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 -"28.8" Degree Nozzle, Downhill azimuth, 1.384" 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

OD Surface Flaw

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 .

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.

$Ref_{Point} := 1.384$ *Reduced Blind Zone; Free span is 0.16 inch*

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).

$Val := 2$

Upper Limit to be selected for stress distribution (e.g. Weld bottom). This is the elevation from Nozzle Bottom. Enter this value below

$UL_{Strs.Dist} := 1.704$ Upper Axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom)

Input Data :-

$L := 0.32$	Initial Flaw Length
$a_0 := 0.661 \cdot 0.12$	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

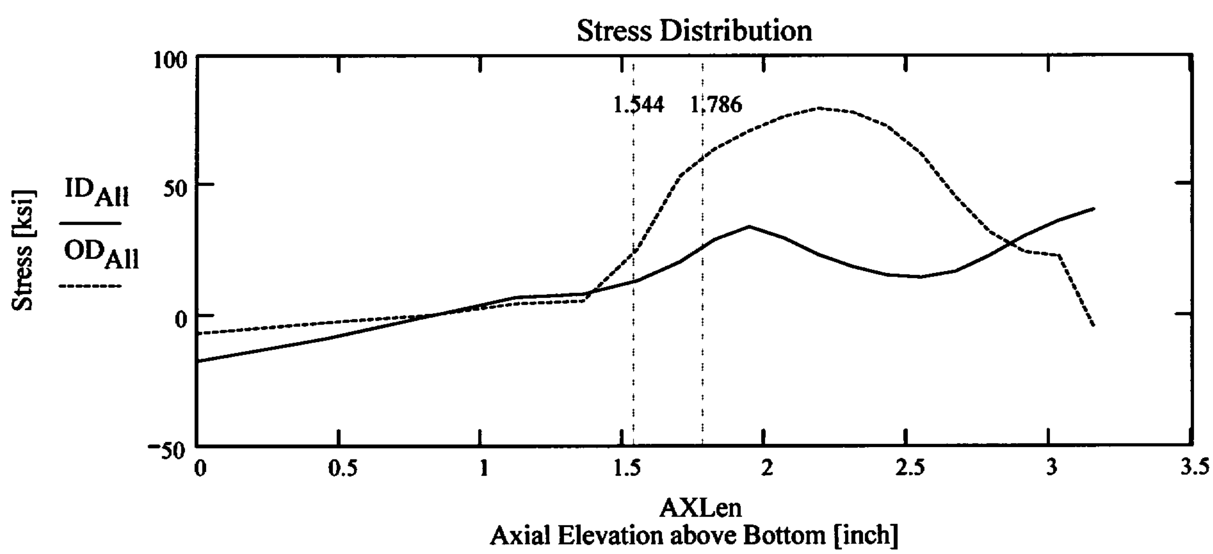
Stress Input Data

Input all available Nodal stress data in the table below. The column designations are as follows:
Column "0" = Axial distance from 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	-17.41	-13.55	-11.11	-8.88	-6.63
1	0.46	-8.49	-6.31	-4.92	-3.71	-2.54
2	0.83	0.09	0.18	0.11	0.19	0.28
3	1.13	7.03	6.95	6.31	5.21	4.65
4	1.36	8.22	10.95	10.85	9.51	5.65
5	1.55	13.27	16.41	16.06	17.13	25.26
6	1.7	20.63	22.24	25.41	43.58	53.78
7	1.83	29.04	28.83	31.29	53.55	64.08
8	1.95	33.95	30.93	36.41	61.6	71.01
9	2.07	29.59	31.79	40.54	64.61	76.42
10	2.19	23.26	29.74	41.2	64.19	79.63
11	2.31	18.69	27.73	41.29	61.78	78.12
12	2.43	15.39	26.1	40.67	58.6	72.78

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



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).

$$Data := \begin{pmatrix} 0 & -17.414 & -13.552 & -11.113 & -8.884 & -6.628 \\ 0.461 & -8.494 & -6.31 & -4.924 & -3.706 & -2.541 \\ 0.83 & 0.089 & 0.179 & 0.11 & 0.186 & 0.284 \\ 1.126 & 7.025 & 6.953 & 6.314 & 5.208 & 4.646 \\ 1.363 & 8.215 & 10.954 & 10.85 & 9.512 & 5.646 \\ 1.552 & 13.266 & 16.41 & 16.061 & 17.131 & 25.256 \\ 1.704 & 20.627 & 22.237 & 25.413 & 43.58 & 53.784 \\ 1.825 & 29.036 & 28.83 & 31.285 & 53.547 & 64.082 \\ 1.946 & 33.945 & 30.929 & 36.407 & 61.6 & 71.01 \\ 2.066 & 29.591 & 31.788 & 40.536 & 64.612 & 76.418 \\ 2.187 & 23.26 & 29.738 & 41.2 & 64.193 & 79.626 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location 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

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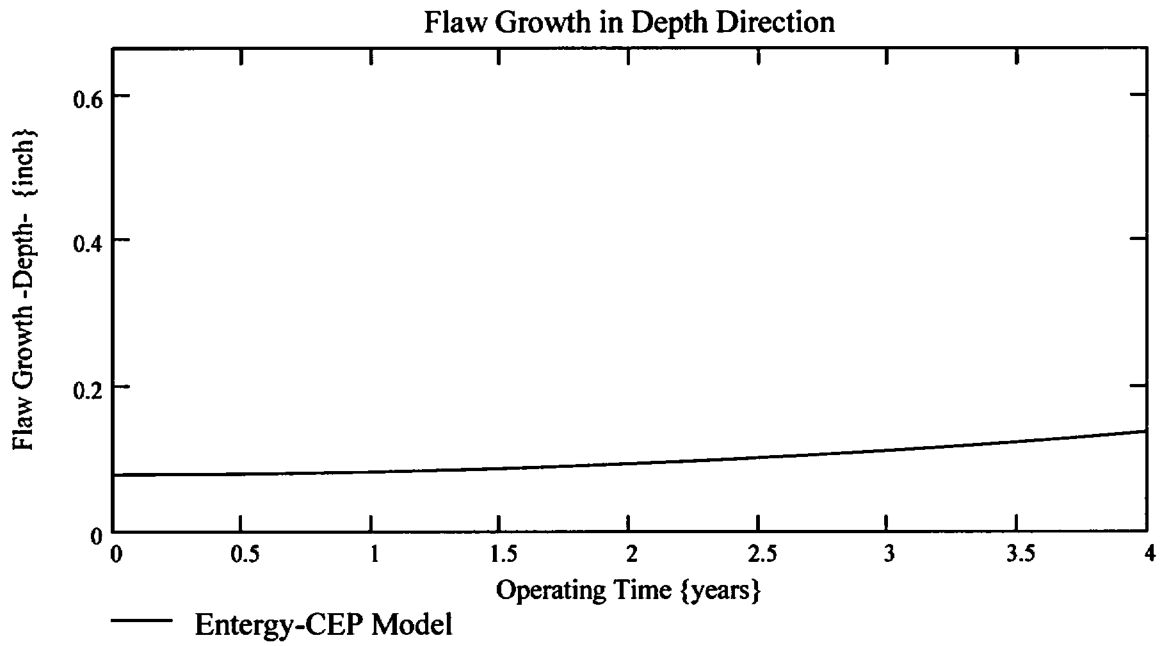
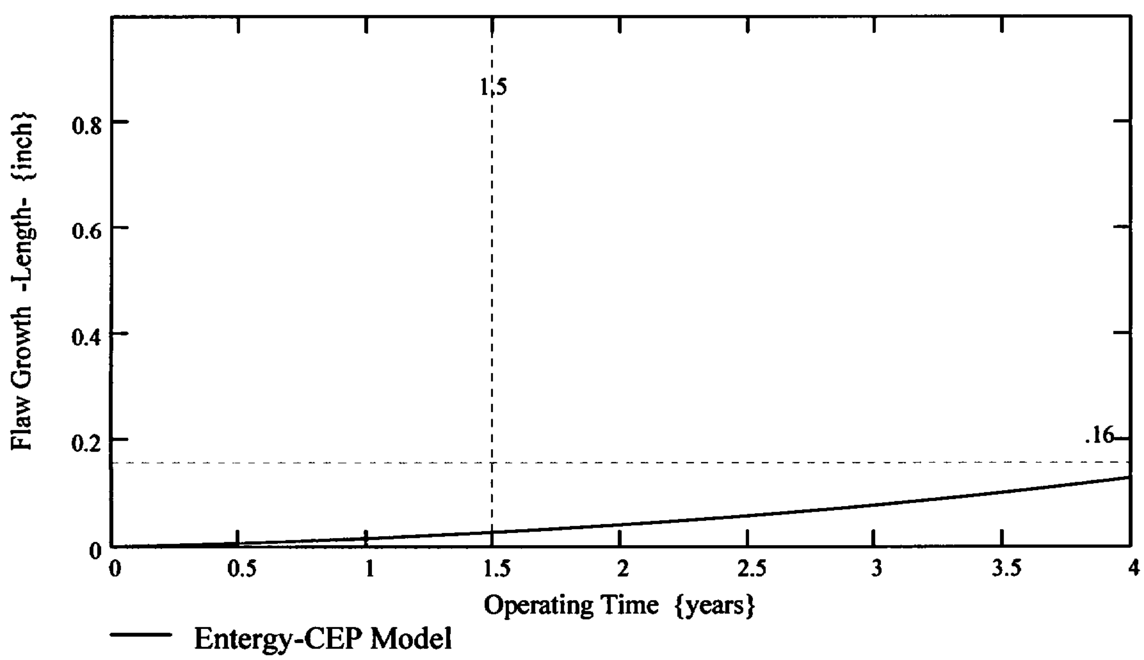
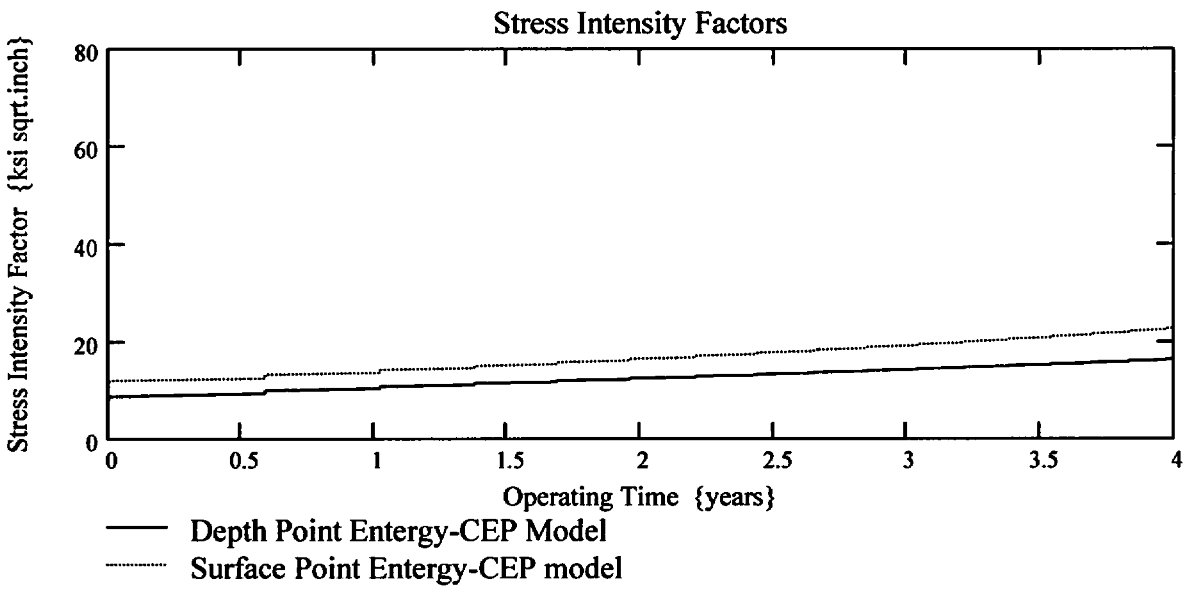
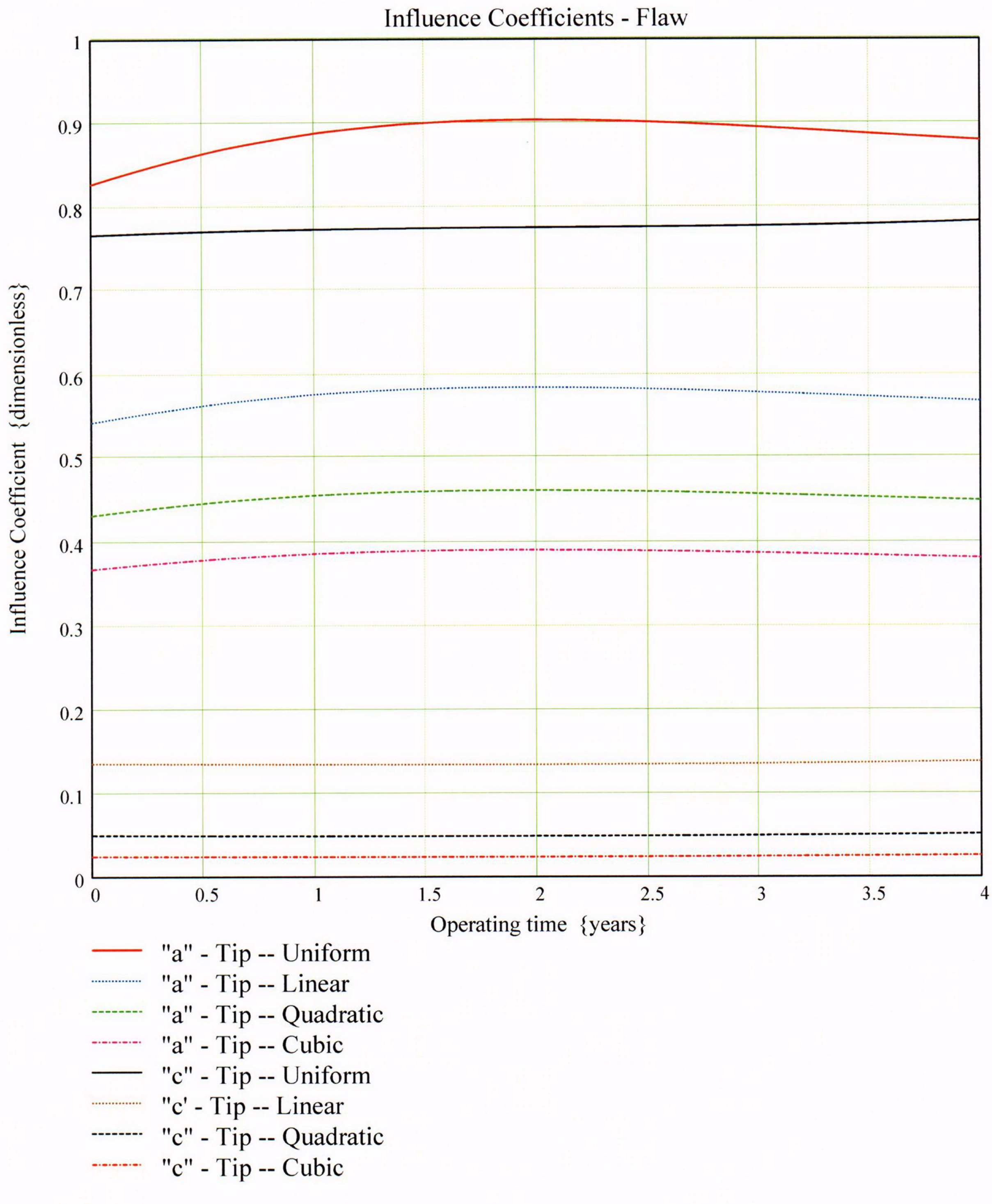
$Prop_{Length} = 0.16$

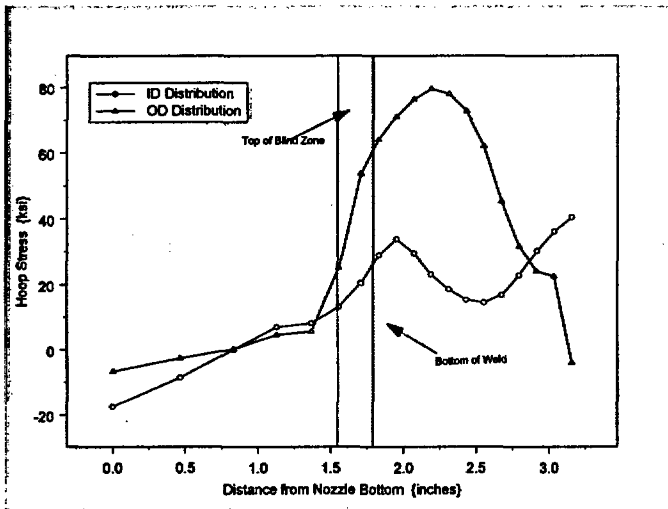


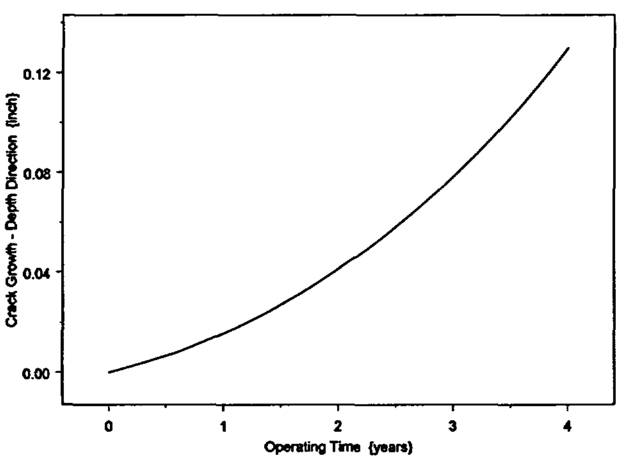


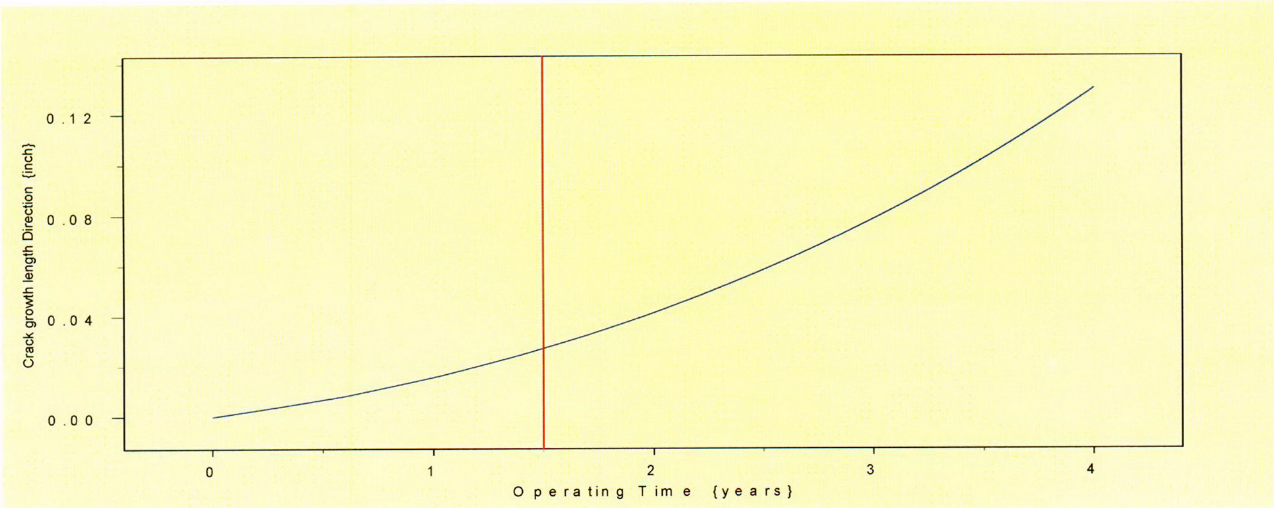

Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point Entergy-CEP Model
Surface Point Entergy-CEP model

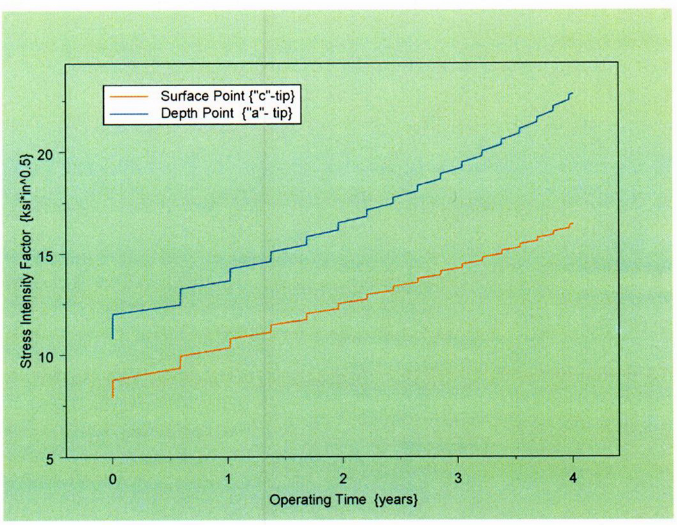

Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
Operating time {years}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1.5
2
2.5
3
3.5
4
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic
"c"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

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(k,5)}} =$
0.827	10.823	7.907
0.827	12.011	8.77
0.827	12.014	8.773
0.827	12.016	8.776
0.827	12.018	8.778
0.828	12.02	8.781
0.828	12.022	8.784
0.828	12.024	8.787
0.828	12.027	8.79
0.829	12.029	8.793
0.829	12.031	8.796
0.829	12.033	8.799
0.829	12.035	8.802
0.829	12.038	8.805
0.83	12.04	8.807
0.83	12.042	8.81


ID Distribution
OD Distribution
Top of Blind Zone
Bottom of Weld
Hoop Stress (ksi)
80
60
40
20
0
-20
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Distance from Nozzle Bottom (inches)


Crack Growth - Depth Direction (inch)
0.12
0.08
0.04
0.00
0
1
2
3
4
Operating Time (years)


Crack growth length Direction {inch}
0.12
0.08
0.04
0.00
0
1
2
3
4
Operating Time {years}


Surface Point {"c"-tip}
Depth Point {"a"- tip}
Stress Intensity Factor {ksi*in^0.5}
20
15
10
5
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 -"28.8"Degree Nozzle, 22.5 degree from Downhill Azimuth, Augmented Analysis 1.544 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.

$BZ := 1.544$ *This is the normal blind zone*

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.

$UL_{Strs.Dist} := 1.8317$ 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 (Based on 10 Ksi average stress)

$od := 4.05$ 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

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

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

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

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

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

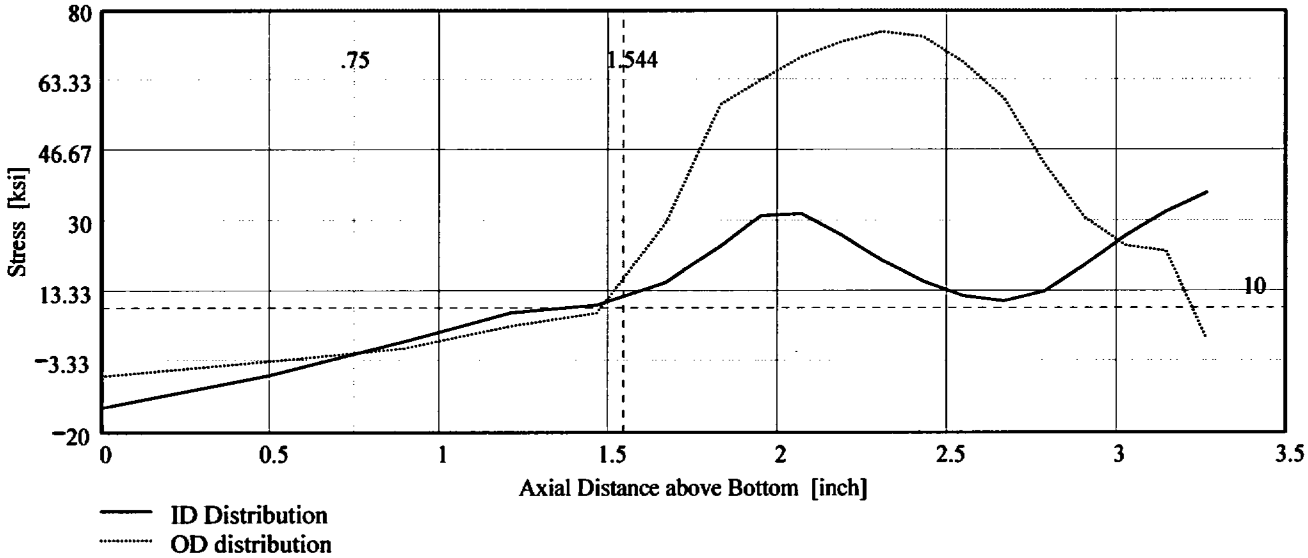
Stress Input Data

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	-14.21	-11.51	-9.79	-8.24	-6.72
1	0.5	-6.49	-5.19	-4.42	-3.8	-3.18
2	0.89	1.55	1.02	0.56	0.26	-0.08
3	1.21	8.43	7.98	7.2	6.19	5.29
4	1.46	10.25	12.71	12.22	11.35	8.36
5	1.67	15.66	18.34	18.7	20.84	29.7
6	1.83	24.32	24.53	26.71	44.52	57.73
7	1.95	31.5	28.7	31.23	53.02	63.55
8	2.07	31.98	30.11	35.63	59.45	69.03
9	2.19	26.83	29.95	38.37	61.12	72.69
10	2.31	20.84	27.29	38.5	59.95	75.04
11	2.43	15.99	24.67	38.16	58.17	73.85

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



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).

$$Data := \begin{pmatrix} 0 & -14.205 & -11.506 & -9.79 & -8.243 & -6.722 \\ 0.495 & -6.493 & -5.188 & -4.425 & -3.796 & -3.176 \\ 0.892 & 1.555 & 1.021 & 0.565 & 0.257 & -0.076 \\ 1.21 & 8.43 & 7.98 & 7.199 & 6.186 & 5.292 \\ 1.464 & 10.247 & 12.709 & 12.22 & 11.35 & 8.364 \\ 1.668 & 15.665 & 18.335 & 18.703 & 20.835 & 29.697 \\ 1.832 & 24.321 & 24.532 & 26.71 & 44.525 & 57.729 \\ 1.951 & 31.496 & 28.696 & 31.228 & 53.015 & 63.555 \\ 2.071 & 31.975 & 30.109 & 35.633 & 59.449 & 69.026 \\ 2.19 & 26.833 & 29.946 & 38.369 & 61.124 & 72.691 \\ 2.31 & 20.84 & 27.287 & 38.5 & 59.952 & 75.043 \end{pmatrix}$$

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

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

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

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

No User Input required beyond this Point

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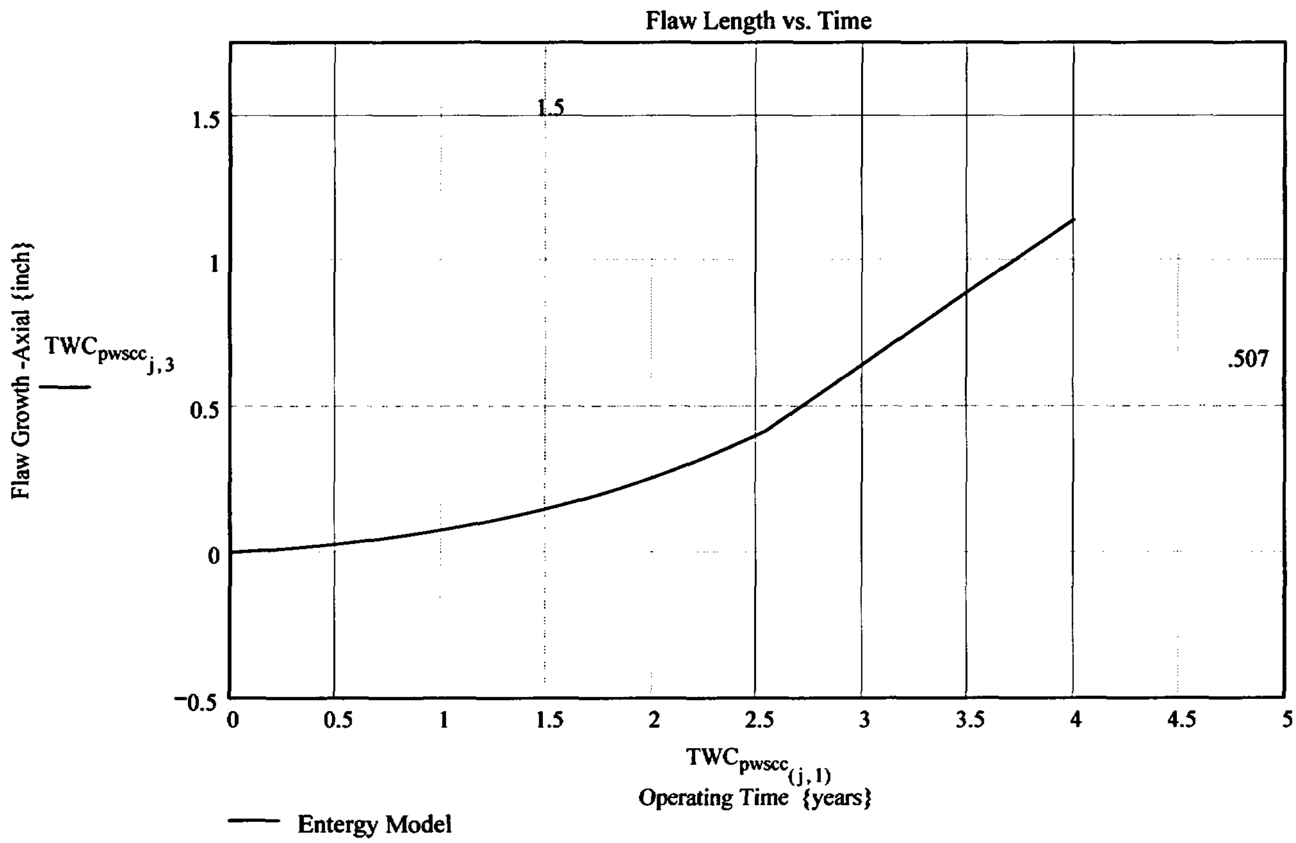
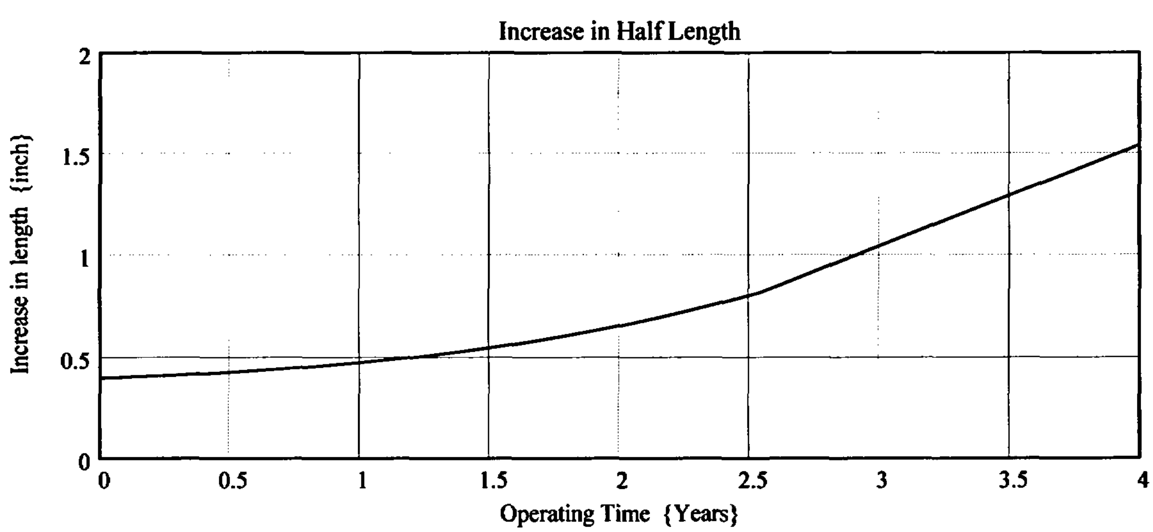
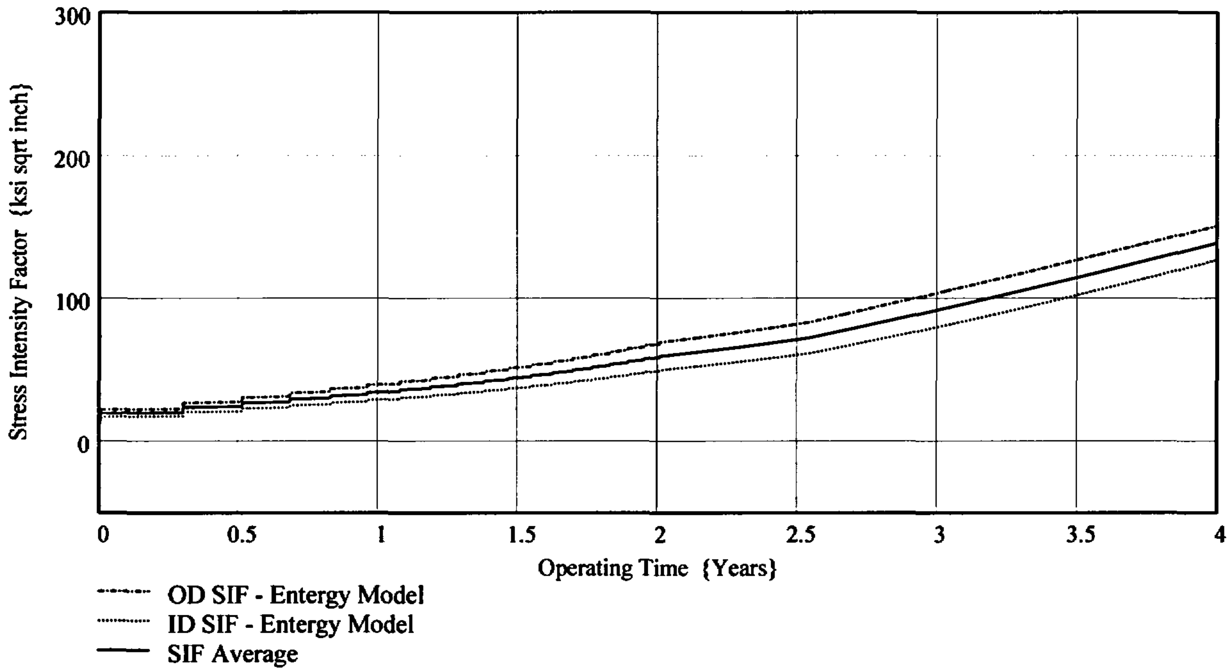
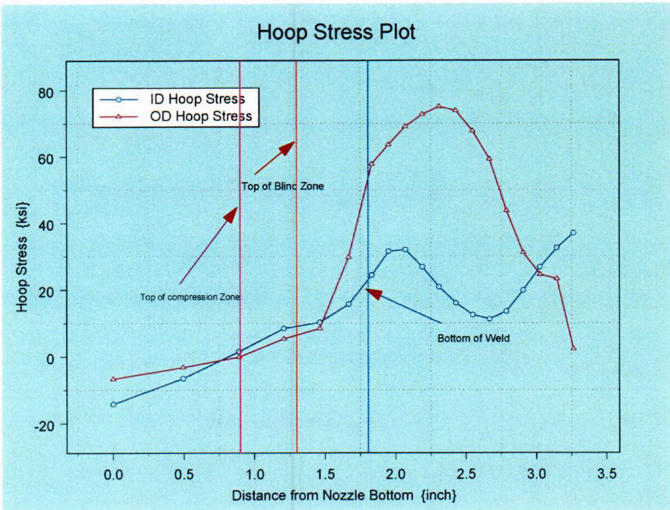
$Prop_{Length} = 0.288$

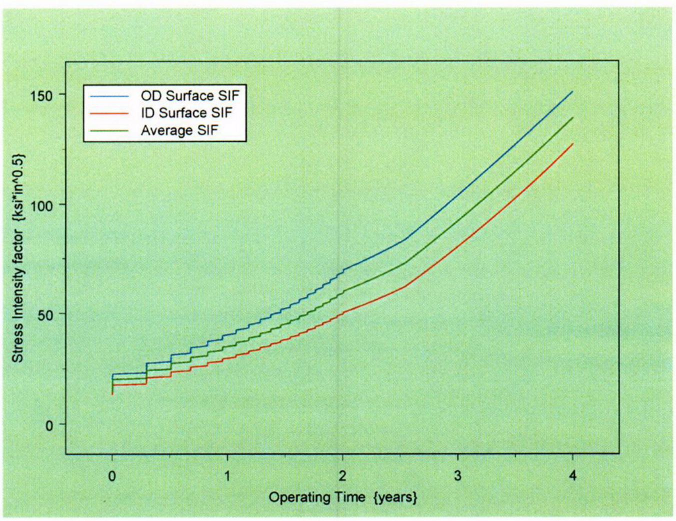


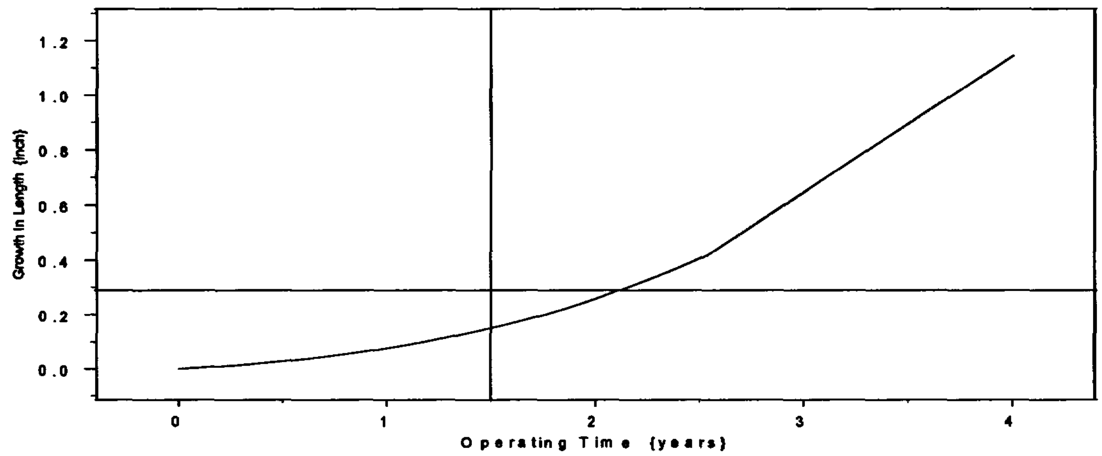



300
200
100
0
Stress Intensity Factor {ksi sqrt inch}
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {Years}
OD SIF - Entergy Model
ID SIF - Entergy Model
SIF Average

$TWC_{pwscc_{(j,6)}} =$	$TWC_{pwscc_{(j,7)}} =$	$TWC_{pwscc_{(j,8)}} =$
16.053	13.281	15.158
22.574	17.602	20.728
22.579	17.606	20.733
22.585	17.61	20.738
22.59	17.615	20.743
22.595	17.619	20.748
22.6	17.623	20.753
22.605	17.627	20.758
22.611	17.631	20.763
22.616	17.636	20.768
22.621	17.64	20.773
22.626	17.644	20.778
22.631	17.648	20.783
22.637	17.652	20.788
22.642	17.657	20.793
22.647	17.661	20.798


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Top of compression Zone
Bottom of Weld
Hoop Stress {ksi}
Distance from Nozzle Bottom {inch}
80
60
40
20
0
-20
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor {ksi*in^0.5}
Operating Time {years}
150
100
50
0
0
1
2
3
4


1.2
1.0
0.8
0.6
0.4
0.2
0.0
Growth in Length (inch)
0
1
2
3
4
Operating Time (years)

Appendix D

Contains Mathcad worksheets for;

1) **Evaluations of Curve Fitting method.**
2) **Demonstration of the validity of the Moving Average method.**
3) **Comparison of SICF for the Edge Crack Formulation and Current model.**
4) **Comparison of Conventional and Current model for OD Surface Crack.**
5) **Comparison of Current model with Conventional model and edge Crack. model for Through-wall Crack.**

This Appendix has five (5) Attachments.

Evaluation of Curve fit for Stress Profile Generation along the Tube Axis

In this worksheet the effect of data set selection for curve fitting, using a third order polynomial is evaluated. The data table below is form a data set used in the CEDM analyses. This data set is imported directly from the Excel spreadsheet provided by Dominion Engineering for the CEDM. The evaluation considers the full data set and a limited data set spanning the region of interest.
The purpose of this evaluation is to demonstrate the need for the proper selection of a subset of nodal stress data (in the region of interest) to ensure the accuracy of the analysis.

Data set imported from Excel spreadsheet.

AllData :=

	0	1	2	3
0	0.0000	-28.3240	-12.1600	-21.0000
1	0.3500	-18.7940	-6.6070	3.6550
2	0.6300	-17.8380	-4.4070	2.0800
3	0.8540	-20.5170	-5.9020	-1.5360
4	1.0340	-19.6630	-5.2880	1.4600
5	1.1780	-17.2030	-0.5150	21.0190
6	1.2930	-8.0230	10.4610	37.2890
7	1.4420	4.7780	24.9030	54.0890
8	1.5910	13.2520	35.2780	66.5170
9	1.7400	16.0010	39.1940	75.0010
10	1.8890	15.8570	40.2350	74.8740
11	2.0380	12.6290	41.2630	66.7770
12	2.1870	10.0610	39.6280	55.0120
13	2.3360	11.1610	35.6460	37.5700
14	2.4850	17.2630	31.3090	24.6930
15	2.6340	27.2640	26.5110	17.4680
16	2.7830	35.4650	27.1090	16.3050
17	2.9930	39.9490	31.3960	12.4040
18	3.0820	39.5470	37.1560	1.4480

$AxlLen := AllData^{\langle 0 \rangle}$ $\quad$ $IDAll := AllData^{\langle 1 \rangle}$ $\quad$ $MidWall := AllData^{\langle 2 \rangle}$ $\quad$ $ODAll := AllData^{\langle 3 \rangle}$

$$Data := \begin{pmatrix} 0 & -28.324 & -12.16 & -21 \\ 0.35 & -18.794 & -6.607 & 3.655 \\ 0.63 & -17.838 & -4.407 & 2.08 \\ 0.854 & -20.517 & -5.902 & -1.536 \\ 1.034 & -19.663 & -5.288 & 1.46 \\ 1.178 & -17.203 & -0.515 & 21.019 \\ 1.293 & -8.023 & 10.461 & 37.289 \\ 1.442 & 4.778 & 24.903 & 54.089 \\ 1.591 & 13.252 & 35.278 & 66.517 \\ 1.74 & 16.001 & 39.194 & 75.001 \end{pmatrix}$$

Selected subset from the data table above

$ALen := Data^{\langle 0 \rangle}$ $ID_{lim} := Data^{\langle 1 \rangle}$ $MW_{lim} := Data^{\langle 2 \rangle}$ $OD_{lim} := Data^{\langle 3 \rangle}$

Regression for the full data set

$RID_{All} := regress(AxlLen, IDAll, 3)$

$RMW_{All} := regress(AxlLen, MidWall, 3)$

$ROD_{All} := regress(AxlLen, ODAll, 3)$

Regression for selected data set

$RID_{data} := regress(ALen, ID_{lim}, 3)$

$RMW_{data} := regress(ALen, MW_{lim}, 3)$

$ROD_{data} := regress(ALen, OD_{lim}, 3)$

$Bottom := 0$ $Top := 3.2$ $WB := 1.74$

$Dist := Top - Bottom$ $Incr := \frac{Dist}{20}$ $D := WB - Bottom$ $Incr1 := \frac{D}{20}$

$L_0 := 0 - Incr$

$Len_0 := 0 - Incrl$

$i := 1..20$

$L_i := L_{i-1} + Incr$

$Len_i := Len_{i-1} + Incrl$

Determination of Stresses at three locations across wall thickness, using the full data set

$$ID_{all_i} := RID_{All_3} + RID_{All_4} \cdot L_i + RID_{All_5} \cdot (L_i)^2 + RID_{All_6} \cdot (L_i)^3$$

$$MW_{all_i} := RMW_{All_3} + RMW_{All_4} \cdot L_i + RMW_{All_5} \cdot (L_i)^2 + RMW_{All_6} \cdot (L_i)^3$$

$$OD_{all_i} := ROD_{All_3} + ROD_{All_4} \cdot L_i + ROD_{All_5} \cdot (L_i)^2 + ROD_{All_6} \cdot (L_i)^3$$

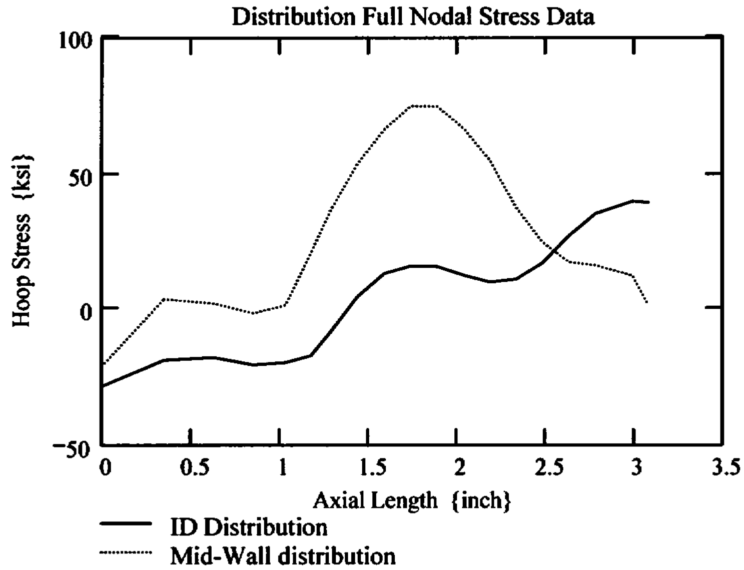
Determination of Stresses at three locations across wall thickness, using the selected data set

$$ID_{data_i} := RID_{data_3} + RID_{data_4} \cdot Len_i + RID_{data_5} \cdot (Len_i)^2 + RID_{data_6} \cdot (Len_i)^3$$

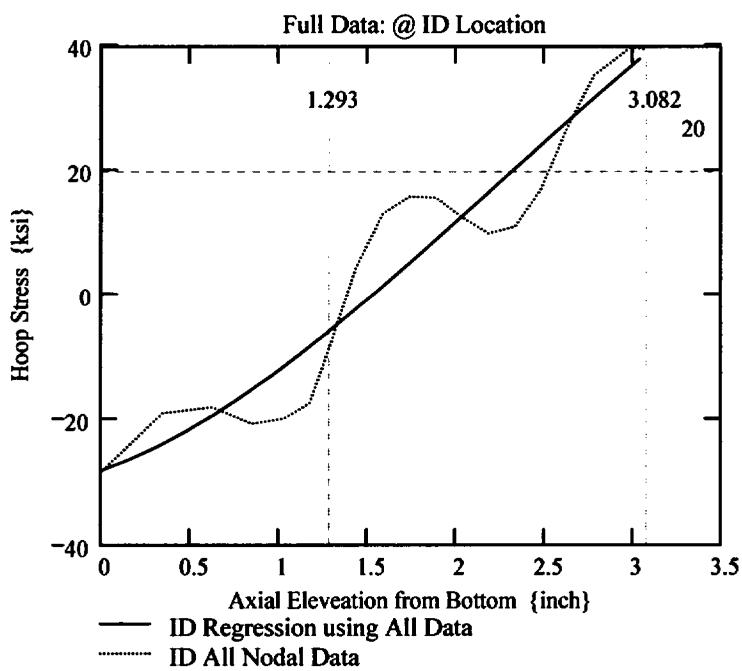
$$MW_{data_i} := RMW_{data_3} + RMW_{data_4} \cdot Len_i + RMW_{data_5} \cdot (Len_i)^2 + (RMW_{data_6}) \cdot (Len_i)^3$$

$$OD_{data_i} := ROD_{data_3} + ROD_{data_4} \cdot Len_i + ROD_{data_5} \cdot (Len_i)^2 + ROD_{data_6} \cdot (Len_i)^3$$

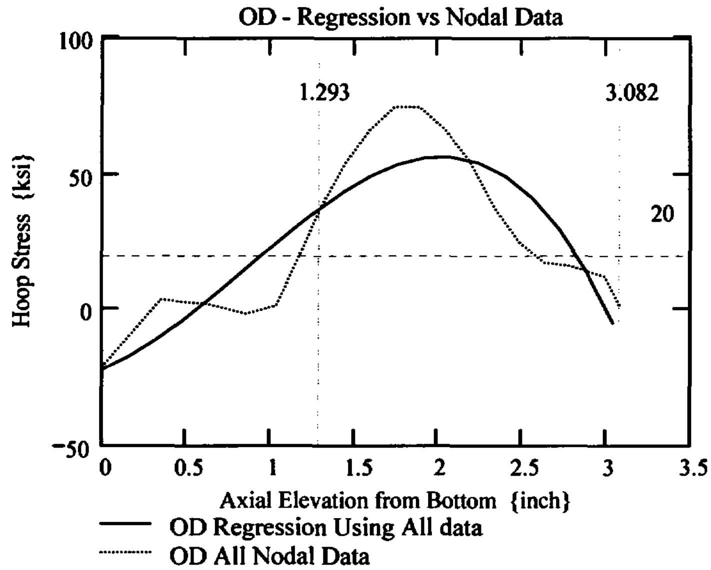
Graphical Display of Results



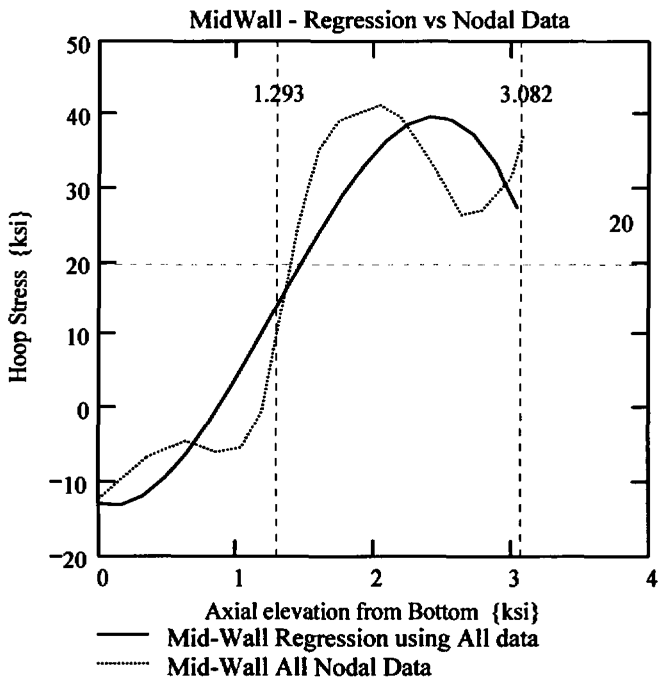
Nodal stress data plotted for the ID and the OD distribution. This plot is based on the full data set.



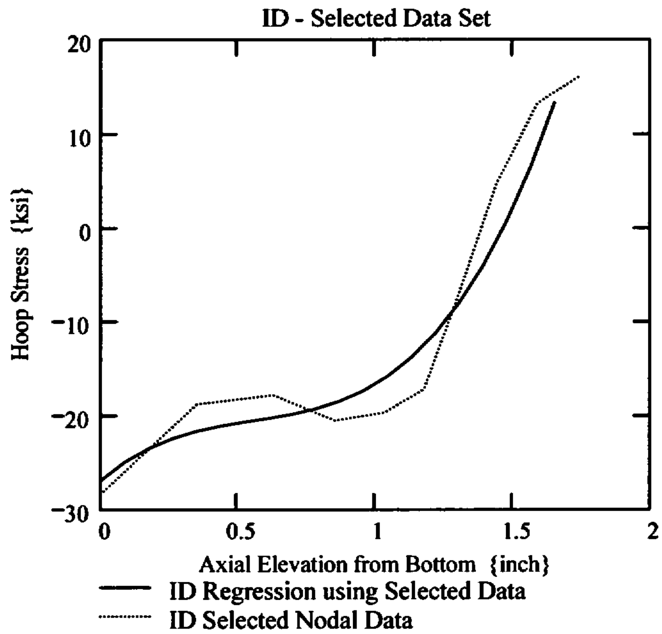
ID Stress Distribution:-
Comparison of regression fit versus the full data set. The third-order polynomial does not provide an accurate fit. The trend in the data is captured.



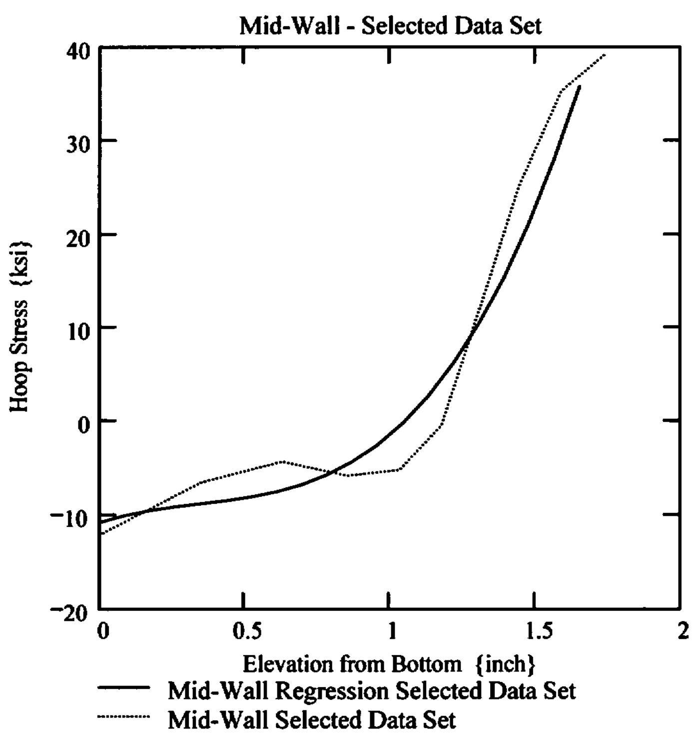
OD Stress Distribution:-
Comparison of regression fit versus the full data set. The third-order polynomial does not provide an accurate fit. The trend in the data is captured.



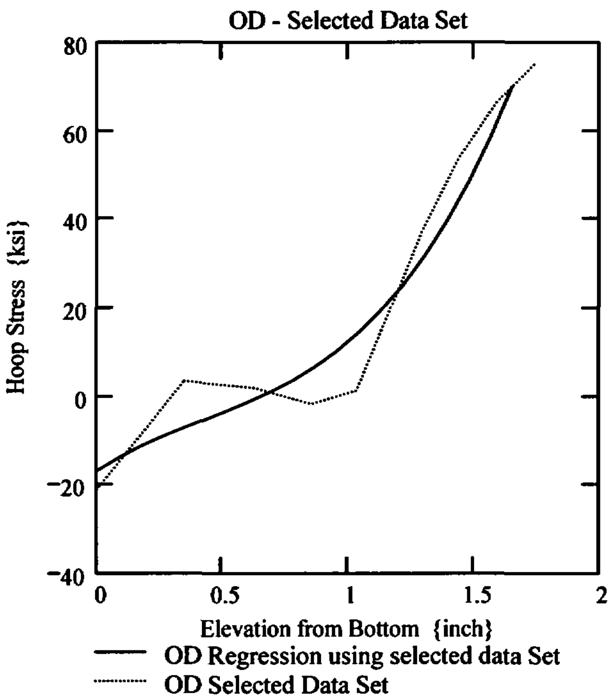
Mid-Wall Stress Distribution:-
Comparison of regression fit versus the full data set. The third-order polynomial does not provide an accurate fit. The trend in the data is captured.



ID Stress Distribution (Selected Data Set):- Comparison of regression fit versus the selected data set. The third-order polynomial provides an accurate fit.



Mid-Wall Stress Distribution (Selected Data Set):- Comparison of regression fit versus the selected data set. The third-order polynomial provides an accurate fit.



OD Stress Distribution (Selected Data Set):- Comparison of regression fit versus the selected data set. The third-order polynomial provides an accurate fit.

Conclusion :- By selecting the data judiciously, in the region of interest, facilitates an accurate regression fit of the data.

Example Worksheet
Developed by Central Engineering Programs, Entergy Operations Inc.

Developed by: J. S. Brihmadesam ***Verified by: B. C. Gray***

Example to Evaluate Moving Stress Averaging Technique

Basis :- In this worksheet the moving average method is exercised to demonstrate that no numerical errors exist. In this example a linear through-wall stress distribution that remains constant over the length of the nozzle is used. Thus the moving average method, if working properly should provide the same linear through-wall distribution at all segments considered.

This worksheet is developed using the stress distribution analysis portion from the working worksheets used in the analyses. The data table in the worksheet was modified with the entry of a linear throughwall stress distribution at all axial height locations. The result of the moving average technique was output as a table.

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 necessary 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 represents the reference point elevation measured upward from the nozzle end.

$$Ref_{Point} := 1.544$$

To place the flaw with respect 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.

$UL_{Strs.Dist} := 2.75$ Upper axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom).

Only input data pertinent to this worksheet are provided. The internal pressure and the information for the PWSCC crack growth, which are not essential to the example problem, have been removed.

Input Data :-

$L := .35$	Initial Flaw Length
$a_0 := 0.035$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID

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

$$c_0 := \frac{L}{2} \qquad R_t := \frac{R_m}{t}$$

The stress input table that is used to import the nodal stress data was modified. The stress input was manually entered as a linear through-wall distribution at all axial height locations. The table entries below shows the entries used.

Stress Input Data

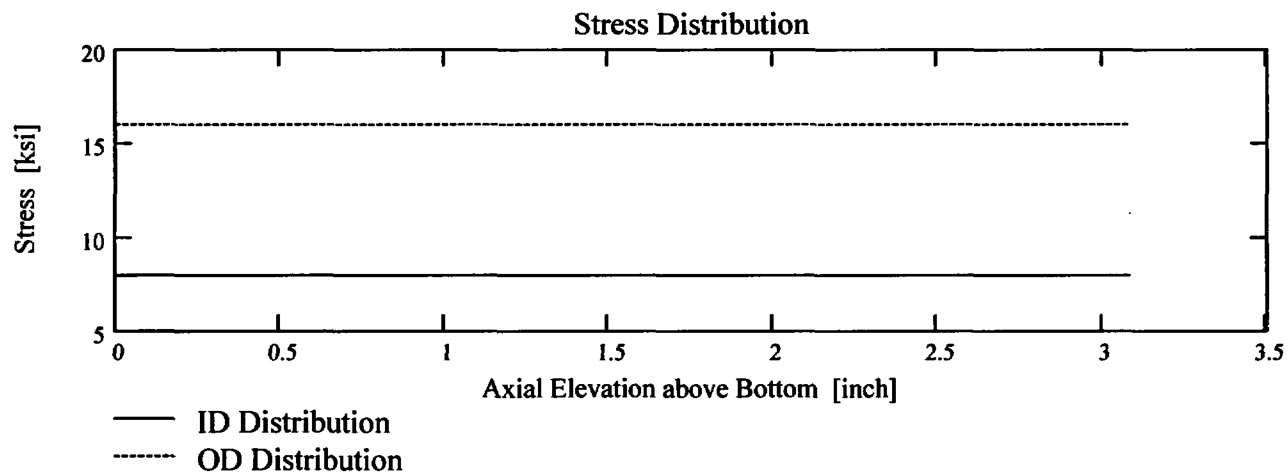
Input all available Nodal stress data in the table below. The column designations are as follows:
Column "0" = Axial distance from minimum to maximum recorded on data sheet (inches)
Column "1" = ID Stress data at each Elevation (ksi)
Column "2" = Quarter Thickness Stress data at each Elevation (ksi)
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	8	10	12	14	16
1	0.35	8	10	12	14	16
2	0.63	8	10	12	14	16
3	0.85	8	10	12	14	16
4	1.03	8	10	12	14	16
5	1.18	8	10	12	14	16
6	1.29	8	10	12	14	16
7	1.44	8	10	12	14	16
8	1.59	8	10	12	14	16
9	1.74	8	10	12	14	16
10	1.89	8	10	12	14	16
11	2.04	8	10	12	14	16

$\mathrm{AXLen} := \mathrm{AllData}^{\langle 0 \rangle}$ $\quad$ $\mathrm{ID}_{\mathrm{All}} := \mathrm{AllData}^{\langle 1 \rangle}$ $\quad$ $\mathrm{OD}_{\mathrm{All}} := \mathrm{AllData}^{\langle 5 \rangle}$

The graph below is a plot of the table data in the previous page. Note the horizontal lines for the ID and OD stress distribution along the nozzle length. Therefore, the input data shows that there is a constant distribution along the nozzle length



$$\text{Data} := \begin{pmatrix} 0 & 8 & 10 & 12 & 14 & 16 \\ 0.35 & 8 & 10 & 12 & 14 & 16 \\ 0.63 & 8 & 10 & 12 & 14 & 16 \\ 0.854 & 8 & 10 & 12 & 14 & 16 \\ 1.034 & 8 & 10 & 12 & 14 & 16 \\ 1.178 & 8 & 10 & 12 & 14 & 16 \\ 1.293 & 8 & 10 & 12 & 14 & 16 \\ 1.442 & 8 & 10 & 12 & 14 & 16 \\ 1.591 & 8 & 10 & 12 & 14 & 16 \\ 1.74 & 8 & 10 & 12 & 14 & 16 \\ 1.889 & 8 & 10 & 12 & 14 & 16 \\ 2.038 & 8 & 10 & 12 & 14 & 16 \\ 2.187 & 8 & 10 & 12 & 14 & 16 \\ 2.336 & 8 & 10 & 12 & 14 & 16 \\ 2.485 & 8 & 10 & 12 & 14 & 16 \\ 2.634 & 8 & 10 & 12 & 14 & 16 \\ 2.783 & 8 & 10 & 12 & 14 & 16 \end{pmatrix}$$

The data matrix to the left is the selection of data from the data table used to input the data. All entries have been selected. The matrix is exactly the same as the input data table

The statements below are the assignment statements defining the column arrays for the axial height followed by the five locations across the tube wall thickness.

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

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

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

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

The statement below defines the flaw location to be used in the analysis, based on the entry for the variable "Val" entered on the first page.

$$FL_{Cntr} := \left| \begin{array}{l} Ref_{Point} - c_0 \;\; \text{if } Val = 1 \\ Ref_{Point} \;\; \text{if } Val = 2 \\ Ref_{Point} + c_0 \;\; \text{otherwise} \end{array} \right.$$

Flaw center Location above Nozzle Bottom

The two statements below are as follows:

1) The statement on the left defines the upper crack tip based on the flaw location determined above.
2) The statement on the right computes the segment height for the segments above the upper crack tip based on twenty equal segments.

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

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

The statements below develops the through-wall stress profiles at the twenty-three segments (three segments for the initial flaw length and twenty segments above the upper tip of the flaw.

Calculation to develop Stress Profiles for Analysis

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

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

$i := 1 .. N + 3$

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

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

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

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

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

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

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

The statements below perform the moving average stress profile calculations. The first profile, at location 1, is the average profile for the initial crack. The remaining profiles are the average profiles for the twenty segments above the upper tip of the crack.

$$j := 1 .. N$$

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

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

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

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

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

Presented below is the output at each location defined for the moving average stress profile. The first element in each array is for the average stress profile for the initial crack. The subsequent elements in each column array are for the equal segments above the upper tip of the flaw. Each column array represents one of the five locations across the wall thickness (marked).

ID	Quarter Thickness	Mid-Wall Thickness	Three -Quarter Wall Thickness	OD
$S_{id_j} =$	$S_{qt_j} =$	$S_{md_j} =$	$S_{tq_j} =$	$S_{od_j} =$
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16
8	10	12	14	16

The output of the moving average evaluation is the same as the input data. This ensures that the moving average technique is functioning properly.

Comparison of Edge Crack Model With Through-wall Model {SICF}

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadesam **Verified by: B. C. Gray**

References :

1) Murakami; "Stress Intensity factors handbook"; 1.3 Single Edge Cracked Plate; page 771.

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"0"degree Nozzle, All Azimuth 1.544 inch above Nozzle Bottom

In this worksheet a comparison between the SICF for an Edge Crack and the axial through-wall crack of the current model are compared. For the edge crack the SICF is dependent on the ratio of crack length to plate height. For the application to the CEDM nozzle the plate height can be assumed at three locations, these are:

1) The nozzle length upto the bottom to the J-weld (the bottom point of fixity for the nozzle)
2) The nozzle length upto the top of the J-weld (the upper point of fixity for the nozzle)
3) The nozzle length assuming no fixity.

For the current model only the SICF for the membrane loading is used for comparison because the SICF for these two conditions are separate and are applied to the SIF for equivalent plate geometry. Hence three is no single SIF that represents a composite SICF. However a comparison using the membrane SICF should facilitate a rational assessment.

The first Input is to locate the Reference Line (eg. top of the Blind Zone). The through-wall 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.

$UL_{Strs.Dist} := 1.796$ Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

The input data below are only for those variables essential to this assessment.

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)

$v := 0.307$ Poissons ratio at 600 deg. F

$R_o := \frac{od}{2}$ $R_i := \frac{id}{2}$ $t := R_o - R_i$ $R_m := R_i + \frac{t}{2}$ $N := 500$

The plate height are set to three elevations as follows:

1) Bottom of the J-weld.
2) Top of the J-weld.
3) Full length of Nozzle.

$b := UL_{Strs.Dist}$ Bottom of J-weld

$b_1 := 2.886$ Top of J-Weld

$b_2 := 20$ Top of Nozzle $Inc := \frac{b}{N}$

It is important to note that the SICF for the Edge Crack model are limited to the a/b ratio (Crack length/height) of 0.6. Therefore, for the crack length when the a/b ratio is violated are as shown below.

Case 1: Plate height equal to nozzle length to bottom of weld:- $b \cdot 0.6 = 1.078$

Case 2: Plate height equal to top of J-weld:- $b_1 \cdot 0.6 = 1.732$

Case 3: Plate height equal to Nozzle Length :- $b_2 \cdot 0.6 = 12$

Calculations :

$a_0 := 0$

$j := 1..N-1$

$a_j := a_{j-1} + \text{Inc}$ $\qquad x_j := \frac{a_j}{b}$ $\qquad x1_j := \frac{a_j}{b_1}$ $\qquad x2_j := \frac{a_j}{b_2}$

Brown and Srawley Model For edge Crack in a Plate

$Fbs_j := 1.12 - 0.231\cdot x_j + 10.55\cdot(x_j)^2 - 21.72\cdot(x_j)^3 + 30.39\cdot(x_j)^4$ Plate height as length below Fillet weld to tube bottom

$Fbs1_j := 1.12 - 0.231\cdot x1_j + 10.55\cdot(x1_j)^2 - 21.72\cdot(x1_j)^3 + 30.39\cdot(x1_j)^4$ Plate height as length below Top of J-weld to tube bottom

$Fbs2_j := 1.12 - 0.231\cdot x2_j + 10.55\cdot(x2_j)^2 - 21.72\cdot(x2_j)^3 + 30.39\cdot(x2_j)^4$ Plate height as Full length of Nozzle

Through-wall Axial crack in a Thick Cylinder (Entergy Model)

$$\lambda_j := \left[\left[12\cdot\left(1-\nu^2\right)\right]^{0.25}\cdot\frac{\frac{a_j}{2}}{(R_m\cdot t)^{0.5}}\right]$$

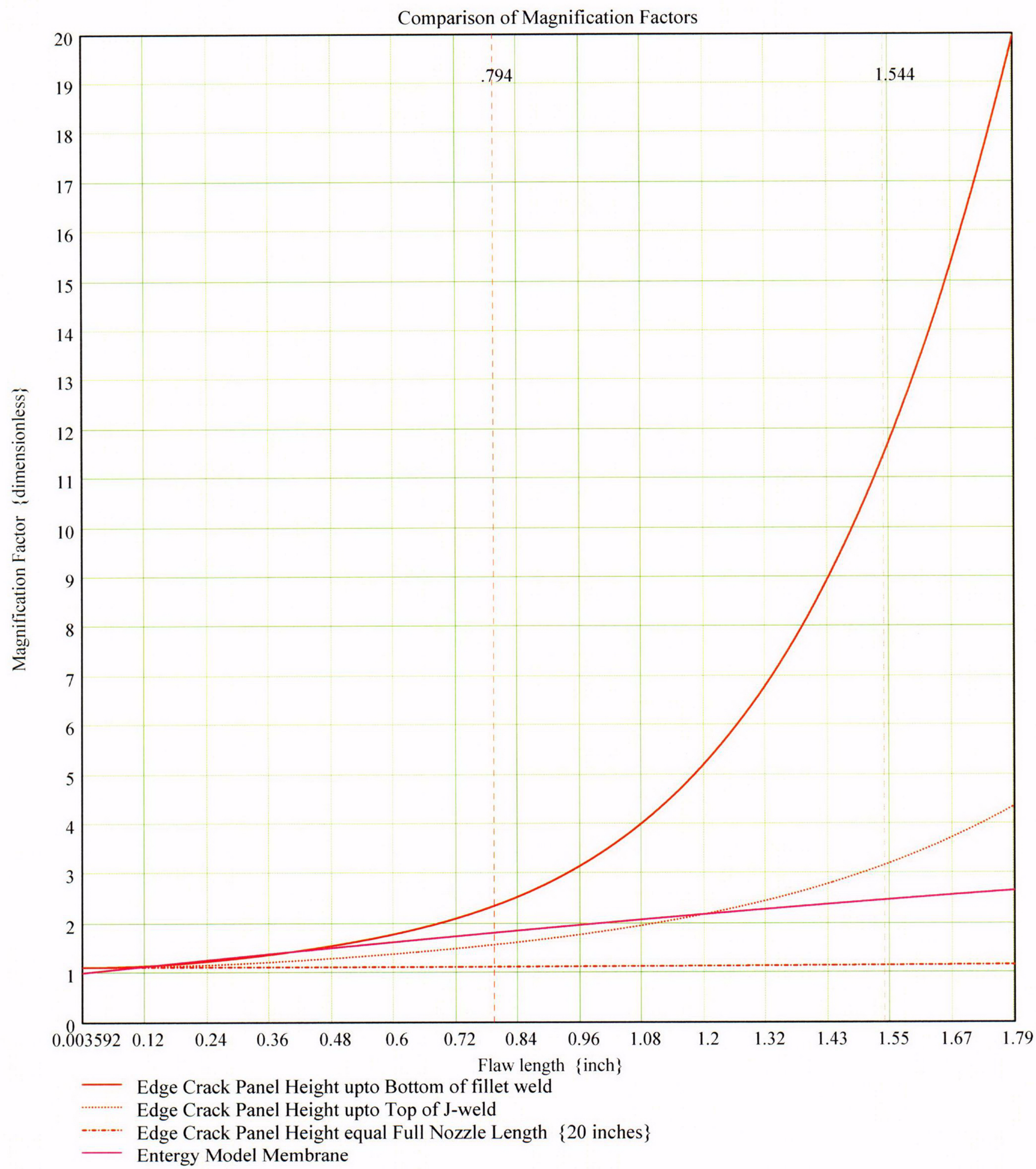
$$AeM_j := 1.009 + 0.3621\cdot\lambda_j + 0.0565\cdot(\lambda_j)^2 - 0.0082\cdot(\lambda_j)^3 + 0.0004\cdot(\lambda_j)^4 - 8.326\cdot 10^{-6}\cdot(\lambda_j)^5$$

$$AeB_j := 0.0029 + 0.0707\cdot(\lambda_j)^1 - 0.0197\cdot(\lambda_j)^2 + 0.0034\cdot(\lambda_j)^3 - 0.0003\cdot(\lambda_j)^4 + 8.8052\cdot 10^{-6}\cdot(\lambda_j)^5$$

$$AbM_j := -0.0063 + 0.919\cdot\lambda_j - 0.168\cdot(\lambda_j)^2 - 0.0052\cdot(\lambda_j)^3 + 0.0008\cdot(\lambda_j)^4 - 2.9701\cdot 10^{-5}\cdot(\lambda_j)^5$$

$$AbB_j := 0.9961 - 0.3806\cdot\lambda_j + 0.1239\cdot(\lambda_j)^2 - 0.0211\cdot(\lambda_j)^3 + 0.0017\cdot(\lambda_j)^4 - 4.9939\cdot 10^{-5}\cdot(\lambda_j)^5$$

$A_{M_j} := AeM_j + AbM_j$ $\qquad A_{B_j} := AeB_j + AbB_j$



Edge Crack- Entergy-Comparison-000.mcd

Comparison of Surface Crack Models : Conventional Model with the Current Model

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

References :
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

Purpose :- This worksheet is used to compare the crack growth and SIF results between the conventional model (using a fixed R/t ratio and a fixed flaw aspect ratio- a/c) and the current model. The current model uses the R/t ratio appropriate to the CEDM nozzle tube geometry and the flaw aspect ratio is not fixed. The flaw aspect ratio is determined at each crack growth interval based on the seperate growth for both the depth direction (a-tip) and the length direction (c-tip). Therefore, the current model permits the evaluation of crack growth through the wall thickness and along the nozzle surface simultaneously. The evaluation, using the same residual stresses distribution, compares the results form both models. The worksheet is essentially the same as that used in the analyses. The only difference is that a separate loop. The graphical presentations towards the end of the worksheet present the comparative results.

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

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 necessary 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 represents the reference point elevation measured upward from the nozzle end.

$$Ref_{Point} := 1.544$$

To place the flaw with respect 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

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

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

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

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

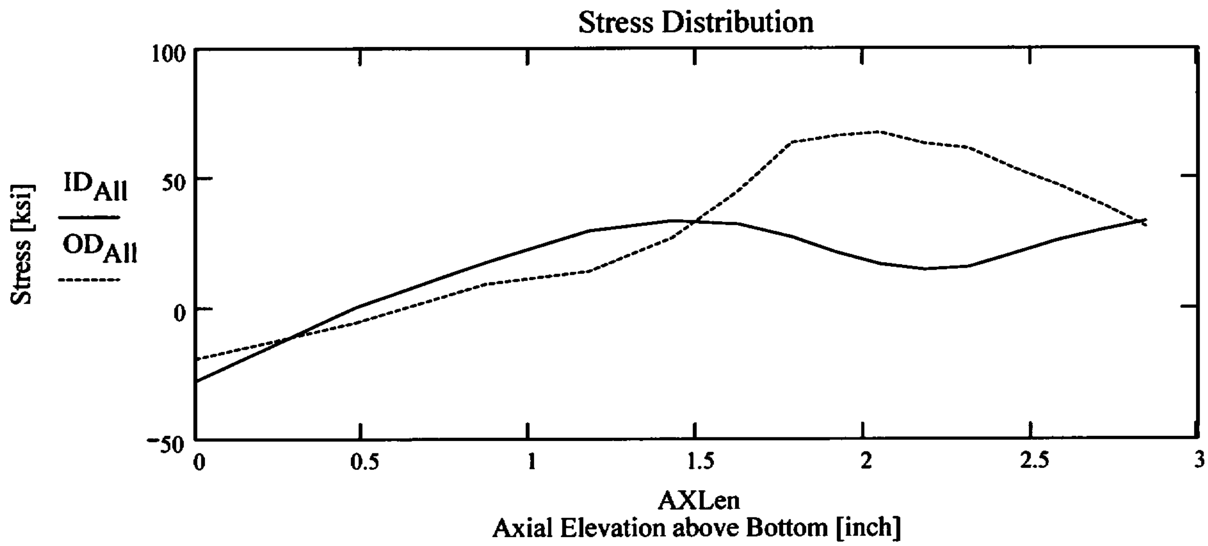
Stress Input Data

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)
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).

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

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

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

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

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

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

Flaw center Location 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

$$j := 1 .. N$$

$$S_{id_j} := \left| \begin{array}{ll} \dfrac{SID_j + SID_{j+1} + SID_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{id_{j-1}} \cdot (j+1) + SID_{j+2}}{j+2} & \text{otherwise} \end{array} \right.$$

$$S_{qt_j} := \left| \begin{array}{ll} \dfrac{SQT_j + SQT_{j+1} + SQT_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{qt_{(j-1)}} \cdot (j+1) + SQT_{j+2}}{j+2} & \text{otherwise} \end{array} \right.$$

$$S_{md_j} := \left| \begin{array}{ll} \dfrac{SMD_j + SMD_{j+1} + SMD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{md_{j-1}} \cdot (j+1) + SMD_{j+2}}{j+2} & \text{otherwise} \end{array} \right.$$

$$S_{tq_j} := \left| \begin{array}{ll} \dfrac{STQ_j + STQ_{j+1} + STQ_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{tq_{j-1}} \cdot (j+1) + STQ_{j+2}}{j+2} & \text{otherwise} \end{array} \right.$$

$$S_{od_j} := \left| \begin{array}{ll} \dfrac{SOD_j + SOD_{j+1} + SOD_{j+2}}{3} & \text{if } j = 1 \\ \dfrac{S_{od_{j-1}} \cdot (j+1) + SOD_{j+2}}{j+2} & \text{otherwise} \end{array} \right.$$

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

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

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

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

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

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

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

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

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

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

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

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

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

Regression of Through-wall Stress distribution to obtain Stress Coefficients through-wall using a Third Order polynomial

$ODRG_{1} := \mathrm{regress}(Y, SIG_{1}, 3)$ $ODRG_{2} := \mathrm{regress}(Y, SIG_{2}, 3)$

$ODRG_{3} := \mathrm{regress}(Y, SIG_{3}, 3)$ $ODRG_{4} := \mathrm{regress}(Y, SIG_{4}, 3)$

$ODRG_{5} := \mathrm{regress}(Y, SIG_{5}, 3)$ $ODRG_{6} := \mathrm{regress}(Y, SIG_{6}, 3)$

$ODRG_{7} := \mathrm{regress}(Y, SIG_{7}, 3)$ $ODRG_{8} := \mathrm{regress}(Y, SIG_{8}, 3)$

$ODRG_{9} := \mathrm{regress}(Y, SIG_{9}, 3)$ $ODRG_{10} := \mathrm{regress}(Y, SIG_{10}, 3)$

$ODRG_{11} := \mathrm{regress}(Y, SIG_{11}, 3)$ $ODRG_{12} := \mathrm{regress}(Y, SIG_{12}, 3)$

$ODRG_{13} := \mathrm{regress}(Y, SIG_{13}, 3)$ $ODRG_{14} := \mathrm{regress}(Y, SIG_{14}, 3)$

$ODRG_{15} := \mathrm{regress}(Y, SIG_{15}, 3)$ $ODRG_{16} := \mathrm{regress}(Y, SIG_{16}, 3)$

$ODRG_{17} := \mathrm{regress}(Y, SIG_{17}, 3)$ $ODRG_{18} := \mathrm{regress}(Y, SIG_{18}, 3)$

$ODRG_{19} := \mathrm{regress}(Y, SIG_{19}, 3)$ $ODRG_{20} := \mathrm{regress}(Y, SIG_{20}, 3)$

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

$$Prop_{Length} := UL_{Strs.Dist} - FL_{Cntr} - c_0 \qquad Prop_{Length} = 0.044$$

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 through-wall 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

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
39	2.025	1.032	0.72	0.568	1.781	0.427	0.181	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

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

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

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

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

"a-Tip" Uniform Term

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

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

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

Linear Term

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

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

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

Quadratic Term

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

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

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

Cubic Term

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

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

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

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

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

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

Cubic Term

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

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

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

Calculations : Recursive calculations to estimate flaw growth.

Recursive Loop for Calculation of PWSCC Crack Growth Entergy Model

$$
\begin{aligned}
CGR_{sambi} := \;& j \leftarrow 0 \\
& a_0 \leftarrow a_0 \\
& c_0 \leftarrow c_0 \\
& NCB_0 \leftarrow C_{blk} \\
& \text{while } j \le I_{lim} \\
& \quad \sigma_0 \leftarrow \begin{array}{|ll}
ODRG_{1_3} & \text{if } c_j \le c_0 \\
ODRG_{2_3} & \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\
ODRG_{3_3} & \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg} \\
ODRG_{4_3} & \text{if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg} \\
ODRG_{5_3} & \text{if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg} \\
ODRG_{6_3} & \text{if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg} \\
ODRG_{7_3} & \text{if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg} \\
ODRG_{8_3} & \text{if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg} \\
ODRG_{9_3} & \text{if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg} \\
ODRG_{10_3} & \text{if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg} \\
ODRG_{11_3} & \text{if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg} \\
ODRG_{12_3} & \text{if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg} \\
ODRG_{13_3} & \text{if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}
\end{array}
\end{aligned}
$$

$$
\begin{aligned}
&ODRG14_{3} && \text{if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg} \\
&ODRG15_{3} && \text{if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg} \\
&ODRG16_{3} && \text{if } c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg} \\
&ODRG17_{3} && \text{if } c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg} \\
&ODRG18_{3} && \text{if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg} \\
&ODRG19_{3} && \text{if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg} \\
&ODRG20_{3} && \text{otherwise}
\end{aligned}
$$

$$
\sigma_1 \leftarrow
\begin{aligned}
&ODRG1_{4} && \text{if } c_j \le c_0 \\
&ODRG2_{4} && \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\
&ODRG3_{4} && \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg} \\
&ODRG4_{4} && \text{if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg} \\
&ODRG5_{4} && \text{if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg} \\
&ODRG6_{4} && \text{if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg} \\
&ODRG7_{4} && \text{if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg} \\
&ODRG8_{4} && \text{if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg} \\
&ODRG9_{4} && \text{if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg} \\
&ODRG10_{4} && \text{if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg} \\
&ODRG11_{4} && \text{if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg} \\
&ODRG12_{4} && \text{if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg} \\
&ODRG13_{4} && \text{if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg} \\
&ODRG14_{4} && \text{if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg} \\
&ODRG15_{4} && \text{if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}
\end{aligned}
$$

$$ODRG_{16_4} \text{ if } c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$$
$$ODRG_{17_4} \text{ if } c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$$
$$ODRG_{18_4} \text{ if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$
$$ODRG_{19_4} \text{ if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$$
$$ODRG_{20_4} \text{ otherwise}$$

$$\sigma_2 \leftarrow \begin{array}{|l} ODRG_{1_5} \text{ if } c_j \le c_0 \\ ODRG_{2_5} \text{ if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\ ODRG_{3_5} \text{ if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg} \\ ODRG_{4_5} \text{ if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg} \\ ODRG_{5_5} \text{ if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg} \\ ODRG_{6_5} \text{ if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg} \\ ODRG_{7_5} \text{ if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg} \\ ODRG_{8_5} \text{ if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg} \\ ODRG_{9_5} \text{ if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg} \\ ODRG_{10_5} \text{ if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg} \\ ODRG_{11_5} \text{ if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg} \\ ODRG_{12_5} \text{ if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg} \\ ODRG_{13_5} \text{ if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg} \\ ODRG_{14_5} \text{ if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg} \\ ODRG_{15_5} \text{ if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg} \\ ODRG_{16_5} \text{ if } c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg} \end{array}$$

$$\begin{array}{ll}
ODRG17_5 & \text{if } c_0 + 15\cdot Inc_{Strs.avg} < c_j \le c_0 + 16\cdot Inc_{Strs.avg} \\
ODRG18_5 & \text{if } c_0 + 16\cdot Inc_{Strs.avg} < c_j \le c_0 + 17\cdot Inc_{Strs.avg} \\
ODRG19_5 & \text{if } c_0 + 17\cdot Inc_{Strs.avg} < c_j \le c_0 + 18\cdot Inc_{Strs.avg} \\
ODRG20_5 & \text{otherwise}
\end{array}$$

$$\sigma_3 \leftarrow \begin{array}{ll}
ODRG1_6 & \text{if } c_j \le c_0 \\
ODRG2_6 & \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\
ODRG3_6 & \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2\cdot Inc_{Strs.avg} \\
ODRG4_6 & \text{if } c_0 + 2\cdot Inc_{Strs.avg} < c_j \le c_0 + 3\cdot Inc_{Strs.avg} \\
ODRG5_6 & \text{if } c_0 + 3\cdot Inc_{Strs.avg} < c_j \le c_0 + 4\cdot Inc_{Strs.avg} \\
ODRG6_6 & \text{if } c_0 + 4\cdot Inc_{Strs.avg} < c_j \le c_0 + 5\cdot Inc_{Strs.avg} \\
ODRG7_6 & \text{if } c_0 + 5\cdot Inc_{Strs.avg} < c_j \le c_0 + 6\cdot Inc_{Strs.avg} \\
ODRG8_6 & \text{if } c_0 + 6\cdot Inc_{Strs.avg} < c_j \le c_0 + 7\cdot Inc_{Strs.avg} \\
ODRG9_6 & \text{if } c_0 + 7\cdot Inc_{Strs.avg} < c_j \le c_0 + 8\cdot Inc_{Strs.avg} \\
ODRG10_6 & \text{if } c_0 + 8\cdot Inc_{Strs.avg} < c_j \le c_0 + 9\cdot Inc_{Strs.avg} \\
ODRG11_6 & \text{if } c_0 + 9\cdot Inc_{Strs.avg} < c_j \le c_0 + 10\cdot Inc_{Strs.avg} \\
ODRG12_6 & \text{if } c_0 + 10\cdot Inc_{Strs.avg} < c_j \le c_0 + 11\cdot Inc_{Strs.avg} \\
ODRG13_6 & \text{if } c_0 + 11\cdot Inc_{Strs.avg} < c_j \le c_0 + 12\cdot Inc_{Strs.avg} \\
ODRG14_6 & \text{if } c_0 + 12\cdot Inc_{Strs.avg} < c_j \le c_0 + 13\cdot Inc_{Strs.avg} \\
ODRG15_6 & \text{if } c_0 + 13\cdot Inc_{Strs.avg} < c_j \le c_0 + 14\cdot Inc_{Strs.avg} \\
ODRG16_6 & \text{if } c_0 + 14\cdot Inc_{Strs.avg} < c_j \le c_0 + 15\cdot Inc_{Strs.avg} \\
ODRG17_6 & \text{if } c_0 + 15\cdot Inc_{Strs.avg} < c_j \le c_0 + 16\cdot Inc_{Strs.avg} \\
ODRG18_6 & \text{if } c_0 + 16\cdot Inc_{Strs.avg} < c_j \le c_0 + 17\cdot Inc_{Strs.avg}
\end{array}$$

$$\begin{vmatrix} ODRG_{19_6} & \text{if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg} \\ ODRG_{20_6} & \text{otherwise} \end{vmatrix}$$

$$\xi_0 \leftarrow \sigma_0$$

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

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

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

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

$$x_0 \leftarrow 0.0$$

$$x_1 \leftarrow 0.25$$

$$x_2 \leftarrow 0.5$$

$$x_3 \leftarrow 0.75$$

$$x_4 \leftarrow 1.0$$

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

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

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

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

$$\sigma_{10} \leftarrow RG_4$$

$$\sigma_{20} \leftarrow RG_5$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$j \leftarrow j + 1$$

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

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

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

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

output

Recursive Loop for Industry Model

{R/t = 4.0 and a/c=0.33 The R/t lower Limit for Original Raju-Newman model and aspect ratio was fixed at 1:6}

$$
\begin{aligned}
CGR_{Bam.Bam} := \; & j \leftarrow 0 \\
& a_0 \leftarrow a_0 \\
& c_0 \leftarrow c_0 \\
& NCB_0 \leftarrow C_{blk} \\
& \text{while } j \le I_{lim} \\
& \quad \sigma_0 \leftarrow ODRG1_3 \\
& \quad \sigma_1 \leftarrow ODRG1_4 \\
& \quad \sigma_2 \leftarrow ODRG1_5 \\
& \quad \sigma_3 \leftarrow ODRG1_6 \\
& \quad \xi_0 \leftarrow \sigma_0 \\
& \quad \xi_1 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.25 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^3 \\
& \quad \xi_2 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.5 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^3 \\
& \quad \xi_3 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.75 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^3 \\
& \quad \xi_4 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{1.0 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^3 \\
& \quad x_0 \leftarrow 0.0 \\
& \quad x_1 \leftarrow 0.25 \\
& \quad x_2 \leftarrow 0.5 \\
& \quad x_3 \leftarrow 0.75 \\
& \quad x_4 \leftarrow 1.0
\end{aligned}
$$

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

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

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

$$\sigma_{00} \leftarrow RG_3$$

$$\sigma_{10} \leftarrow RG_4$$

$$\sigma_{20} \leftarrow RG_5$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$j \leftarrow j + 1$$

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

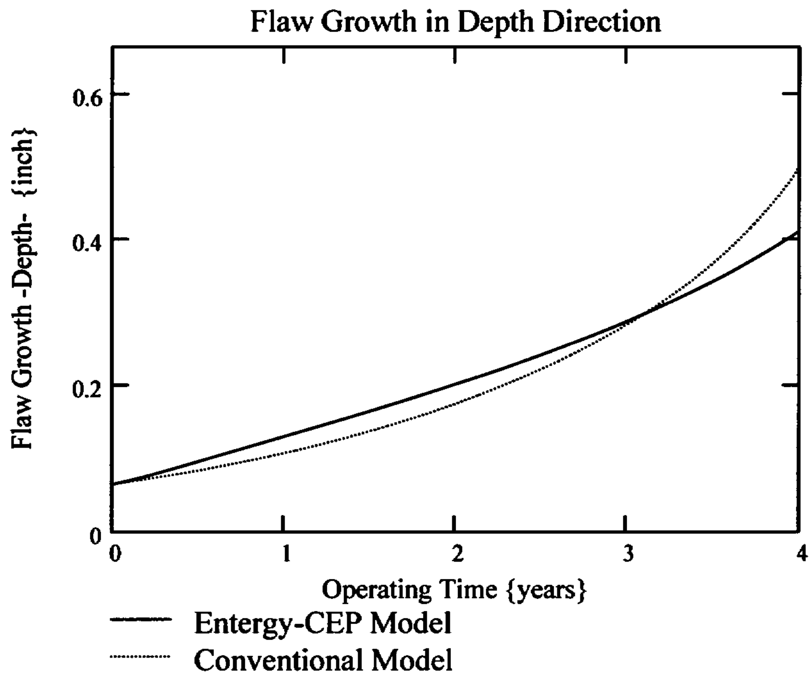
$$c_j \leftarrow c_{j-1} + D_{cg_{j-1}}$$

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

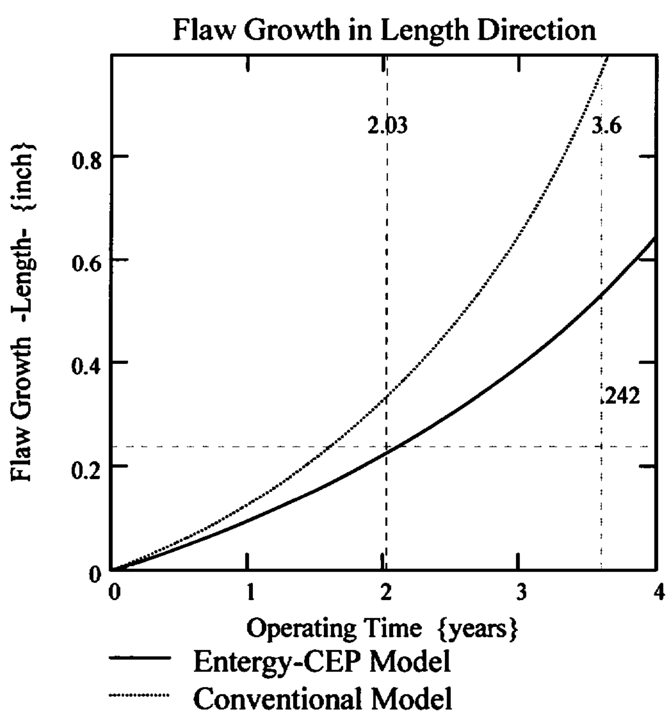
$$NCB_j \leftarrow NCB_{j-1} + C_{blk}$$

$$output$$

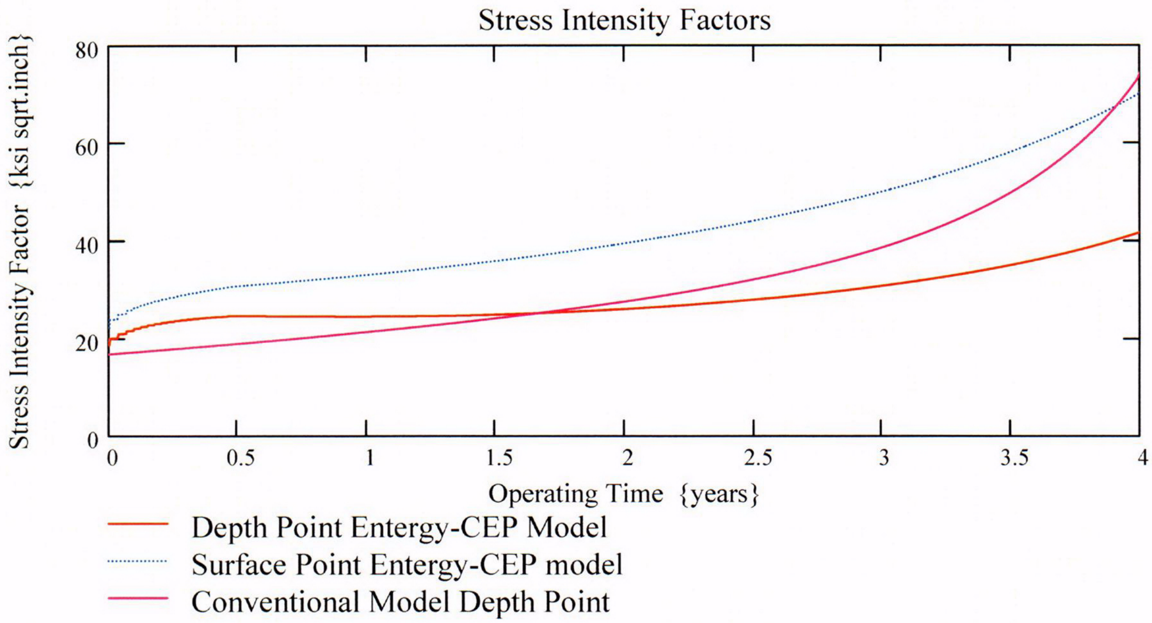
$$k := 0 .. I_{lim}$$



The Current model, in the time period of interest provides a higher growth.

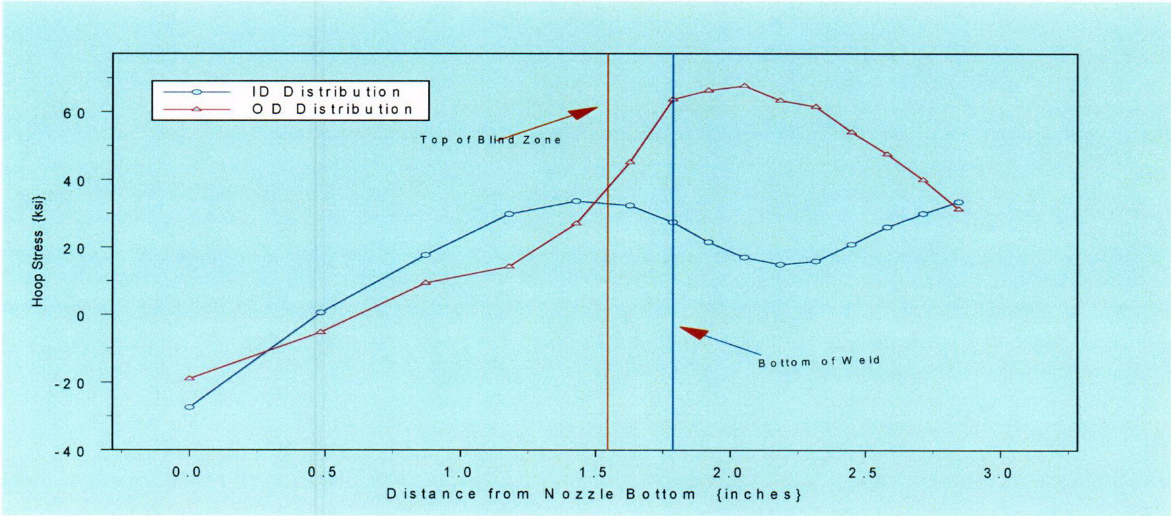


The flaw growth in the length direction for the conventional model is controlled by the flaw aspect ratio. Hence the observed higher growth rate for the conventional model doe not signify a truly higher growth rate.

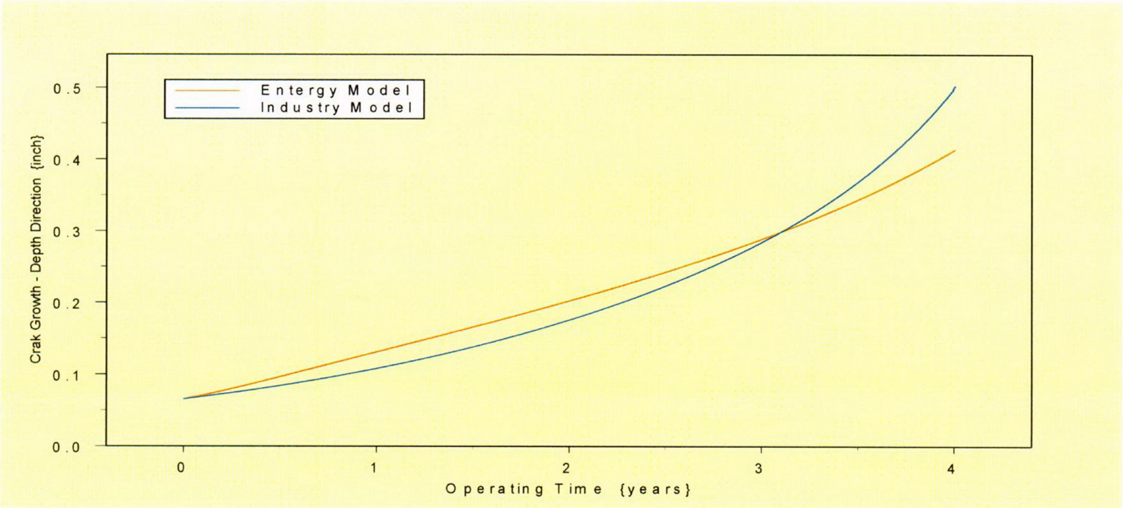


The SIF comparison shows that the current model has higher SIF for the period of interest (one operating cycle). The conventional model SIF rises above the current model SIF for the depth point (a-tip) but remains below that for the surface point (c-tip).

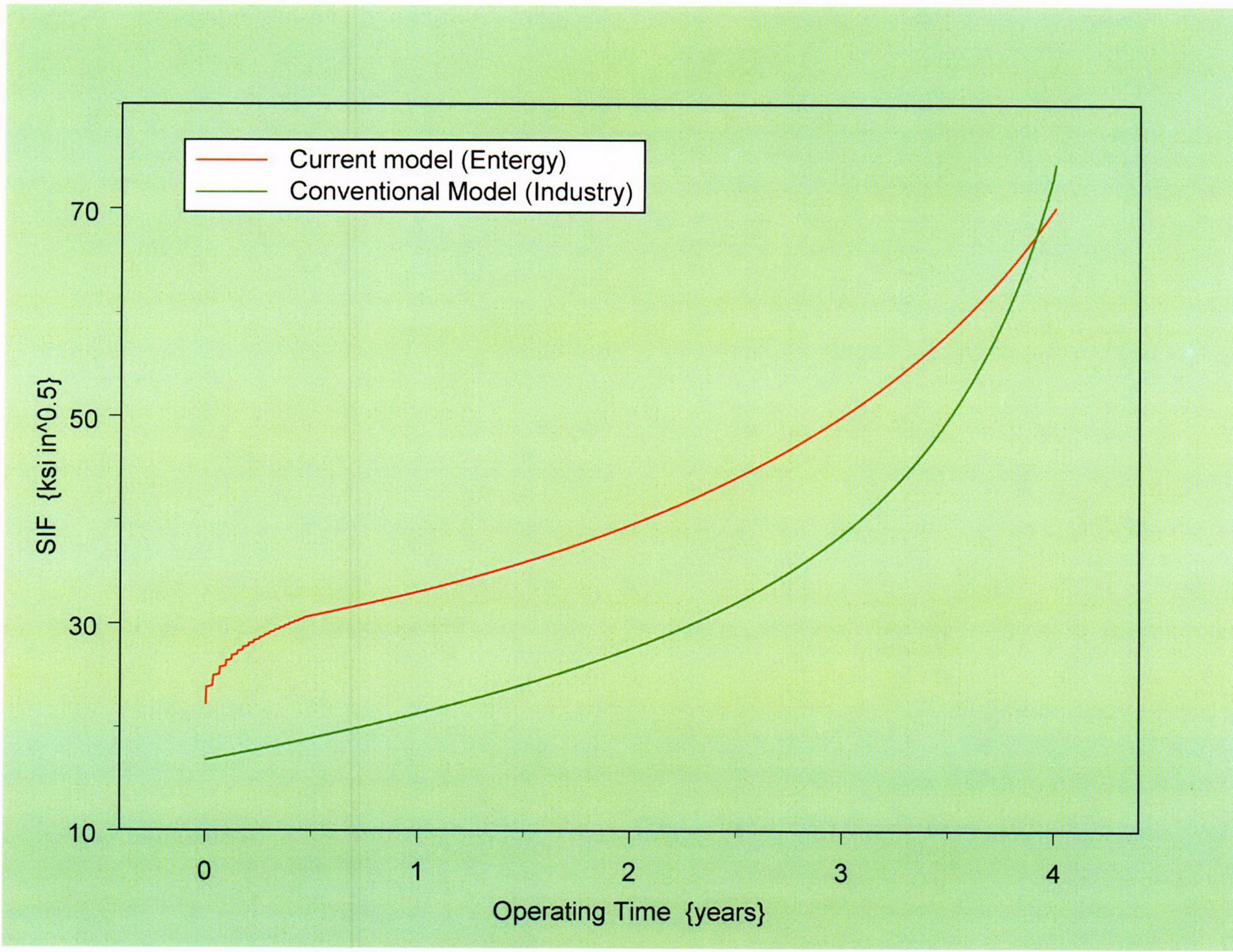
Axum plot showing the ID and the OD stress distribution for the CEDM



Axum plot showing the comparison for Crack growth between Conventional and Current Model



Axum plot showing the SIF comparison between the Conventional and Current Models



Comparison for Through-wall Cracks

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadesam **Verified by: B. C. Gray**

References :

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

Purpose :- This worksheet is used to compare the results from the conventional model, edge crack model and the current model. The SIF comparison is made between the conventional model and the current model. The crack growth and SIF comparisons are made between the edge crack and current model. The SIF equations for the conventional model are included in the current model's recursive loop structure. The edge crack is modeled separately in a recursive loop immediately following the loop for the current model. Graphical results show the comparisons at the end.

The salient differences between the three models considered are:

1) Current model is based on λ, which is limited to 20. The closed form solutions are based on a thick wall cylinder. The applied stresses are based on a moving average. Therefore an increase in the stress field as the crack advances is considered in the analyses
2) The conventional model is based on a Center Cracked Panel with a SICF of 1.0. The applied stresses are at the initial flaw location and remain constant over the entire crack growth regime.
3) The edge crack model uses the plate height (b) equal to the nozzle length from the bottom of the nozzle to below the weld. The initial flaw length (a) is equal to the blind zone (1.544 inches). When this is done the ratioa/b (crack-length/plate-height) is larger than the validity limit of 0.6. Therefore, the estimated SIF is considered non-representative.

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 through-wall 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.

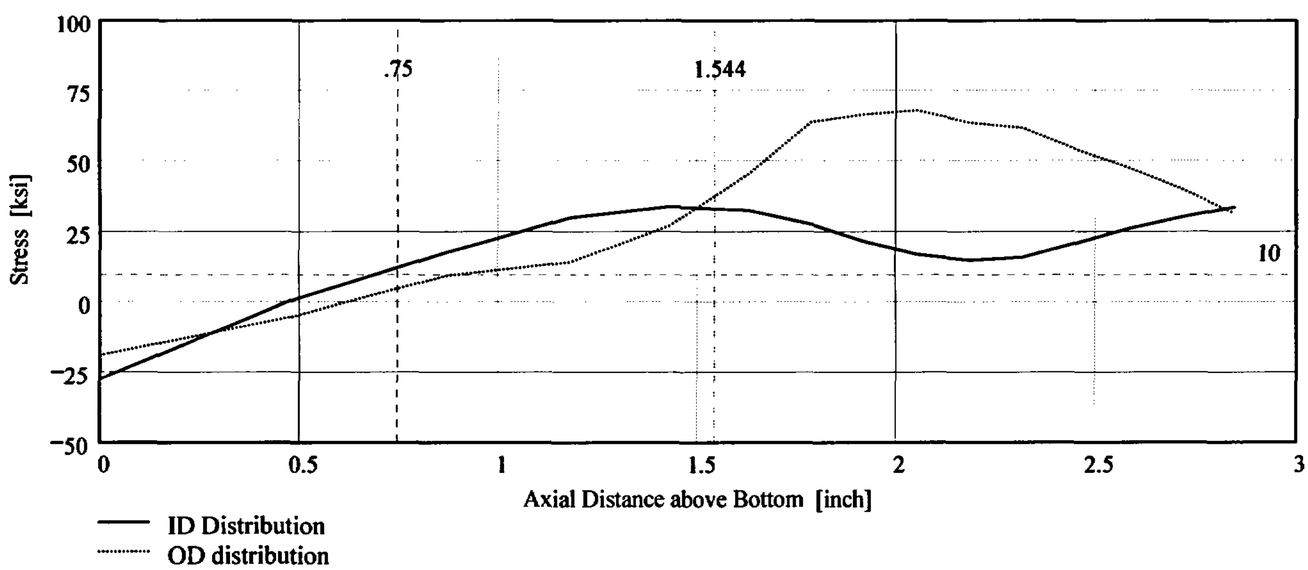
Stress Input Data

Import the Required data from applicable Excel spread Sheet. The column designations are as follows:
Column "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

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



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).

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

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

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

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

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

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

$RID_{All} := regress(AllAxl, AllID, 3)$ $\quad ROD_{All} := regress(AllAxl, AllOD, 3)$

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

$$j := 1..N$$

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

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

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

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

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

Stress Distributions for use in Fracture Mechanics Analysis

	Membrane Stress σ_m	Bending Stress σ_b	OD Stress S_{od}	ID Stress S_{id}	Membrane stress (Edge Crack) $\sigma_{m.all}$
	0	0	0	0	0
0	0	0	0	0	0
1	15.27	-4.731	8.303	17.766	5.53
2	18.819	-4.823	11.761	21.408	12.037
3	21.119	-4.766	14.117	23.65	16.08
4	22.794	-4.625	15.934	25.184	18.889
5	24.115	-4.426	17.454	26.306	20.99
6	25.215	-4.184	18.796	27.164	22.646
7	26.169	-3.905	20.029	27.839	24.005
8	27.022	-3.594	21.193	28.381	25.153
9	27.802	-3.254	22.314	28.821	26.146
10	28.53	-2.885	23.41	29.18	27.022
11	29.217	-2.489	24.493	29.471	27.807
12	29.874	-2.066	25.572	29.705	28.518
13	30.507	-1.617	26.655	29.889	29.169
14	31.122	-1.142	27.745	30.029	29.77
15	31.723	-0.64	28.848	30.128	30.329

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

$Prop_{Length} = 0.486$

Calculations : Recursive calculations to estimate flaw growth

Recursive loop for Entergy Model and Industry Model

$$
\begin{aligned}
TWC_{pwscc} := \;& i \leftarrow 0 \\
& l_0 \leftarrow l \\
& NCB_0 \leftarrow C_{blk} \\
& \text{while } i \le I_{lim} \\
& \quad \sigma_{m.appld} \leftarrow \begin{cases}
\sigma_{m_1} & \text{if } l_i \le l_0 \\
\sigma_{m_2} & \text{if } l_0 < l_i \le l_0 + Inc_{Strs.avg} \\
\sigma_{m_3} & \text{if } l_0 + Inc_{Strs.avg} < l_i \le l_0 + 2 \cdot Inc_{Strs.avg} \\
\sigma_{m_4} & \text{if } l_0 + 2 \cdot Inc_{Strs.avg} < l_i \le l_0 + 3 \cdot Inc_{Strs.avg} \\
\sigma_{m_5} & \text{if } l_0 + 3 \cdot Inc_{Strs.avg} < l_i \le l_0 + 4 \cdot Inc_{Strs.avg} \\
\sigma_{m_6} & \text{if } l_0 + 4 \cdot Inc_{Strs.avg} < l_i \le l_0 + 5 \cdot Inc_{Strs.avg} \\
\sigma_{m_7} & \text{if } l_0 + 5 \cdot Inc_{Strs.avg} < l_i \le l_0 + 6 \cdot Inc_{Strs.avg} \\
\sigma_{m_8} & \text{if } l_0 + 6 \cdot Inc_{Strs.avg} < l_i \le l_0 + 7 \cdot Inc_{Strs.avg} \\
\sigma_{m_9} & \text{if } l_0 + 7 \cdot Inc_{Strs.avg} < l_i \le l_0 + 8 \cdot Inc_{Strs.avg} \\
\sigma_{m_{10}} & \text{if } l_0 + 8 \cdot Inc_{Strs.avg} < l_i \le l_0 + 9 \cdot Inc_{Strs.avg} \\
\sigma_{m_{11}} & \text{if } l_0 + 9 \cdot Inc_{Strs.avg} < l_i \le l_0 + 10 \cdot Inc_{Strs.avg} \\
\sigma_{m_{12}} & \text{if } l_0 + 10 \cdot Inc_{Strs.avg} < l_i \le l_0 + 11 \cdot Inc_{Strs.avg} \\
\sigma_{m_{13}} & \text{if } l_0 + 11 \cdot Inc_{Strs.avg} < l_i \le l_0 + 12 \cdot Inc_{Strs.avg} \\
\sigma_{m_{14}} & \text{if } l_0 + 12 \cdot Inc_{Strs.avg} < l_i \le l_0 + 13 \cdot Inc_{Strs.avg} \\
\sigma_{m_{15}} & \text{if } l_0 + 13 \cdot Inc_{Strs.avg} < l_i \le l_0 + 14 \cdot Inc_{Strs.avg} \\
\sigma_{m_{16}} & \text{if } l_0 + 14 \cdot Inc_{Strs.avg} < l_i \le l_0 + 15 \cdot Inc_{Strs.avg} \\
\sigma_{m_{17}} & \text{if } l_0 + 15 \cdot Inc_{Strs.avg} < l_i \le l_0 + 16 \cdot Inc_{Strs.avg} \\
\sigma_{m_{18}} & \text{if } l_0 + 16 \cdot Inc_{Strs.avg} < l_i \le l_0 + 17 \cdot Inc_{Strs.avg} \\
\sigma_{m_{19}} & \text{if } l_0 + 17 \cdot Inc_{Strs.avg} < l_i \le l_0 + 18 \cdot Inc_{Strs.avg} \\
\sigma_{m_{20}} & \text{otherwise}
\end{cases}
\end{aligned}
$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$K_{\alpha_i} \leftarrow \begin{array}{|l} 9.0 \text{ if } K_{\alpha_i} \le 9.0 \\ K_{\alpha_i} \text{ otherwise} \end{array}$

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

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

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

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

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

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

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

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

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

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

output... ← KmembrnOD

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

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

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

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

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

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

$i \leftarrow i + 1$

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

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

output

Recursive Loop For Edge Crack Model

$$TWCEDG_{pwscc} :=$$

$$i \leftarrow 0$$

$$L1_0 \leftarrow |L_1|$$

$$NCB_0 \leftarrow C_{blk}$$

$$\text{while } i \le I_{lim}$$

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

$$b \leftarrow UL_{Strs.Dist}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

$$i \leftarrow i + 1$$

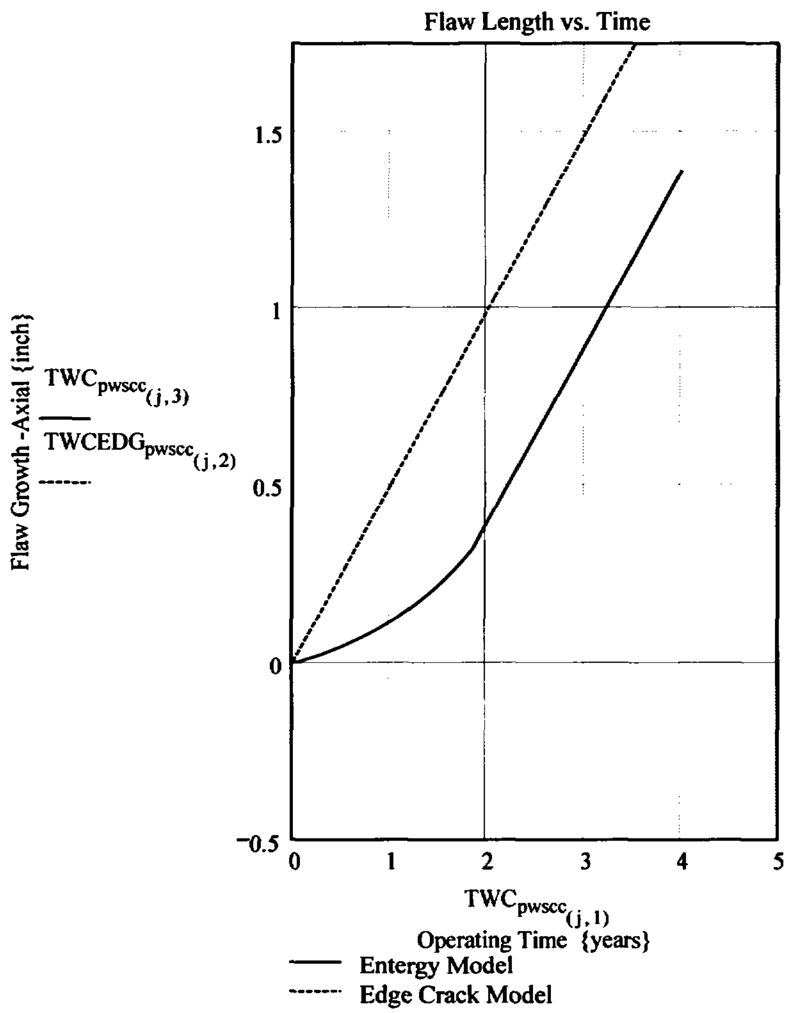
$$L1_i \leftarrow L1_{i-1} + D_{lengrth_{i-1}}$$

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

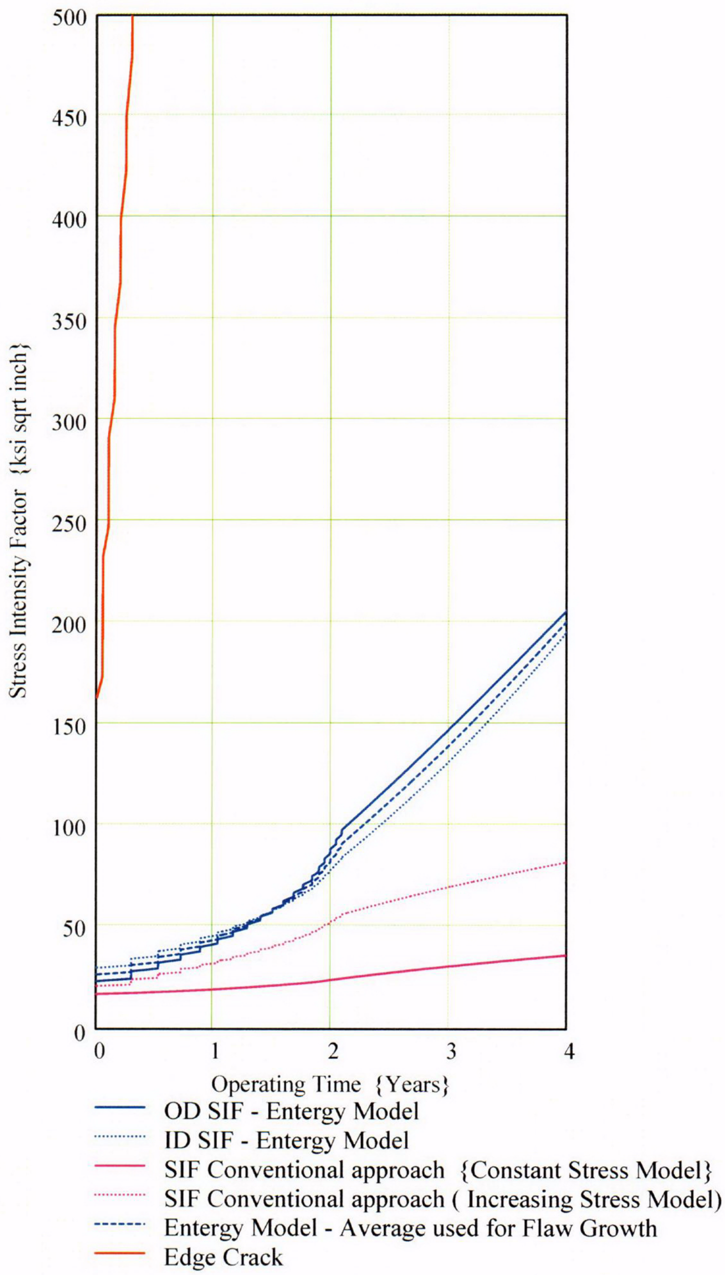
output

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

$Prop_{Length} = 0.486$



Comparison for crack growth between Edge Crack and Current Model. The edge crack mc provides a constant crack growth rate equal tc the asymptotic growth rate of about 05. inch/year. The edge crack model produces a SIF much greater than the asymptotic value ot ksi* in^0.5 or 80 Mpa*m^0.5. This is because the "a/b" ratio (crack-length/plate-height) is significantly greater than the validity limit of 0.(In order to meet the "a/b" ratio validity limit of (the crack length, for the assumed plate height cannot be greater than 1.073 inches, which is lower than the blind zone length of 1.544 inch(As shown in attachment 3 of this appendix, assuming a longer plate height produces SICF that can be lower than the membrane compon SICF. Therefore, the SICF for the modeled ed crack configuration is considered incorrect because the validity regime is violated (since a ratio is in excess of 0.6).



The SIF for the current model is always higher than the conventional model. Hence the estimated crack growth produced by the current model will be higher than that produced by the conventional model. Hence the current model is shown to be more conservative than the conventional model. The SIF for the edge crack is very high owing to the large SICF produce by a large a/b ratio, which is beyond the validity limit for the determination of the SICF (discussed in the previous figure).

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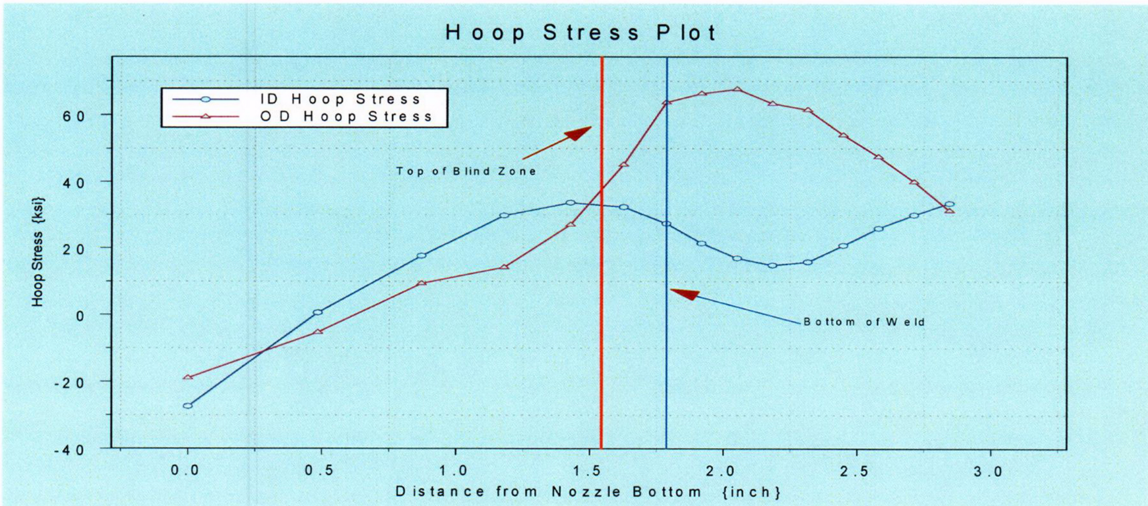
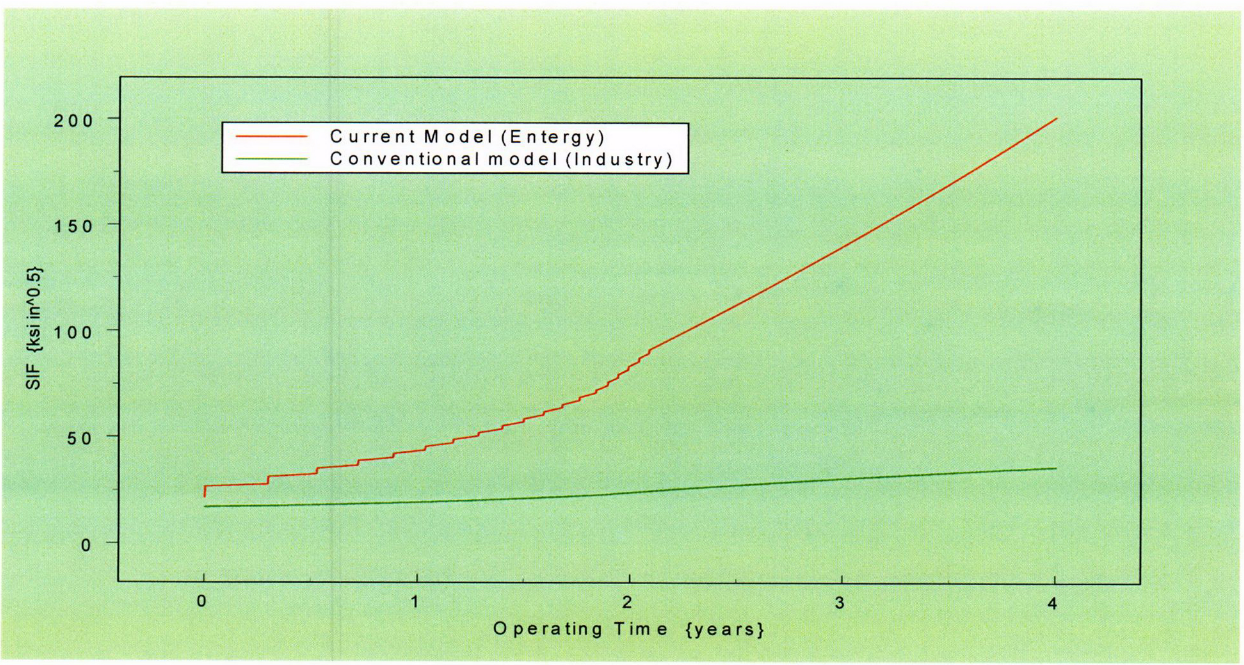
Axum Plot for the ID and OD Stress distribution along nozzle length used in the comparison



Axum plot showing the comparison for the SIF between the Current and Conventional Models.



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ENCLOSURE 5

CNRO-2003-00033

LICENSEE-IDENTIFIED COMMITMENTS

LICENSEE-IDENTIFIED COMMITMENTS

COMMITMENT	TYPE (Check one) ONE-TIME ACTION	CONTINUING COMPLIANCE	SCHEDULED COMPLETION DATE
1. The final results of the inspections will be included in the 60-day report submitted to the NRC in accordance with Section IV.E of the Order.	X		60 days after startup from the next refueling outage
2. If the NRC staff finds that the crack-growth formula in MRP-55 is unacceptable, Entergy shall revise its analysis that justifies relaxation of the Order within 30 days after the NRC informs Entergy of an NRC-approved crack-growth formula.	X		Within 30 days after the NRC informs Entergy of an NRC-approved crack-growth formula.
3. If Entergy's revised analysis (#2, above) shows that the crack growth acceptance criteria are exceeded prior to the end of Operating Cycle 17 (following the upcoming refueling outage), Entergy will, within 72 hours, submit to the NRC written justification for continued operation.	X		Within 72 hours from completing the revised analysis in #2, above.
4. If the revised analysis (#2, above) shows that the crack growth acceptance criteria are exceeded during the subsequent operating cycle, Entergy shall, within 30 days, submit the revised analysis for NRC review.	X		Within 30 days from completing the revised analysis in #2, above.
5. If the revised analysis (#2, above) shows that the crack growth acceptance criteria are not exceeded during either Operating Cycle 17 or the subsequent operating cycle, Entergy shall, within 30 days, submit a letter to the NRC confirming that its analysis has been revised.	X		Within 30 days from completing the revised analysis in #2, above.
6. Any future crack-growth analyses performed for Operating Cycle 17 and future cycles for RPV head penetrations will be based on an acceptable crack growth rate formula.		X	N/A