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" Degree Nozzle, Mid-Plane Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

OD Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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

$UL_{Strs.Dist} := 2.999$ 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

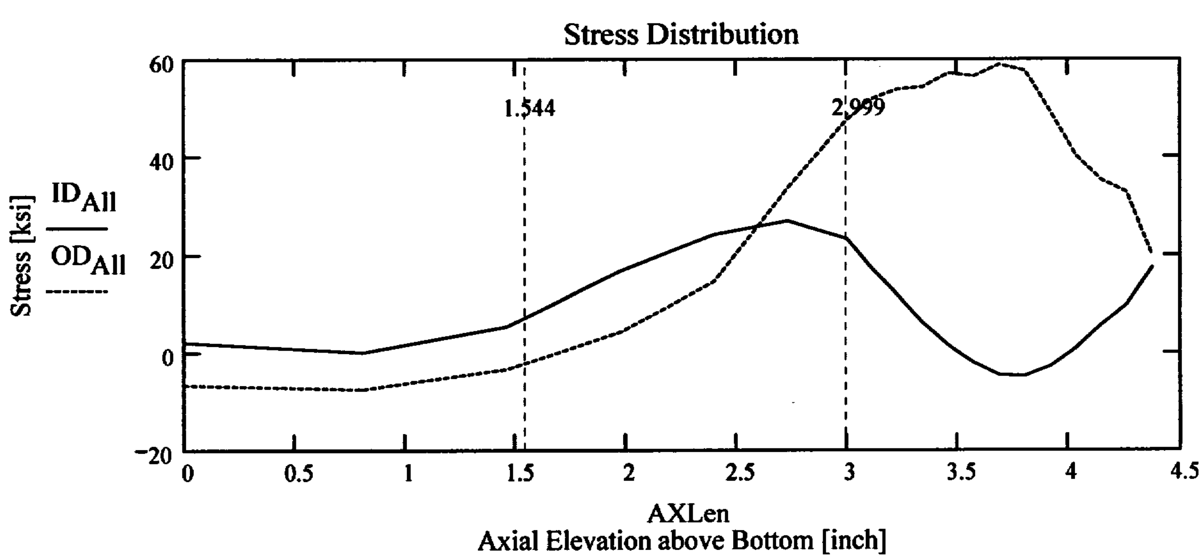
Stress Input Data

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	2.08	-0.87	-2.96	-4.82	-6.75
1	0.81	0.09	-2.37	-4.27	-6	-7.55
2	1.46	5.28	1.69	-0.79	-2.49	-3.47
3	1.98	16.88	12.42	9.56	6.91	4.32
4	2.4	24.14	20.89	18.11	16.59	14.51
5	2.73	26.96	22.67	20.69	24.84	33.52
6	3	23.28	20.9	21.71	37.11	47.4
7	3.11	17.16	17.1	20.74	41.09	51.76
8	3.23	11.72	14.42	21.34	43.54	53.69
9	3.34	6	11.11	20.91	43.83	54.15
10	3.46	1.44	8.09	20.38	43.02	57.02
11	3.57	-2.17	5.89	19.93	42.41	56.41
12	3.69	-4.72	4.86	19.99	40.42	58.85
13	3.8	-4.92	4.88	20.34	38.45	57.62

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



Observing the stress distribution select the region in the table above labeled $Data_{All}$ that represents the region of interest. This needs to be done especially for distributions that have a large compressive stress at the nozzle bottom and high tensile stresses at the J-weld location. 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).

$$Data := \begin{pmatrix} 0 & 2.079 & -0.875 & -2.96 & -4.82 & -6.75 \\ 0.811 & 0.091 & -2.37 & -4.267 & -6.004 & -7.552 \\ 1.46 & 5.283 & 1.686 & -0.786 & -2.49 & -3.469 \\ 1.98 & 16.881 & 12.419 & 9.564 & 6.907 & 4.319 \\ 2.397 & 24.144 & 20.894 & 18.115 & 16.59 & 14.513 \\ 2.731 & 26.962 & 22.672 & 20.686 & 24.842 & 33.523 \\ 2.999 & 23.279 & 20.902 & 21.706 & 37.111 & 47.395 \\ 3.113 & 17.161 & 17.101 & 20.743 & 41.091 & 51.762 \\ 3.228 & 11.722 & 14.424 & 21.34 & 43.543 & 53.688 \\ 3.343 & 6.004 & 11.108 & 20.912 & 43.833 & 54.154 \\ 3.457 & 1.439 & 8.085 & 20.38 & 43.021 & 57.025 \\ 3.572 & -2.175 & 5.891 & 19.929 & 42.405 & 56.415 \\ 3.687 & -4.725 & 4.858 & 19.994 & 40.425 & 58.85 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

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

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

No User Input is required beyond this Point

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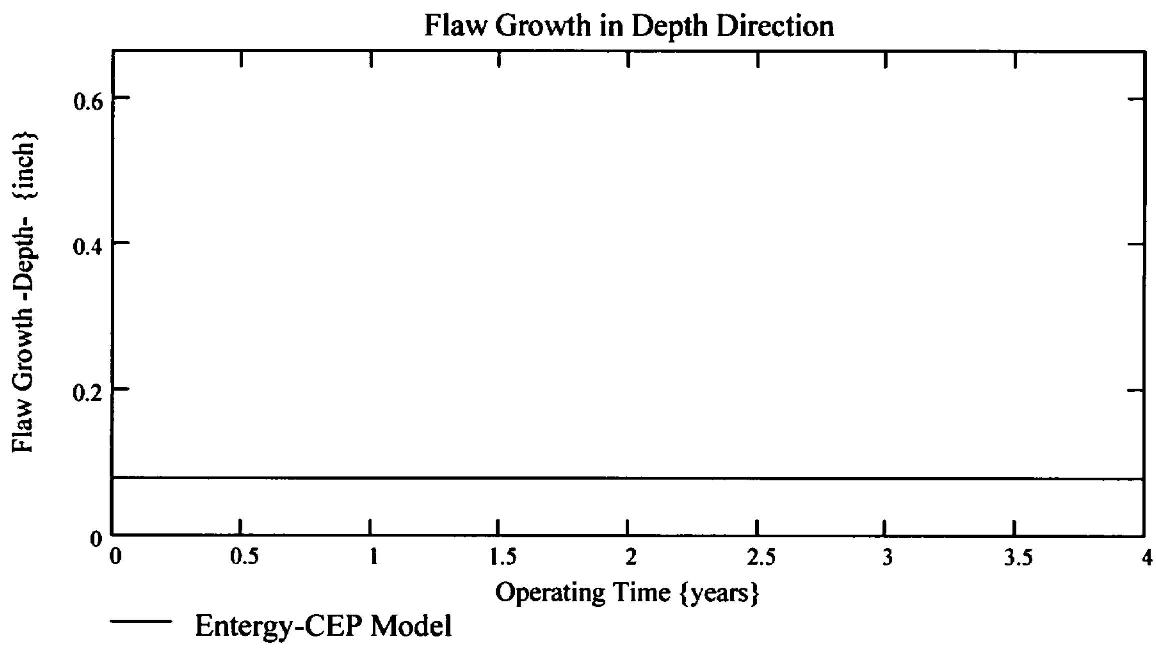
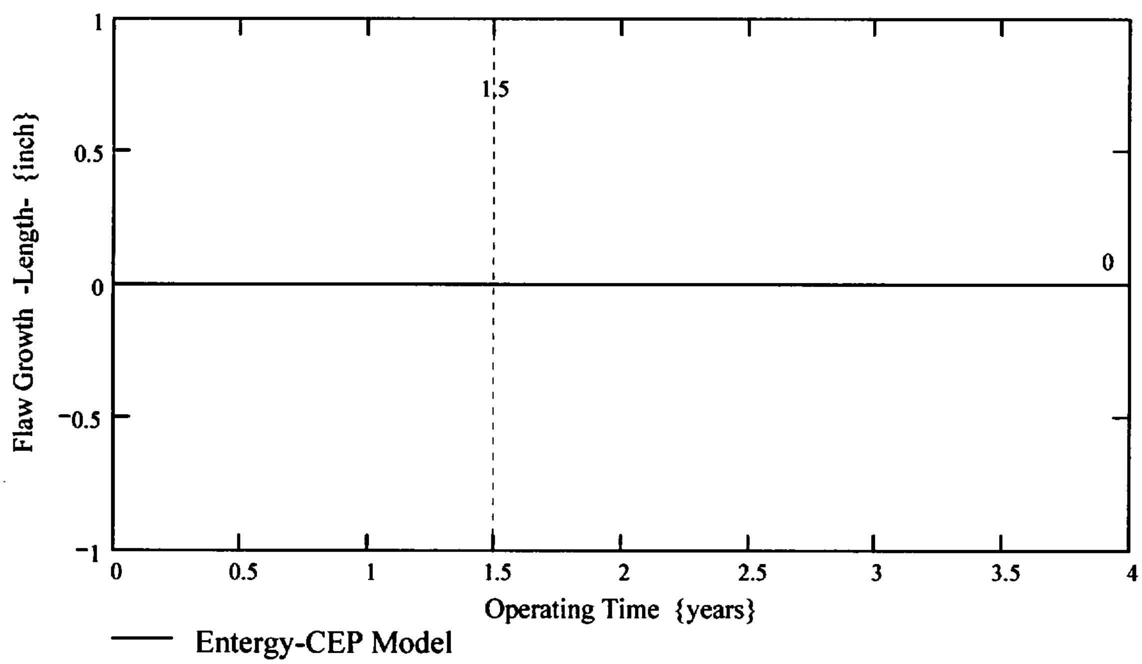
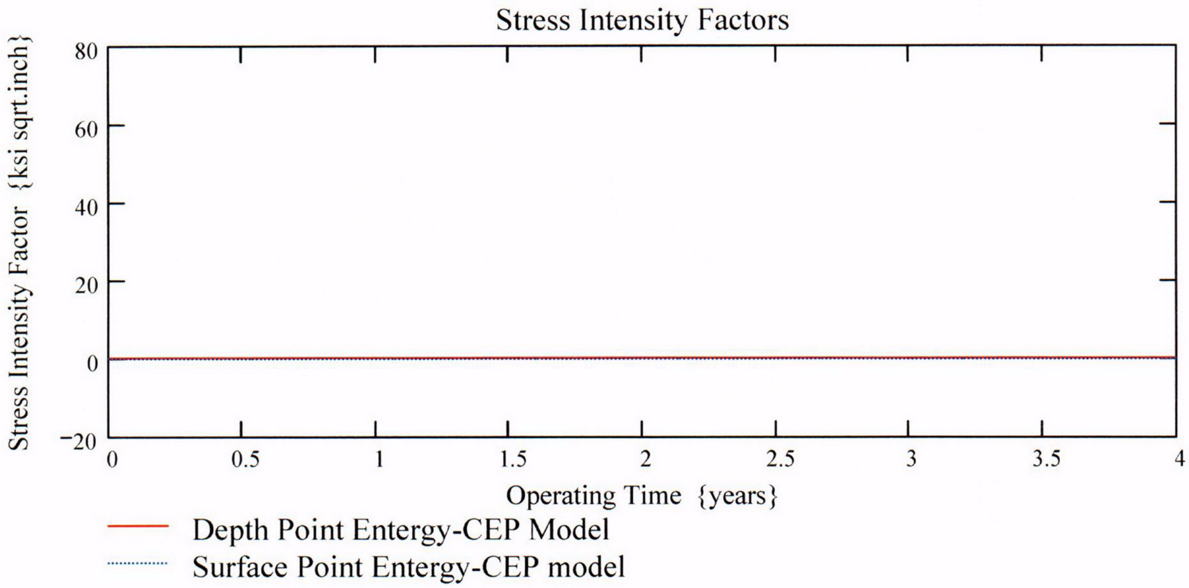
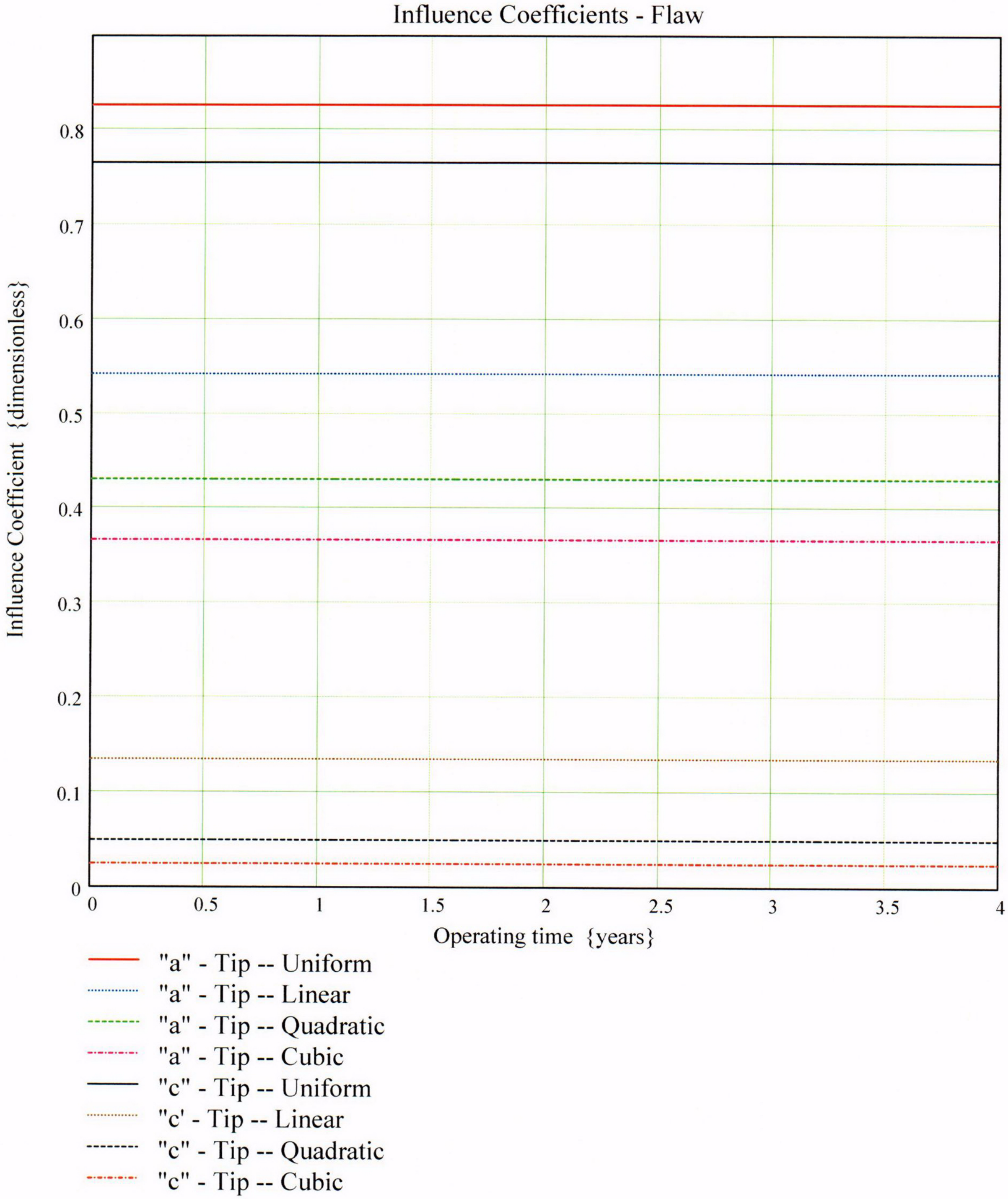
$Prop_{Length} = 1.295$






Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
−20
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}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic
"c" - Tip -- Cubic

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

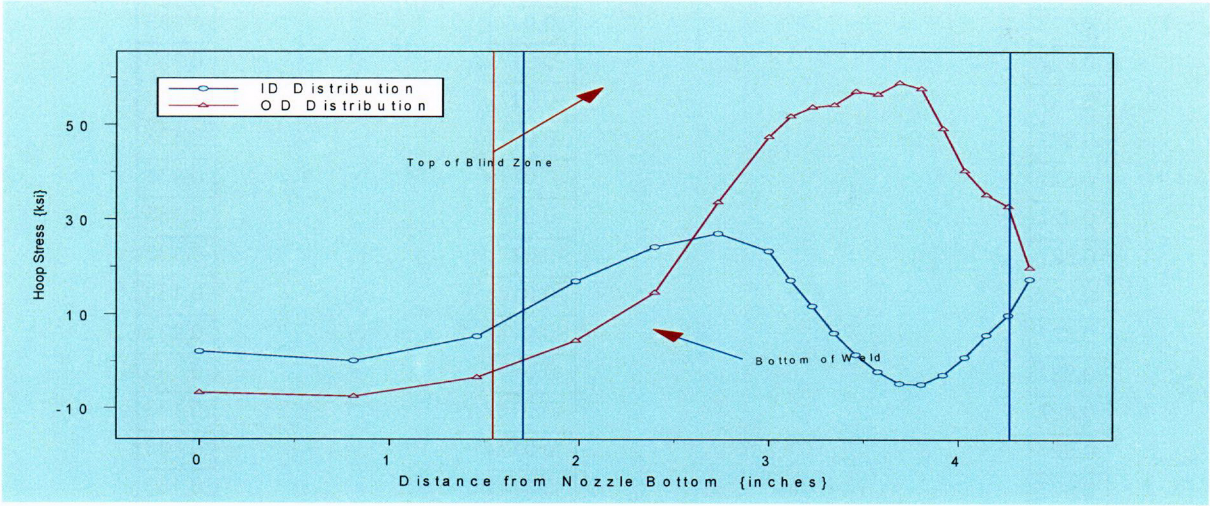
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827

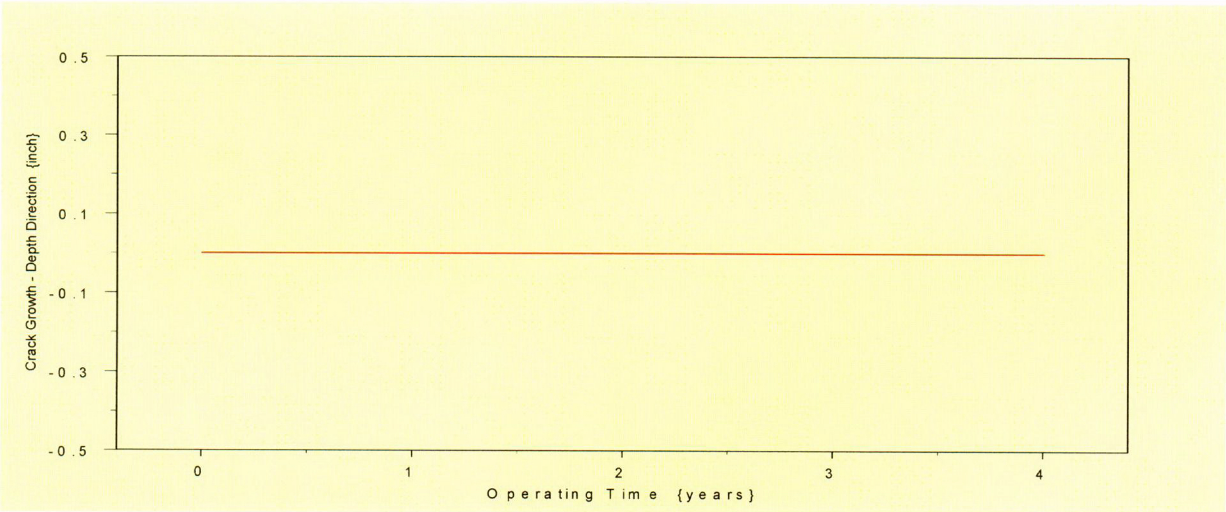
$CGR_{sambi_{(k,6)}} =$

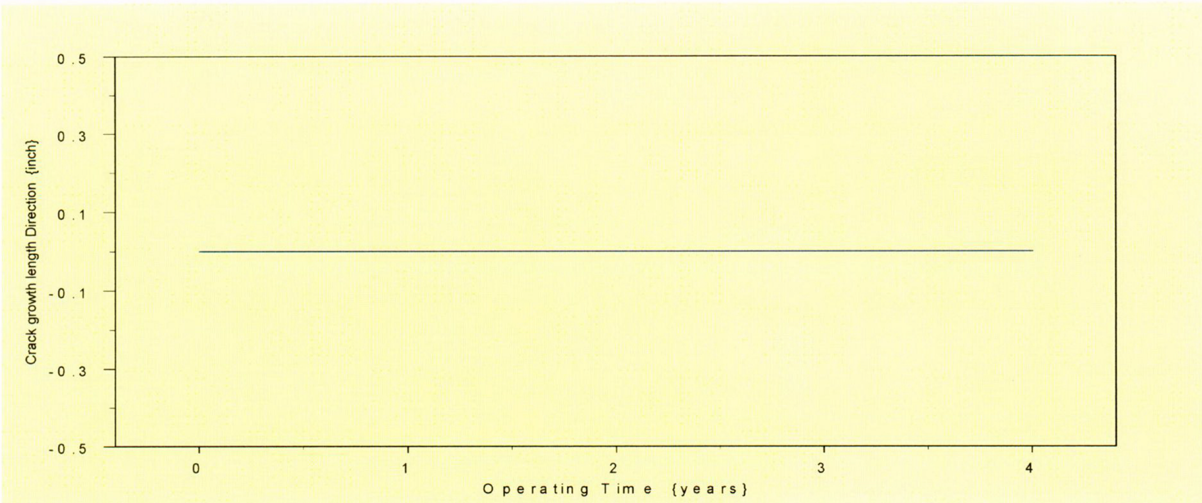
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017
-0.017

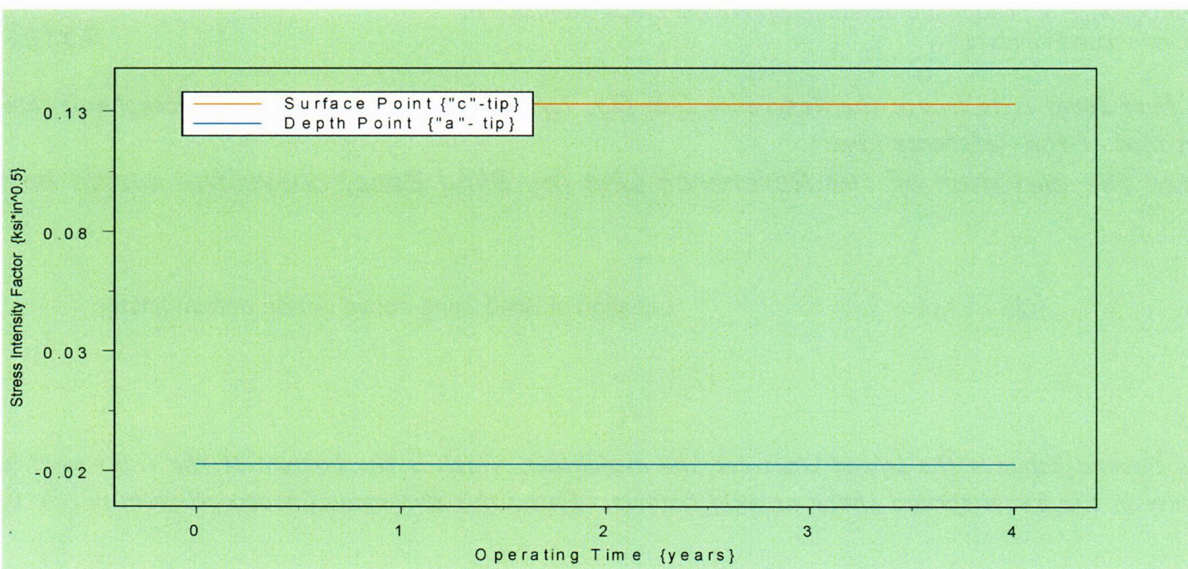
$CGR_{sambi_{(k,5)}} =$

0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133
0.133


ID Distribution
OD Distribution
Top of Blind Zone
Bottom of Weld
Hoop Stress {ksi}
50
30
10
-10
0
1
2
3
4
Distance from Nozzle Bottom {inches}


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


0.5
0.3
0.1
-0.1
-0.3
-0.5
Crack growth length Direction {inch}
0
1
2
3
4
Operating Time {years}


Surface Point {"c"-tip}
Depth Point {"a"- tip}
0.13
0.08
0.03
-0.02
Stress Intensity Factor {ksi*in^0.5}
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"Degree Nozzle, Mid-Plane Azimuth, 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.

$BZ := 1.544$ 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.

$UL_{Strs.Dist} := 2.999$ Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

Input Data :-

$L := 0.25$	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.

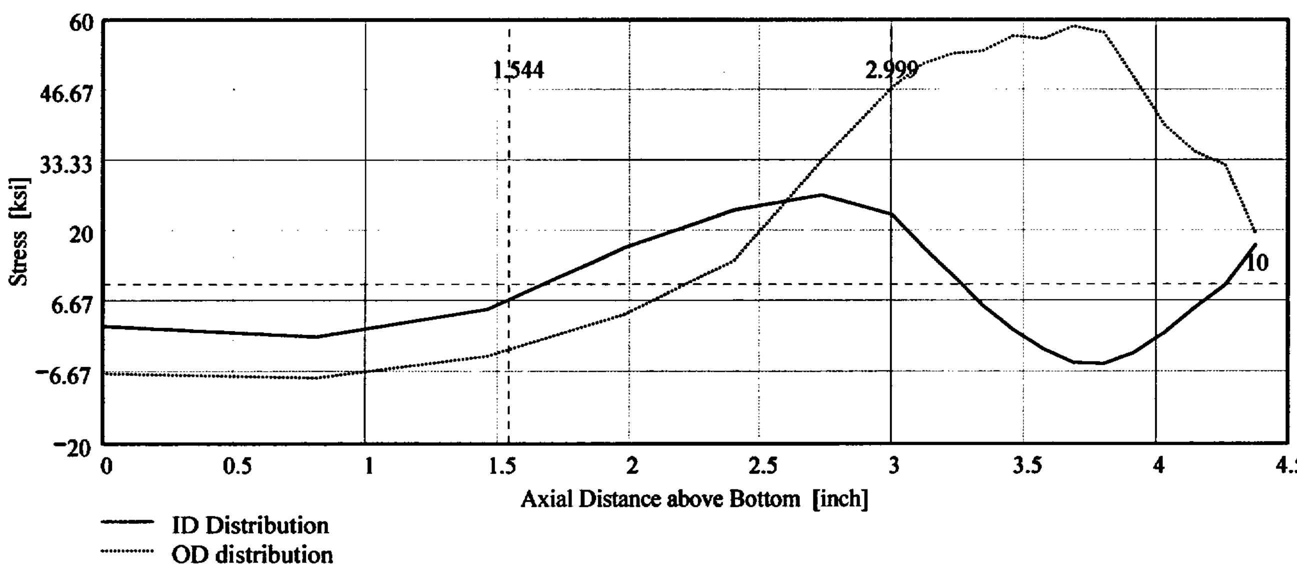
Stress Input Data

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	2.08	-0.87	-2.96	-4.82	-6.75
1	0.81	0.09	-2.37	-4.27	-6	-7.55
2	1.46	5.28	1.69	-0.79	-2.49	-3.47
3	1.98	16.88	12.42	9.56	6.91	4.32
4	2.4	24.14	20.89	18.11	16.59	14.51
5	2.73	26.96	22.67	20.69	24.84	33.52
6	3	23.28	20.9	21.71	37.11	47.4
7	3.11	17.16	17.1	20.74	41.09	51.76
8	3.23	11.72	14.42	21.34	43.54	53.69
9	3.34	6	11.11	20.91	43.83	54.15
10	3.46	1.44	8.09	20.38	43.02	57.02
11	3.57	-2.17	5.89	19.93	42.41	56.41

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



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

Data :=

0	2.079	-0.875	-2.96	-4.82	-6.75
0.811	0.091	-2.37	-4.267	-6.004	-7.552
1.46	5.283	1.686	-0.786	-2.49	-3.469
1.98	16.881	12.419	9.564	6.907	4.319
2.397	24.144	20.894	18.115	16.59	14.513
2.731	26.962	22.672	20.686	24.842	33.523
2.999	23.279	20.902	21.706	37.111	47.395
3.113	17.161	17.101	20.743	41.091	51.762
3.228	11.722	14.424	21.34	43.543	53.688
3.343	6.004	11.108	20.912	43.833	54.154
3.457	1.439	8.085	20.38	43.021	57.025

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

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

$FL_{Cntr} := BZ - l$ 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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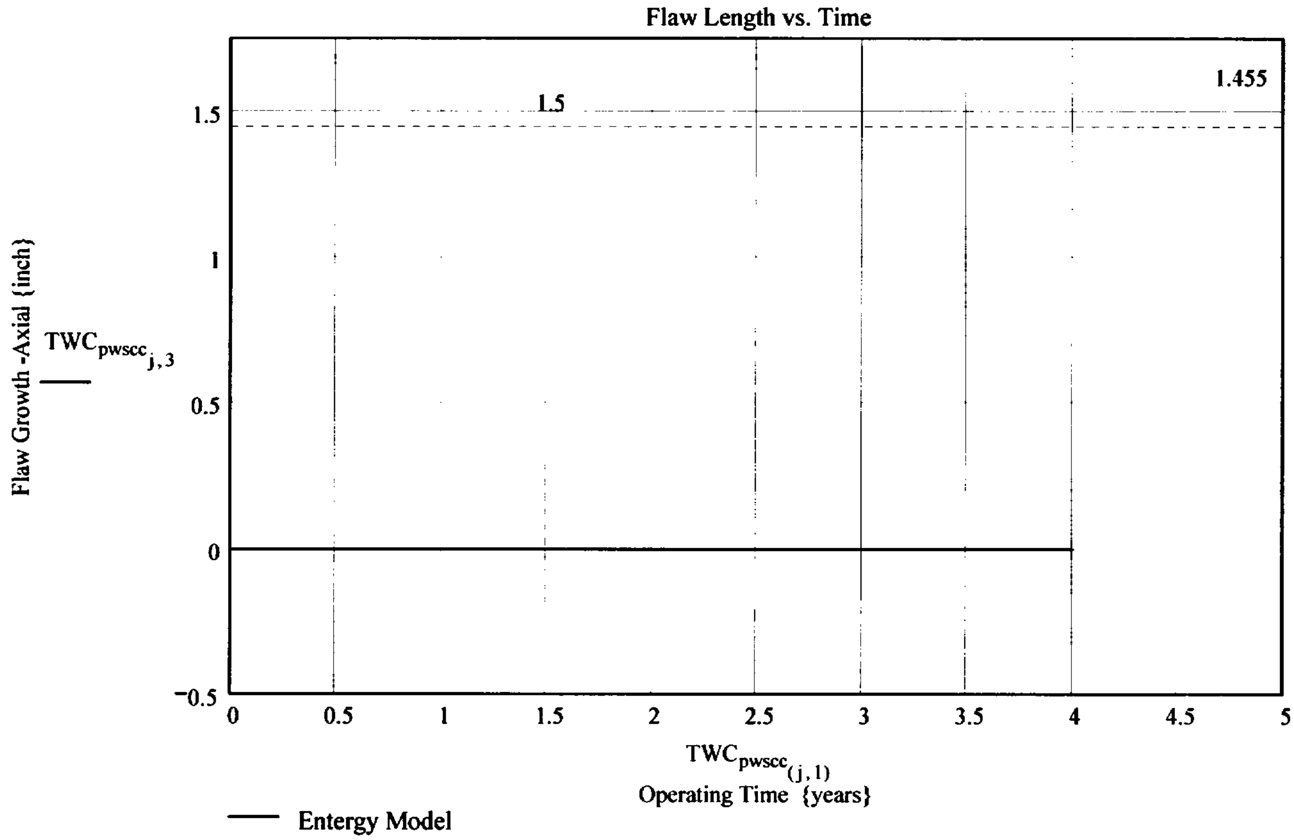
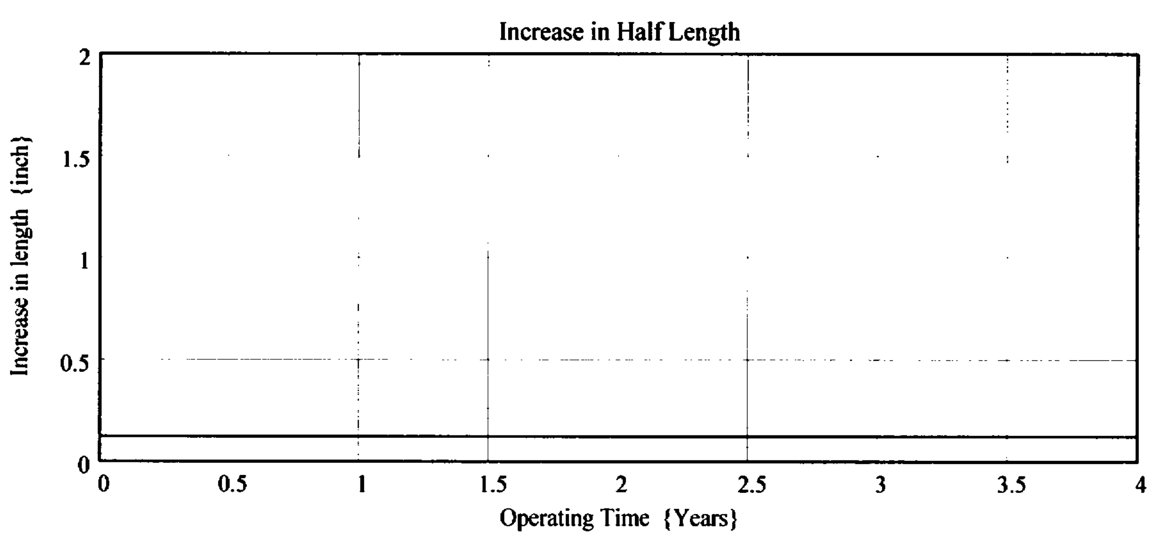
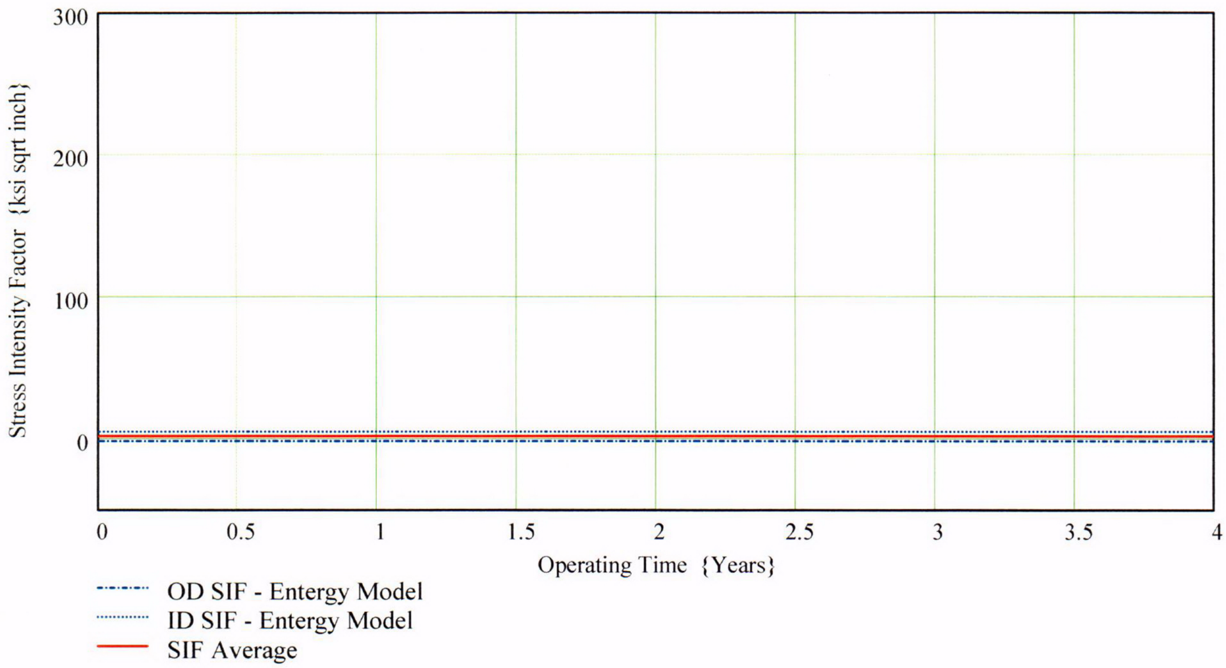
$Prop_{Length} = 1.455$






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

$TWC_{pwscc_{(j,6)}} =$

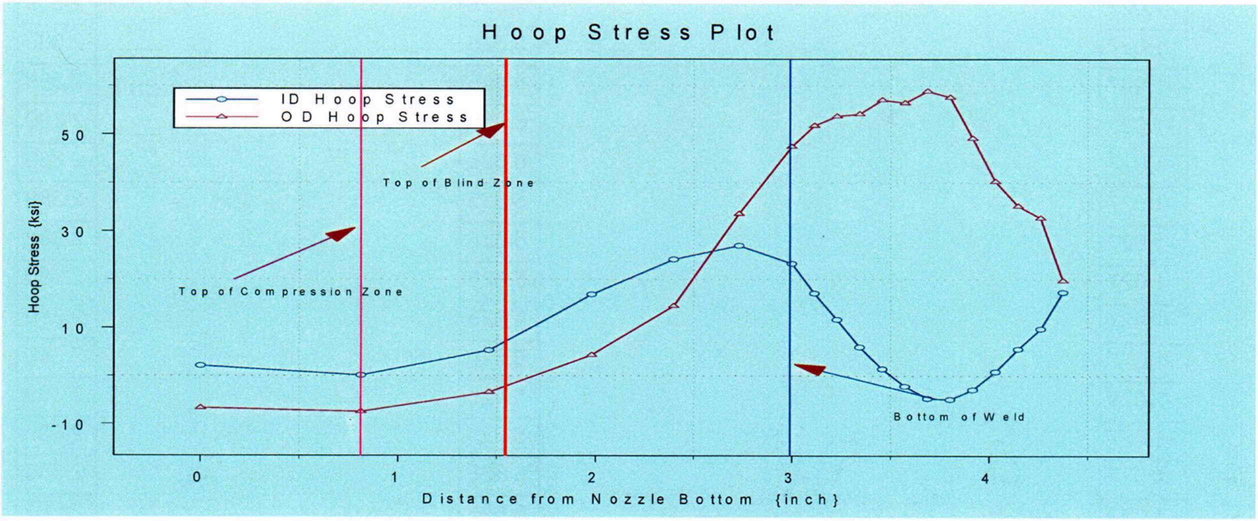
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027
-1.027

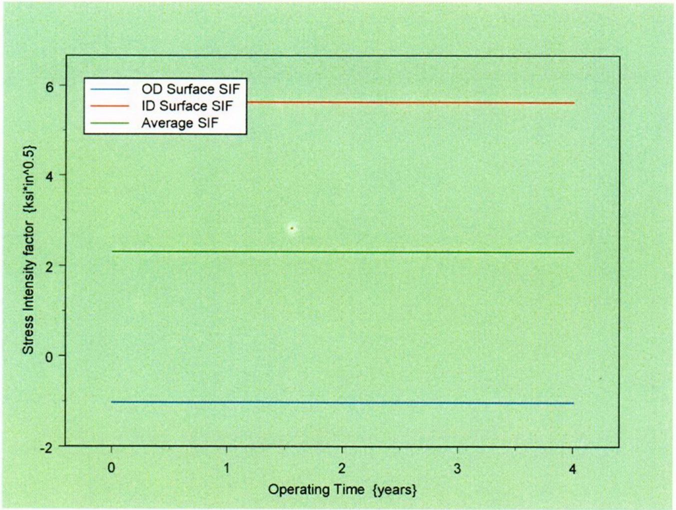
$TWC_{pwscc_{(j,7)}} =$

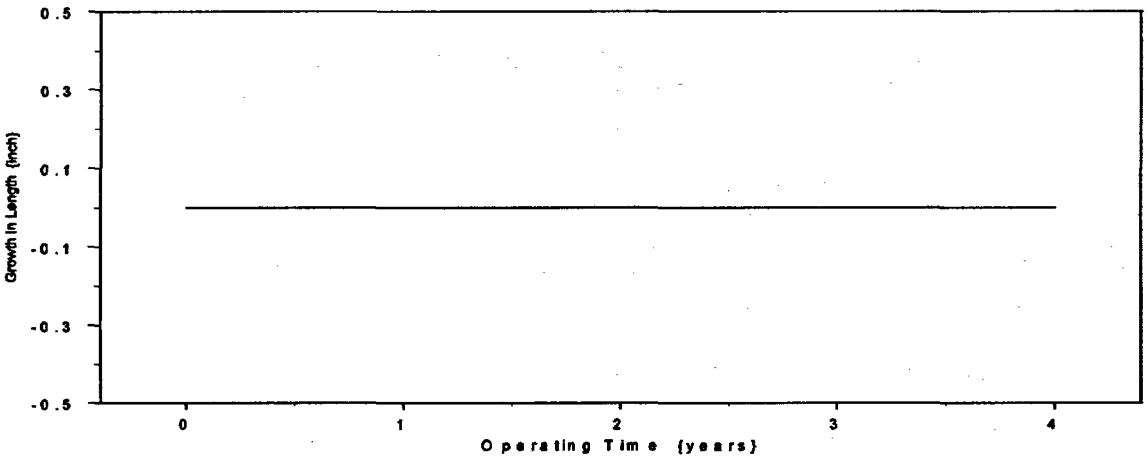
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625
5.625

$TWC_{pwscc_{(j,8)}} =$

2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389
2.389


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Top of Compression Zone
Bottom of Weld
Hoop Stress {ksi}
50
30
10
-10
0
1
2
3
4
Distance from Nozzle Bottom {inch}


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor {ksi*in^0.5}
6
4
2
0
-2
0
1
2
3
4
Operating Time {years}


0.5
0.3
0.1
-0.1
-0.3
-0.5
Growth in Length (inch)
0
1
2
3
4
Operating Time (years)

Primary Water Stress Corrosion Crack Growth Analysis ID flaw;
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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 -"49" Degree Nozzle, Downhill Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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.

$UL_{Strs.Dist} := 1.889$ 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 (Twice detectable length)
$a_0 := 0.661 \cdot 0.07$	Initial Flaw Depth (Minimum Detecteble Depth was 5% TW)
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

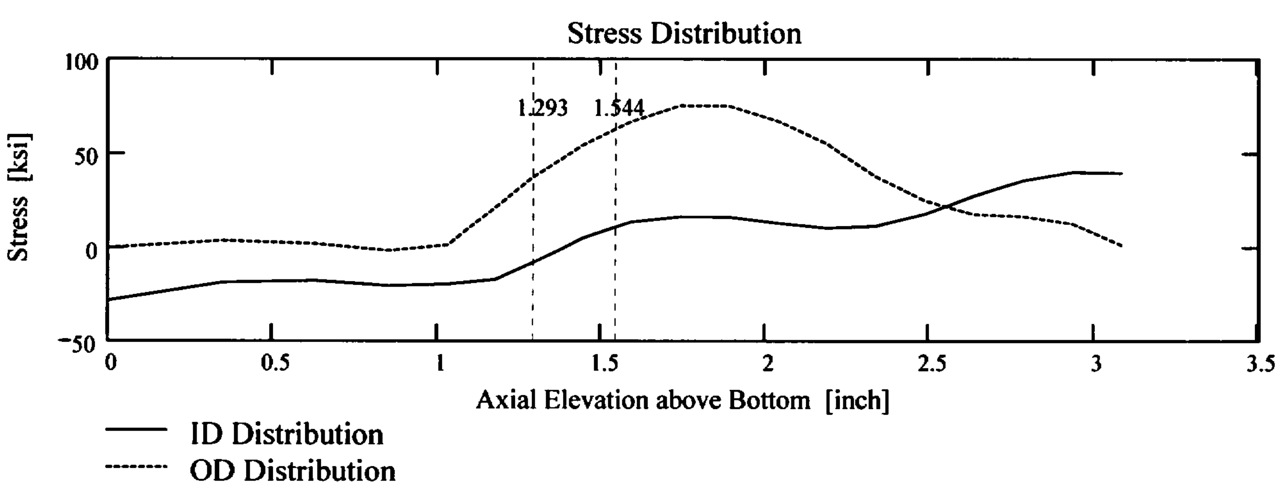
Stress Input Data

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

AllData :=

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

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



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

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

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

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

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

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

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

Flaw center Location 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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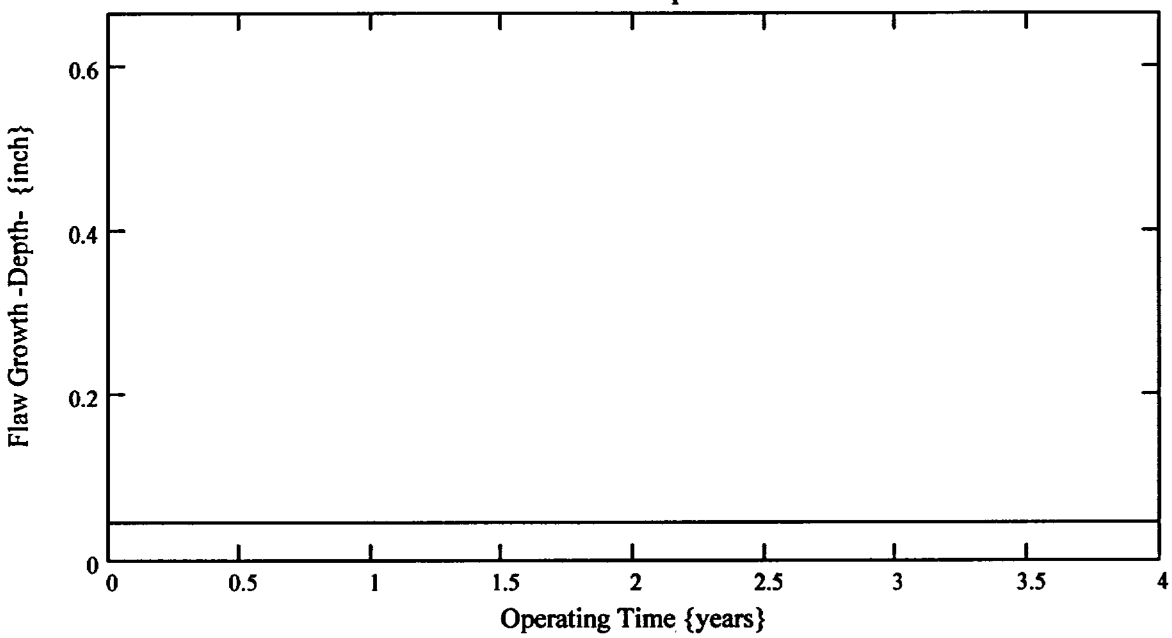
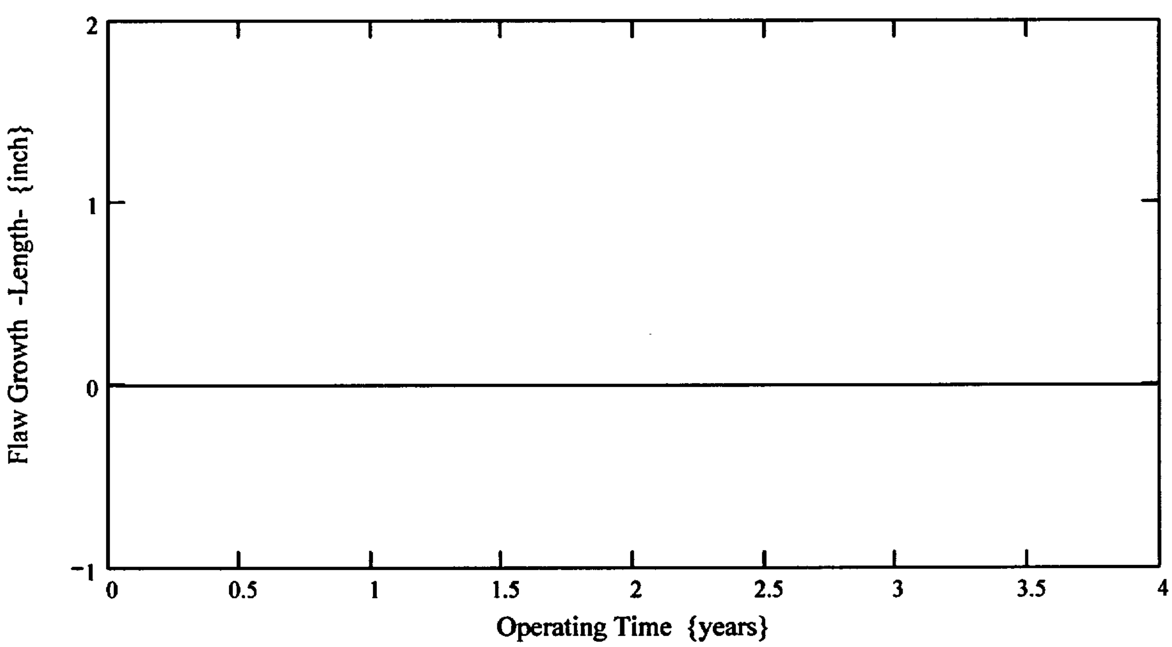
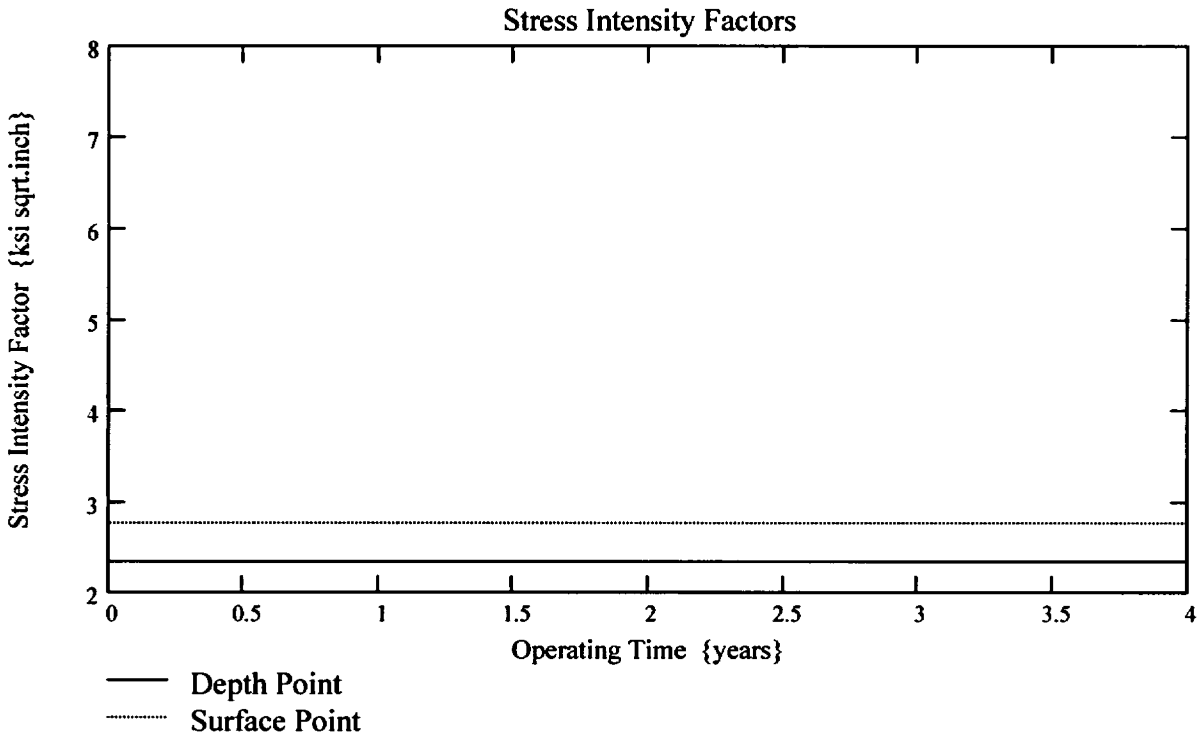
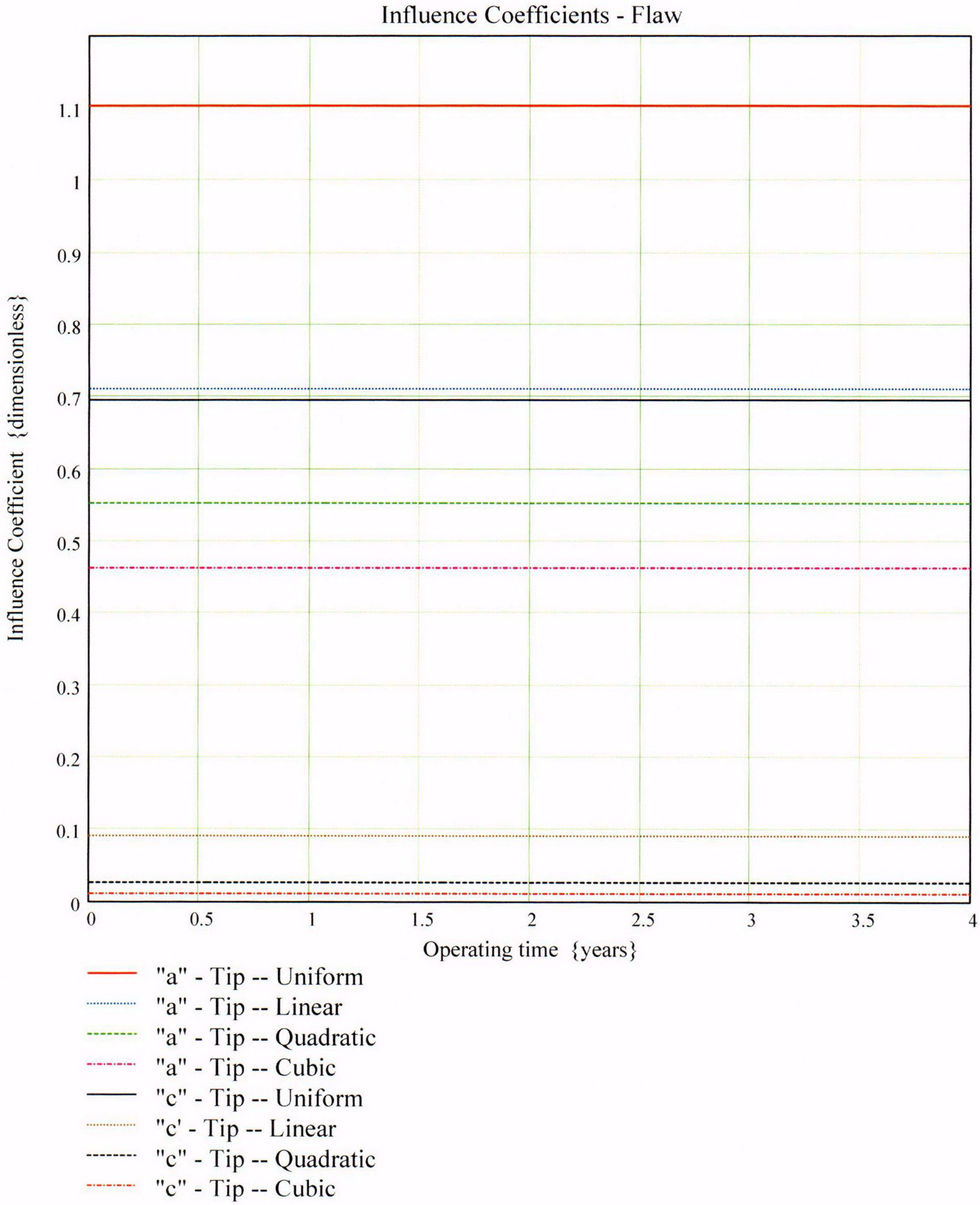
$Prop_{Length} = 0.185$

Flaw Growth in Depth Direction

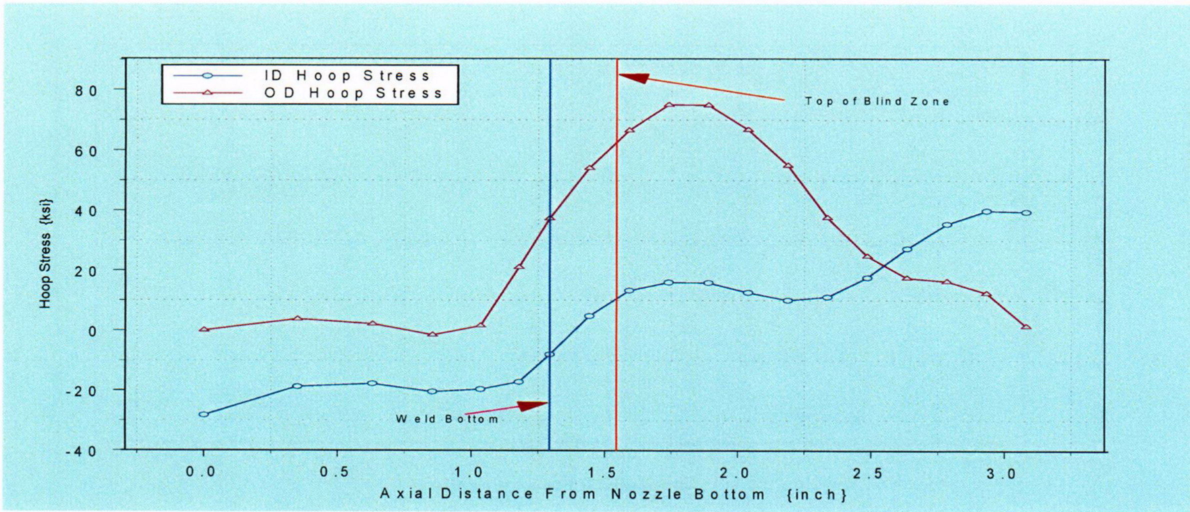


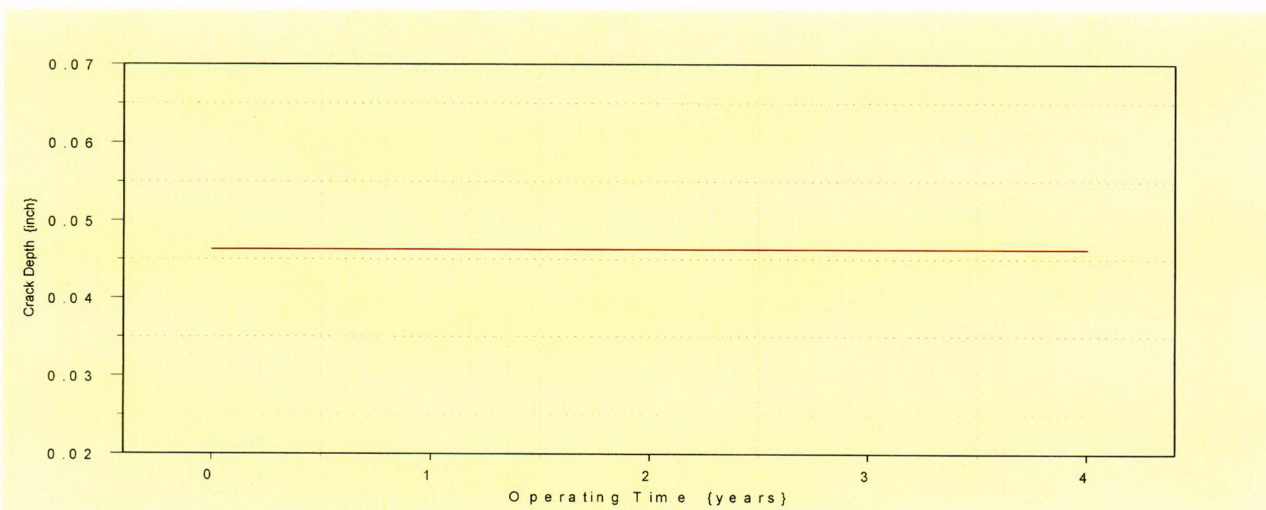


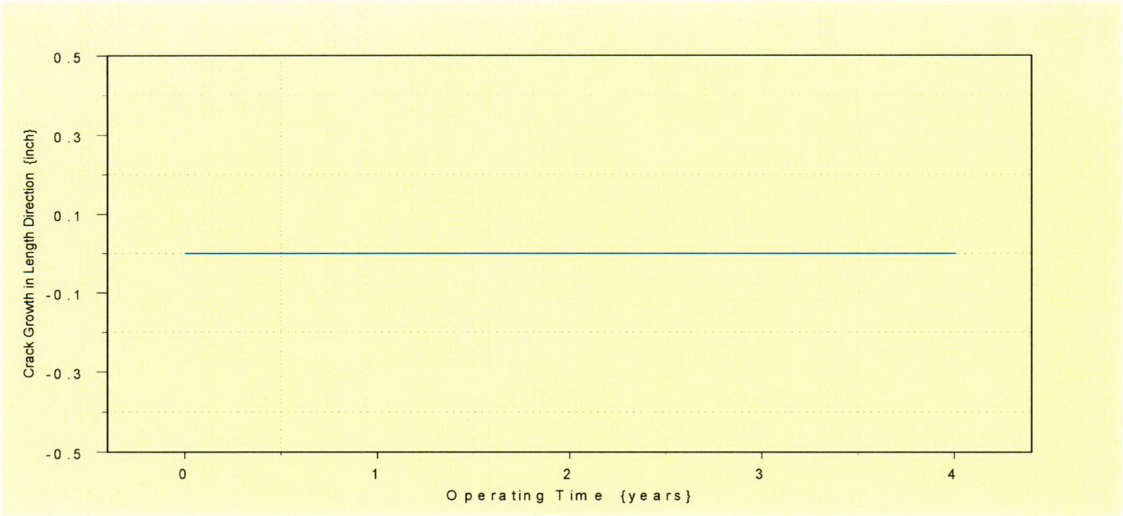

Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
8
7
6
5
4
3
2
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point
Surface Point

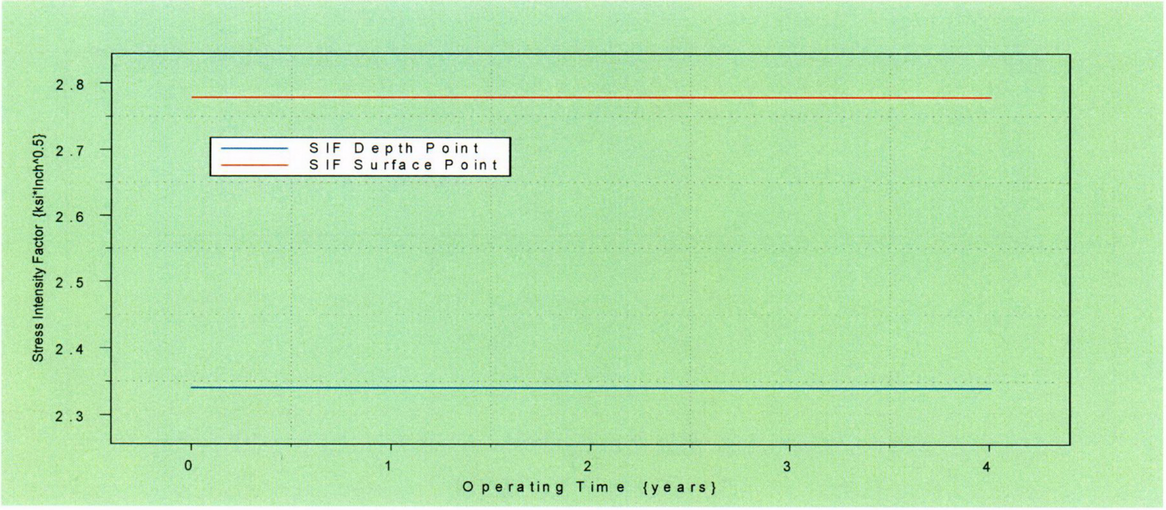

Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
Operating time {years}
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic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

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(k,5)}} =$
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34
1.103	2.778	2.34


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


Crack Depth {inch}
0.07
0.06
0.05
0.04
0.03
0.02
0
1
2
3
4
Operating Time {years}


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


Stress Intensity Factor {ksi*inch^0.5}
2.8
2.7
2.6
2.5
2.4
2.3
SIF Depth Point
SIF Surface Point
0
1
2
3
4
Operating Time {years}

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

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

Refrences :

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

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"49" Degree Nozzle, Uphill Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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.

$UL_{Strs.Dist} := 6.628$ 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 (Twice detectable length)
$a_0 := 0.661 \cdot 0.07$	Initial Flaw Depth (Minimum Detecteble Depth was 5% TW)
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

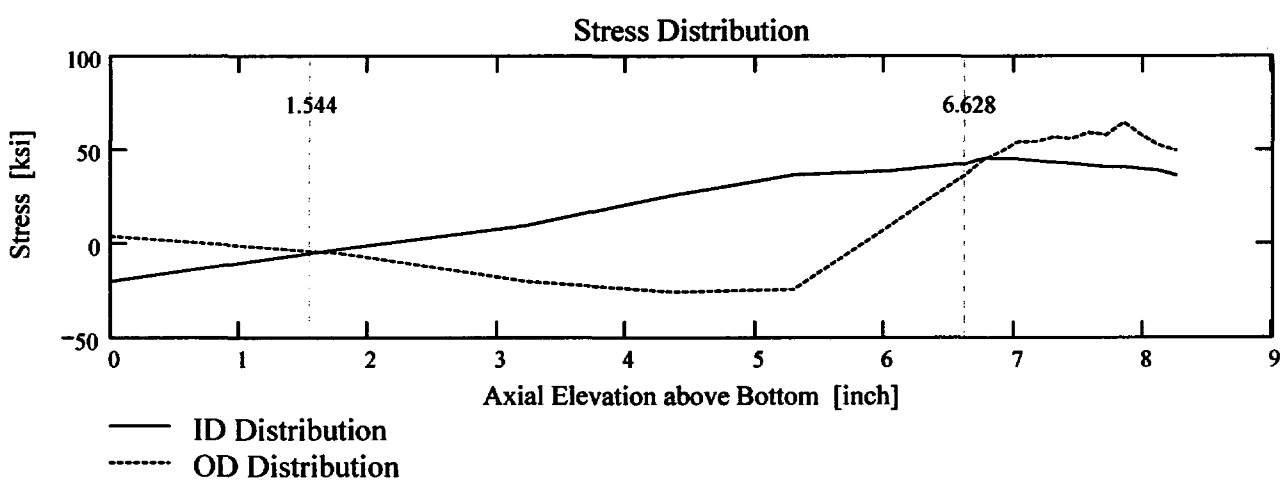
Stress Input Data

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

AllData :=

	0	1	2	3	4	5
0	0	-20.18	-11.45	-5.94	-1.16	3.7
1	1.79	-3.02	-4.38	-5.44	-5.51	-5.34
2	3.23	9.4	12.13	-0.26	-12.62	-20.23
3	4.38	25.65	24.71	14.58	-15.3	-25.69
4	5.3	36.18	33.79	26.29	-5.92	-24.31
5	6.04	38.11	35.03	31.43	21.21	8.83
6	6.63	42.19	38.1	36.25	40.68	36.41
7	6.76	45.07	42.22	42.74	47.55	44.23
8	6.9	44.97	43.61	46.01	49.99	48.8
9	7.03	44.7	44.12	47.02	51.04	54.11

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



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

$$Data := \begin{pmatrix} 0 & -20.175 & -11.45 & -5.94 & -1.163 & 3.704 \\ 1.792 & -3.024 & -4.378 & -5.443 & -5.511 & -5.341 \\ 3.228 & 9.398 & 12.134 & -0.258 & -12.622 & -20.232 \\ 4.378 & 25.65 & 24.71 & 14.577 & -15.299 & -25.689 \\ 5.299 & 36.179 & 33.787 & 26.287 & -5.925 & -24.306 \\ 6.037 & 38.106 & 35.028 & 31.43 & 21.215 & 8.834 \\ 6.628 & 42.186 & 38.102 & 36.248 & 40.684 & 36.405 \\ 6.764 & 45.067 & 42.217 & 42.736 & 47.553 & 44.235 \\ 6.899 & 44.968 & 43.606 & 46.007 & 49.995 & 48.803 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location 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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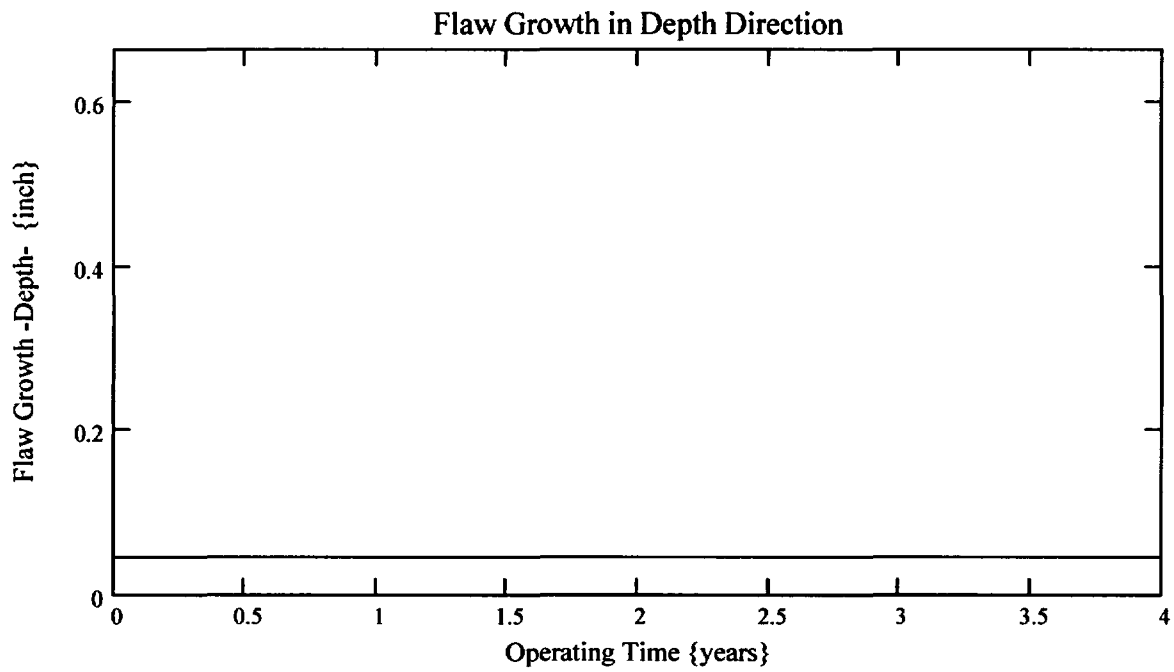
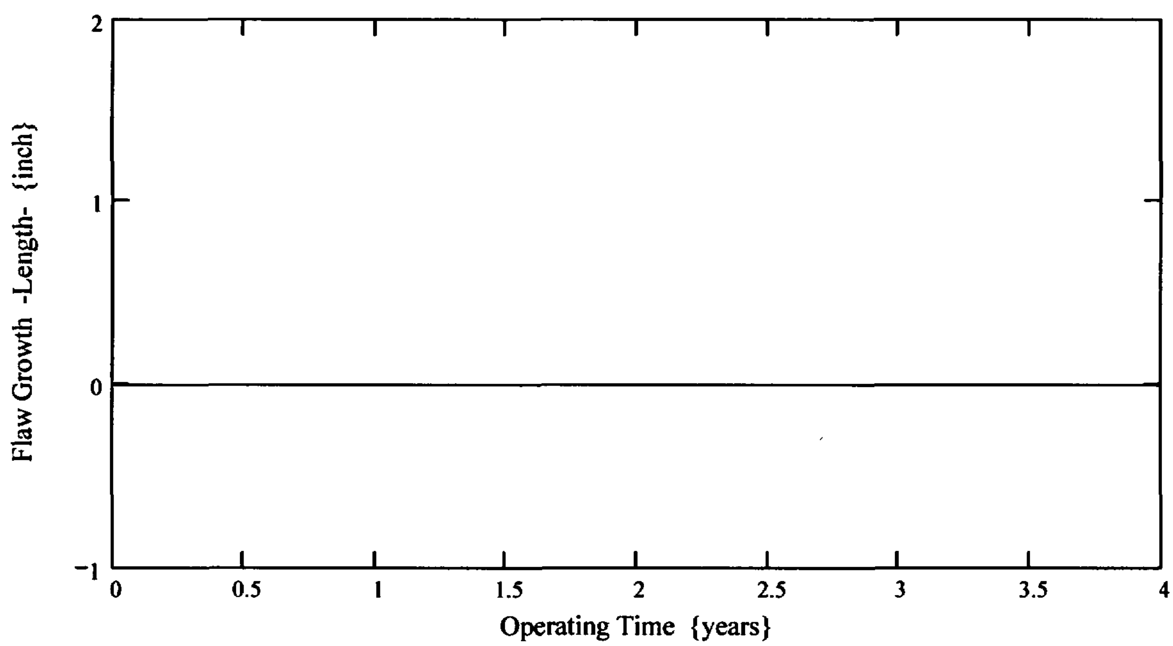
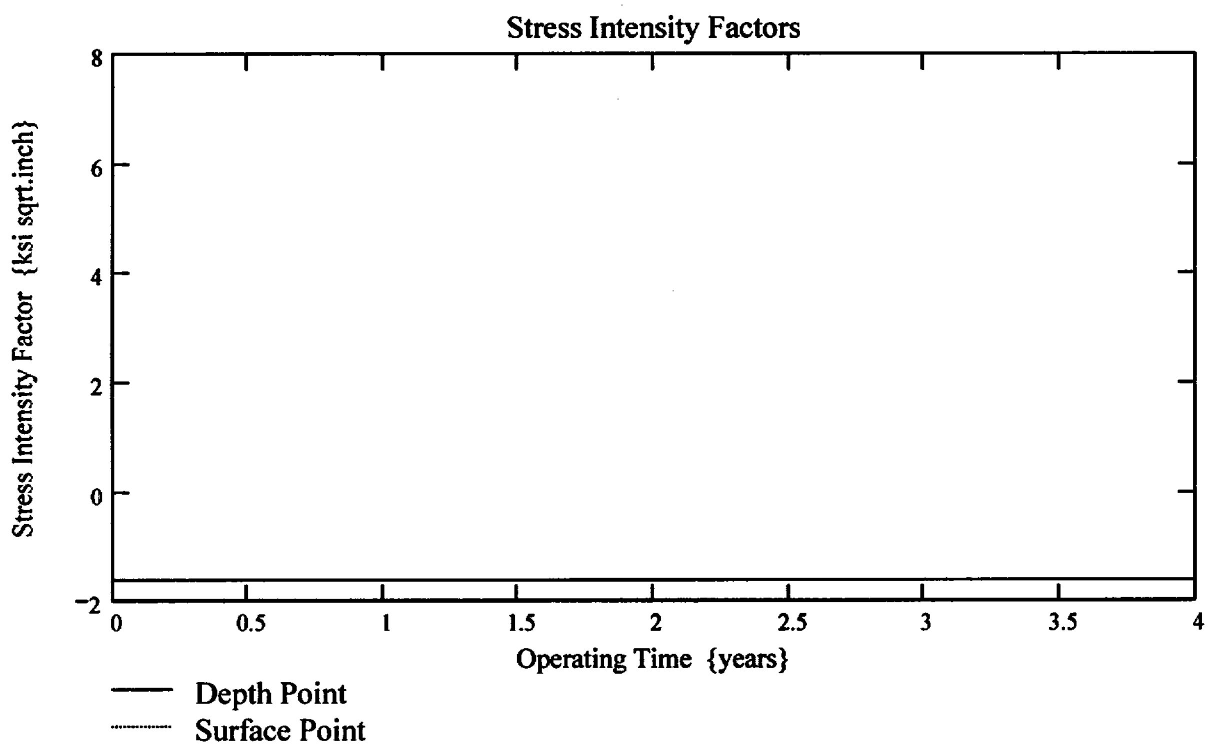
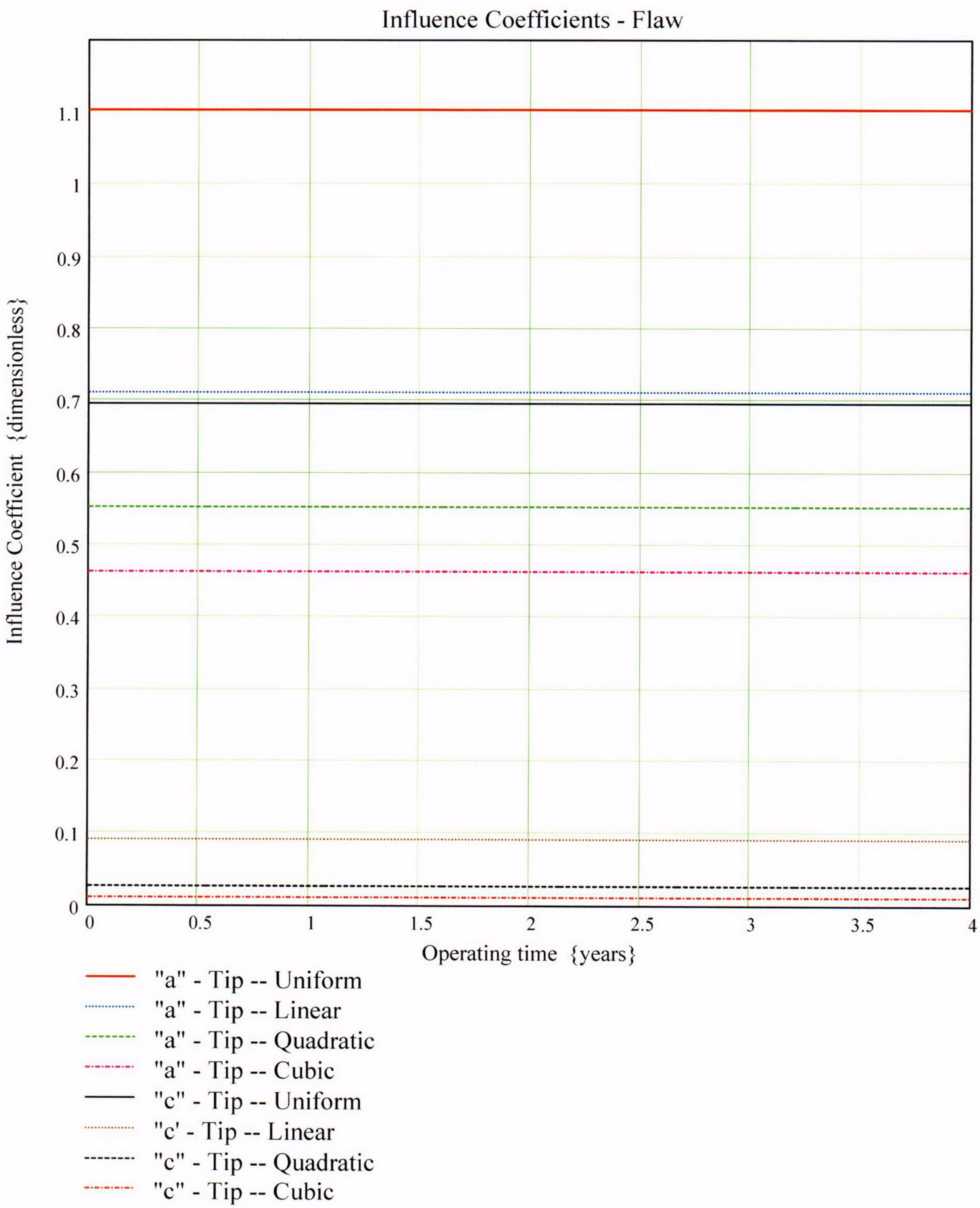
$Prop_{Length} = 4.924$






Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
8
6
4
2
0
−2
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point
Surface Point


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

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

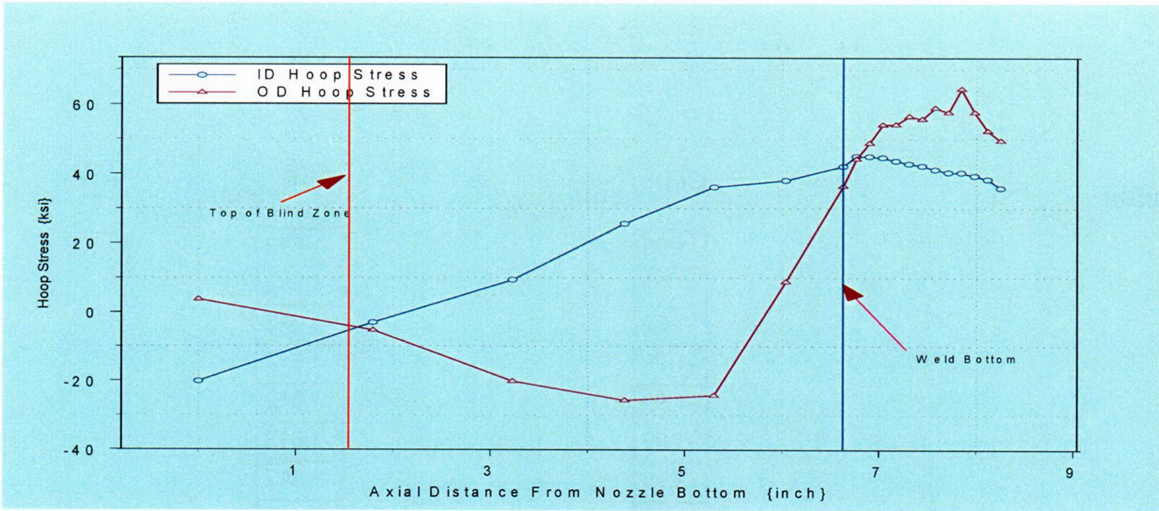
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103

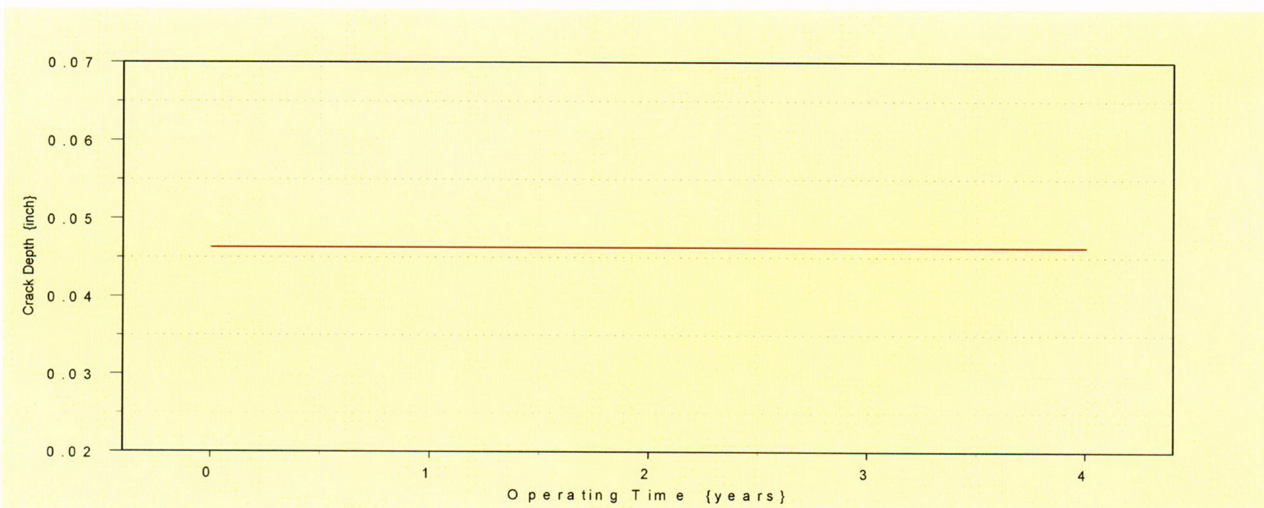
$CGR_{sambi_{(k,6)}} =$

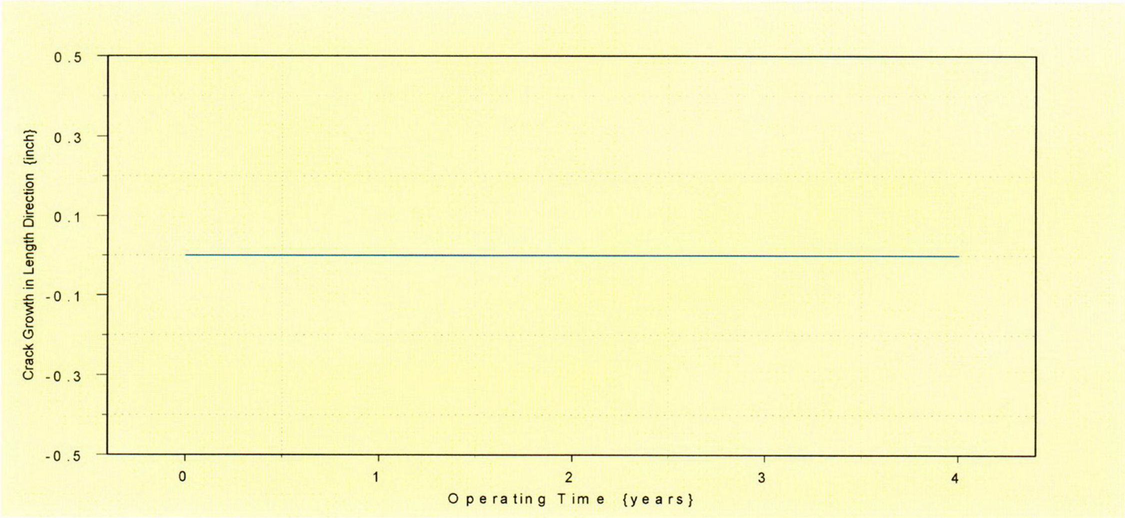
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99
-1.99

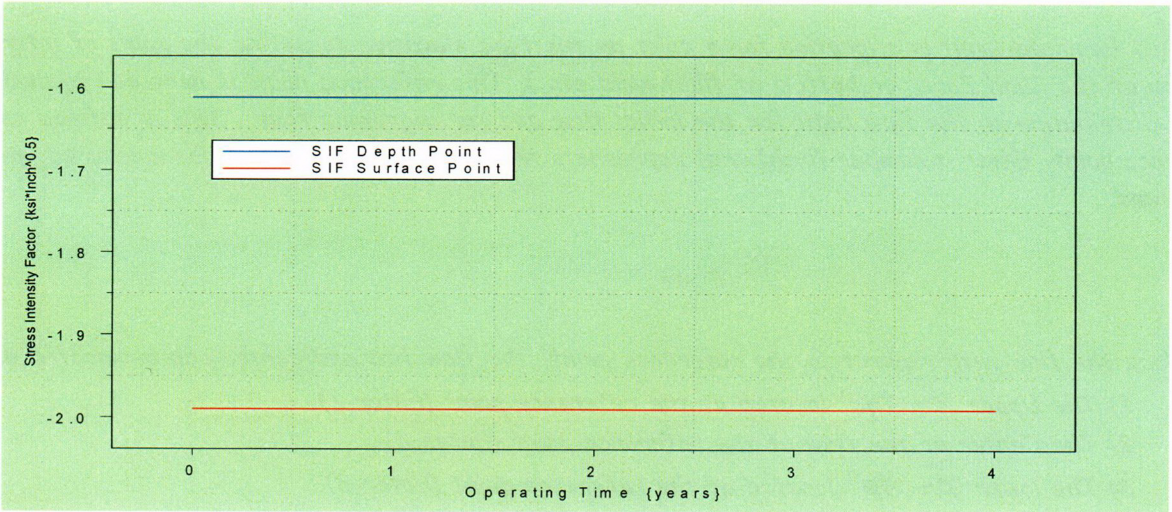
$CGR_{sambi_{(k,5)}} =$

-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612
-1.612


ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Weld Bottom
Hoop Stress (ksi)
60
40
20
0
-20
-40
1
3
5
7
9
Axial Distance From Nozzle Bottom {inch}


Crack Depth {inch}
0.07
0.06
0.05
0.04
0.03
0.02
0
1
2
3
4
Operating Time {years}


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


-1.6
-1.7
-1.8
-1.9
-2.0
Stress Intensity Factor {ksi*inch^0.5}
SIF Depth Point
SIF Surface Point
0
1
2
3
4
Operating Time {years}

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 -"49" Degree Nozzle, Uphill Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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.

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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

$UL_{Strs.Dist} := 6.628$ 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

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

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

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

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

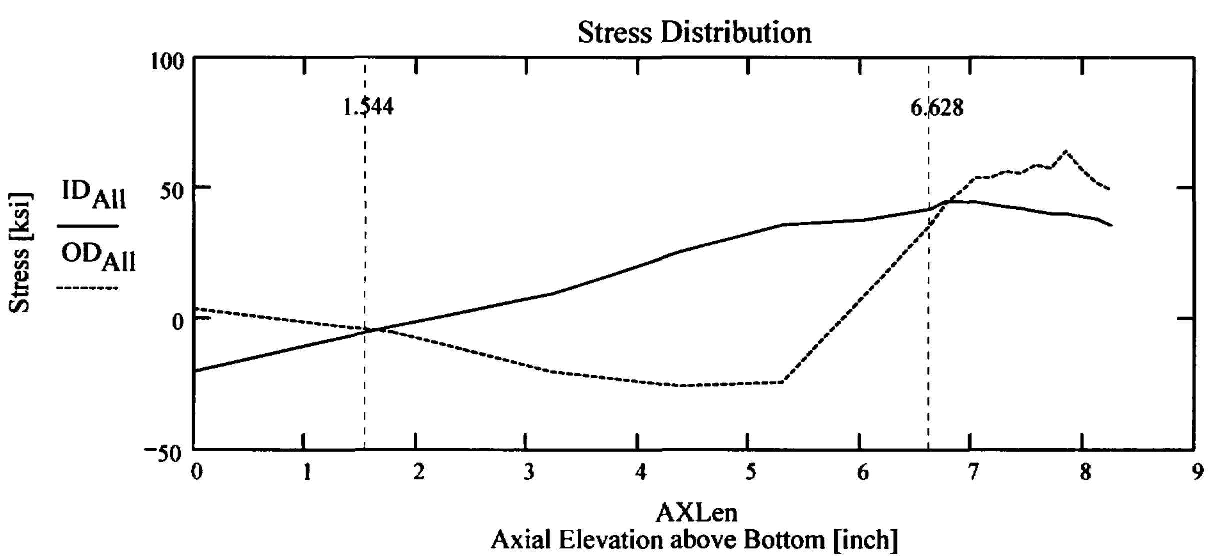
Stress Input Data

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

AllData :=

	0	1	2	3	4	5
0	0	-20.18	-11.45	-5.94	-1.16	3.7
1	1.79	-3.02	-4.38	-5.44	-5.51	-5.34
2	3.23	9.4	12.13	-0.26	-12.62	-20.23
3	4.38	25.65	24.71	14.58	-15.3	-25.69
4	5.3	36.18	33.79	26.29	-5.92	-24.31
5	6.04	38.11	35.03	31.43	21.21	8.83
6	6.63	42.19	38.1	36.25	40.68	36.41
7	6.76	45.07	42.22	42.74	47.55	44.23
8	6.9	44.97	43.61	46.01	49.99	48.8
9	7.03	44.7	44.12	47.02	51.04	54.11
10	7.17	43.72	43.97	47.64	50.17	54.17

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



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).

$$Data := \begin{pmatrix} 0 & -20.175 & -11.45 & -5.94 & -1.163 & 3.704 \\ 1.792 & -3.024 & -4.378 & -5.443 & -5.511 & -5.341 \\ 3.228 & 9.398 & 12.134 & -0.258 & -12.622 & -20.232 \\ 4.378 & 25.65 & 24.71 & 14.577 & -15.299 & -25.689 \\ 5.299 & 36.179 & 33.787 & 26.287 & -5.925 & -24.306 \\ 6.037 & 38.106 & 35.028 & 31.43 & 21.215 & 8.834 \\ 6.628 & 42.186 & 38.102 & 36.248 & 40.684 & 36.405 \\ 6.764 & 45.067 & 42.217 & 42.736 & 47.553 & 44.235 \\ 6.899 & 44.968 & 43.606 & 46.007 & 49.995 & 48.803 \\ 7.035 & 44.695 & 44.12 & 47.021 & 51.043 & 54.113 \\ 7.17 & 43.723 & 43.973 & 47.639 & 50.172 & 54.17 \end{pmatrix}$$

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

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

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

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

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

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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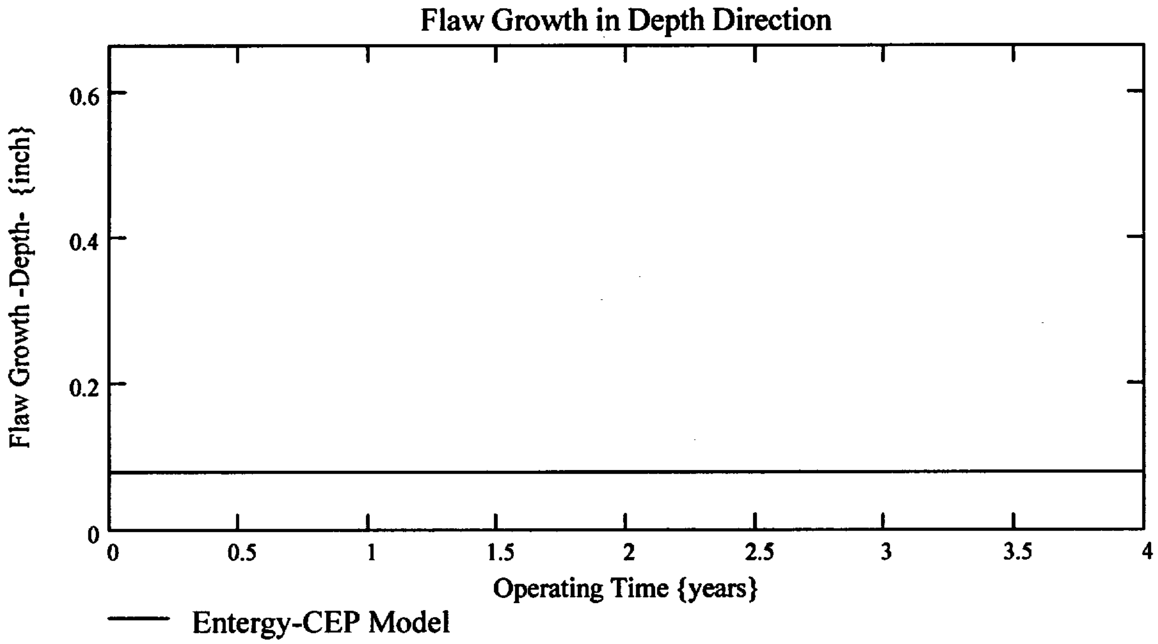
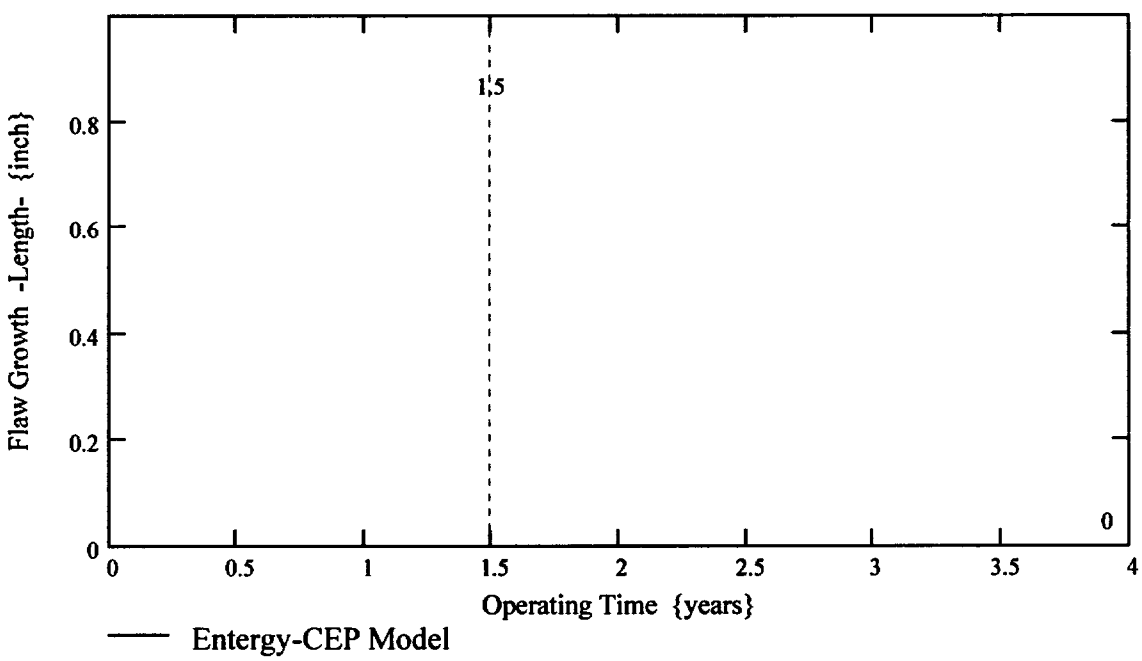
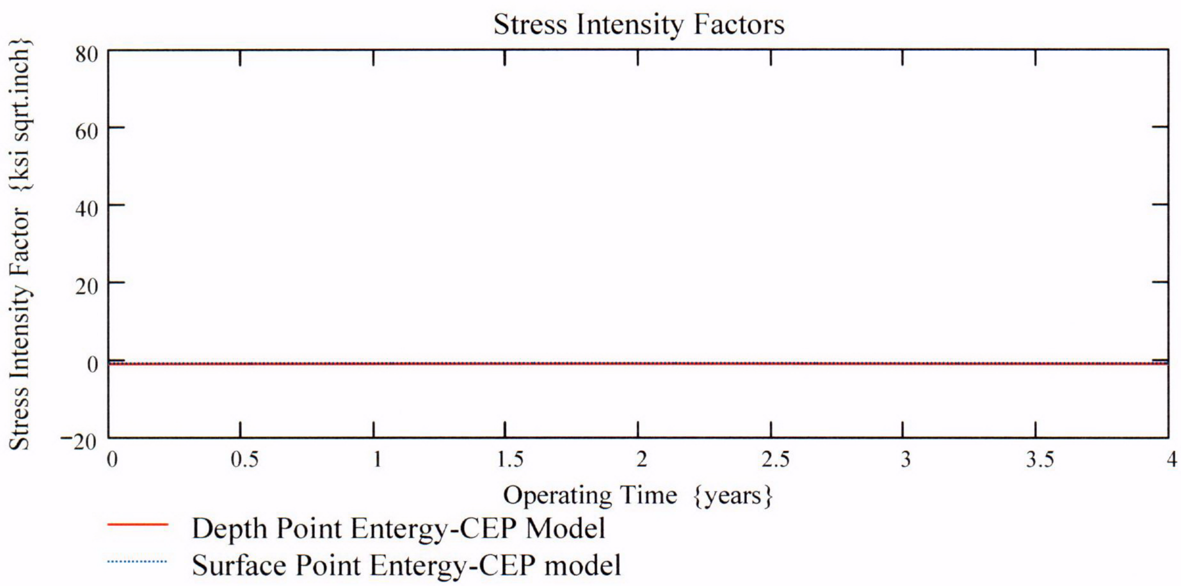
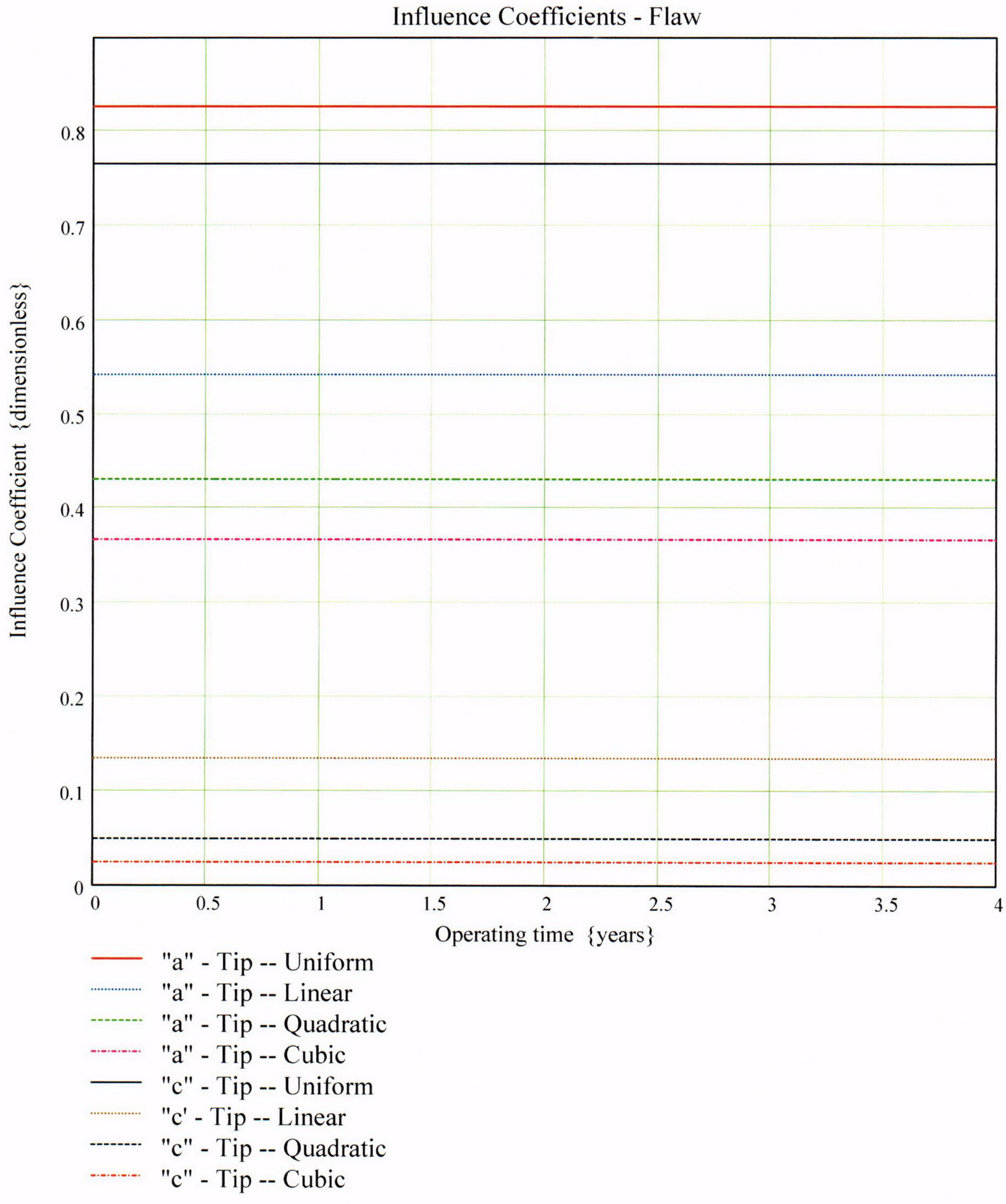
$Prop_{Length} = 4.924$

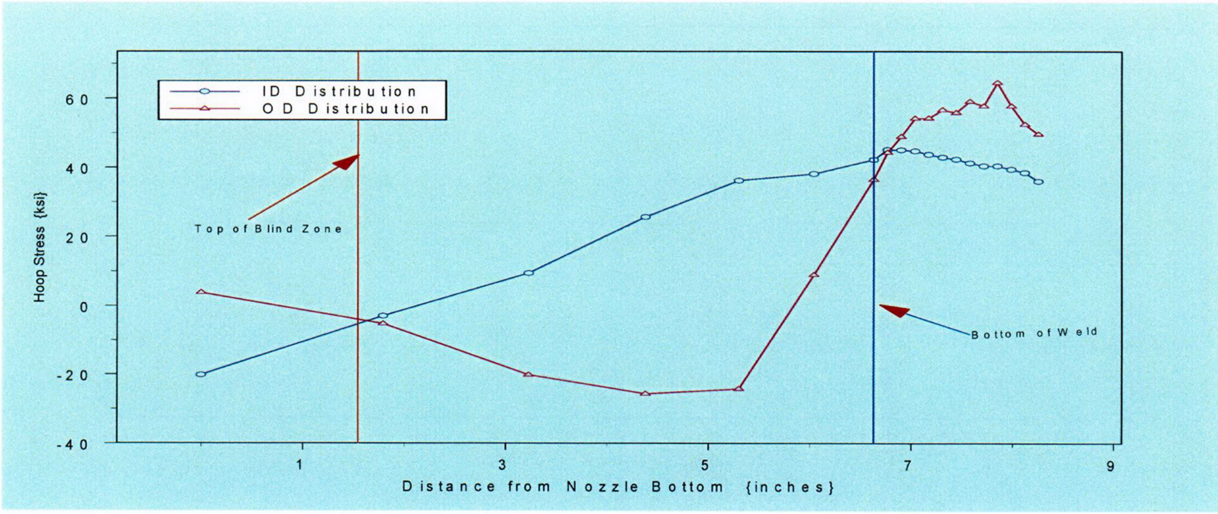


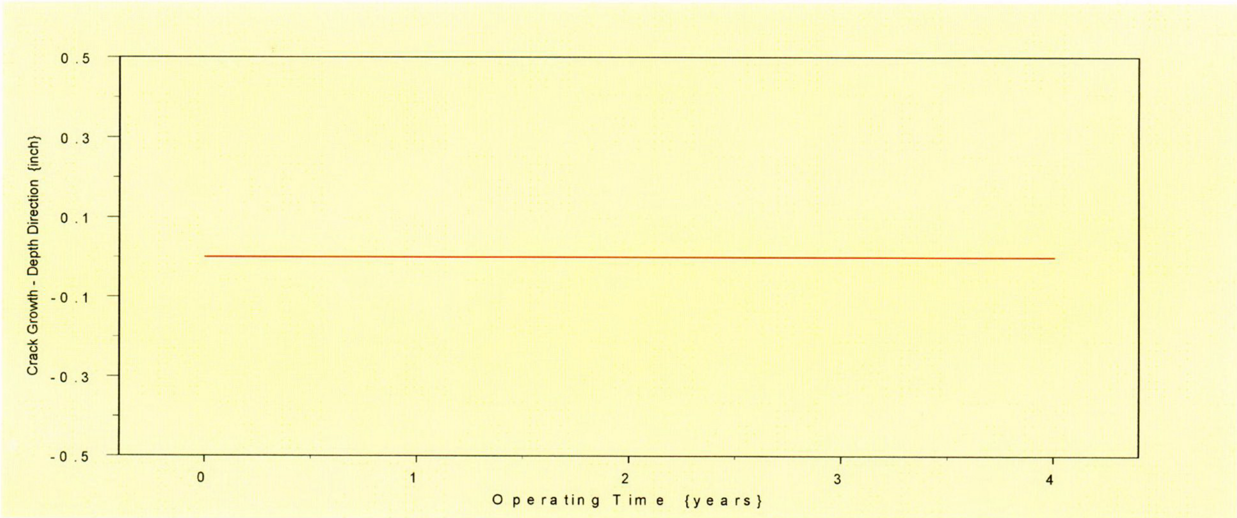


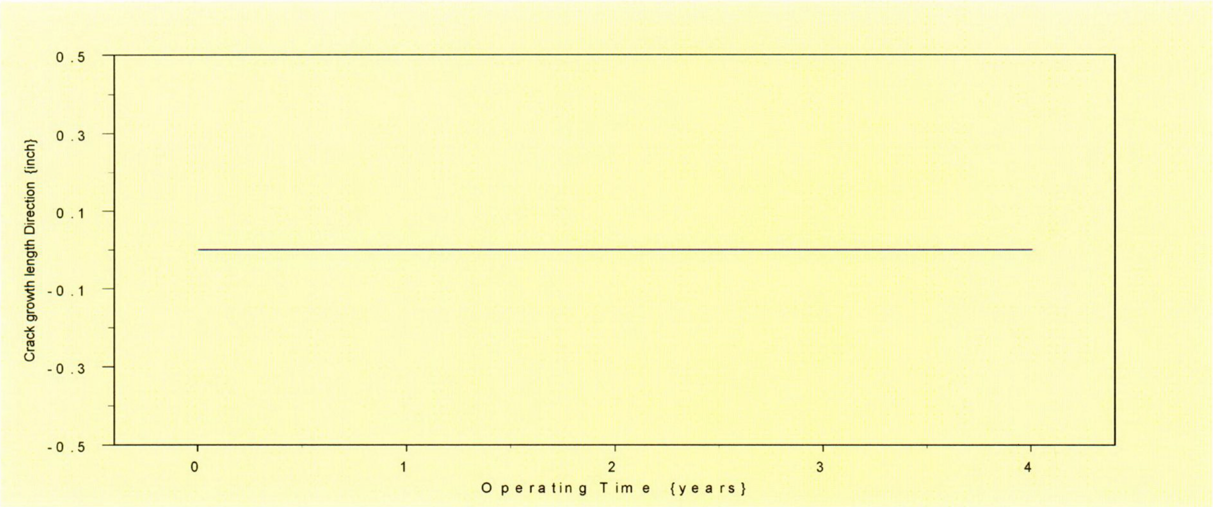

Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
−20
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point Entergy-CEP Model
Surface Point Entergy-CEP model

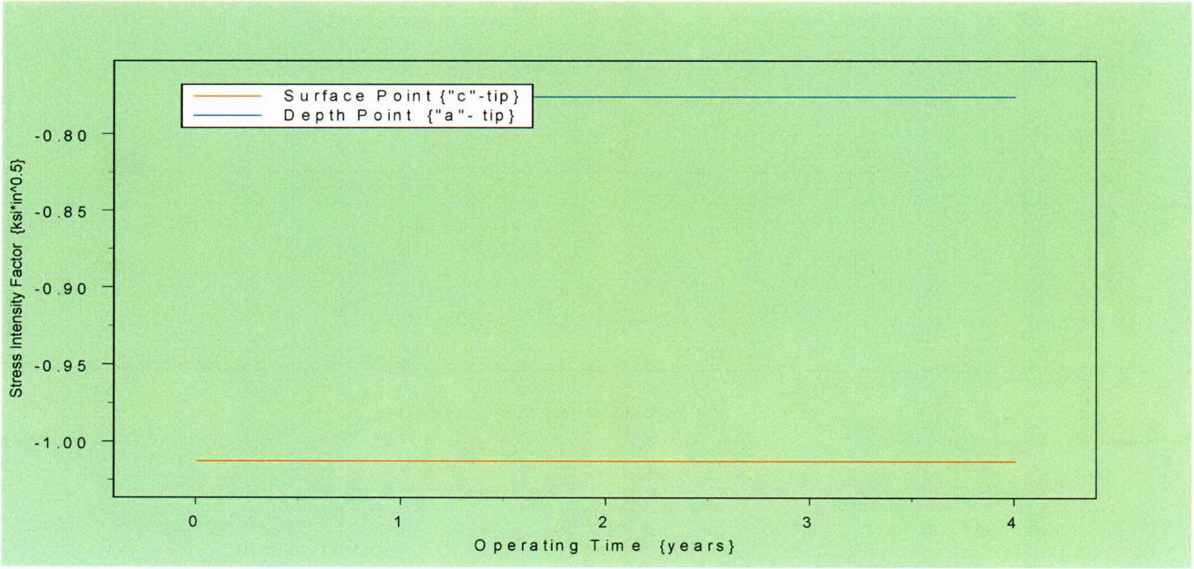

Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic
"c"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

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(k,5)}} =$
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013
0.827	-0.776	-1.013


ID Distribution
OD Distribution
Top of Blind Zone
Bottom of Weld
Hoop Stress (ksi)
Distance from Nozzle Bottom (inches)
60
40
20
0
-20
-40
1
3
5
7
9


Crack Growth - Depth Direction (inch)
Operating Time (years)
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
1
2
3
4


0.5
0.3
0.1
-0.1
-0.3
-0.5
Crack growth length Direction {inch}
0
1
2
3
4
Operating Time {years}


Surface Point {"c"-tip}
Depth Point {"a"- tip}
-0.80
-0.85
-0.90
-0.95
-1.00
Stress Intensity Factor {ksi*in^0.5}
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 -"49"Degree Nozzle, Uphill Azimuth, 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.

$BZ := 1.544$ 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.

$UL_{Strs.Dist} := 6.628$ Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

Input Data :-

$L := 0.25$	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
$\nu := 0.307$	Poissons ratio @ 600 F
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

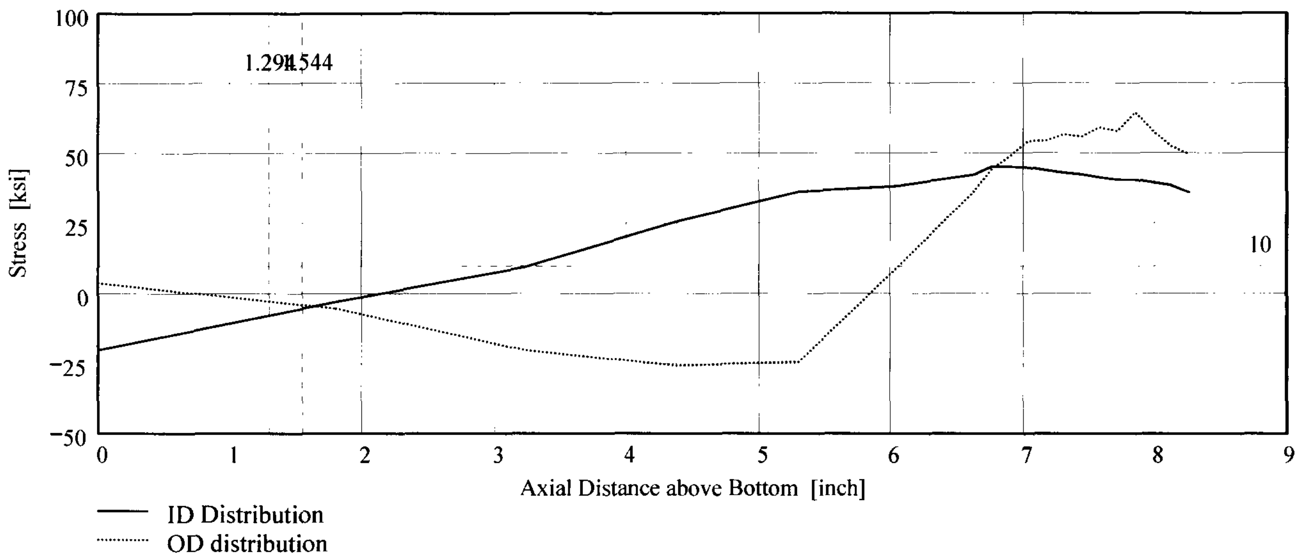
Stress Input Data

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	-20.18	-11.45	-5.94	-1.16	3.7
1	1.79	-3.02	-4.38	-5.44	-5.51	-5.34
2	3.23	9.4	12.13	-0.26	-12.62	-20.23
3	4.38	25.65	24.71	14.58	-15.3	-25.69
4	5.3	36.18	33.79	26.29	-5.92	-24.31
5	6.04	38.11	35.03	31.43	21.21	8.83
6	6.63	42.19	38.1	36.25	40.68	36.41
7	6.76	45.07	42.22	42.74	47.55	44.23
8	6.9	44.97	43.61	46.01	49.99	48.8
9	7.03	44.7	44.12	47.02	51.04	54.11
10	7.17	43.72	43.97	47.64	50.17	54.17
11	7.31	42.93	43.82	47.52	52.33	56.55

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



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

Data :=

0	−20.175	−11.45	−5.94	−1.163	3.704
1.792	−3.024	−4.378	−5.443	−5.511	−5.341
3.228	9.398	12.134	−0.258	−12.622	−20.232
4.378	25.65	24.71	14.577	−15.299	−25.689
5.299	36.179	33.787	26.287	−5.925	−24.306
6.037	38.106	35.028	31.43	21.215	8.834
6.628	42.186	38.102	36.248	40.684	36.405
6.764	45.067	42.217	42.736	47.553	44.235
6.899	44.968	43.606	46.007	49.995	48.803
7.035	44.695	44.12	47.021	51.043	54.113
7.17	43.723	43.973	47.639	50.172	54.17
7.305	42.926	43.816	47.515	52.325	56.546

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

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

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

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

No User Input required beyond this Point

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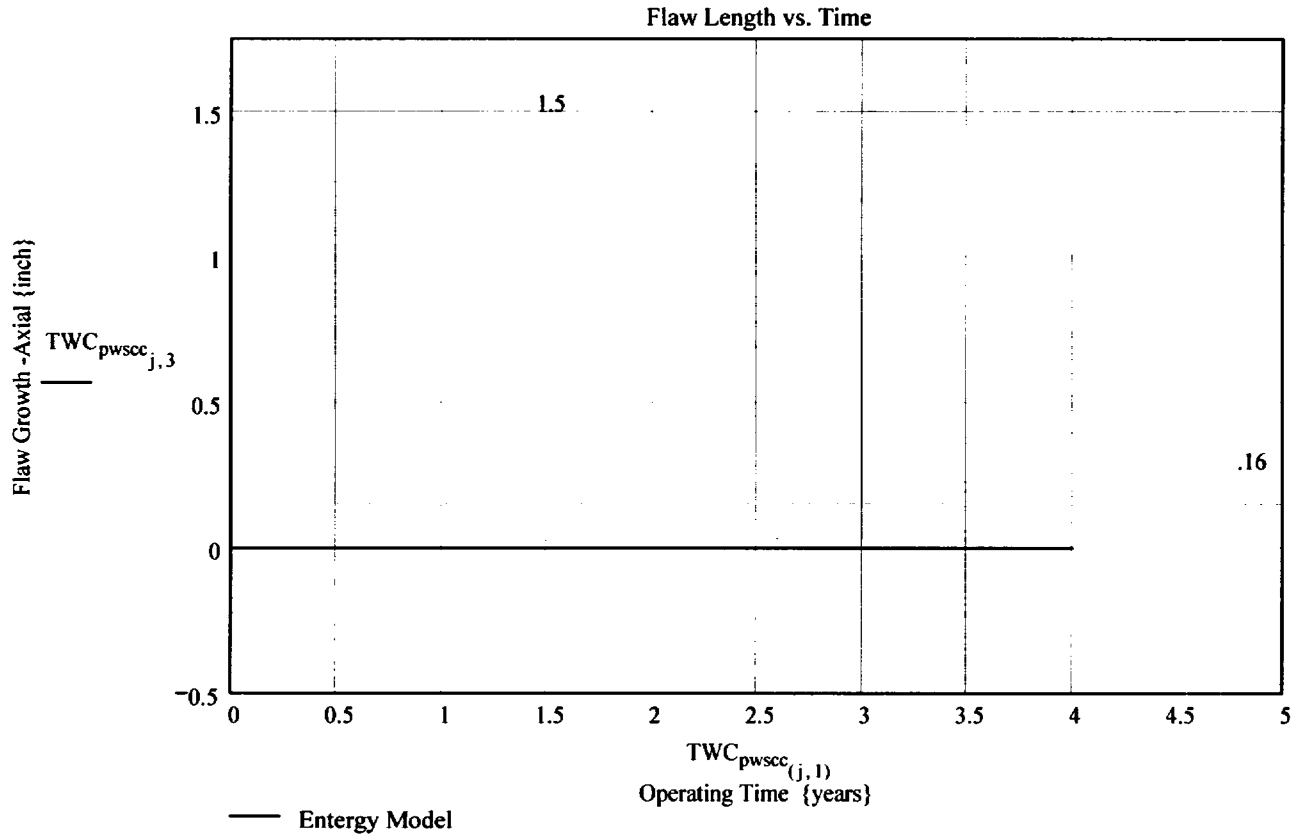
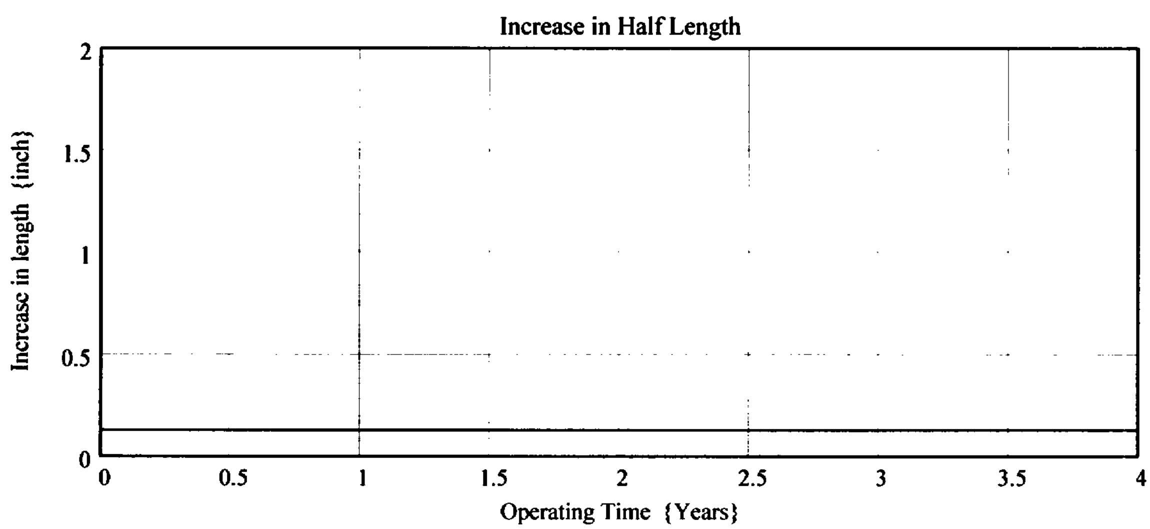
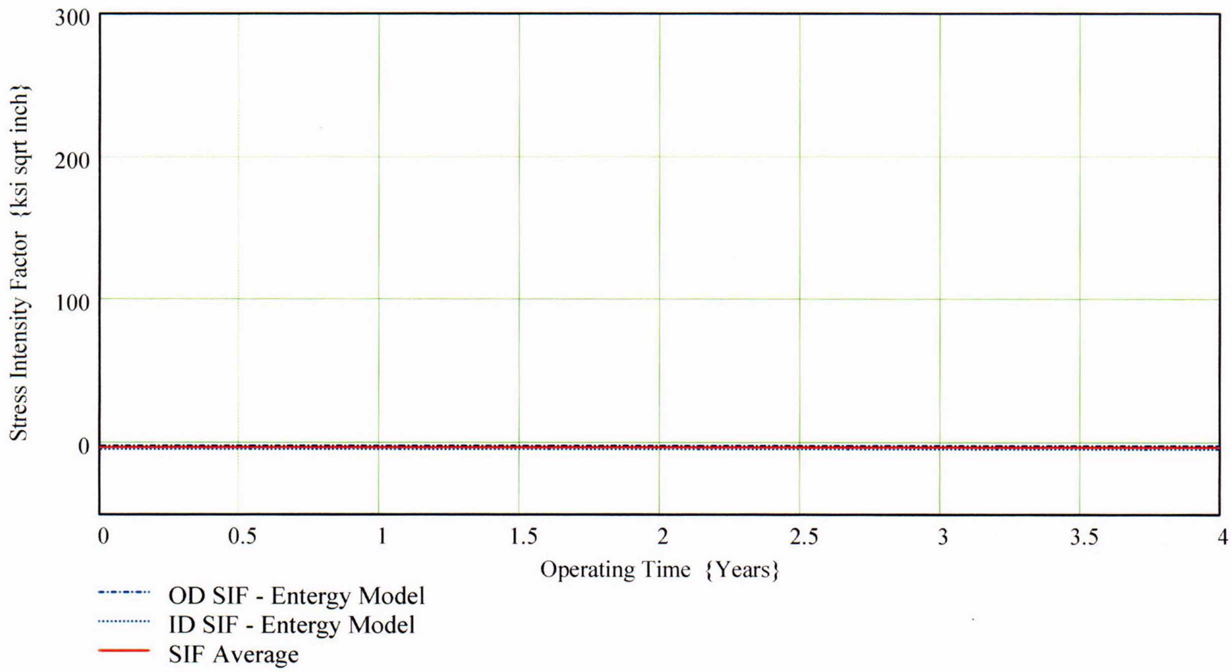
$Prop_{Length} = 5.084$






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

$TWC_{pwscc_{(j,6)}} =$

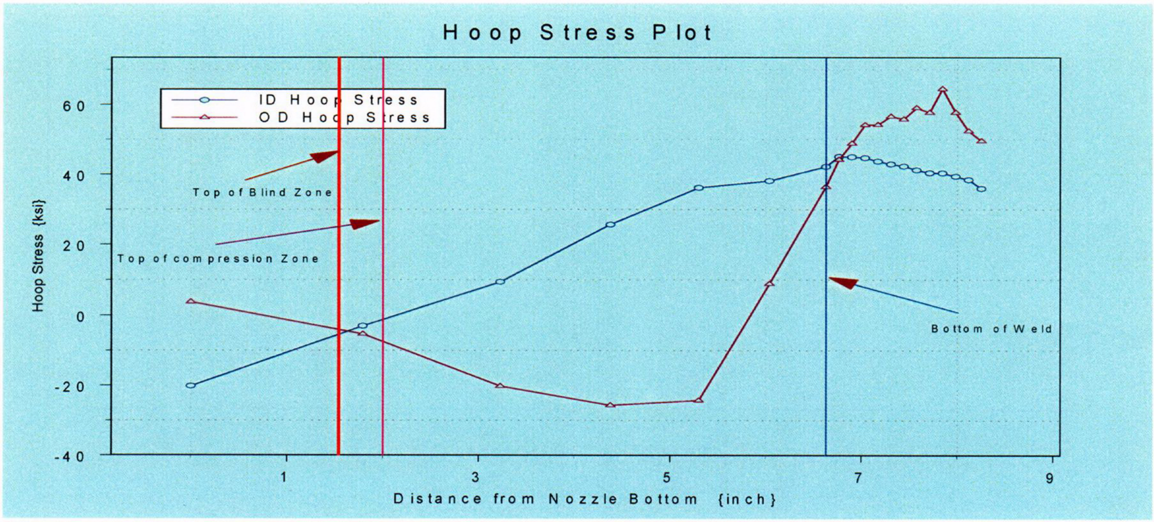
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672
-1.672

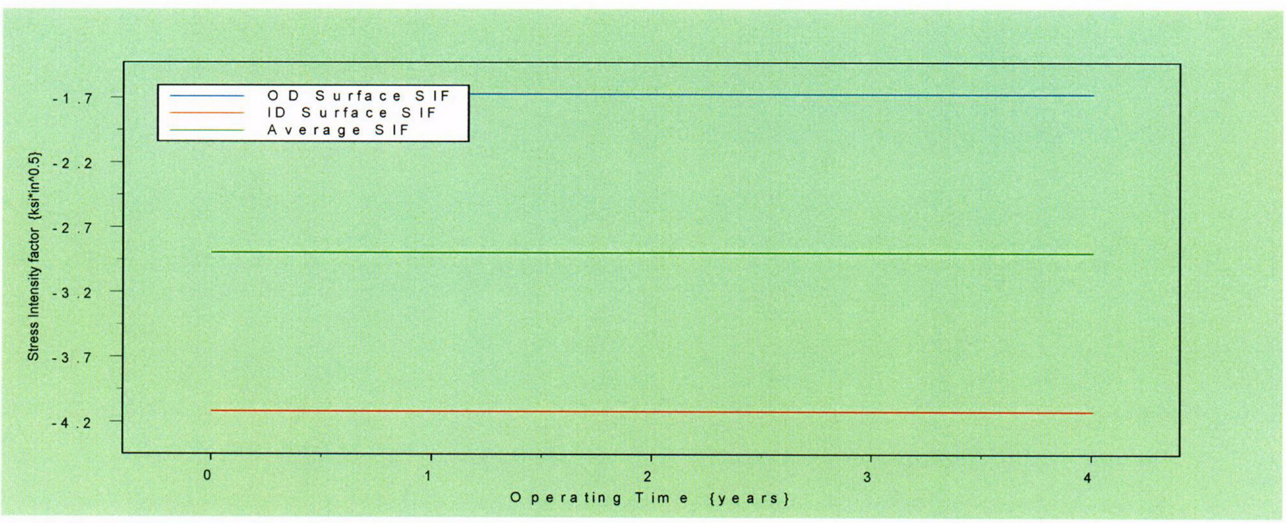
$TWC_{pwscc_{(j,7)}} =$

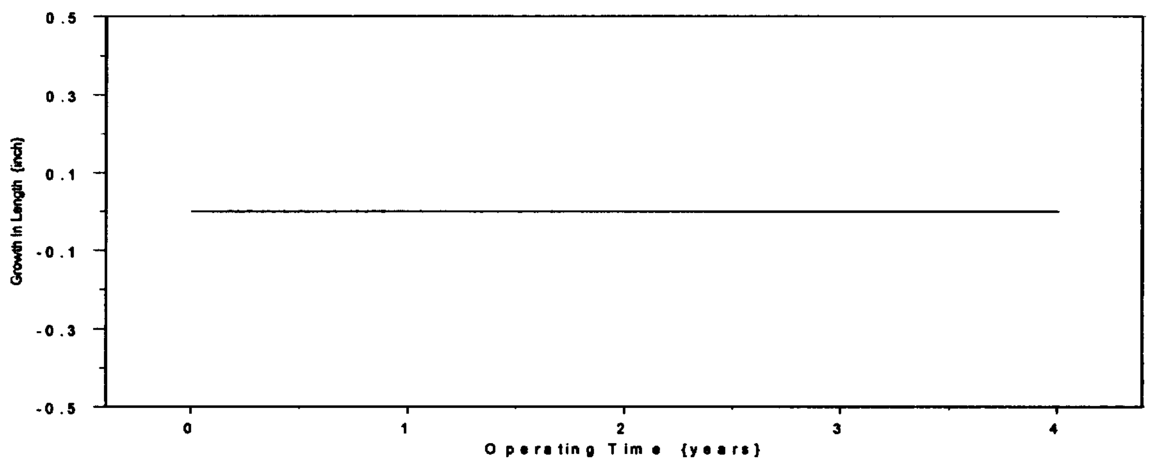
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119
-4.119

$TWC_{pwscc_{(j,8)}} =$

-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952
-2.952


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Top of compression Zone
Bottom of Weld
Hoop Stress {ksi}
60
40
20
0
-20
-40
1
3
5
7
9
Distance from Nozzle Bottom {inch}


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor {ksi*in^0.5}
-1.7
-2.2
-2.7
-3.2
-3.7
-4.2
0
1
2
3
4
Operating Time {years}



Developed by:

Verified by:

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

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

Refrences :

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

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"49" Degree Nozzle, Mid-Plane Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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.

$UL_{Strs.Dist} := 4.034$ 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 (Twice detectable length)
$a_0 := 0.661 \cdot 0.07$	Initial Flaw Depth (Minimum Detecteble Depth was 5% TW)
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

Stress Input Data

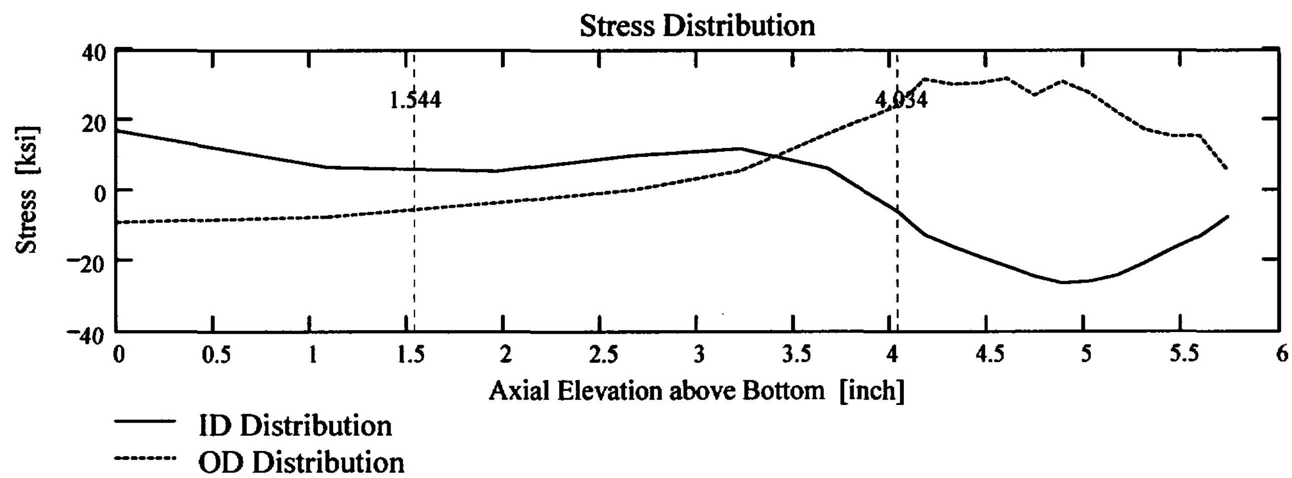
Input all available Nodal stress data in the table below. The column designations are as follows:

Column "0" = Axial distance from minimum to maximum recorded on data sheet (inches)
Column "1" = ID Stress data at each Elevation (ksi)
Cloumn "2" = Quarter Thickness Stress data at each Elevation (ksi)
Cloumn "3" = Mid Thickness Stress data at each Elevation (ksi)
Column "4" = Three quarter Thickness Stress data at each Elevation (ksi)
Column "5" = OD Stress data at each Elevation (ksi)

AllData :=

	0	1	2	3	4	5
0	0	17.35	8.19	2.28	-3.06	-8.64
1	1.09	6.89	1.47	-2.22	-5.44	-7.2
2	1.96	5.78	2.36	0.75	-0.95	-3.23
3	2.66	10.29	7.15	5.32	3.43	0.49
4	3.23	12.24	7.03	6.83	7.24	5.95
5	3.67	6.58	4.66	5.87	12.45	16.38
6	4.03	-5.62	-1.3	4.18	17.86	24.28
7	4.18	-12.25	-6.01	2.74	20.52	31.88
8	4.32	-15.64	-9.13	2.2	21.5	30.45
9	4.46	-18.61	-11.79	1.32	20.22	30.79

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



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

$$Data := \begin{pmatrix} 0 & 17.354 & 8.186 & 2.284 & -3.064 & -8.637 \\ 1.091 & 6.892 & 1.47 & -2.224 & -5.444 & -7.199 \\ 1.964 & 5.781 & 2.359 & 0.754 & -0.955 & -3.232 \\ 2.664 & 10.289 & 7.148 & 5.324 & 3.428 & 0.494 \\ 3.225 & 12.243 & 7.028 & 6.829 & 7.244 & 5.952 \\ 3.674 & 6.579 & 4.659 & 5.865 & 12.453 & 16.377 \\ 4.034 & -5.621 & -1.296 & 4.184 & 17.859 & 24.278 \\ 4.176 & -12.251 & -6.006 & 2.741 & 20.517 & 31.88 \\ 4.317 & -15.641 & -9.131 & 2.2 & 21.496 & 30.446 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location above Nozzle Bottom

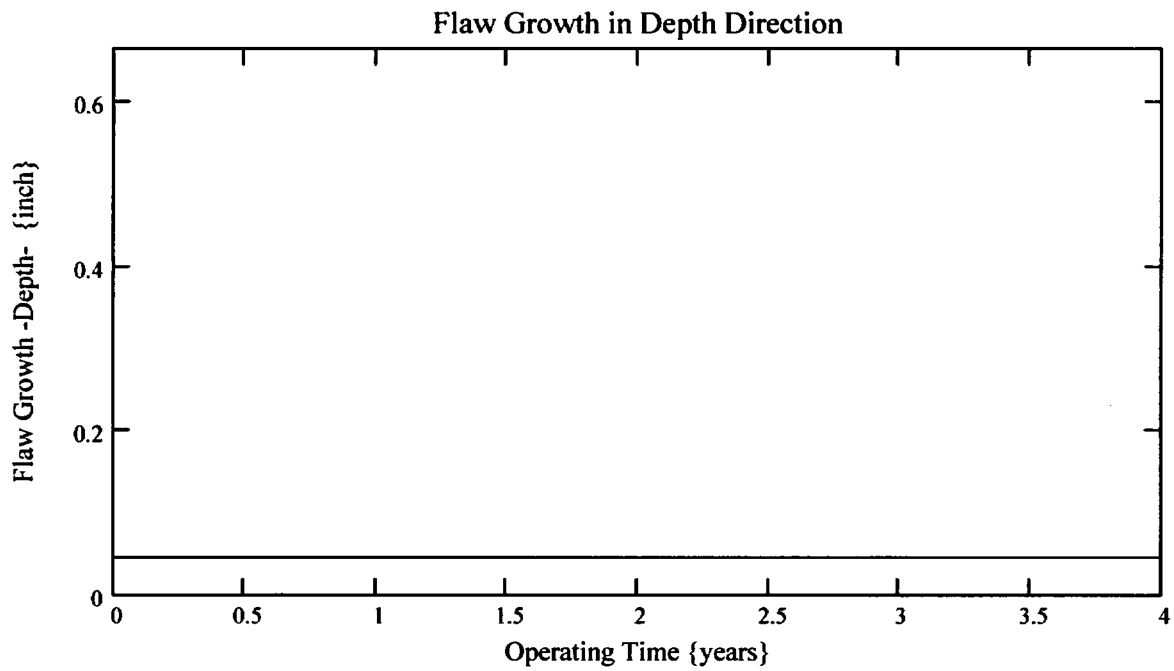
$$U_{Tip} := FL_{Cntr} + c_0$$

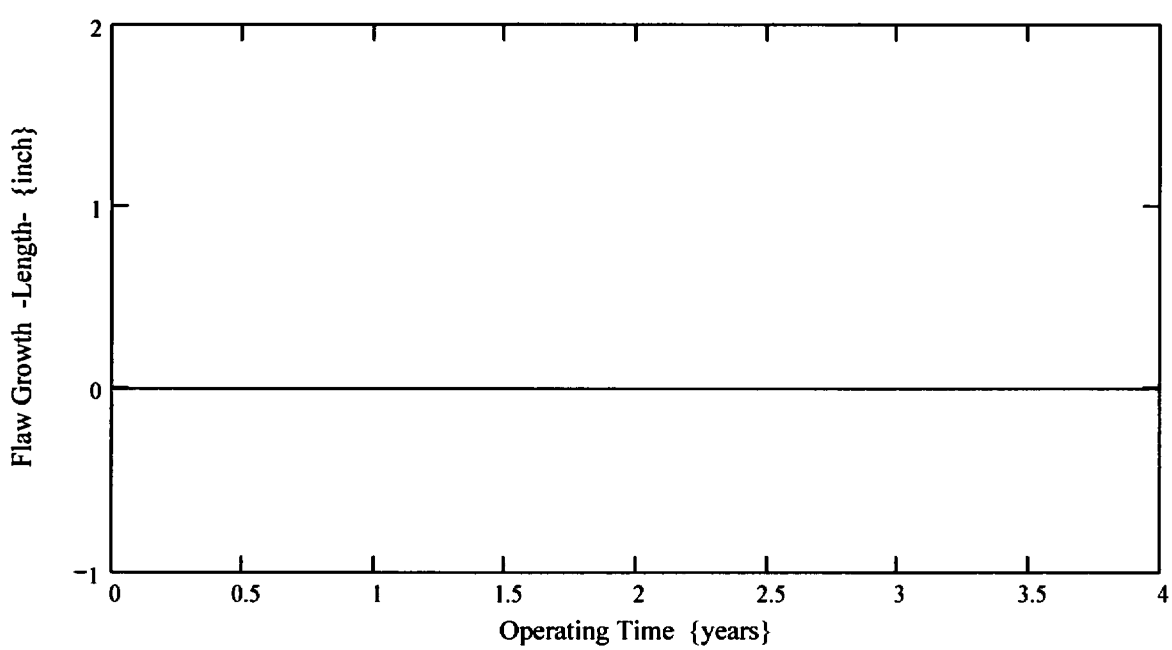
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

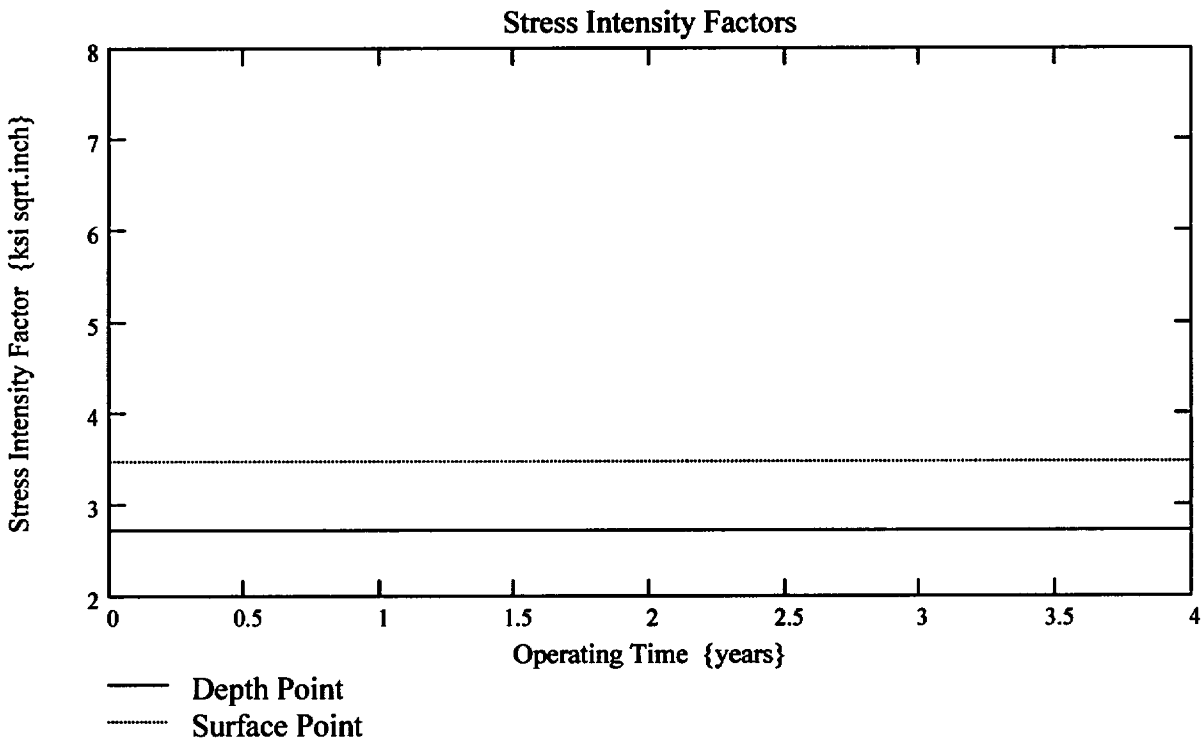
No User Input is required beyond this Point

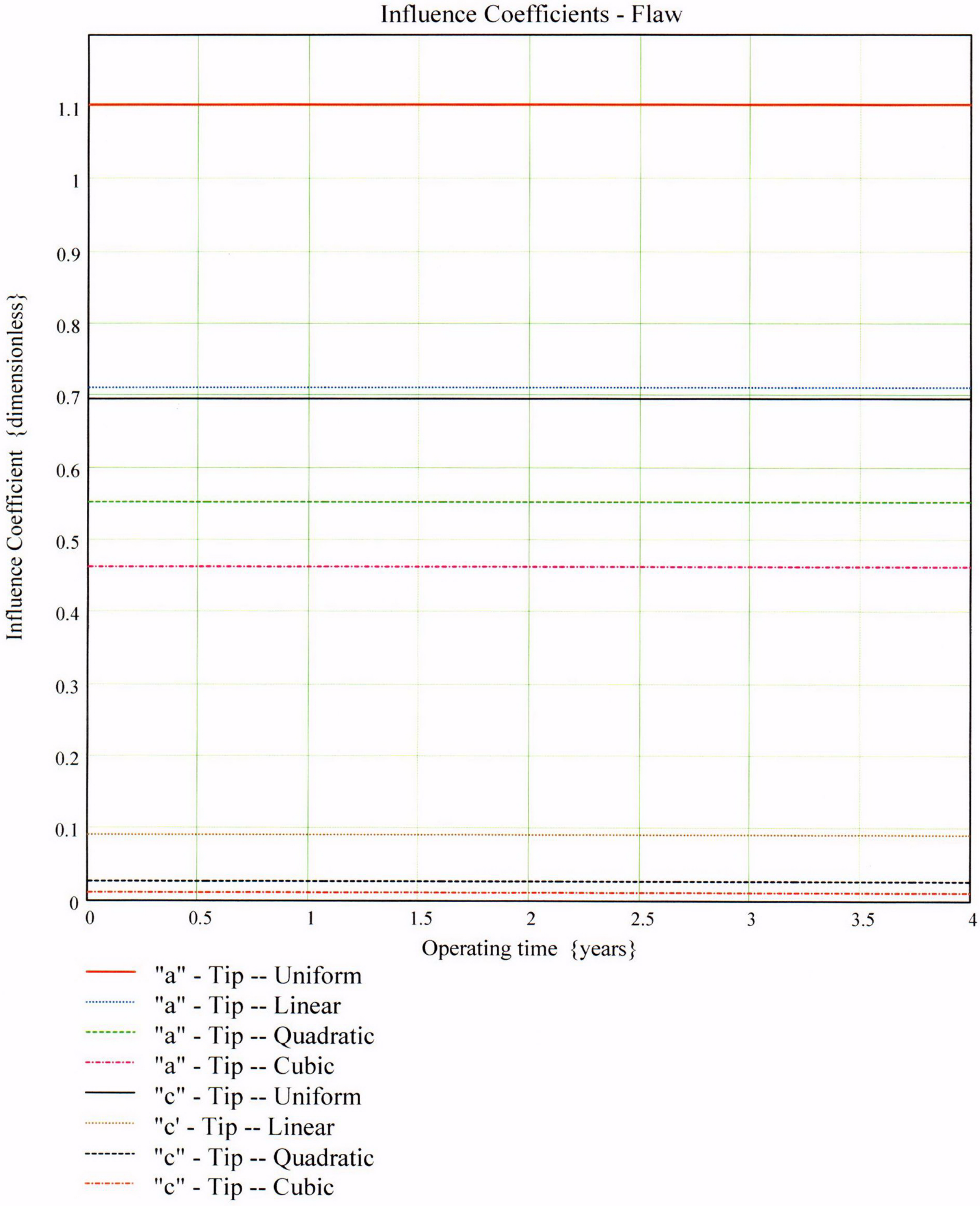
Sat Aug 09 10:59:39 AM 2003

$Prop_{Length} = 2.33$






Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
8
7
6
5
4
3
2
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point
Surface Point


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

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

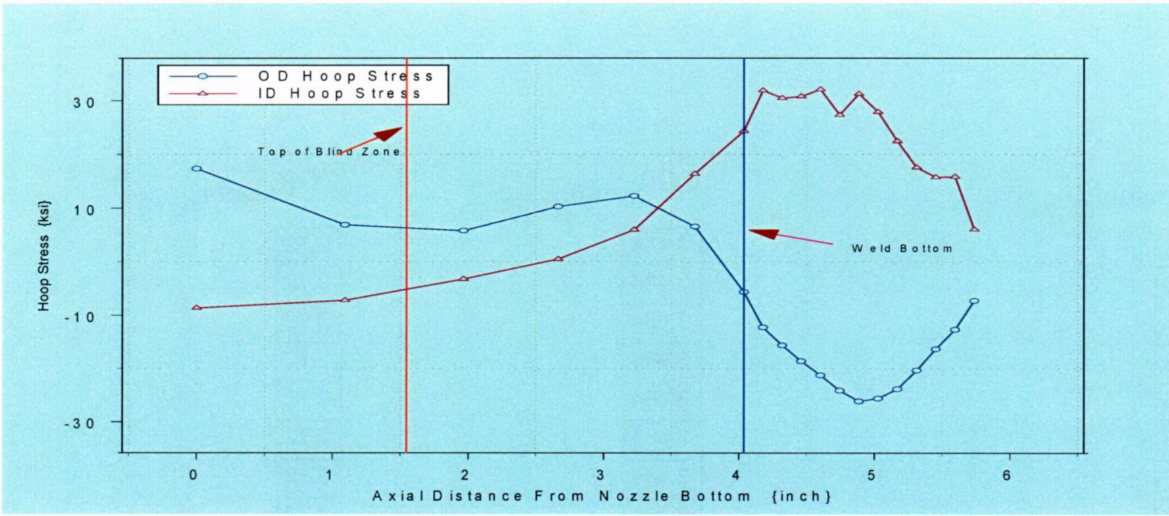
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103

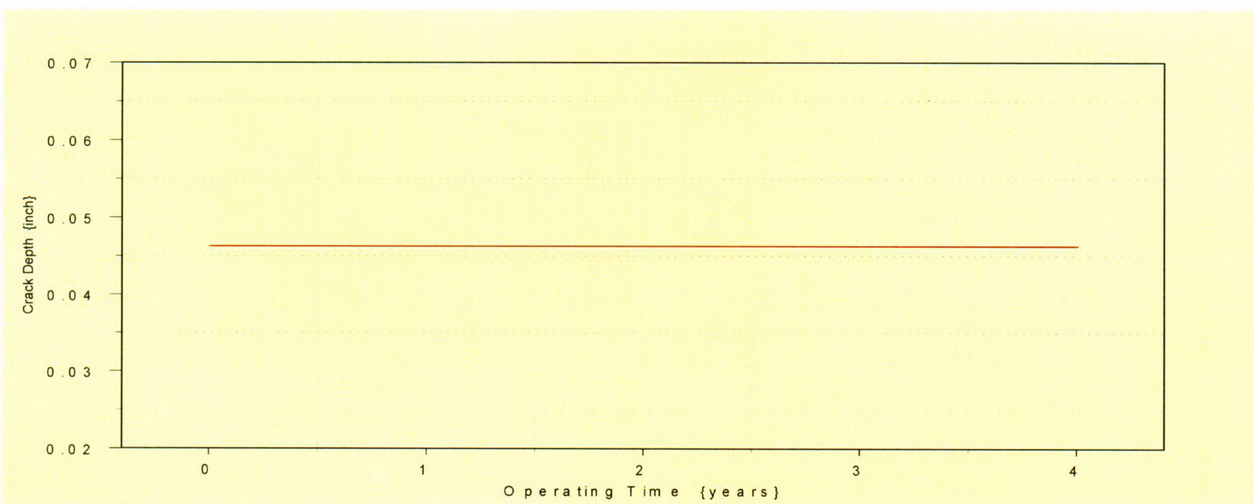
$CGR_{sambi_{(k,6)}} =$

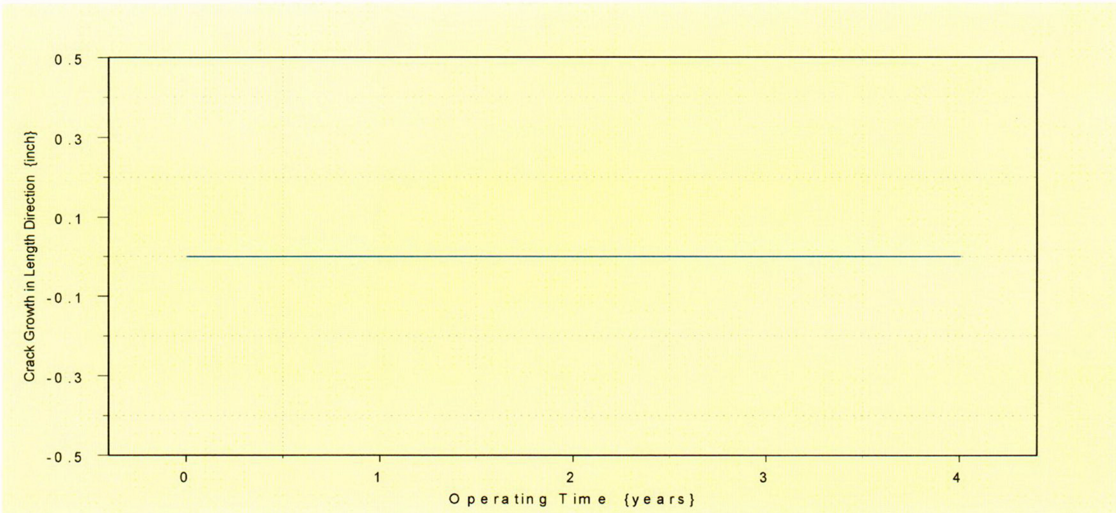
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484
3.484

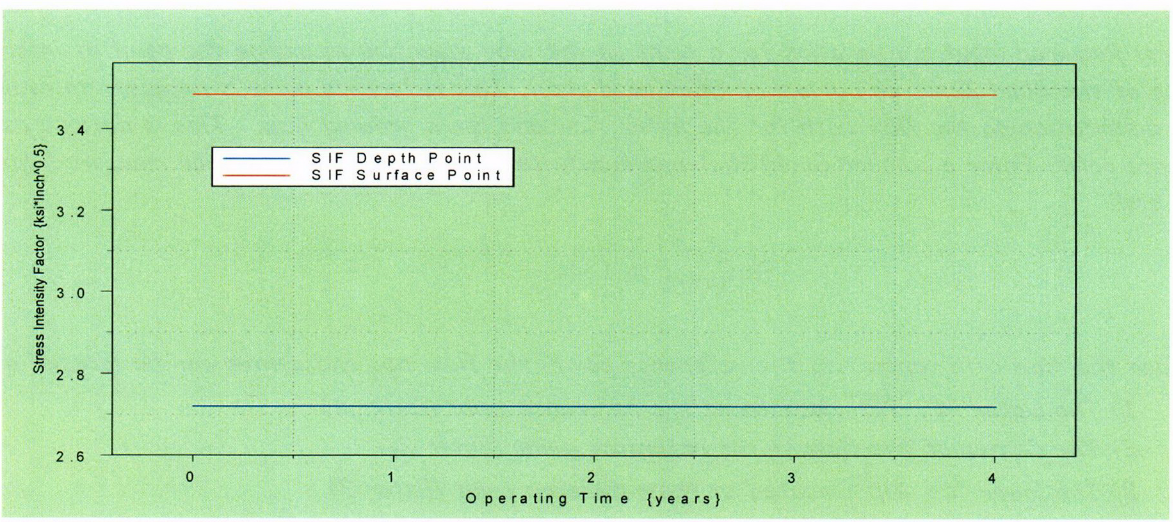
$CGR_{sambi_{(k,5)}} =$

2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72
2.72


OD Hoop Stress
ID Hoop Stress
Top of Blind Zone
Weld Bottom
Hoop Stress (ksi)
30
10
-10
-30
0
1
2
3
4
5
6
Axial Distance From Nozzle Bottom {inch}


Crack Depth {inch}
0.07
0.06
0.05
0.04
0.03
0.02
0
1
2
3
4
Operating Time {years}


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


3.4
3.2
3.0
2.8
2.6
Stress Intensity Factor {ksi*Inch^0.5}
SIF Depth Point
SIF Surface Point
0
1
2
3
4
Operating Time {years}

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 -"49" Degree Nozzle, Mid-Plane Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

OD Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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

$UL_{Strs.Dist} := 4.034$ 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

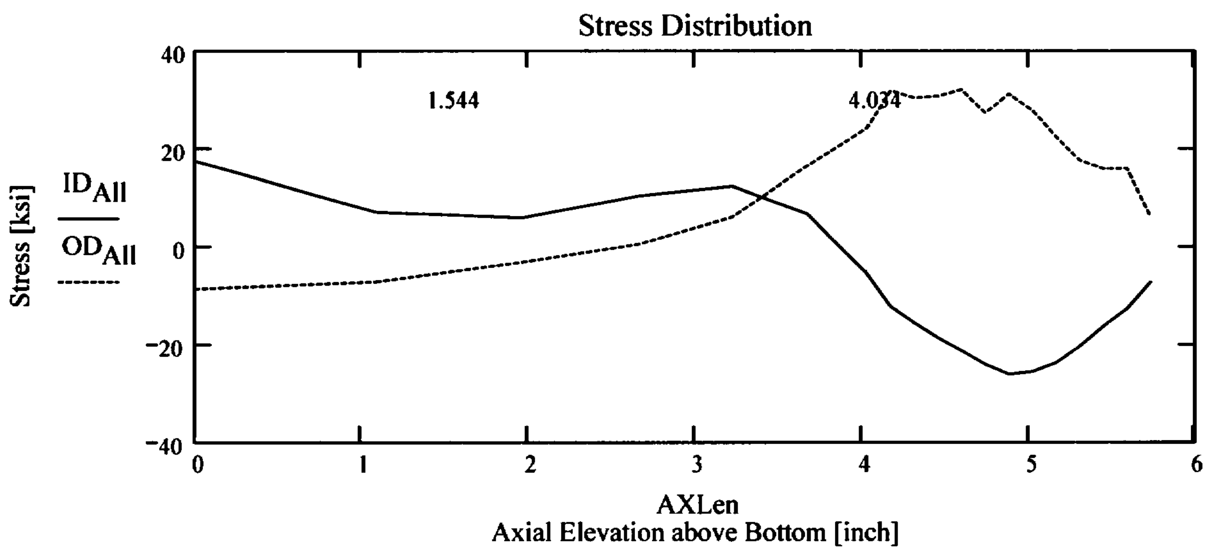
Stress Input Data

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	17.35	8.19	2.28	-3.06	-8.64
1	1.09	6.89	1.47	-2.22	-5.44	-7.2
2	1.96	5.78	2.36	0.75	-0.95	-3.23
3	2.66	10.29	7.15	5.32	3.43	0.49
4	3.23	12.24	7.03	6.83	7.24	5.95
5	3.67	6.58	4.66	5.87	12.45	16.38
6	4.03	-5.62	-1.3	4.18	17.86	24.28
7	4.18	-12.25	-6.01	2.74	20.52	31.88
8	4.32	-15.64	-9.13	2.2	21.5	30.45
9	4.46	-18.61	-11.79	1.32	20.22	30.79
10	4.6	-21.26	-13.55	0.57	19.39	32.09

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



Observing the stress distribution select the region in the table above labeled $Data_{All}$ that represents the region of interest. This needs to be done especially for distributions that have a large compressive stress at the nozzle bottom and high tensile stresses at the J-weld location. 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).

$$Data := \begin{pmatrix} 0 & 17.354 & 8.186 & 2.284 & -3.064 & -8.637 \\ 1.091 & 6.892 & 1.47 & -2.224 & -5.444 & -7.199 \\ 1.964 & 5.781 & 2.359 & 0.754 & -0.955 & -3.232 \\ 2.664 & 10.289 & 7.148 & 5.324 & 3.428 & 0.494 \\ 3.225 & 12.243 & 7.028 & 6.829 & 7.244 & 5.952 \\ 3.674 & 6.579 & 4.659 & 5.865 & 12.453 & 16.377 \\ 4.034 & -5.621 & -1.296 & 4.184 & 17.859 & 24.278 \\ 4.176 & -12.251 & -6.006 & 2.741 & 20.517 & 31.88 \\ 4.317 & -15.641 & -9.131 & 2.2 & 21.496 & 30.446 \\ 4.459 & -18.614 & -11.785 & 1.319 & 20.216 & 30.786 \\ 4.601 & -21.257 & -13.548 & 0.574 & 19.393 & 32.088 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

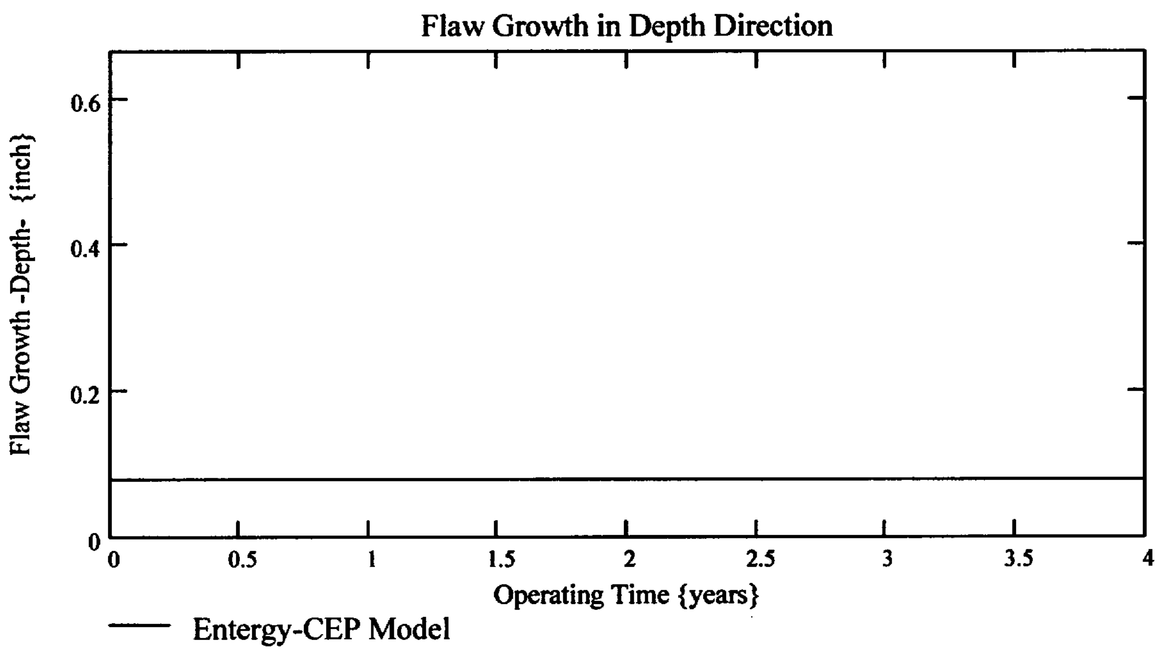
$U_{Tip} := FL_{Cntr} + c_0$

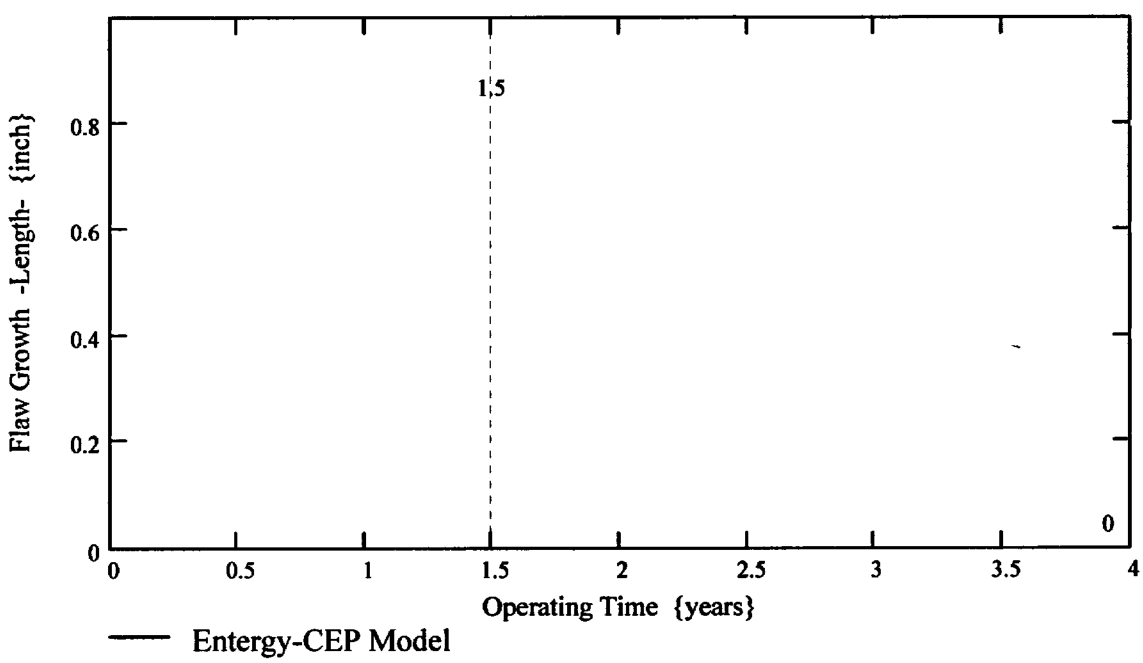
$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$

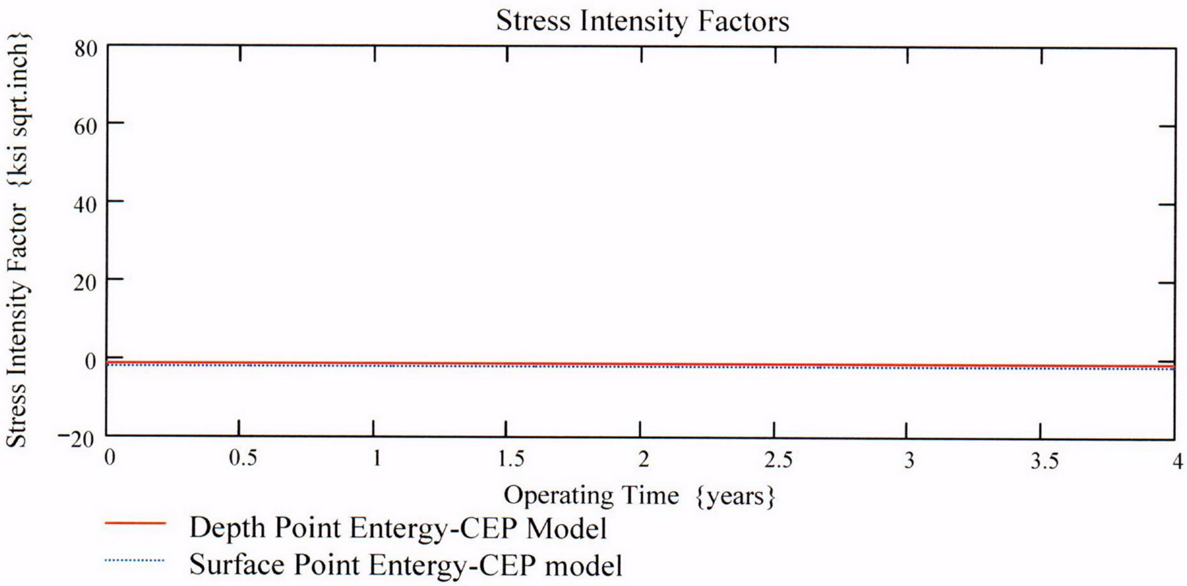
No User Input is required beyond this Point

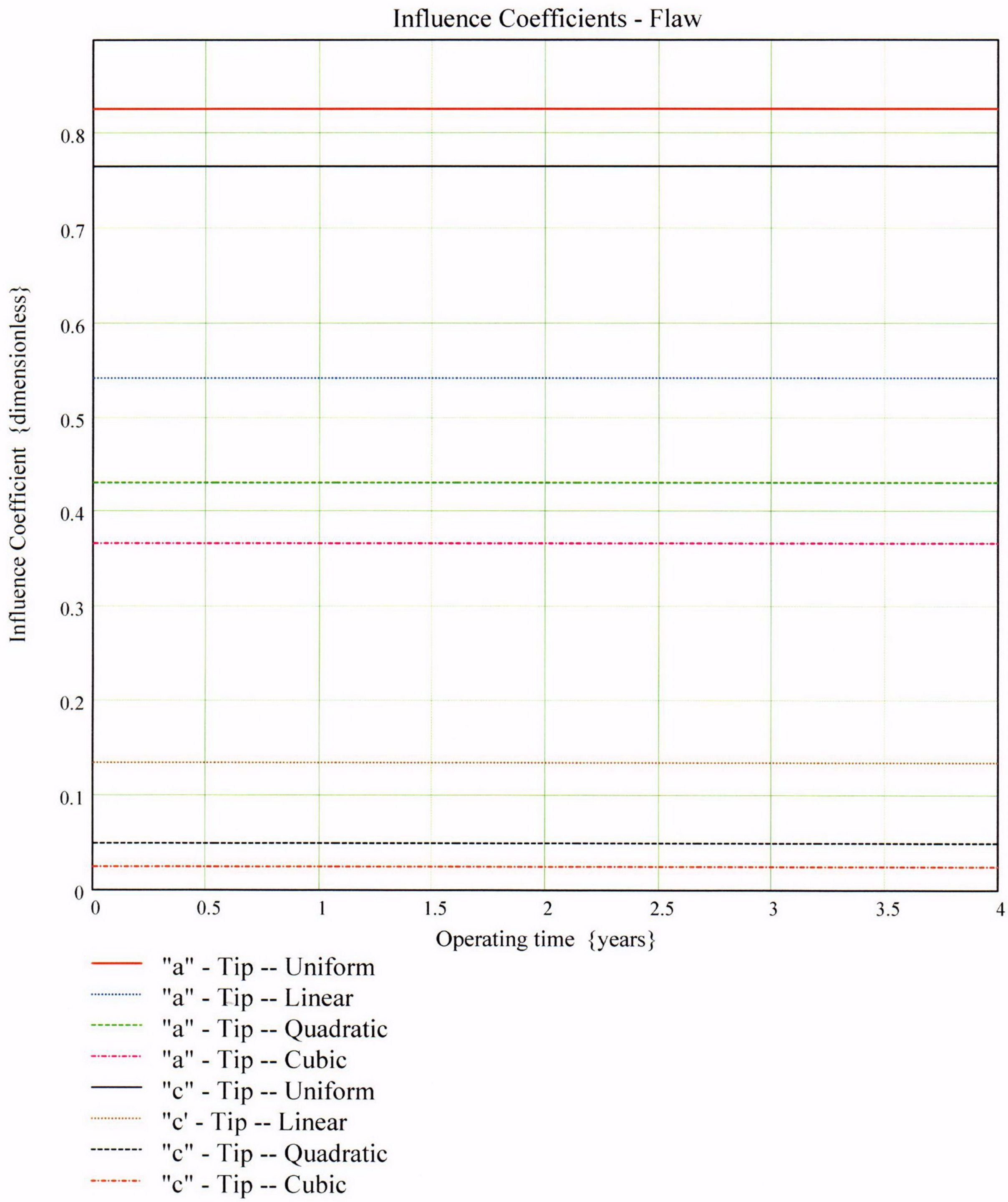
Sat Aug 09 10:21:18 AM 2003

$Prop_{Length} = 2.33$






Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
−20
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}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic
"c" - Tip -- Cubic

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

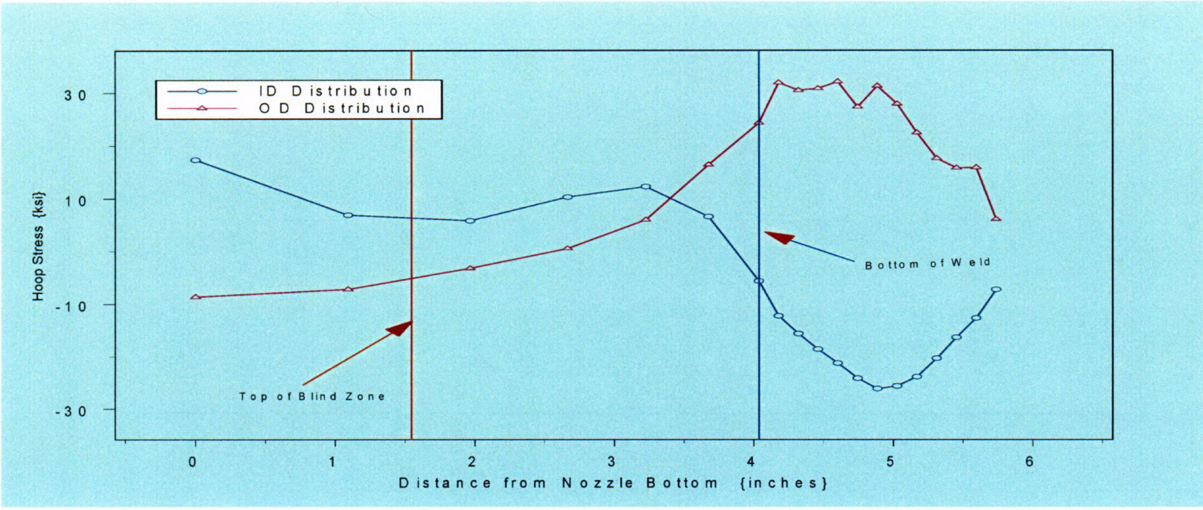
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827

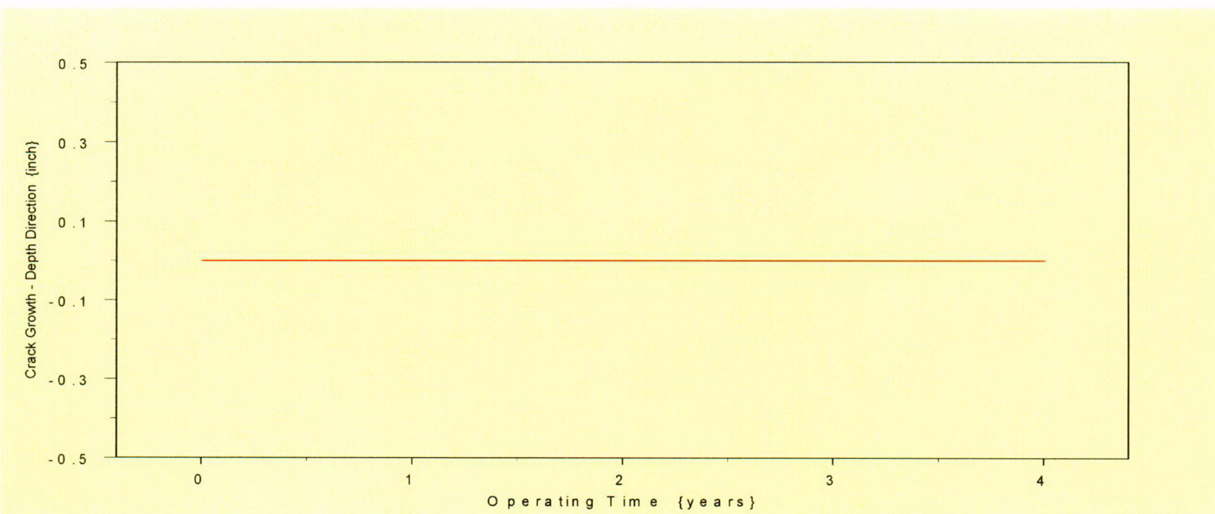
$CGR_{sambi_{(k,6)}} =$

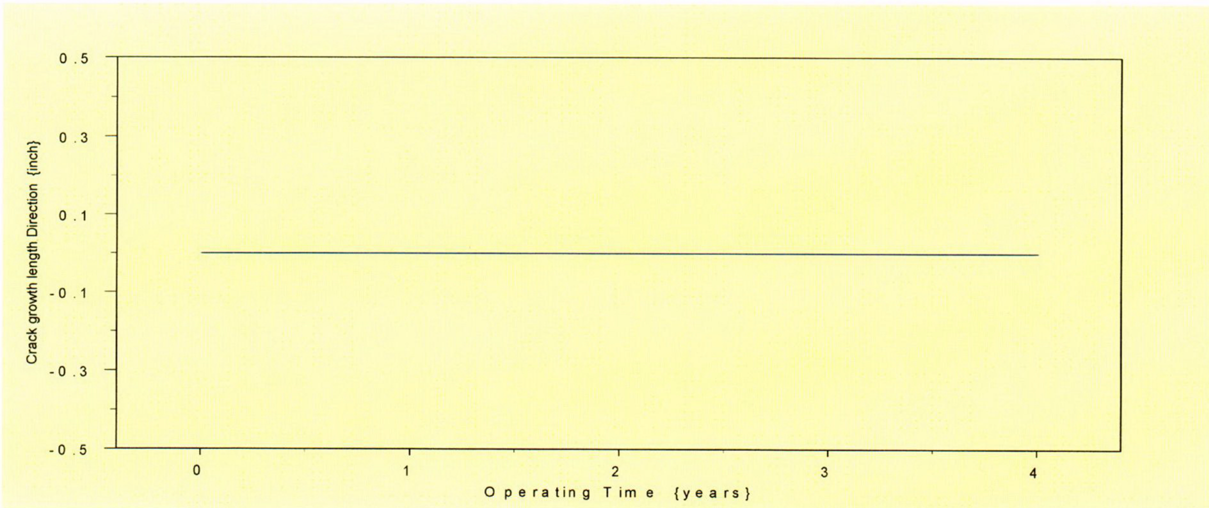
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939
-1.939

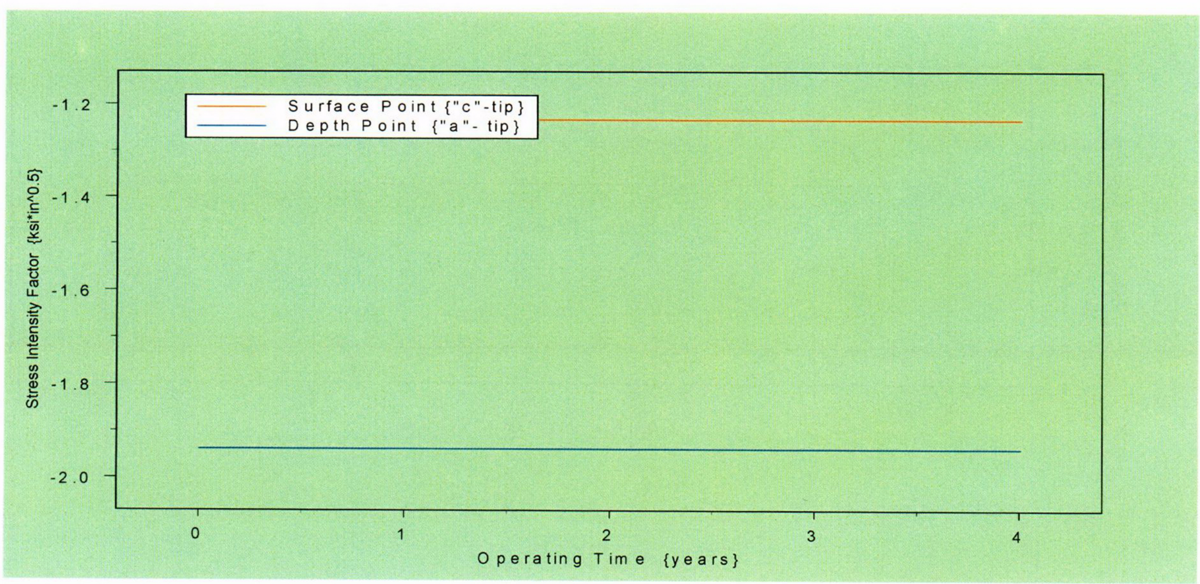
$CGR_{sambi_{(k,5)}} =$

-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233
-1.233


ID Distribution
OD Distribution
Hoop Stress {ksi}
30
10
-10
-30
Bottom of Weld
Top of Blind Zone
0
1
2
3
4
5
6
Distance from Nozzle Bottom {inches}


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


0.5
0.3
0.1
-0.1
-0.3
-0.5
Crack growth length Direction {inch}
0
1
2
3
4
Operating Time {years}


Surface Point {"c"-tip}
Depth Point {"a"- tip}
-1.2
-1.4
-1.6
-1.8
-2.0
Stress Intensity Factor {ksi*in^0.5}
0
1
2
3
4
Operating Time {years}