$

$output_{(j,5)} \leftarrow K_{a_j}$

$output_{(j,6)} \leftarrow K_{c_j}$

$output_{(j,7)} \leftarrow \frac{NCB_j}{365 \cdot 24}$

$output_{(j,8)} \leftarrow G_{au_j}$

$output_{(j,9)} \leftarrow G_{al_j}$

$output_{(j,10)} \leftarrow G_{aq_j}$

$output_{(j,11)} \leftarrow G_{ac_j}$

$output_{(j,12)} \leftarrow G_{cu_j}$

$output_{(j,13)} \leftarrow G_{cl_j}$

$output_{(j,14)} \leftarrow G_{cq_j}$

$output_{(j,15)} \leftarrow G_{cc_j}$

$j \leftarrow j + 1$

$a_j \leftarrow a_{j-1} + D_{ag_{j-1}}$

$$c_j \leftarrow c_{j-1} + D_{cg_{j-1}}$$

$$a_j \leftarrow \begin{cases} t & \text{if } a_j \geq t \\ a_j & \text{otherwise} \end{cases}$$

$$NCB_j \leftarrow NCB_{j-1} + C_{blk}$$

output

Recursive Loop for Industry Model

{R/t = 4.0 and a/c=3 The R/t lower Limit for Original Raju-Newman model and aspect ratio a/2c was fixed at 6}

$$CGR_{Bam.Bam} :=$$

$j \leftarrow 0$

$a_0 \leftarrow a_0$

$c_0 \leftarrow c_0$

$NCB_0 \leftarrow C_{blk}$

while $j \le I_{lim}$

$\sigma_0 \leftarrow ODRG1_3$

$\sigma_1 \leftarrow ODRG1_4$

$\sigma_2 \leftarrow ODRG1_5$

$\sigma_3 \leftarrow ODRG1_6$

$\xi_0 \leftarrow \sigma_0$

$$\xi_1 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.25 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^3$$

$$\xi_2 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.5 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^3$$

$$\xi_3 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.75 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^3$$

$$\xi_4 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{1.0 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^3$$

$x_0 \leftarrow 0.0$

$x_1 \leftarrow 0.25$

$x_2 \leftarrow 0.5$

$x_3 \leftarrow 0.75$

$x_4 \leftarrow 1.0$

$X \leftarrow \text{stack}(x_0, x_1, x_2, x_3, x_4)$

$ST \leftarrow \text{stack}(\xi_0, \xi_1, \xi_2, \xi_3, \xi_4)$

$RG \leftarrow \text{regress}(X, ST, 3)$

$\sigma_{00} \leftarrow RG_3$

$\sigma_{10} \leftarrow RG_4$

$\sigma_{20} \leftarrow RG_5$

$\sigma_{30} \leftarrow RG_6$

$AR_j \leftarrow \dfrac{a_j}{c_j}$

$AT_j \leftarrow \dfrac{a_j}{t}$

$G_{au_j} \leftarrow f_{aU}(4, .3, AT_j)$

$G_{al_j} \leftarrow f_{aL}(4, .3, AT_j)$

$G_{aq_j} \leftarrow f_{aQ}(4, .3, AT_j)$

$G_{ac_j} \leftarrow f_{aC}(4, .3, AT_j)$

$$Q_j \leftarrow \begin{cases} 1 + 1.464 \cdot \left(\dfrac{a_j}{c_j}\right)^{1.65} & \text{if } c_j \geq a_j \\ 1 + 1.464 \cdot \left(\dfrac{c_j}{a_j}\right)^{1.65} & \text{otherwise} \end{cases}$$

$$K_{a_j} \leftarrow \left(\frac{\pi \cdot a_j}{Q_j}\right)^{0.5} \cdot \left(\sigma_{00} \cdot G_{au_j} + \sigma_{10} \cdot G_{al_j} + \sigma_{20} \cdot G_{aq_j} + \sigma_{30} \cdot G_{ac_j}\right)$$

$K_{\alpha_j} \leftarrow K_{a_j} \cdot 1.099$

$$K_{\alpha_j} \leftarrow \begin{cases} 9.0 & \text{if } K_{\alpha_j} \leq 9.0 \\ K_{\alpha_j} & \text{otherwise} \end{cases}$$

$D_{a_j} \leftarrow C_0 \cdot \left(K_{\alpha_j} - 9.0\right)^{1.16}$

$$D_{ag_j} \leftarrow \begin{cases} D_{a_j} \cdot CF_{inhr} \cdot C_{blk} & \text{if } K_{\alpha_j} < 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} & \text{otherwise} \end{cases}$$

$$D_{cg_j} \leftarrow D_{ag_j} \cdot 3$$

$$output_{(j,0)} \leftarrow j$$

$$output_{(j,1)} \leftarrow a_j$$

$$output_{(j,2)} \leftarrow c_j - c_0$$

$$output_{(j,3)} \leftarrow D_{ag_j}$$

$$output_{(j,4)} \leftarrow D_{cg_j}$$

$$output_{(j,5)} \leftarrow K_{a_j}$$

$$output_{(j,7)} \leftarrow \frac{NCB_j}{365 \cdot 24}$$

$$output_{(j,8)} \leftarrow G_{au_j}$$

$$output_{(j,9)} \leftarrow G_{al_j}$$

$$output_{(j,10)} \leftarrow G_{aq_j}$$

$$output_{(j,11)} \leftarrow G_{ac_j}$$

$$j \leftarrow j + 1$$

$$a_j \leftarrow a_{j-1} + D_{ag_{j-1}}$$

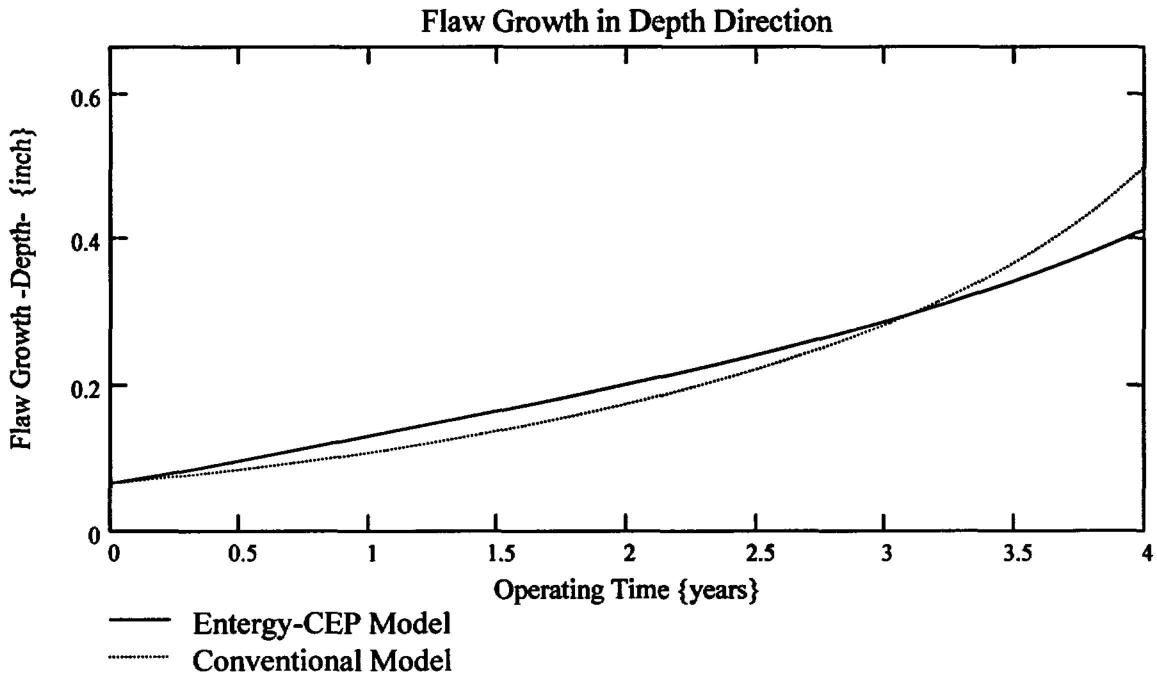
$$c_j \leftarrow c_{j-1} + D_{cg_{j-1}}$$

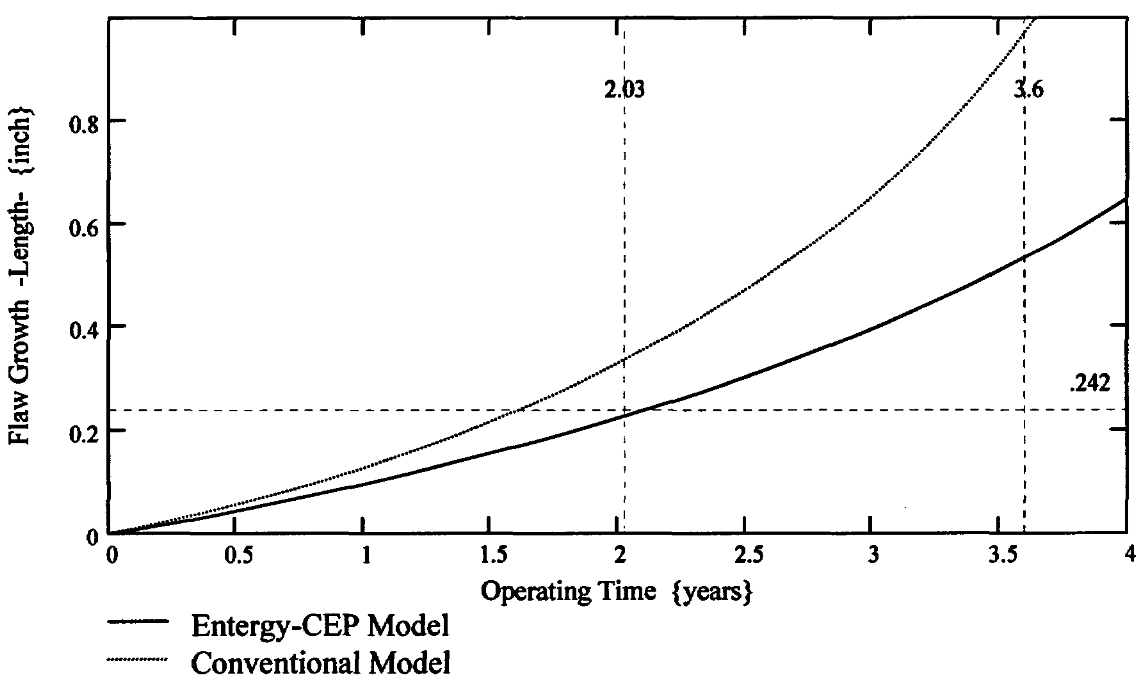
$$a_j \leftarrow \begin{cases} t & \text{if } a_j \geq t \\ a_j & \text{otherwise} \end{cases}$$

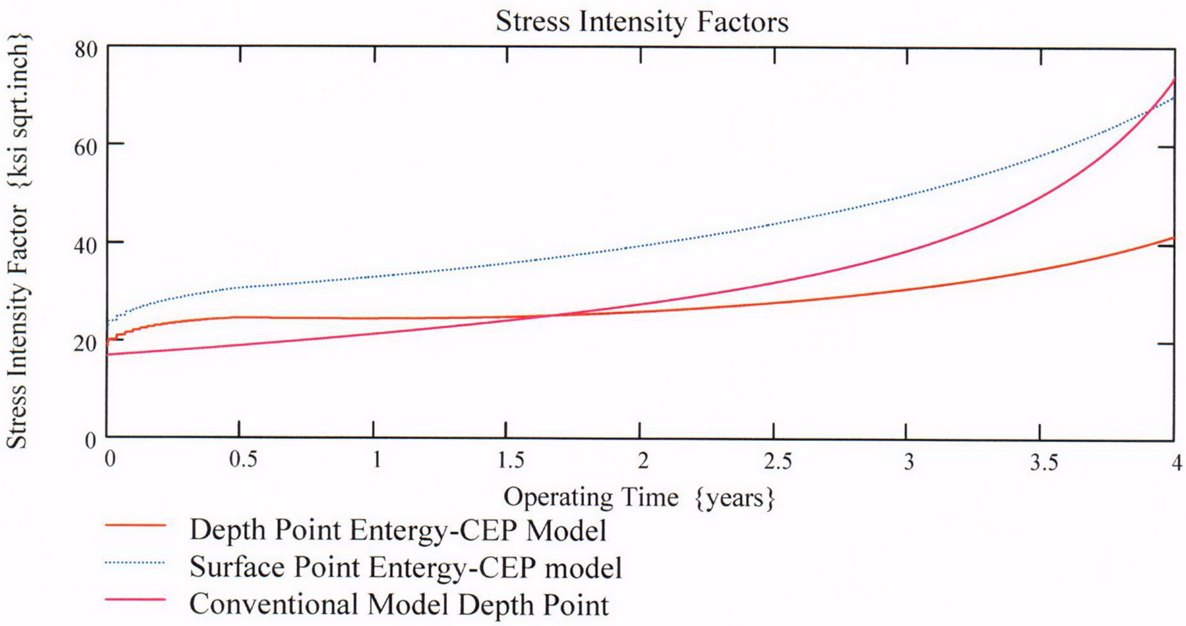
$$NCB_j \leftarrow NCB_{j-1} + C_{blk}$$

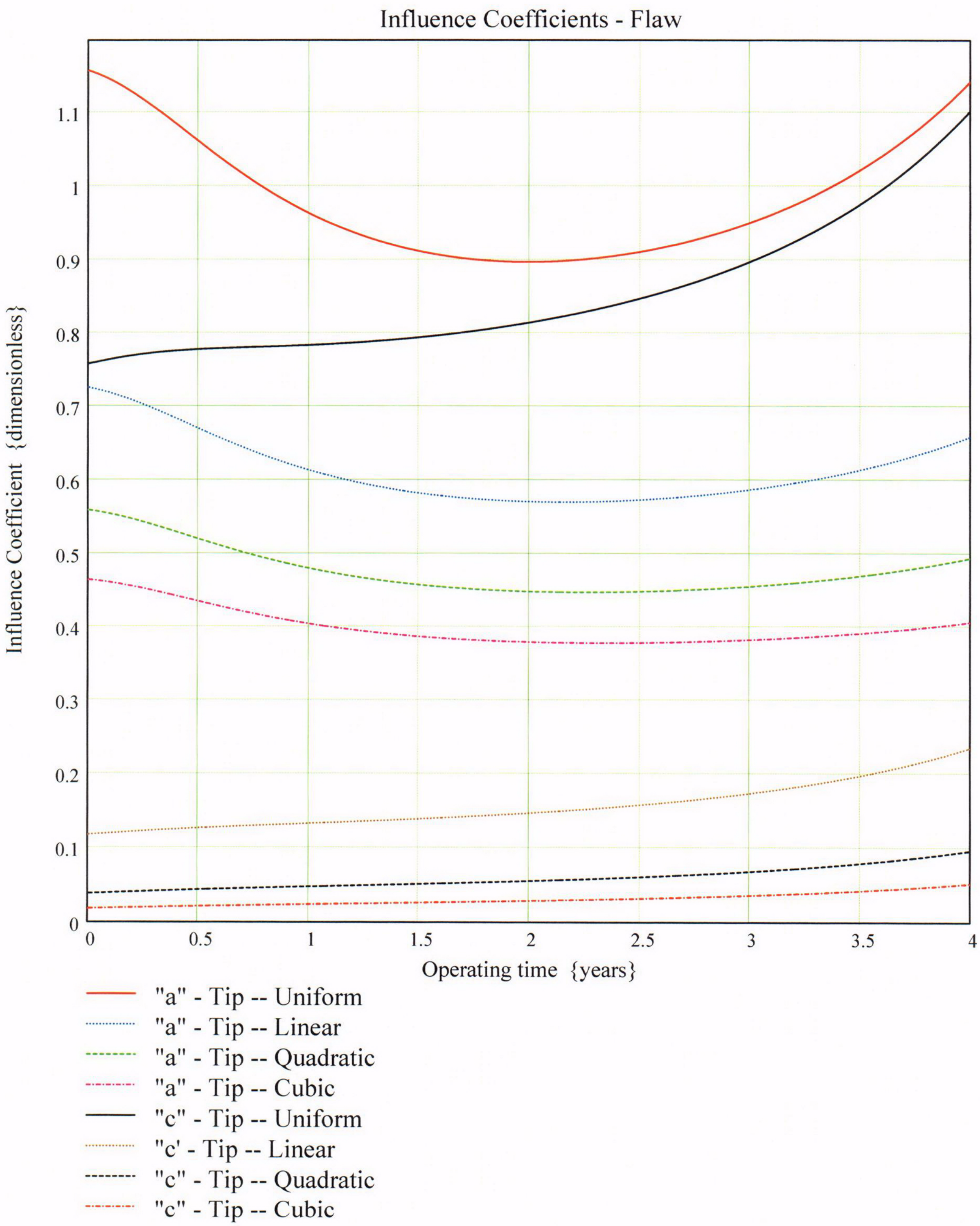
output

$$k := 0 .. I_{lim}$$

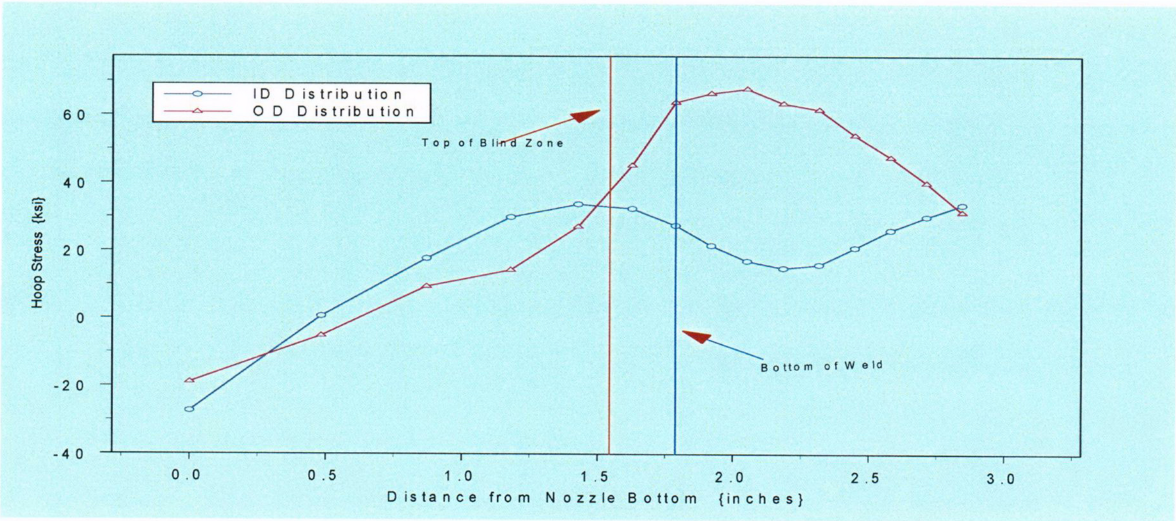

Flaw Growth in Depth Direction
Flaw Growth -Depth- {inch}
0
0.2
0.4
0.6
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Entergy-CEP Model
Conventional Model

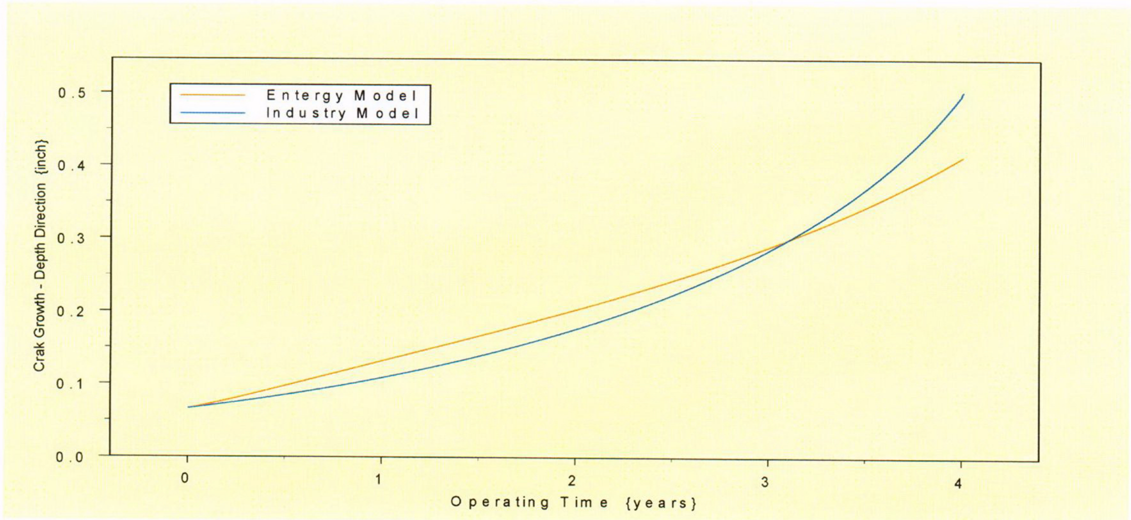

Flaw Growth -Length- {inch}
0
0.2
0.4
0.6
0.8
2.03
3.6
.242
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Entergy-CEP Model
Conventional Model


Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point Entergy-CEP Model
Surface Point Entergy-CEP model
Conventional Model Depth Point


Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic
"c" - Tip -- Cubic

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(k,5)}} =$
1.158	22.27	18.751
1.158	23.876	20.044
1.158	23.887	20.052
1.158	23.898	20.061
1.157	23.909	20.07
1.157	23.92	20.078
1.157	23.931	20.086
1.156	23.942	20.095
1.156	23.953	20.103
1.156	23.963	20.111
1.156	23.974	20.12
1.155	23.985	20.128
1.155	23.996	20.136
1.155	24.985	20.93
1.154	24.997	20.939
1.154	25.008	20.947


ID Distribution
OD Distribution
Top of Blind Zone
Bottom of Weld
Hoop Stress {ksi}
60
40
20
0
-20
-40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Distance from Nozzle Bottom {inches}


Entergy Model
Industry Model
Crak Growth - Depth Direction {inch}
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
Operating Time {years}

Developed by:
J. S. Brihmadesam

Verified by:
B. C. Gray

Primary Water Stress Corrosion Crack Growth Analysis ID flaw;
Developed by Central Engineering Porgrams, Entergy Operations Inc.

Developed by: J. S. Brihmadesam

Verified by: B. C. Gray

Refrences :
1) "Stress Intensity factors for Part-through Surface cracks"; NASA TM-11707; July 1992.
2) Crack Growth of Alloy 600 Base Metal in PWR Environments; EPRI MRP Report MRP 55 Rev. 1, 2002

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8.8" Degree Nozzle, "0" Degree Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

Mean Radius -to- Thickness Ratio:- "R_m/t" -- between 1.0 and 300.0

Note : ***Used the Metric form of the equation from EPRI MRP 55-Rev. 1.***
The correction is applied in the determination of the crack extension to obtain the value in inch/hr.

ID Surface Flaw

The first Required input is a location for a point on the tube elevation to define the point of interest (e.g. The top of the Blind Zone, or bottom of fillet weld etc.). This reference point is necessar to evaluate the stress distribution on the flaw both for the initial flaw and for a growing flaw. This is defined as the reference point. Enter a number (inch) that represnets the reference point elevation measured upward from the nozzle end.

$$Ref_{Point} := 1.544$$

To place the flaw with repsect to the reference point, the flaw tips and center can be located as follows:

1) The Upper "c- tip" located at the reference point (Enter 1)
2) The Center of the flaw at the reference point (Enter 2)
3) The lower "c- tip" located at the reference point (Enter 3).

$$Val := 1$$

The Input Below is the Upper Limit for the evaluation, which is the bottom of the fillet weld leg. This is shown on the Excel spread sheet as weld bottom. Enter this dimension (measured from nozzle bottom) below.

$UL_{Strs.Dist} := 2.05$ Upper axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom).

Input Data :-

$L := .35$	Initial Flaw Length
$a_0 := 0.035$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

$R_o := \frac{od}{2}$ $\quad R_{id} := \frac{id}{2}$ $\quad t := R_o - R_{id}$ $\quad R_m := R_{id} + \frac{t}{2}$ $\quad Tim_{opr} := Years \cdot 365 \cdot 24$

$CF_{inhr} := 1.417 \cdot 10^5$ $\quad C_{blk} := \frac{Tim_{opr}}{I_{lim}}$ $\quad Prnt_{blk} := \left|\frac{I_{lim}}{50}\right|$ $\quad c_0 := \frac{L}{2}$ $\quad R_t := \frac{R_m}{t}$

$$C_{01} := e^{\left[\frac{-Q_g}{1.103 \cdot 10^{-3}} \cdot \left(\frac{1}{T+459.67} - \frac{1}{T_{ref}+459.67}\right)\right]} \cdot \alpha_{0c}$$ Temperature Correction for Coefficient Alpha

$C_0 := C_{01}$ — 75 th percentile MRP-55 Revision 1

Stress Input Data

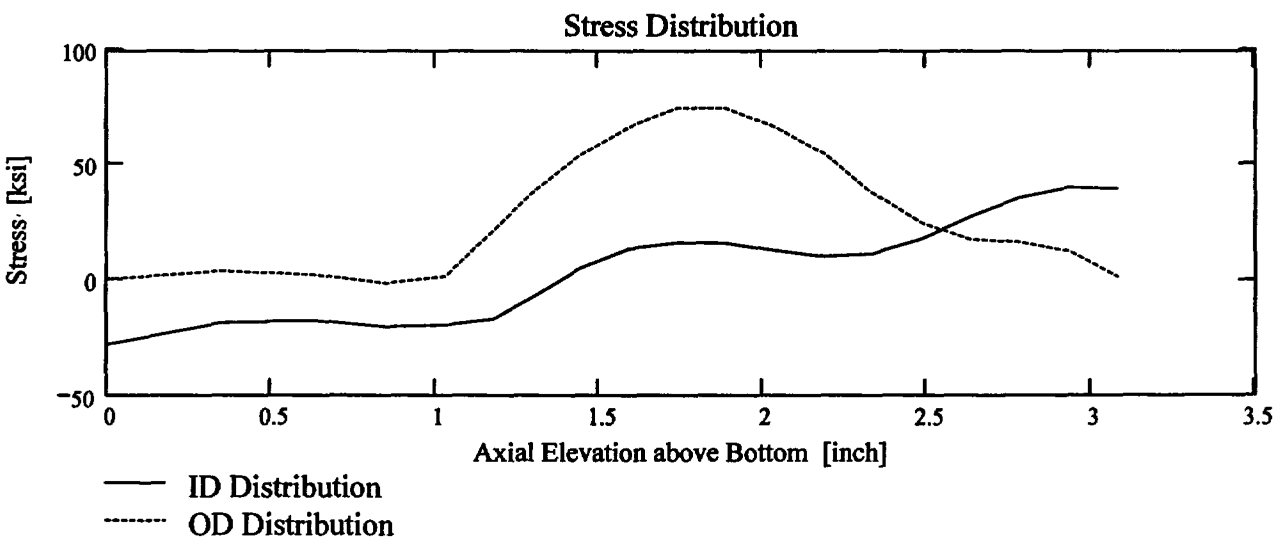
Input all available Nodal stress data in the table below. The column designations are as follows:
- ***Column "0" = Axial distance from minimum to maximum recorded on data sheet (inches)***
- ***Column "1" = ID Stress data at each Elevation (ksi)***
- ***Cloumn "2" = Quarter Thickness Stress data at each Elevation (ksi)***
- ***Cloumn "3" = Mid Thickness Stress data at each Elevation (ksi)***
- ***Column "4" = Three quarter Thickness Stress data at each Elevation (ksi)***
- ***Column "5" = OD Stress data at each Elevation (ksi)***

AllData :=

	0	1	2	3	4	5
0	0	-28.32	-18.3	-12.16	-6.2	-0.02
1	0.35	-18.79	-12.49	-6.61	-1.37	3.65
2	0.63	-17.84	-10.52	-4.41	-0.48	2.08
3	0.85	-20.52	-12.97	-5.9	-0.87	-1.54
4	1.03	-19.66	-11.83	-5.29	0.23	1.46
5	1.18	-17.2	-10.59	-0.52	16.33	21.02
6	1.29	-8.02	-2.2	10.46	32.66	37.29
7	1.44	4.78	9.56	24.9	38.18	54.09
8	1.59	13.25	18.57	35.28	52.81	66.52
9	1.74	16	22.02	39.19	62.95	75
10	1.89	15.86	23.14	40.23	64.33	74.87
11	2.04	12.63	23.76	41.26	58.67	66.78

DATA FROM EXCEL SPREADSHE[illegible]

$AXLen := AllData^{\langle 0 \rangle}$ $ID_{All} := AllData^{\langle 1 \rangle}$ $OD_{All} := AllData^{\langle 5 \rangle}$



Observing the stress distribution select the region in the table above labeled $Data_{All}$ that represents the region of interest. This needs to be done especially for distributions that have a large compressive stress at the nozzle bottom and high tensile stresses at the J-weld location. Higlight the region in the above table representing the region to be selected (click on the first cell for selection and drag the mouse whilst holding the left mosue button down. Once this is done click the right mouse button and select "Copy Selection"; this will copy the selected area on to the clipboard. Then click on the "Matrix" below (to the right of the dtat statement) to highlight the entire matrix and delete it from the edit menu. When the Mathcad input symbol appears, use the paste function in the tool bar to paste the selection.

$$Data := \begin{pmatrix} 0 & -28.324 & -18.299 & -12.16 & -6.201 & -0.021 \\ 0.35 & -18.794 & -12.495 & -6.607 & -1.366 & 3.655 \\ 0.63 & -17.838 & -10.518 & -4.407 & -0.477 & 2.08 \\ 0.854 & -20.517 & -12.968 & -5.902 & -0.874 & -1.536 \\ 1.034 & -19.663 & -11.831 & -5.288 & 0.227 & 1.46 \\ 1.178 & -17.203 & -10.587 & -0.515 & 16.326 & 21.019 \\ 1.293 & -8.023 & -2.205 & 10.461 & 32.658 & 37.289 \\ 1.442 & 4.778 & 9.557 & 24.903 & 38.177 & 54.089 \\ 1.591 & 13.252 & 18.569 & 35.278 & 52.808 & 66.517 \\ 1.74 & 16.001 & 22.017 & 39.194 & 62.945 & 75.001 \\ 1.889 & 15.857 & 23.14 & 40.235 & 64.335 & 74.874 \\ 2.038 & 12.629 & 23.76 & 41.263 & 58.673 & 66.777 \end{pmatrix}$$

DATA USED FOR ANALYSIS

$Axl := Data^{\langle 0 \rangle}$ $MD := Data^{\langle 3 \rangle}$ $ID := Data^{\langle 1 \rangle}$ $TQ := Data^{\langle 4 \rangle}$ $QT := Data^{\langle 2 \rangle}$ $OD := Data^{\langle 5 \rangle}$

$R_{ID} := regress(Axl, ID, 3)$ $R_{QT} := regress(Axl, QT, 3)$

$R_{OD} := regress(Axl, OD, 3)$

$R_{MD} := regress(Axl, MD, 3)$ $R_{TQ} := regress(Axl, TQ, 3)$

THIRD ORDER POLYNOMIAL FIT
(ALONG TUBE AXIS)

$$FL_{Cntr} := \begin{cases} Ref_{Point} - c_0 & \text{if } Val = 1 \\ Ref_{Point} & \text{if } Val = 2 \\ Ref_{Point} + c_0 & \text{otherwise} \end{cases}$$

Flaw center Location above Nozzle Bottom

$$U_{Tip} := FL_{Cntr} + c_0$$

$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

No User Input is required beyond this Point

Calculation to develop Stress Profiles for Analysis

$N := 20$ *Number of locations for stress profiles*

$$Loc_0 := FL_{Cntr} - L$$

$$i := 1..N + 3$$

$$Incr_i := \begin{cases} c_0 & \text{if } i < 4 \\ Inc_{Strs.avg} & \text{otherwise} \end{cases}$$

$$Loc_i := Loc_{i-1} + Incr_i$$

$$SID_i := R_{ID_3} + R_{ID_4} \cdot Loc_i + R_{ID_5} \cdot (Loc_i)^2 + R_{ID_6} \cdot (Loc_i)^3$$

$$SQT_i := R_{QT_3} + R_{QT_4} \cdot Loc_i + R_{QT_5} \cdot (Loc_i)^2 + R_{QT_6} \cdot (Loc_i)^3$$

$$SMD_i := R_{MD_3} + R_{MD_4} \cdot Loc_i + R_{MD_5} \cdot (Loc_i)^2 + R_{MD_6} \cdot (Loc_i)^3$$

$$STQ_i := R_{TQ_3} + R_{TQ_4} \cdot Loc_i + R_{TQ_5} \cdot (Loc_i)^2 + R_{TQ_6} \cdot (Loc_i)^3$$

$$SOD_i := R_{OD_3} + R_{OD_4} \cdot Loc_i + R_{OD_5} \cdot (Loc_i)^2 + R_{OD_6} \cdot (Loc_i)^3$$

$$j := 1..N$$

$$S_{id_j} := \begin{cases} \dfrac{SID_j + SID_{j+1} + SID_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{id_{j-1}} \cdot (j+1) + SID_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{qt_j} := \begin{cases} \dfrac{SQT_j + SQT_{j+1} + SQT_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{qt_{(j-1)}} \cdot (j+1) + SQT_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{md_j} := \begin{cases} \dfrac{SMD_j + SMD_{j+1} + SMD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{md_{j-1}} \cdot (j+1) + SMD_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

$$S_{tq_j} := \begin{cases} \dfrac{STQ_j + STQ_{j+1} + STQ_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{tq_{j-1}} \cdot (j+1) + STQ_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

~~INITIAL FLAW~~ LOCATION

LOCATIONS ABOVE FLAW

$$S_{od_j} := \begin{cases} \dfrac{SOD_j + SOD_{j+1} + SOD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{od_{j-1}} \cdot (j+1) + SOD_{j+2}}{j+2} & \text{otherwise} \end{cases}$$

Stress Distribution for ID Flaws (i.e. ID to OD Stress distribution)

$u_0 := 0.000$ $u_1 := 0.25$ $u_2 := 0.50$ $u_3 := 0.75$ $u_4 := 1.00$

$$Y := \text{stack}(u_0, u_1, u_2, u_3, u_4)$$

$SIG_1 := \text{stack}(S_{id_1}, S_{qt_1}, S_{md_1}, S_{tq_1}, S_{od_1})$ $SIG_2 := \text{stack}(S_{id_2}, S_{qt_2}, S_{md_2}, S_{tq_2}, S_{od_2})$

$SIG_3 := \text{stack}(S_{id_3}, S_{qt_3}, S_{md_3}, S_{tq_3}, S_{od_3})$ $SIG_4 := \text{stack}(S_{id_4}, S_{qt_4}, S_{md_4}, S_{tq_4}, S_{od_4})$

$SIG_5 := \text{stack}(S_{id_5}, S_{qt_5}, S_{md_5}, S_{tq_5}, S_{od_5})$ $SIG_6 := \text{stack}(S_{id_6}, S_{qt_6}, S_{md_6}, S_{tq_6}, S_{od_6})$

$SIG_7 := \text{stack}(S_{id_7}, S_{qt_7}, S_{md_7}, S_{tq_7}, S_{od_7})$ $SIG_8 := \text{stack}(S_{id_8}, S_{qt_8}, S_{md_8}, S_{tq_8}, S_{od_8})$

$SIG_9 := \text{stack}(S_{id_9}, S_{qt_9}, S_{md_9}, S_{tq_9}, S_{od_9})$ $SIG_{10} := \text{stack}(S_{id_{10}}, S_{qt_{10}}, S_{md_{10}}, S_{tq_{10}}, S_{od_{10}})$

$SIG_{11} := \text{stack}(S_{id_{11}}, S_{qt_{11}}, S_{md_{11}}, S_{tq_{11}}, S_{od_{11}})$ $SIG_{12} := \text{stack}(S_{id_{12}}, S_{qt_{12}}, S_{md_{12}}, S_{tq_{12}}, S_{od_{12}})$

$SIG_{13} := \text{stack}(S_{id_{13}}, S_{qt_{13}}, S_{md_{13}}, S_{tq_{13}}, S_{od_{13}})$ $SIG_{14} := \text{stack}(S_{id_{14}}, S_{qt_{14}}, S_{md_{14}}, S_{tq_{14}}, S_{od_{14}})$

$SIG_{15} := \text{stack}(S_{id_{15}}, S_{qt_{15}}, S_{md_{15}}, S_{tq_{15}}, S_{od_{15}})$ $SIG_{16} := \text{stack}(S_{id_{16}}, S_{qt_{16}}, S_{md_{16}}, S_{tq_{16}}, S_{od_{16}})$

$SIG_{17} := \text{stack}(S_{id_{17}}, S_{qt_{17}}, S_{md_{17}}, S_{tq_{17}}, S_{od_{17}})$ $SIG_{18} := \text{stack}(S_{id_{18}}, S_{qt_{18}}, S_{md_{18}}, S_{tq_{18}}, S_{od_{18}})$

$SIG_{19} := stack\left(S_{id_{19}}, S_{qt_{19}}, S_{md_{19}}, S_{tq_{19}}, S_{od_{19}}\right)$ $SIG_{20} := stack\left(S_{id_{20}}, S_{qt_{20}}, S_{md_{20}}, S_{tq_{20}}, S_{od_{20}}\right)$

Regression of Throughwall Stress distribution to obtain Stress coefficients throughwall using a Third Order polynomial

$IDRG_1 := regress\left(Y, SIG_1, 3\right)$ $IDRG_2 := regress\left(Y, SIG_2, 3\right)$

$IDRG_3 := regress\left(Y, SIG_3, 3\right)$ $IDRG_4 := regress\left(Y, SIG_4, 3\right)$

$IDRG_5 := regress\left(Y, SIG_5, 3\right)$ $IDRG_6 := regress\left(Y, SIG_6, 3\right)$

$IDRG_7 := regress\left(Y, SIG_7, 3\right)$ $IDRG_8 := regress\left(Y, SIG_8, 3\right)$

$IDRG_9 := regress\left(Y, SIG_9, 3\right)$ $IDRG_{10} := regress\left(Y, SIG_{10}, 3\right)$

$IDRG_{11} := regress\left(Y, SIG_{11}, 3\right)$ $IDRG_{12} := regress\left(Y, SIG_{12}, 3\right)$

$IDRG_{13} := regress\left(Y, SIG_{13}, 3\right)$ $IDRG_{14} := regress\left(Y, SIG_{14}, 3\right)$

$IDRG_{15} := regress\left(Y, SIG_{15}, 3\right)$ $IDRG_{16} := regress\left(Y, SIG_{16}, 3\right)$

$IDRG_{17} := regress\left(Y, SIG_{17}, 3\right)$ $IDRG_{18} := regress\left(Y, SIG_{18}, 3\right)$

$IDRG_{19} := regress\left(Y, SIG_{19}, 3\right)$ $IDRG_{20} := regress\left(Y, SIG_{20}, 3\right)$

Stress Distribution in the tube. ***Stress influence coefficients obtained from thrid order polynomial curve fit to the throughwall stress distribution***

$Prop_{Length} := UL_{Strs.Dist} - U_{Tip}$ $\qquad Prop_{Length} = 0.506$

Data Files for Flaw Shape Factors from NASA SC04 Model

{NO INPUT Required}

Mettu Raju Newman Sivakumar Forman Solution of ID Part throughwall Flaw in Cylinder

Jsb :=

	0	1	2
0	1.000	0.200	0.000
1	1.000	0.200	0.200
2	1.000	0.200	0.500
3	1.000	0.200	0.800
4	1.000	0.200	1.000
5	1.000	0.400	0.000
6	1.000	0.400	0.200
7	1.000	0.400	0.500
8	1.000	0.400	0.800
9	1.000	0.400	1.000
10	1.000	1.000	0.000
11	1.000	1.000	0.200
12	1.000	1.000	0.500
13	1.000	1.000	0.800
14	1.000	1.000	1.000
15	2.000	0.200	0.000
16	2.000	0.200	0.200
17	2.000	0.200	0.500
18	2.000	0.200	0.800
19	2.000	0.200	1.000
20	2.000	0.400	0.000
21	2.000	0.400	0.200
22	2.000	0.400	0.500
23	2.000	0.400	0.800

Column 0 = R/t ratio

Column 1 = a/c ratio

Column 3 = a/t ratio

23	2.000	0.400	0.800
24	2.000	0.400	1.000
25	2.000	1.000	0.000
26	2.000	1.000	0.200
27	2.000	1.000	0.500
28	2.000	1.000	0.800
29	2.000	1.000	1.000
30	4.000	0.200	0.000
31	4.000	0.200	0.200
32	4.000	0.200	0.500
33	4.000	0.200	0.800
34	4.000	0.200	1.000
35	4.000	0.400	0.000
36	4.000	0.400	0.200
37	4.000	0.400	0.500
38	4.000	0.400	0.800
39	4.000	0.400	1.000
40	4.000	1.000	0.000
41	4.000	1.000	0.200
42	4.000	1.000	0.500
43	4.000	1.000	0.800
44	4.000	1.000	1.000
45	10.000	0.200	0.000
46	10.000	0.200	0.200
47	10.000	0.200	0.500
48	10.000	0.200	0.800
49	10.000	0.200	1.000
50	10.000	0.400	0.000
51	10.000	0.400	0.200
52	10.000	0.400	0.500
53	10.000	0.400	0.800
54	10.000	0.400	1.000
55	10.000	1.000	0.000
56	10.000	1.000	0.200
57	10.000	1.000	0.500
58	10.000	1.000	0.800
59	10.000	1.000	1.000
60	300.000	0.200	0.000
61	300.000	0.200	0.200
62	300.000	0.200	0.500
63	300.000	0.200	0.800
64	300.000	0.200	1.000
65	300.000	0.400	0.000
66	300.000	0.400	0.200

67	300.000	0.400	0.500
68	300.000	0.400	0.800
69	300.000	0.400	1.000
70	300.000	1.000	0.000
71	300.000	1.000	0.200
72	300.000	1.000	0.500
73	300.000	1.000	0.800
74	300.000	1.000	1.000

U = Uniform; L = Linear; Q = Quadratic; C = Cubic

"Q-tip" (columns 0–3) | "C-tip" (columns 4–7)

Sambi :=

	0 U	1 L	2 Q	3 C	4 U	5 L	6 Q	7 C
0	1.076	0.693	0.531	0.434	0.608	0.083	0.023	0.009
1	1.056	0.647	0.495	0.408	0.615	0.085	0.027	0.013
2	1.395	0.767	0.557	0.446	0.871	0.171	0.069	0.038
3	2.53	1.174	0.772	0.58	1.554	0.363	0.155	0.085
4	3.846	1.615	0.995	0.716	2.277	0.544	0.233	0.127
5	1.051	0.689	0.536	0.444	0.74	0.112	0.035	0.015
6	1.011	0.646	0.504	0.421	0.745	0.119	0.041	0.02
7	1.149	0.694	0.529	0.435	0.916	0.181	0.073	0.04
8	1.6	0.889	0.642	0.51	1.334	0.307	0.132	0.073
9	2.087	1.093	0.761	0.589	1.752	0.421	0.183	0.101
10	0.992	0.704	0.534	0.506	1.044	0.169	0.064	0.032
11	0.987	0.701	0.554	0.491	1.08	0.182	0.067	0.034
12	1.01	0.709	0.577	0.493	1.116	0.2	0.078	0.041
13	1.07	0.73	0.623	0.523	1.132	0.218	0.095	0.051
14	1.128	0.75	0.675	0.556	1.131	0.229	0.11	0.06
15	1.049	0.673	0.519	0.427	0.6	0.078	0.021	0.008
16	1.091	0.661	0.502	0.413	0.614	0.083	0.025	0.012
17	1.384	0.764	0.556	0.446	0.817	0.15	0.058	0.031
18	2.059	1.033	0.708	0.545	1.3	0.291	0.123	0.067
19	2.739	1.301	0.858	0.643	1.783	0.421	0.18	0.099
20	1.075	0.674	0.527	0.436	0.73	0.072	0.044	0.021
21	1.045	0.659	0.511	0.425	0.76	0.122	0.043	0.021
22	1.16	0.71	0.536	0.441	0.919	0.197	0.064	0.034

23	1.51	0.854	0.623	0.498	1.231	0.271	0.114	0.062
24	1.876	0.995	0.71	0.555	1.519	0.317	0.161	0.089
25	1.037	0.732	0.594	0.505	1.132	0.192	0.07	0.035
26	1.003	0.707	0.577	0.493	1.113	0.19	0.071	0.036
27	1.023	0.714	0.58	0.495	1.155	0.207	0.08	0.042
28	1.129	0.774	0.619	0.521	1.286	0.247	0.098	0.052
29	1.242	0.84	0.661	0.549	1.416	0.285	0.115	0.061
30	1.003	0.649	0.511	0.43	0.577	0.07	0.015	0.005
31	1.097	0.666	0.511	0.426	0.606	0.079	0.023	0.01
32	1.405	0.776	0.567	0.46	0.797	0.141	0.054	0.028
33	1.959	0.996	0.692	0.542	1.201	0.262	0.108	0.059
34	2.461	1.197	0.808	0.619	1.586	0.37	0.154	0.085
35	1.024	0.668	0.528	0.451	0.737	0.11	0.033	0.015
36	1.057	0.666	0.52	0.439	0.77	0.123	0.042	0.021
37	1.193	0.715	0.545	0.454	0.924	0.174	0.068	0.036
38	1.443	0.828	0.614	0.509	1.219	0.263	0.109	0.059
39	1.665	0.934	0.681	0.565	1.487	0.339	0.143	0.078
40	1.005	0.72	0.597	0.518	1.119	0.188	0.068	0.034
41	1.009	0.713	0.588	0.511	1.128	0.194	0.072	0.037
42	1.041	0.726	0.594	0.515	1.191	0.214	0.082	0.043
43	1.105	0.768	0.623	0.536	1.316	0.248	0.097	0.05
44	1.162	0.81	0.653	0.558	1.428	0.277	0.109	0.055
45	0.973	0.635	0.499	0.446	0.579	0.07	0.016	0.005
46	1.115	0.673	0.514	0.438	0.607	0.079	0.023	0.01
47	1.427	0.783	0.571	0.462	0.791	0.138	0.052	0.027
48	1.872	0.96	0.671	0.529	1.179	0.253	0.104	0.056
49	2.23	1.108	0.757	0.594	1.548	0.356	0.149	0.081
50	0.992	0.656	0.52	0.443	0.733	0.109	0.032	0.014
51	1.072	0.672	0.523	0.441	0.777	0.125	0.043	0.021
52	1.217	0.723	0.549	0.456	0.936	0.176	0.069	0.036
53	1.393	0.806	0.601	0.493	1.219	0.259	0.106	0.056
54	1.521	0.875	0.647	0.528	1.469	0.328	0.135	0.071
55	0.994	0.715	0.59	0.518	1.114	0.187	0.068	0.035
56	1.015	0.715	0.588	0.512	1.14	0.197	0.074	0.038
57	1.05	0.729	0.596	0.515	1.219	0.221	0.085	0.044
58	1.09	0.76	0.618	0.532	1.348	0.255	0.099	0.051
59	1.118	0.788	0.639	0.55	1.456	0.282	0.109	0.056
60	0.936	0.62	0.486	0.405	0.582	0.068	0.015	0.005
61	1.145	0.681	0.514	0.42	0.613	0.081	0.024	0.011
62	1.459	0.79	0.569	0.454	0.79	0.138	0.051	0.026
63	1.774	0.917	0.641	0.501	1.148	0.239	0.096	0.051
64	1.974	1.008	0.696	0.537	1.482	0.328	0.134	0.07
65	0.982	0.651	0.512	0.427	0.721	0.103	0.031	0.013

66	1.095	0.677	0.52	0.431	0.782	0.127	0.045	0.022
67	1.244	0.727	0.546	0.446	0.946	0.18	0.071	0.037
68	1.37	0.791	0.585	0.473	1.201	0.253	0.102	0.054
69	1.438	0.838	0.618	0.496	1.413	0.31	0.126	0.066

$W := Jsb^{\langle 0 \rangle}$ $\quad X := Jsb^{\langle 1 \rangle}$ $\quad Y := Jsb^{\langle 2 \rangle}$

$a_U := Sambi^{\langle 0 \rangle}$ $\quad a_L := Sambi^{\langle 1 \rangle}$ $\quad a_Q := Sambi^{\langle 2 \rangle}$ $\quad a_C := Sambi^{\langle 3 \rangle}$

$c_U := Sambi^{\langle 4 \rangle}$ $\quad c_L := Sambi^{\langle 5 \rangle}$ $\quad c_Q := Sambi^{\langle 6 \rangle}$ $\quad c_C := Sambi^{\langle 7 \rangle}$

$$n := \begin{cases} 3 & \text{if } R_t \le 4.0 \\ 2 & \text{otherwise} \end{cases}$$

"a-Tip" Uniform Term

$M_{aU} := \text{augment}(W, X, Y)$ $\quad V_{aU} := a_U$ $\quad R_{aU} := \text{regress}(M_{aU}, V_{aU}, n)$

$$f_{aU}(W,X,Y) := \text{interp}\left[R_{aU}, M_{aU}, V_{aU}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aU}(4,.4,.8) = 1.424$ *Check Calculation*

Linear Term

$M_{aL} := \text{augment}(W, X, Y)$ $\quad V_{aL} := a_L$ $\quad R_{aL} := \text{regress}(M_{aL}, V_{aL}, n)$

$$f_{aL}(W,X,Y) := \mathrm{interp}\left[R_{aL}, M_{aL}, V_{aL}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aL}(4,.4,.8) = 0.827$ *Check Calculation*

Quadratic Term

$M_{aQ} := \mathrm{augment}(W,X,Y)$ $V_{aQ} := a_Q$ $R_{aQ} := \mathrm{regress}(M_{aQ}, V_{aQ}, n)$

$$f_{aQ}(W,X,Y) := \mathrm{interp}\left[R_{aQ}, M_{aQ}, V_{aQ}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aQ}(4,.4,.8) = 0.614$ *Check Calculation*

Cubic Term

$M_{aC} := \mathrm{augment}(W,X,Y)$ $V_{aC} := a_C$ $R_{aC} := \mathrm{regress}(M_{aC}, V_{aC}, n)$

$$f_{aC}(W,X,Y) := \mathrm{interp}\left[R_{aC}, M_{aC}, V_{aC}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{aC}(4,.4,.8) = 0.502$ *Check Calculation*

"*C*" Tip Coefficients

Uniform Term

$M_{cU} := \mathrm{augment}(W,X,Y)$ $V_{cU} := c_U$ $R_{cU} := \mathrm{regress}(M_{cU}, V_{cU}, n)$

$$f_{cU}(W,X,Y) := \text{interp}\left[R_{cU}, M_{cU}, V_{cU}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cU}(4,.4,.8) = 1.222$ *Check Calculation*

Linear Term

$M_{cL} := \text{augment}(W,X,Y)$ $V_{cL} := c_L$ $R_{cL} := \text{regress}(M_{cL}, V_{cL}, n)$

$$f_{cL}(W,X,Y) := \text{interp}\left[R_{cL}, M_{cL}, V_{cL}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cL}(2,.4,.8) = 0.282$ *Check Calculation*

Quadratic Term

$M_{cQ} := \text{augment}(W,X,Y)$ $V_{cQ} := c_Q$ $R_{cQ} := \text{regress}(M_{cQ}, V_{cQ}, n)$

$$f_{cQ}(W,X,Y) := \text{interp}\left[R_{cQ}, M_{cQ}, V_{cQ}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cQ}(4,.4,.8) = 0.11$ *Check Calculation*

Cubic Term

$M_{cC} := \text{augment}(W,X,Y)$ $V_{cC} := c_C$ $R_{cC} := \text{regress}(M_{cC}, V_{cC}, n)$

$$f_{cC}(W,X,Y) := \text{interp}\left[R_{cC}, M_{cC}, V_{cC}, \begin{pmatrix} W \\ X \\ Y \end{pmatrix}\right]$$

$f_{cC}(4,.4,.8) = 0.059$ *Check Calculation*

Calculations : Recursive calculations to estimate flaw growth

Recursive Loop for Calculation of PWSCC Crack Growth

$$
\begin{aligned}
CGR_{sambi} := \; & j \leftarrow 0 \\
& a_0 \leftarrow a_0 \\
& c_0 \leftarrow c_0 \\
& NCB_0 \leftarrow C_{blk} \\
& \text{while } j \le I_{lim} \\
& \quad \sigma_0 \leftarrow \begin{cases}
IDRG_{1_3} & \text{if } c_j \le c_0 \\
IDRG_{2_3} & \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\
IDRG_{3_3} & \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg} \\
IDRG_{4_3} & \text{if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg} \\
IDRG_{5_3} & \text{if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg} \\
IDRG_{6_3} & \text{if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg} \\
IDRG_{7_3} & \text{if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg} \\
IDRG_{8_3} & \text{if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg} \\
IDRG_{9_3} & \text{if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg} \\
IDRG_{10_3} & \text{if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}
\end{cases}
\end{aligned}
$$

Assignment of uniform stress coefficient throughwall distribution based on flaw location

$IDRG11_3$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$

$IDRG12_3$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$

$IDRG13_3$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$

$IDRG14_3$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$

$IDRG15_3$ if $c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$

$IDRG16_3$ if $c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$

$IDRG17_3$ if $c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$

$IDRG18_3$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$IDRG19_3$ if $c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$

$IDRG20_3$ otherwise

$\sigma_1 \leftarrow$

$IDRG1_4$ if $c_j \le c_0$

$IDRG2_4$ if $c_0 < c_j \le c_0 + Inc_{Strs.avg}$

$IDRG3_4$ if $c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$

$IDRG4_4$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$

$IDRG5_4$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$

$IDRG6_4$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$

$IDRG7_4$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$

$IDRG8_4$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$

$IDRG9_4$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$

$IDRG10_4$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$

$IDRG11_4$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$

$IDRG12_4$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$

Assignment of Linear Stress Coefficient throughwall distribution based on flaw location

$IDRG13_4$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$

$IDRG14_4$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$

$IDRG15_4$ if $c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$

$IDRG16_4$ if $c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$

$IDRG17_4$ if $c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$

$IDRG18_4$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$IDRG19_4$ if $c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$

$IDRG20_4$ otherwise

$\sigma_2 \leftarrow$ $IDRG1_5$ if $c_j \le c_0$

$IDRG2_5$ if $c_0 < c_j \le c_0 + Inc_{Strs.avg}$

$IDRG3_5$ if $c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$

$IDRG4_5$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$

$IDRG5_5$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$

$IDRG6_5$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$

$IDRG7_5$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$

$IDRG8_5$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$

$IDRG9_5$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$

$IDRG10_5$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$

$IDRG11_5$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$

$IDRG12_5$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$

$IDRG13_5$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$

Assignment of Quadratic Stress Coefficient Throughwall Distribution Based on Flaw Location

$IDRG_{14_5}$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$

$IDRG_{15_5}$ if $c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$

$IDRG_{16_5}$ if $c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$

$IDRG_{17_5}$ if $c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$

$IDRG_{18_5}$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$IDRG_{19_5}$ if $c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$

$IDRG_{20_5}$ otherwise

$\sigma_3 \leftarrow$ $IDRG_{1_6}$ if $c_j \le c_0$

$IDRG_{2_6}$ if $c_0 < c_j \le c_0 + Inc_{Strs.avg}$

$IDRG_{3_6}$ if $c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$

$IDRG_{4_6}$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$

$IDRG_{5_6}$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$

$IDRG_{6_6}$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$

$IDRG_{7_6}$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$

$IDRG_{8_6}$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$

$IDRG_{9_6}$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$

$IDRG_{10_6}$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$

$IDRG_{11_6}$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$

$IDRG_{12_6}$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$

$IDRG_{13_6}$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$

$IDRG_{14_6}$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$

$IDRG_{15_6}$ if $c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$

[Assignment of Cubic Strain Coefficient Through wall Distribution Based on Flaw Location.]

$IDRG_{16_6}$ if $c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$

$IDRG_{17_6}$ if $c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$

$IDRG_{18_6}$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$IDRG_{19_6}$ if $c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$

$IDRG_{20_6}$ otherwise

$\xi_0 \leftarrow \sigma_0$

$$\xi_1 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.25 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^3$$

$$\xi_2 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.5 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^3$$

$$\xi_3 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.75 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^3$$

$$\xi_4 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{1.0 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^3$$

← DETERMINATION of Stress Distribution along Crack depth using the Through wall distribution.

$x_0 \leftarrow 0.0$

$x_1 \leftarrow 0.25$

$x_2 \leftarrow 0.5$

$x_3 \leftarrow 0.75$

$x_4 \leftarrow 1.0$

$X \leftarrow stack(x_0, x_1, x_2, x_3, x_4)$

$ST \leftarrow stack(\xi_0, \xi_1, \xi_2, \xi_3, \xi_4)$

$RG \leftarrow regress(X, ST, 3)$

Regression Coefficient determination for stress distribution along flaw depth

$\sigma_{00} \leftarrow RG_3 + P_{Int}$

← Internal Pressure added to "uniform term" (Flaw free pressurized")

$\sigma_{10} \leftarrow RG_4$

$\sigma_{20} \leftarrow RG_5$

$$\sigma_{30} \leftarrow RG_6$$

$$AR_j \leftarrow \frac{a_j}{c_j}$$

$$AT_j \leftarrow \frac{a_j}{t}$$

RAJU-NEWMANN FULL MODEL (NASA - SC04 model)

$$G_{au_j} \leftarrow f_{aU}(R_t, AR_j, AT_j)$$

$$G_{al_j} \leftarrow f_{aL}(R_t, AR_j, AT_j)$$

$$G_{aq_j} \leftarrow f_{aQ}(R_t, AR_j, AT_j)$$

$$G_{ac_j} \leftarrow f_{aC}(R_t, AR_j, AT_j)$$

$$G_{cu_j} \leftarrow f_{cU}(R_t, AR_j, AT_j)$$

$$G_{cl_j} \leftarrow f_{cL}(R_t, AR_j, AT_j)$$

$$G_{cq_j} \leftarrow f_{cQ}(R_t, AR_j, AT_j)$$

$$G_{cc_j} \leftarrow f_{cC}(R_t, AR_j, AT_j)$$

Interpolation to Obtain Flow influence Coefficients

$$Q_j \leftarrow \begin{cases} 1 + 1.464 \cdot \left(\frac{a_j}{c_j}\right)^{1.65} & \text{if } c_j \ge a_j \\ 1 + 1.464 \cdot \left(\frac{c_j}{a_j}\right)^{1.65} & \text{otherwise} \end{cases}$$

$$K_{a_j} \leftarrow \left(\frac{\pi \cdot a_j}{Q_j}\right)^{0.5} \cdot \left(\sigma_{00} \cdot G_{au_j} + \sigma_{10} \cdot G_{al_j} + \sigma_{20} \cdot G_{aq_j} + \sigma_{30} \cdot G_{ac_j}\right)$$

← 'K' at depth point ("a-tip")

$$K_{c_j} \leftarrow \left(\frac{\pi \cdot c_j}{Q_j}\right)^{0.5} \cdot \left(\sigma_{00} \cdot G_{cu_j} + \sigma_{10} \cdot G_{cl_j} + \sigma_{20} \cdot G_{cq_j} + \sigma_{30} \cdot G_{cc_j}\right)$$

← 'K' at Surface Pt. ("c-tip")

$$K_{\alpha_j} \leftarrow K_{a_j} \cdot 1.099$$

$$K_{\gamma_j} \leftarrow K_{c_j} \cdot 1.099$$

← Conversion of 'K' from US to Metric Ksi√in → MPa√m

$$K_{\alpha_j} \leftarrow \begin{cases} 9.0 & \text{if } K_{\alpha_j} \le 9.0 \\ K_{\alpha_j} & \text{otherwise} \end{cases}$$

← Threshold determination

$$K_{\gamma_j} \leftarrow \begin{cases} 9.0 & \text{if } K_{\gamma_j} \le 9.0 \\ K_{\gamma_j} & \text{otherwise} \end{cases}$$

Threshold determination

$$D_{a_j} \leftarrow C_0 \cdot \left(K_{\alpha_j} - 9.0\right)^{1.16}$$

da - in m/sec

$$D_{ag_j} \leftarrow \begin{cases} D_{a_j} \cdot CF_{inhr} \cdot C_{blk} & \text{if } K_{\alpha_j} < 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} & \text{otherwise} \end{cases}$$

da for time increment in ~~in/hr~~ inch

$$D_{c_j} \leftarrow C_0 \cdot \left(K_{\gamma_j} - 9.0\right)^{1.16}$$

Conversion from m/sec to in/hr

$$D_{cg_j} \leftarrow \begin{cases} D_{c_j} \cdot CF_{inhr} \cdot C_{blk} & \text{if } K_{\gamma_j} < 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} & \text{otherwise} \end{cases}$$

da for time increment in inch

$output(j,0) \leftarrow j$

$output(j,1) \leftarrow a_j$

$output(j,2) \leftarrow c_j - c_0$

$output(j,3) \leftarrow D_{ag_j}$

$output(j,4) \leftarrow D_{cg_j}$

Outputs

$output(j,5) \leftarrow K_{a_j}$

$output(j,6) \leftarrow K_{c_j}$

$output(j,7) \leftarrow \dfrac{NCB_j}{365 \cdot 24}$

$output(j,8) \leftarrow G_{au_j}$

$output(j,9) \leftarrow G_{al_j}$

$output(j,10) \leftarrow G_{aq_j}$

$output(j,11) \leftarrow G_{ac_j}$

$output(j,12) \leftarrow G_{cu_j}$

$output(j,13) \leftarrow G_{cl_j}$

$$\text{output}_{(j,14)} \leftarrow G_{cq_j}$$

$$\text{output}_{(j,15)} \leftarrow G_{cc_j}$$

$$j \leftarrow j + 1$$

$$a_j \leftarrow a_{j-1} + D_{ag_{j-1}}$$

$$c_j \leftarrow c_{j-1} + D_{cg_{j-1}}$$

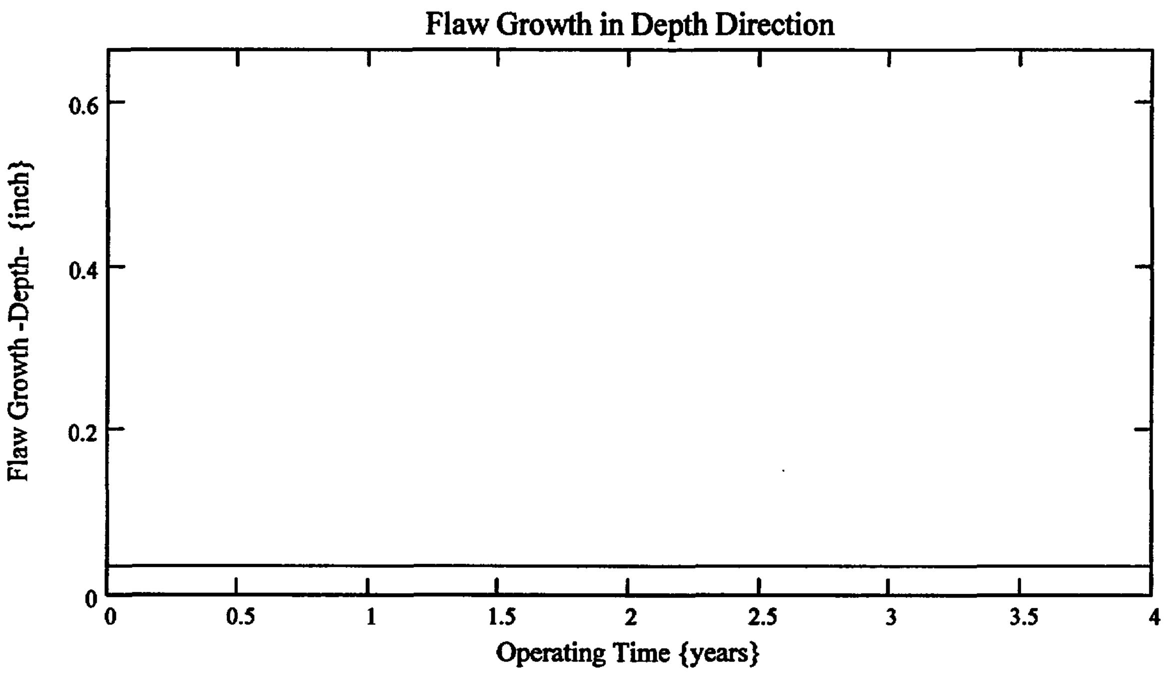
$$a_j \leftarrow \begin{cases} t & \text{if } a_j \geq t \\ a_j & \text{otherwise} \end{cases}$$

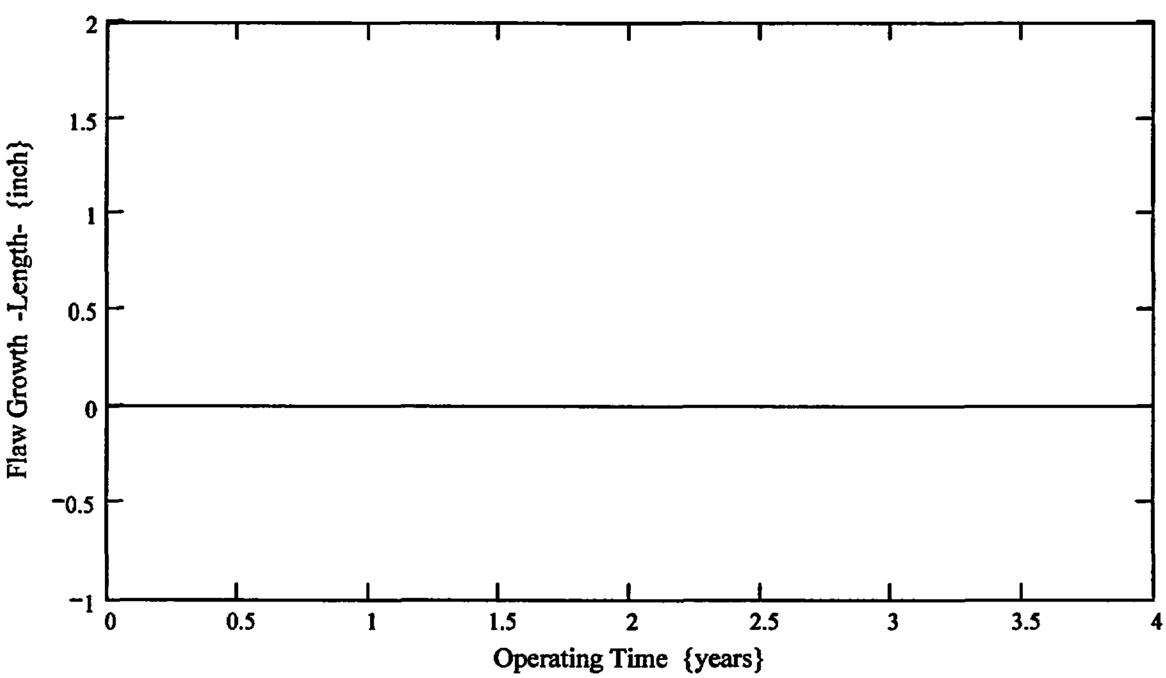
$$NCB_j \leftarrow NCB_{j-1} + C_{blk}$$

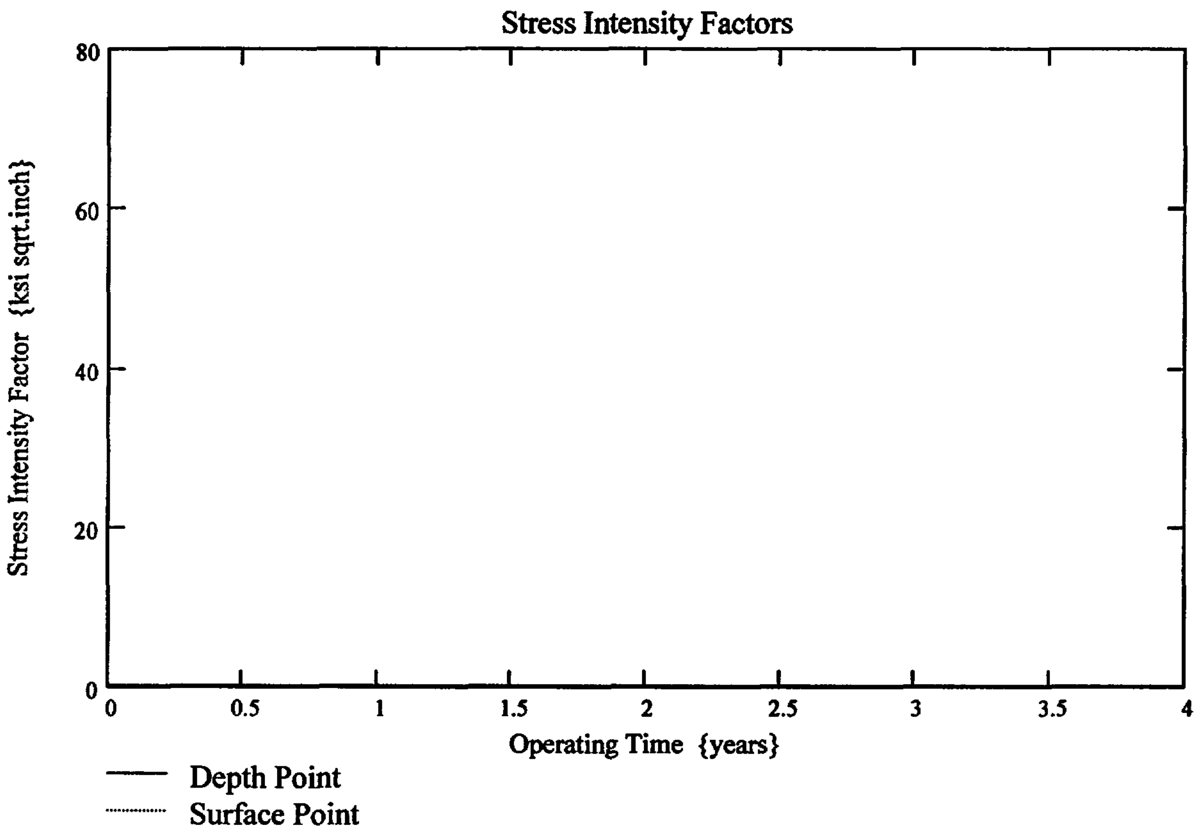
$$\text{output}$$

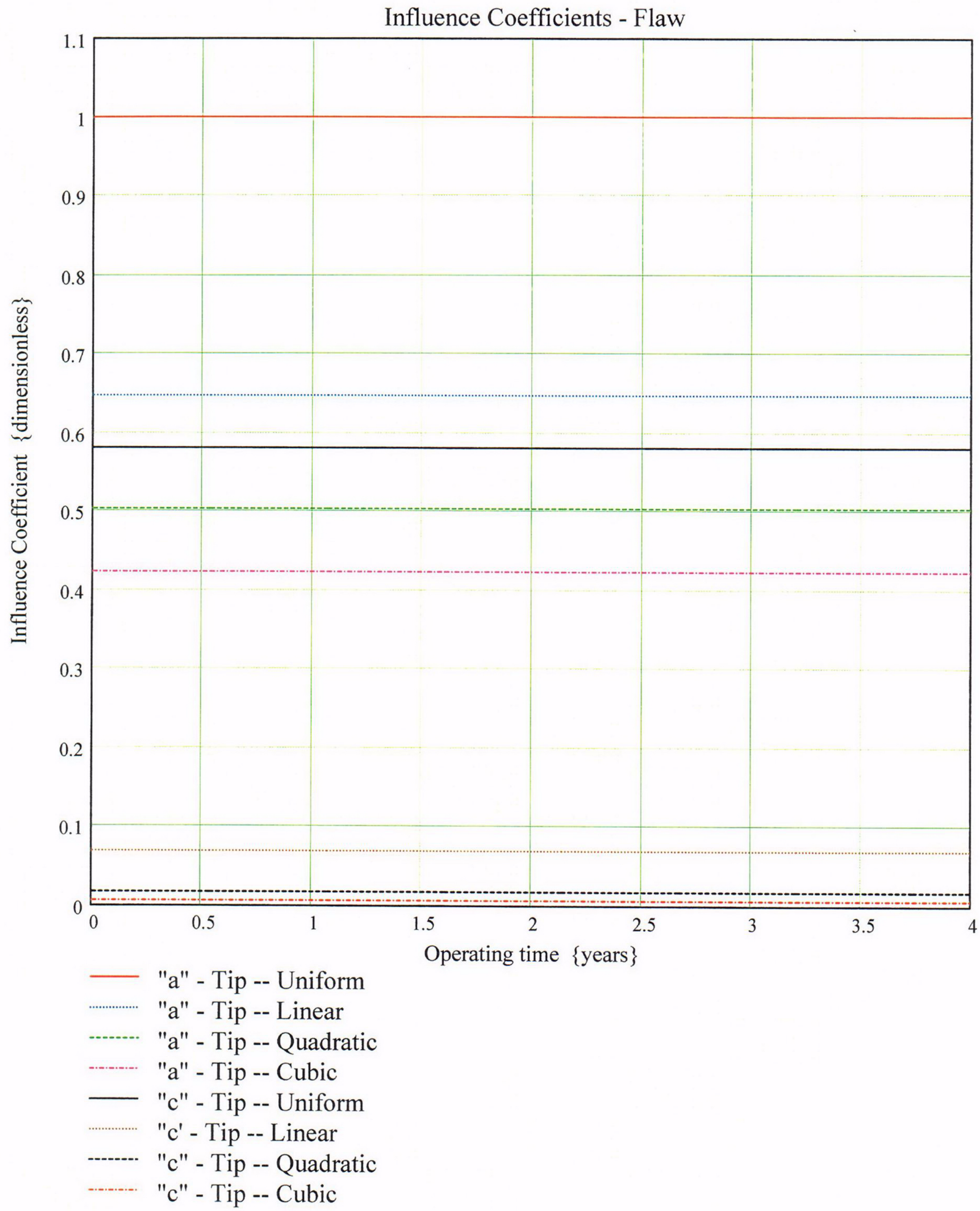
$$k := 0 .. I_{lim}$$

$\text{Prop}_{\text{Length}} = 0.506$






Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point
Surface Point


Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic
"c" - Tip -- Cubic

$CGR_{sambi_{(k,8)}} =$

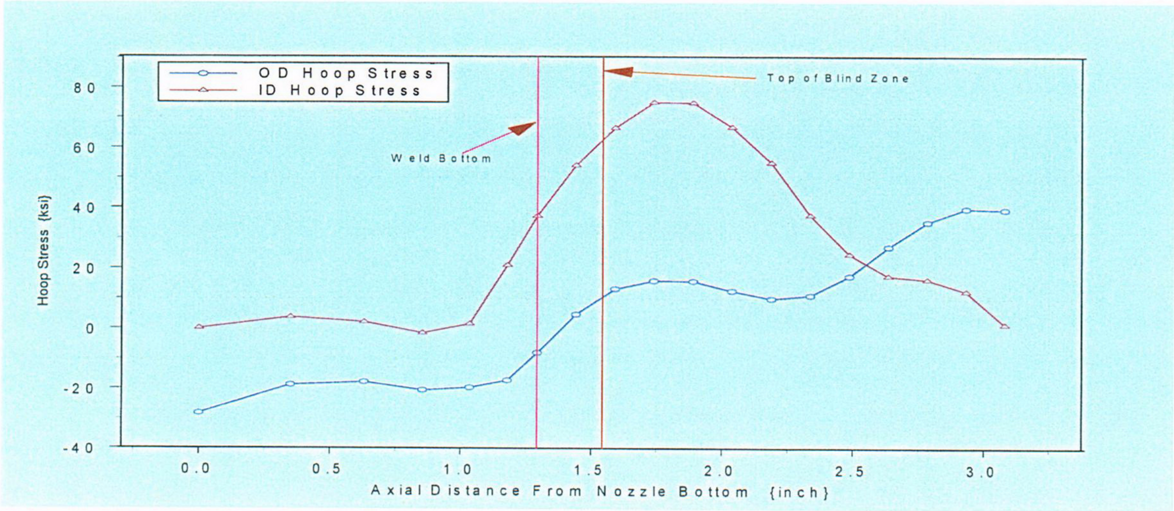
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1

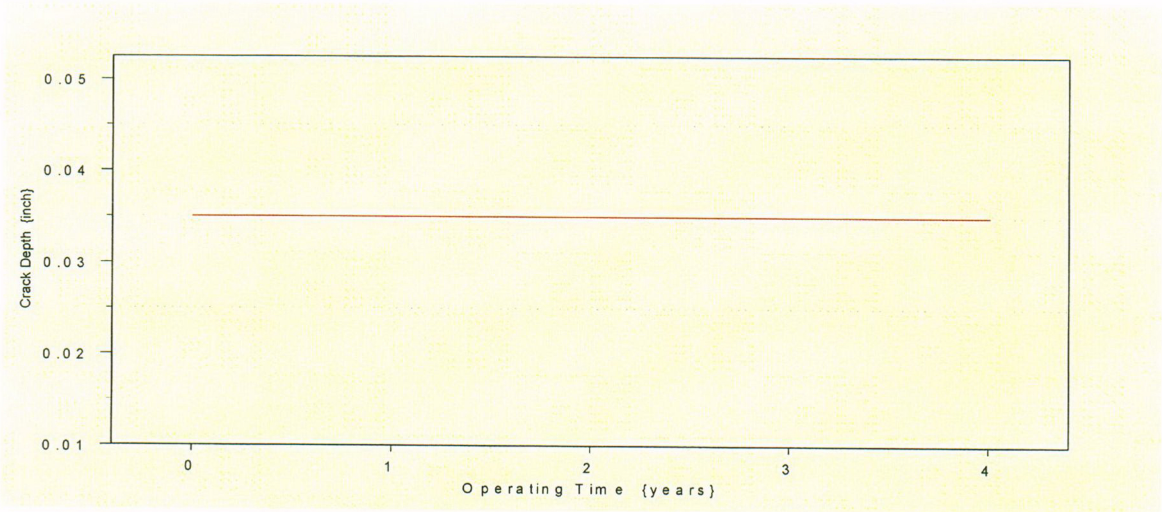
$CGR_{sambi_{(k,6)}} =$

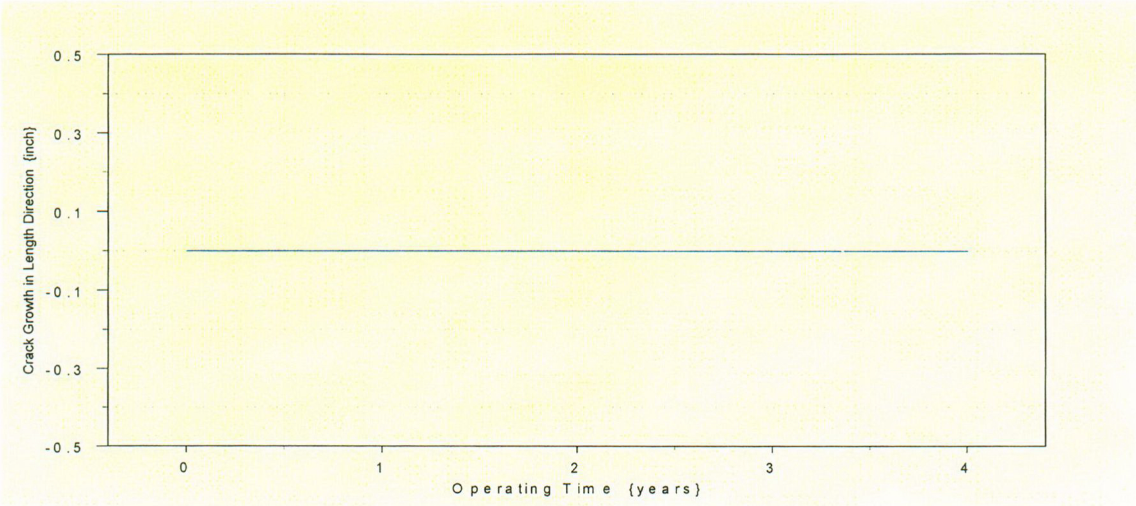
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163
0.163

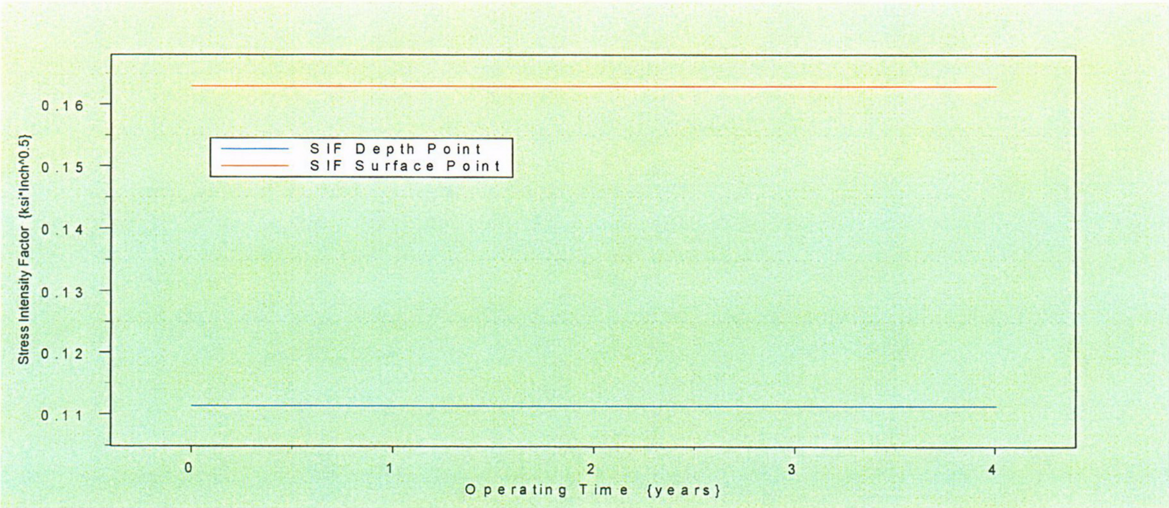
$CGR_{sambi_{(k,5)}} =$

0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111
0.111


O D Hoop Stress
ID Hoop Stress
Top of Blind Zone
Weld Bottom
Hoop Stress (ksi)
80
60
40
20
0
-20
-40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Axial Distance From Nozzle Bottom {inch}


Crack Depth {inch}
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
Operating Time {years}


Crack Growth in Length Direction {inch}
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
1
2
3
4
Operating Time {years}


Stress Intensity Factor {ksi*Inch^0.5}
0.16
0.15
0.14
0.13
0.12
0.11
SIF Depth Point
SIF Surface Point
0
1
2
3
4
Operating Time {years}