Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw

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

Arkansas Nuclear One Unit 1

Component : Reactor Vessel CRDM -"0" Degree Nozzle, "All" Azimuth

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 the Freespan length from the NDE data sheet (Excel spread sheet)

$FS_{nde.data.sheet} := 1.040$

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).

$Val := 2$

Enter the Upper Extent of the Stress Distribution used for the analysis

$UL_{Strs.Dist} := 1.629$ Upper Axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom)

$Ref_{Point} := UL_{Strs.Dist} - FS_{nde.data.sheet}$

The regions highlighted below remain constant for ANO-1 analysis and should not be changed

Input Data :-

$L := 0.35$	Initial Flaw Length
$a_0 := 0.09872$	Initial Flaw Depth
$od := 4.00$	Tube OD
$id := 2.765$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 2$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 600$	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

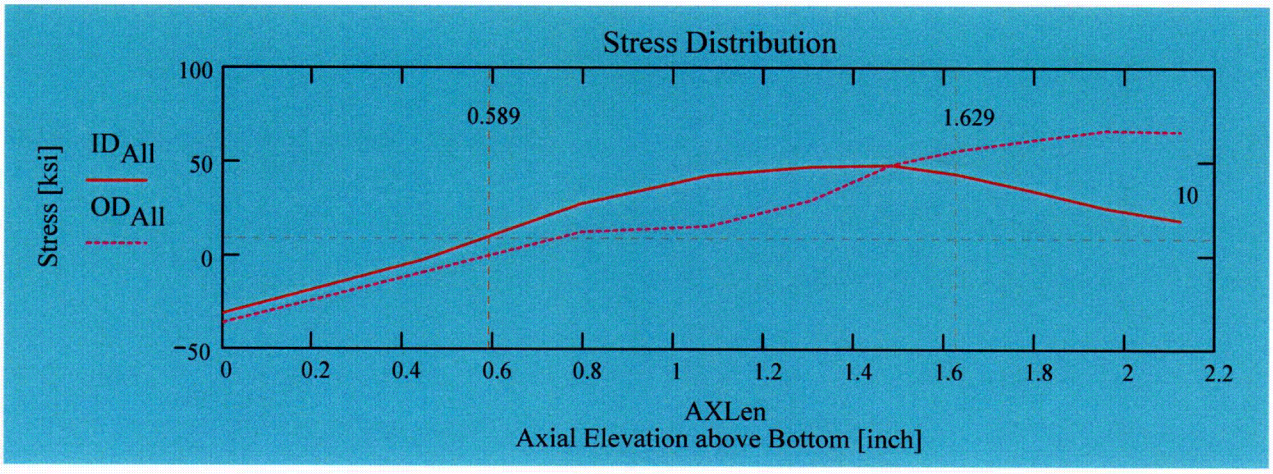
Stress Input Data

Import 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	-30.99	-30.92	-31.72	-35.43	-35.97
1	0.44	-2.37	-4.15	-6.02	-7.41	-9
2	0.79	27.86	23.57	19.7	18	12.78
3	1.08	42.8	38.7	32.04	24.15	15.99
4	1.3	47.38	40.95	35.62	31.78	29.73
5	1.48	48.17	40.84	37.03	40.9	48.51
6	1.63	43.48	39.76	38.46	47.75	56
7	1.79	35.07	35.43	38.78	48.73	61.47
8	1.96	25.7	30.81	38.83	51.73	66.52
9	2.12	19.18	27.11	38.58	52.69	65.89

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



$Ref_{Point} = 0.589$

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).

$$Data := \begin{pmatrix} 0 & -30.99 & -30.92 & -31.719 & -35.433 & -35.967 \\ 0.441 & -2.37 & -4.15 & -6.024 & -7.411 & -9.003 \\ 0.793 & 27.862 & 23.567 & 19.705 & 17.995 & 12.782 \\ 1.076 & 42.802 & 38.705 & 32.039 & 24.149 & 15.988 \\ 1.303 & 47.376 & 40.949 & 35.624 & 31.779 & 29.726 \\ 1.484 & 48.173 & 40.841 & 37.026 & 40.902 & 48.506 \\ 1.629 & 43.475 & 39.757 & 38.459 & 47.748 & 55.999 \\ 1.794 & 35.074 & 35.427 & 38.776 & 48.731 & 61.472 \\ 1.959 & 25.697 & 30.809 & 38.834 & 51.732 & 66.515 \end{pmatrix}$$

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

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

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

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

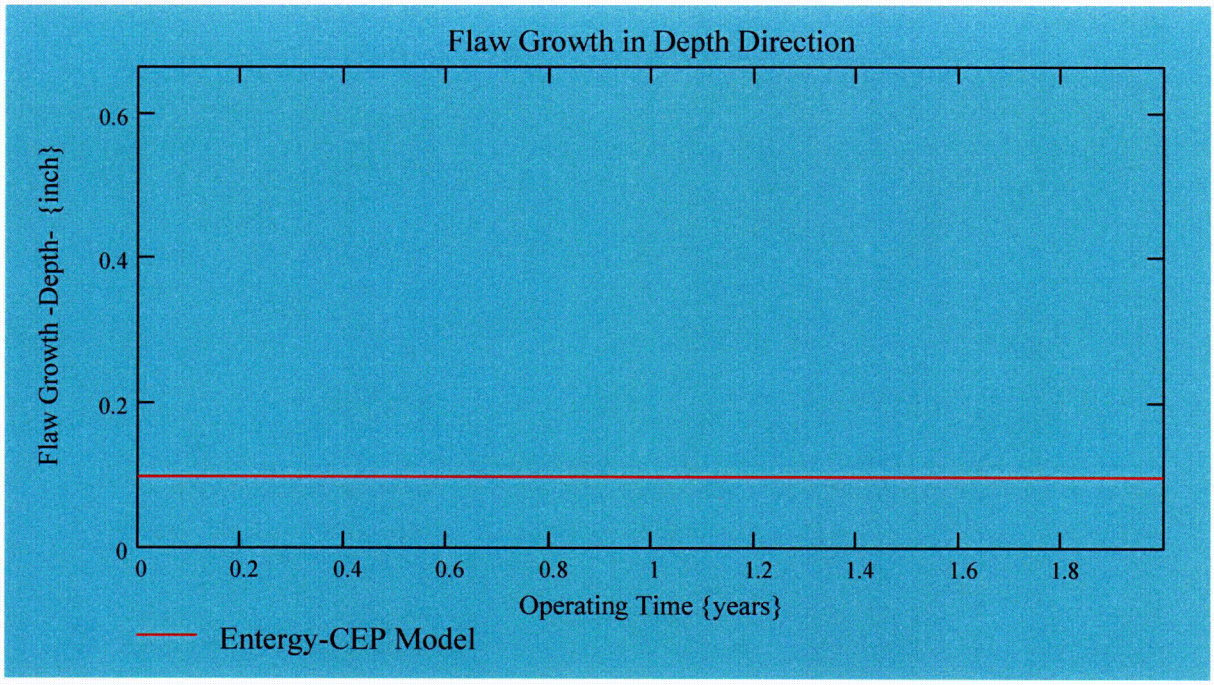
Flaw center Location Location above Nozzle Bottom

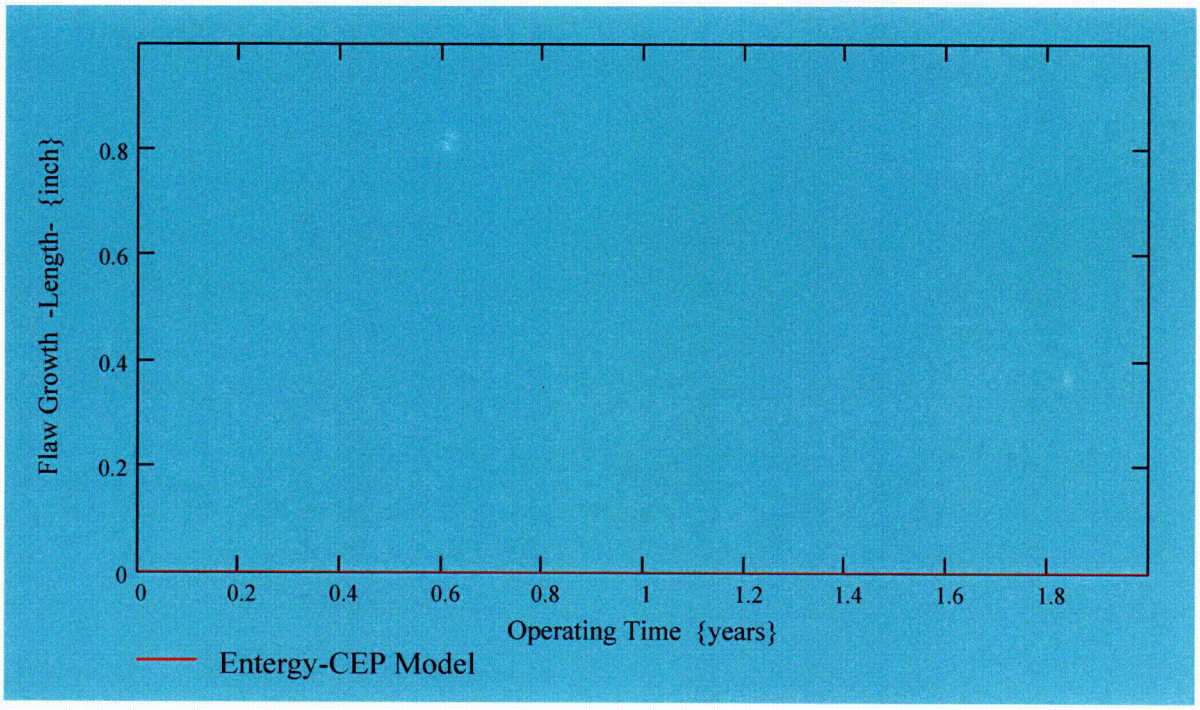
$U_{Tip} := FL_{Cntr} + c_0$

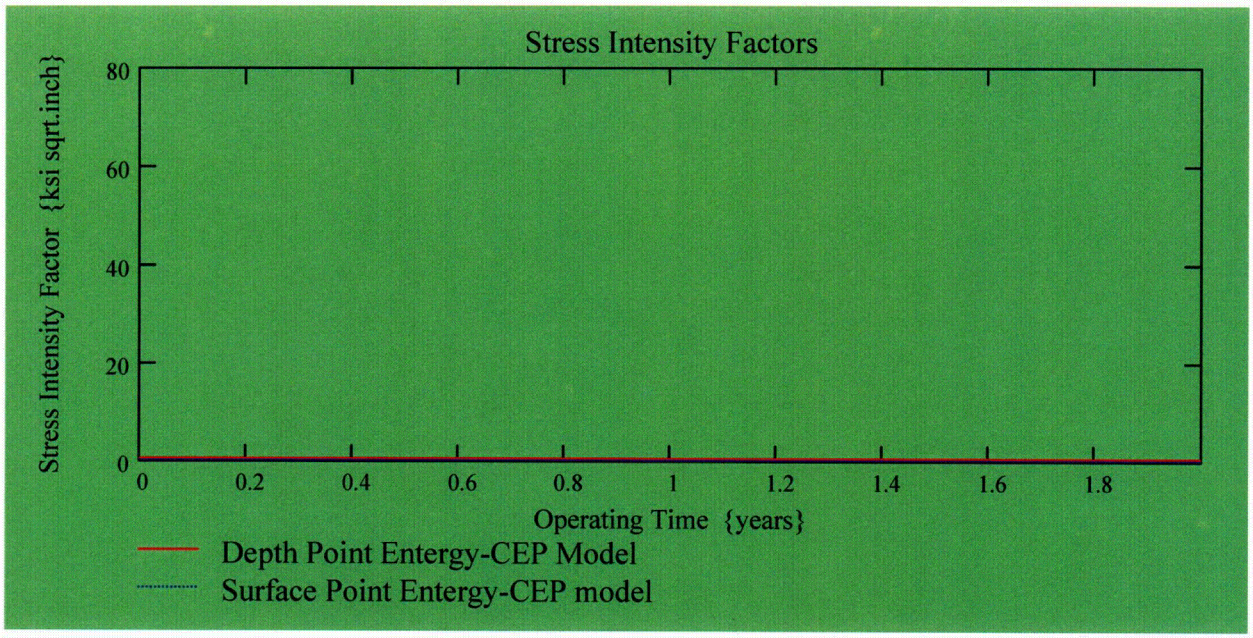
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

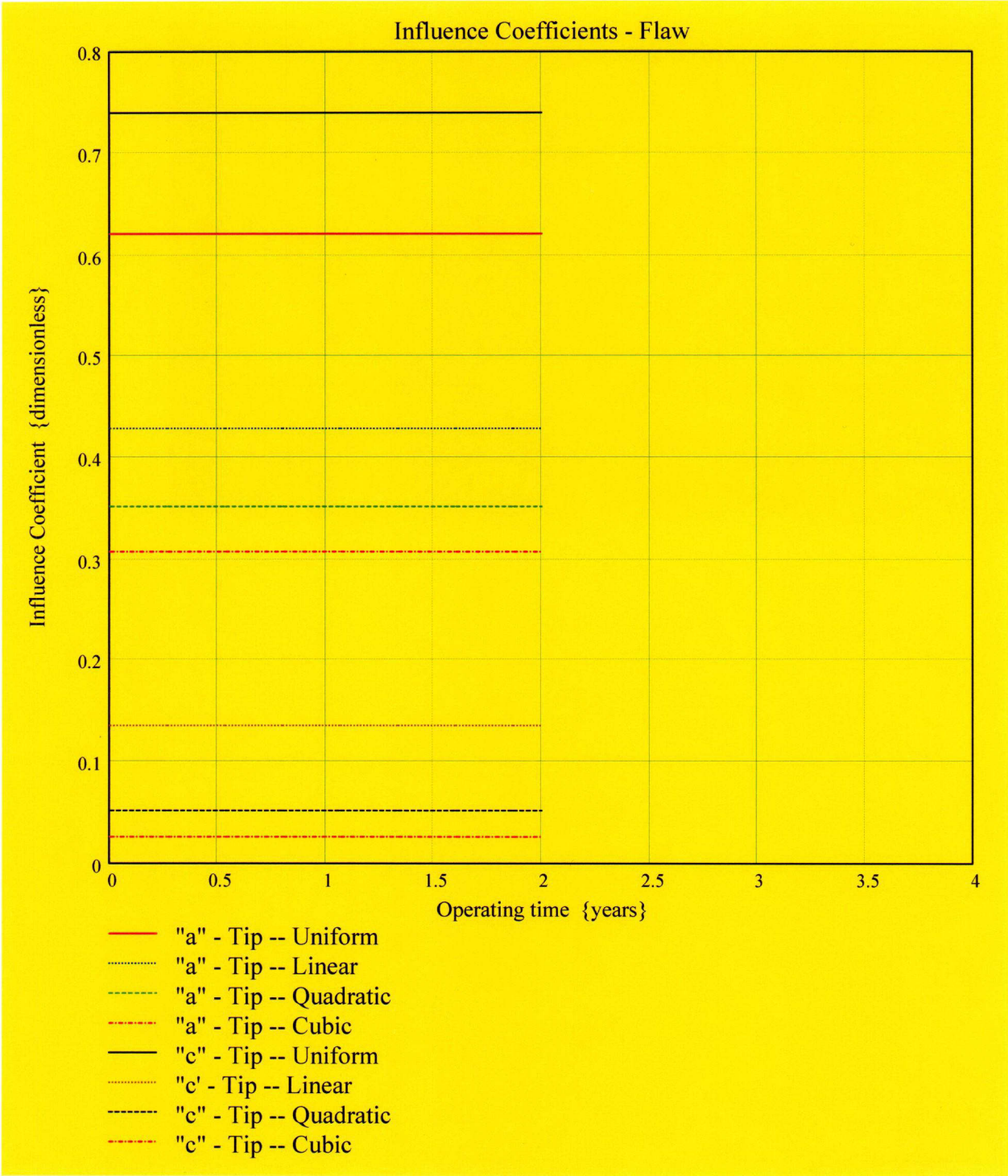
No User Input is required beyond this Point

$Prop_{Length} = 0.865$






Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Operating Time {years}
Depth Point Entergy-CEP Model
Surface Point Entergy-CEP model


Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
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

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

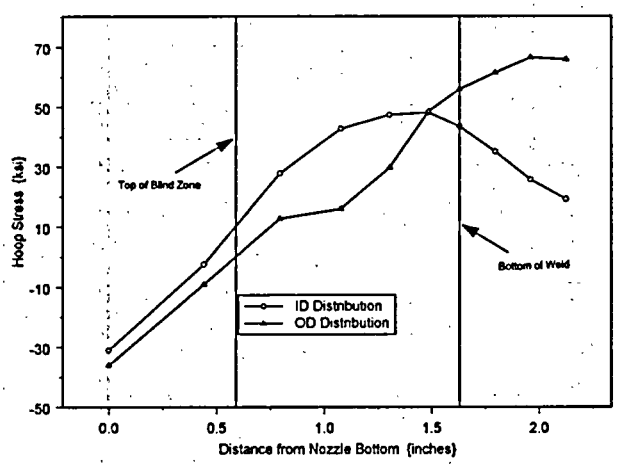
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621
0.621

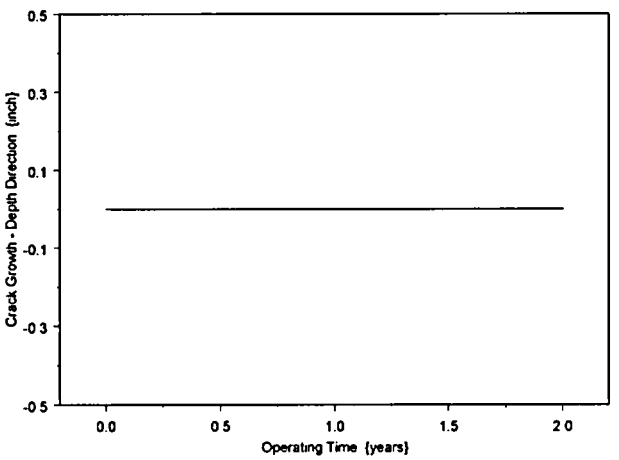
$CGR_{sambi_{(k,6)}} =$

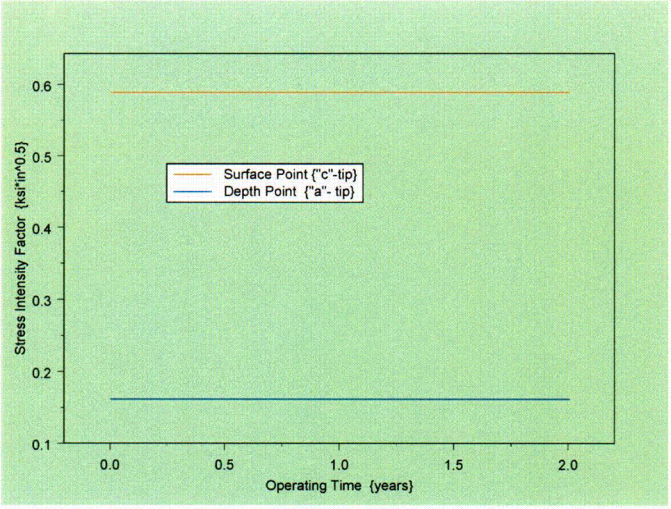
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162
0.162

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

0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589
0.589


70
50
30
10
-10
-30
-50
Hoop Stress (ksi)
Top of Blind Zone
Bottom of Weld
ID Distribution
OD Distribution
0.0
0.5
1.0
1.5
2.0
Distance from Nozzle Bottom (inches)


0.5
0.3
0.1
-0.1
-0.3
-0.5
Crack Growth - Depth Direction (inch)
0.0
0.5
1.0
1.5
2.0
Operating Time (years)


Stress Intensity Factor {ksi*in^0.5}
0.6
0.5
0.4
0.3
0.2
0.1
Surface Point {"c"-tip}
Depth Point {"a"- tip}
0.0
0.5
1.0
1.5
2.0
Operating Time {years}

Stress Corrosion Crack Growth Analysis Through-wall flaw

Developed by Central Engineering Programs, Entergy Operations Inc.

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

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

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

Arkansas Nuclear One Unit 1

Component : Reactor Vessel CRDM -"0"degree Nozzle, "All" Azimuths

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 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.

$UL_{Strs.Dist} := 1.629$ Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom to bottom of Fillet Weld)

The Second Input is needed 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 Length of the Freespan from NDE Data sheet

$FS_{nde.data.sheet} := 1.040$ Length of Freespan Obtained from NDE

$BZ := UL_{Strs.Dist} - FS_{nde.data.sheet}$ Location of Blind Zone above nozzle bottom (inch)

The Highlighted Entries below remains constant for ANO-1 and should not be changed

Input Data :-

$L := 0.25$	Initial Crack Length TW axial Based on Stress Distribution. Bottom end of Crack to be set @ approximately 10ksi.
$od := 4.00$	Tube OD
$id := 2.765$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 2$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 600$	Estimate of Operating Temperature
$\nu := 0.307$	Poissons ratio @ 600 F
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

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

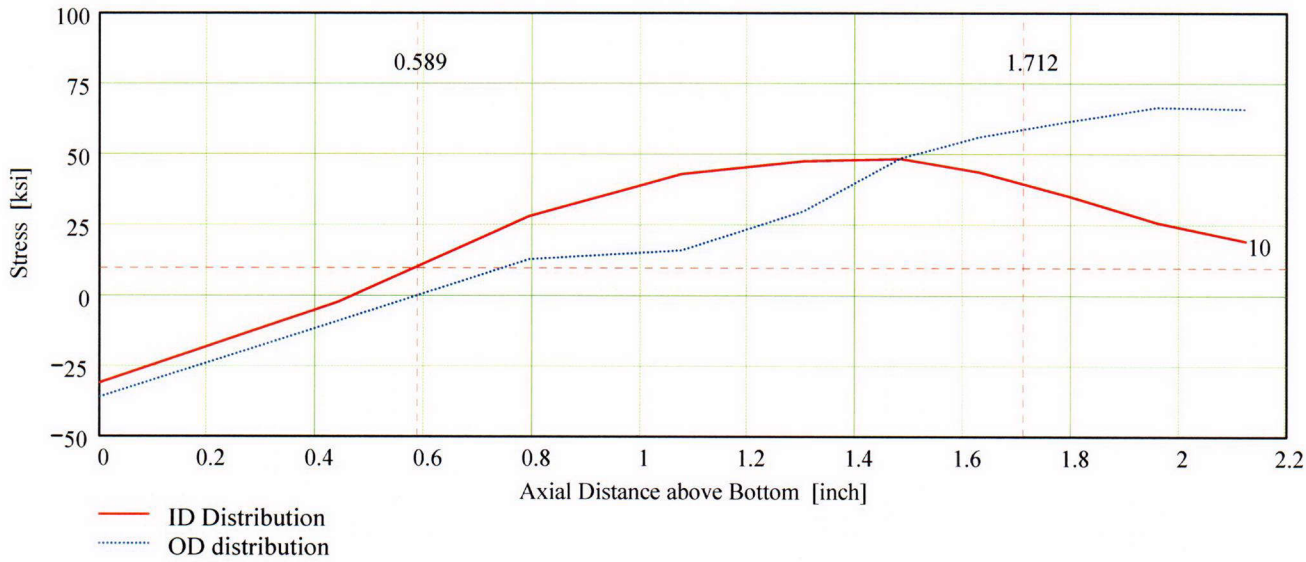
Stress Input Data

Import the Required data from applicable Excel spread Sheet. The column designations are as follows:
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	-30.99	-30.92	-31.72	-35.43	-35.97
1	0.44	-2.37	-4.15	-6.02	-7.41	-9
2	0.79	27.86	23.57	19.7	18	12.78
3	1.08	42.8	38.7	32.04	24.15	15.99
4	1.3	47.38	40.95	35.62	31.78	29.73
5	1.48	48.17	40.84	37.03	40.9	48.51
6	1.63	43.48	39.76	38.46	47.75	56
7	1.79	35.07	35.43	38.78	48.73	61.47
8	1.96	25.7	30.81	38.83	51.73	66.52
9	2.12	19.18	27.11	38.58	52.69	65.89

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



BZ = 0.589

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).

$$Data := \begin{pmatrix} 0 & -30.99 & -30.92 & -31.719 & -35.433 & -35.967 \\ 0.441 & -2.37 & -4.15 & -6.024 & -7.411 & -9.003 \\ 0.793 & 27.862 & 23.567 & 19.705 & 17.995 & 12.782 \\ 1.076 & 42.802 & 38.705 & 32.039 & 24.149 & 15.988 \\ 1.303 & 47.376 & 40.949 & 35.624 & 31.779 & 29.726 \\ 1.484 & 48.173 & 40.841 & 37.026 & 40.902 & 48.506 \\ 1.629 & 43.475 & 39.757 & 38.459 & 47.748 & 55.999 \\ 1.794 & 35.074 & 35.427 & 38.776 & 48.731 & 61.472 \\ 1.959 & 25.697 & 30.809 & 38.834 & 51.732 & 66.515 \\ 2.124 & 19.183 & 27.111 & 38.578 & 52.687 & 65.89 \end{pmatrix}$$

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

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

$FL_{Cntr} := BZ - l$ 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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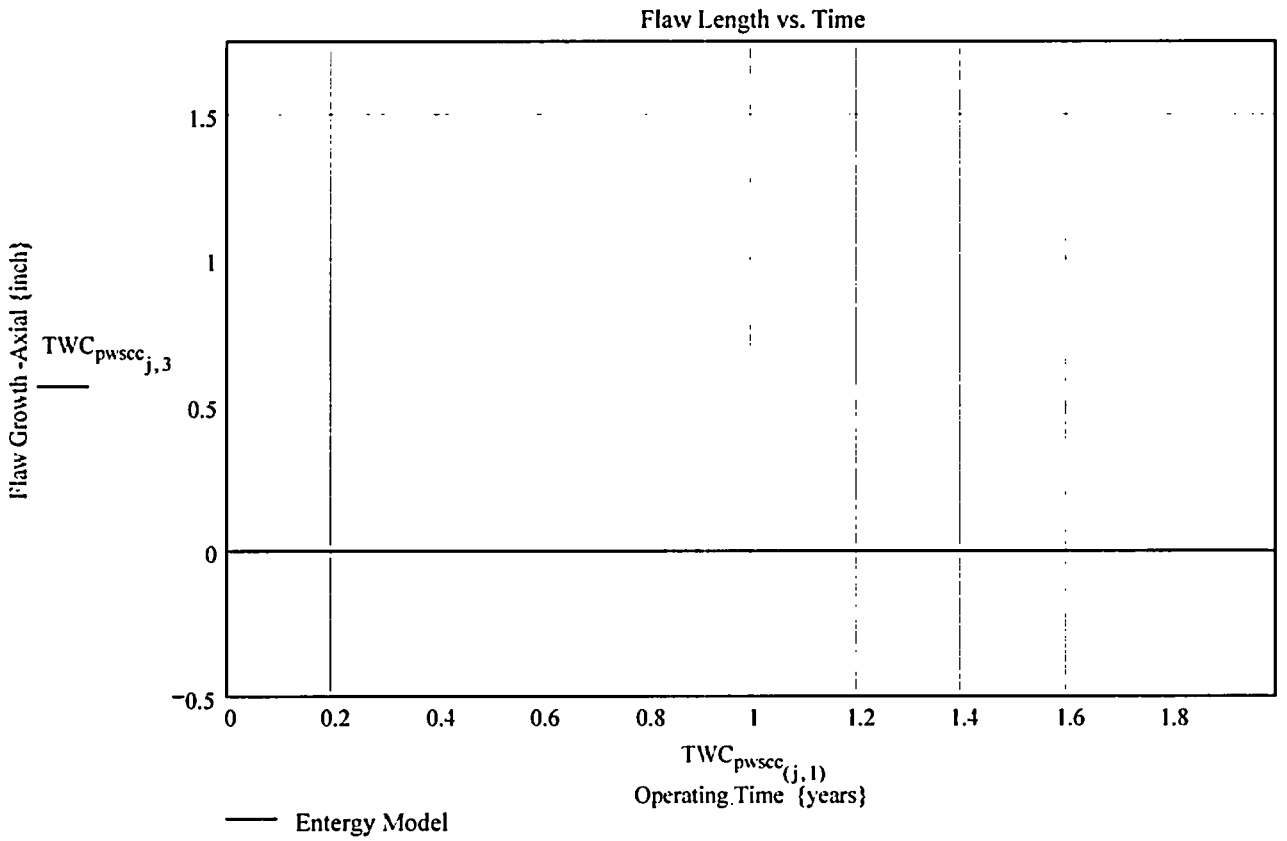
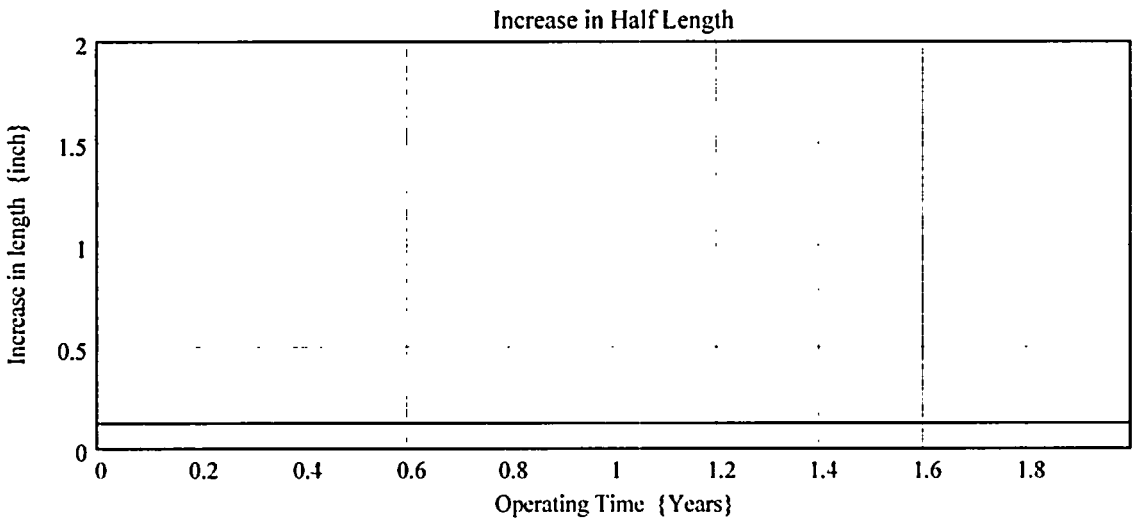
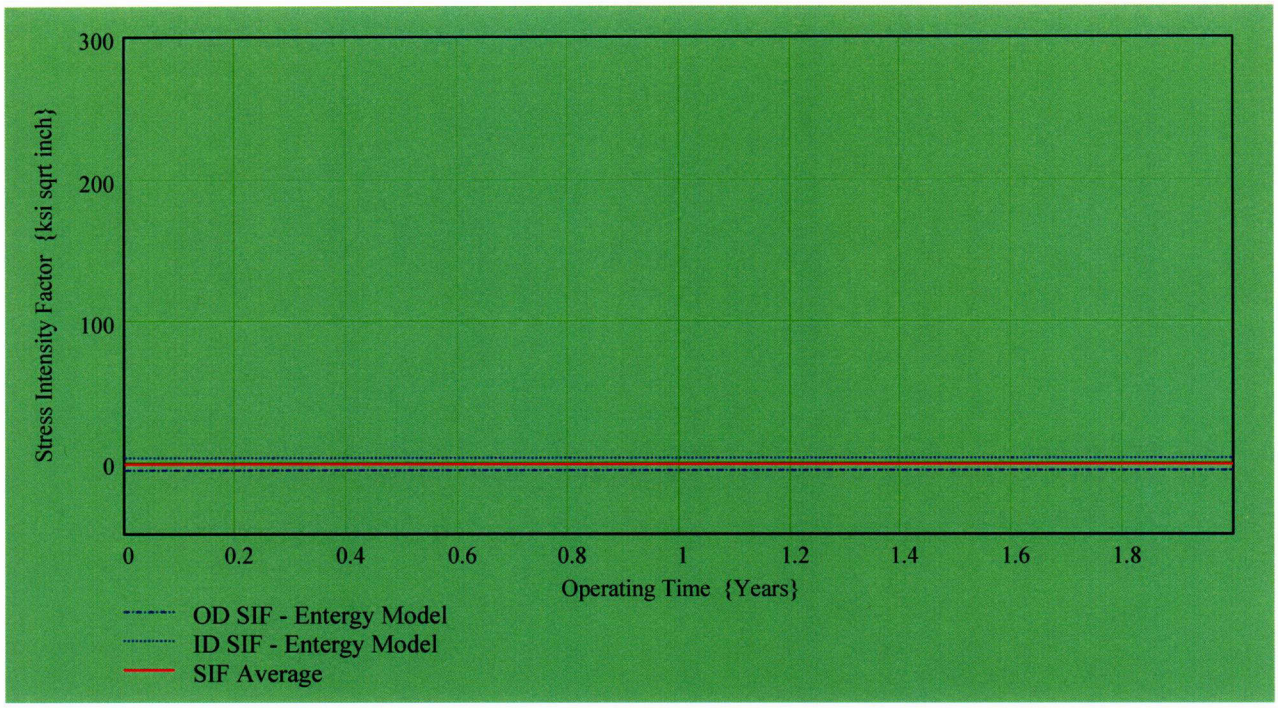
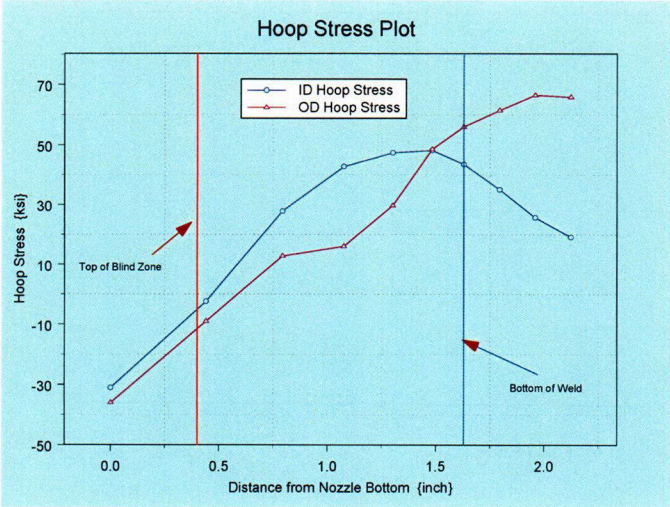
$Prop_{Length} = 1.04$

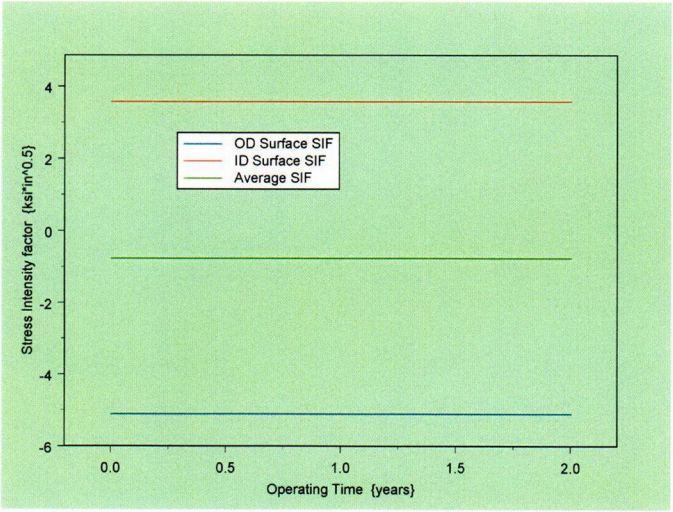


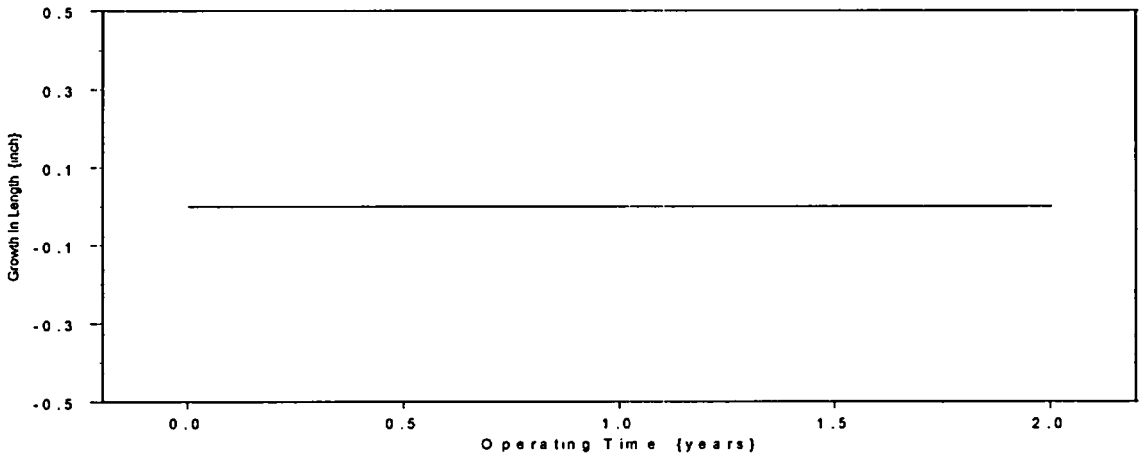



300
200
100
0
Stress Intensity Factor {ksi sqrt inch}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Operating Time {Years}
OD SIF - Entergy Model
ID SIF - Entergy Model
SIF Average

$TWC_{pwscc_{(j,6)}}$ =	$TWC_{pwscc_{(j,7)}}$ =	$TWC_{pwscc_{(j,8)}}$ =
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692
-5.109	3.575	-0.692


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Bottom of Weld
Hoop Stress {ksi}
70
50
30
10
-10
-30
-50
0.0
0.5
1.0
1.5
2.0
Distance from Nozzle Bottom {inch}


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor {ksi*in^0.5}
4
2
0
-2
-4
-6
0.0
0.5
1.0
1.5
2.0
Operating Time {years}


0.5
0.3
0.1
-0.1
-0.3
-0.5
Growth in Length (inch)
0.0
0.5
1.0
1.5
2.0
Operating Time (years)

Primary Water Stress Corrosion Crack Growth Analysis ID flaw;
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

Arkansas Nuclear One Unit 1

Component : Reactor Vessel CRDM -"18.2" Degree Nozzle, "Downhill" Azimuth

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 the Freespan length obtained from the nDE data sheet (Excel spread sheet)

$FS_{nde.data.sheet} := 0.430$

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).

$Val := 2$

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.

$UL_{Strs.Dist} := 1.712$ Upper axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom to bottom of Fillet Weld).

$Ref_{Point} := UL_{Strs.Dist} - FS_{nde.data.sheet}$

The highlighted region below remians constant for ANO-1 and should not be changed

Input Data :-

$L := 0.35$	Initial Flaw Length
$a_0 := 0.06787$	Initial Flaw Depth
$od := 4.00$	Tube OD
$id := 2.765$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 2$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 600$	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

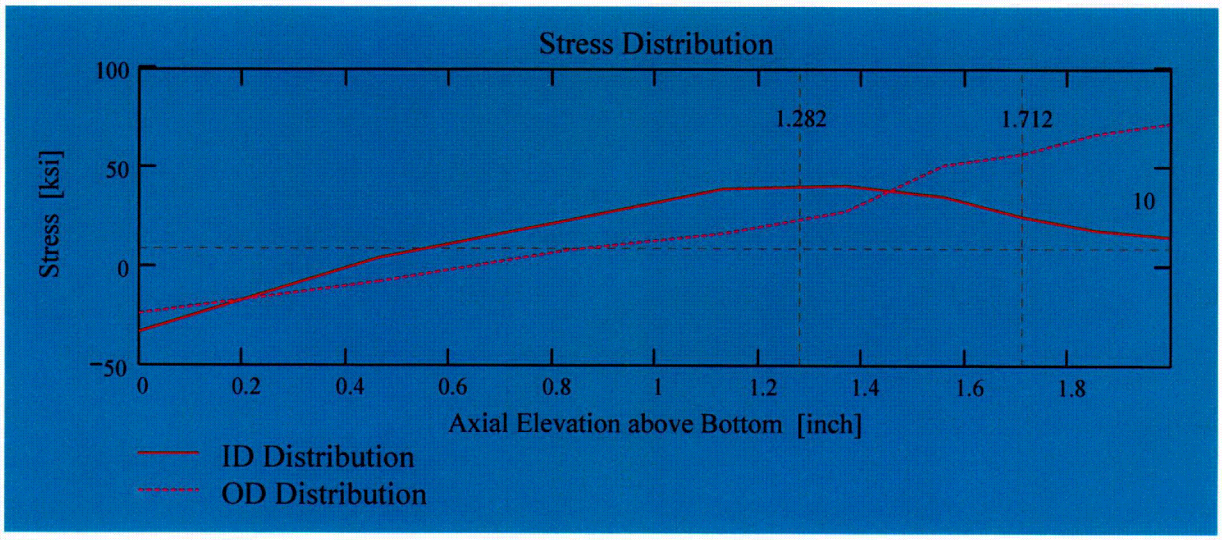
Stress Input Data

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)
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	-32.98	-29.55	-27.62	-25.63	-23.66
1	0.46	4.42	1.43	-2.62	-5.98	-7.49
2	0.83	23.6	20.13	17.47	13.58	8.56
3	1.13	39.38	33.76	28.59	23.55	16.9
4	1.37	41.08	35.6	32.56	29.09	28.07
5	1.56	35.47	35.03	34.72	41.39	51.48
6	1.71	25.31	30.93	36.76	48.63	57.32
7	1.85	18.48	26.76	37.58	49.67	67.27
8	2	15.18	24.43	37.51	53.17	72.59

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



$Ref_{Point} = 1.282$

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. Highlight 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 mouse 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 data 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.

$$Data := \begin{pmatrix} 0 & -32.98 & -29.552 & -27.619 & -25.631 & -23.659 \\ 0.463 & 4.418 & 1.431 & -2.622 & -5.982 & -7.485 \\ 0.834 & 23.603 & 20.133 & 17.472 & 13.58 & 8.558 \\ 1.131 & 39.381 & 33.757 & 28.588 & 23.549 & 16.901 \\ 1.369 & 41.077 & 35.596 & 32.564 & 29.095 & 28.069 \\ 1.56 & 35.472 & 35.035 & 34.721 & 41.389 & 51.476 \\ 1.712 & 25.309 & 30.935 & 36.756 & 48.633 & 57.324 \\ 1.854 & 18.476 & 26.759 & 37.578 & 49.667 & 67.274 \end{pmatrix}$$

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

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

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

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

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

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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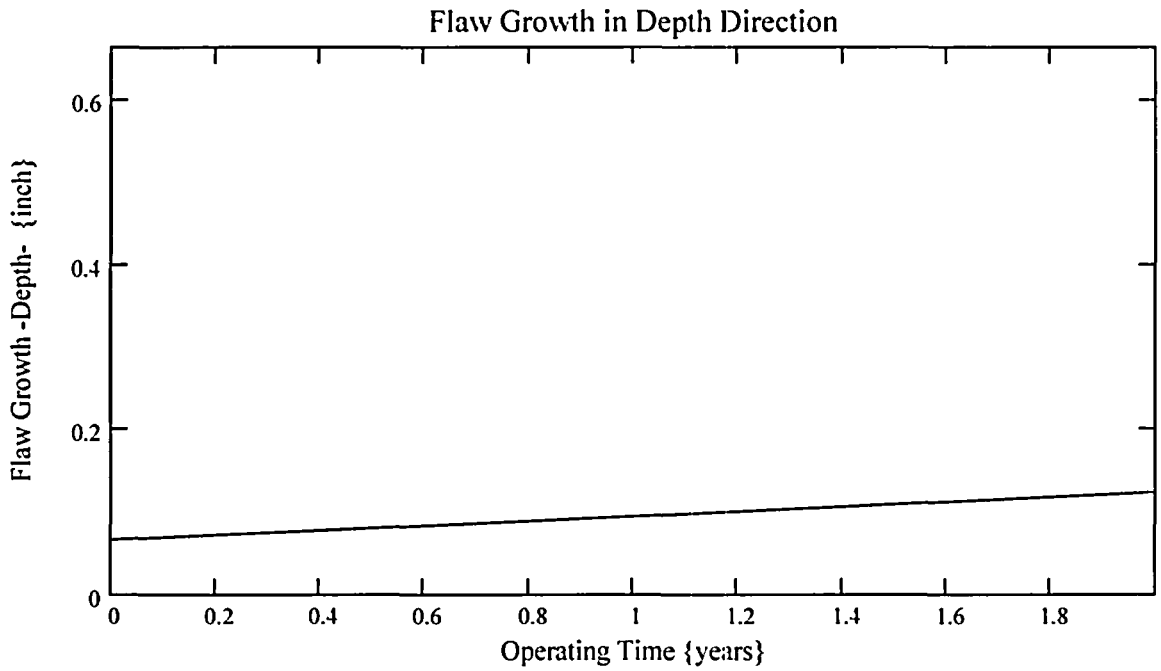
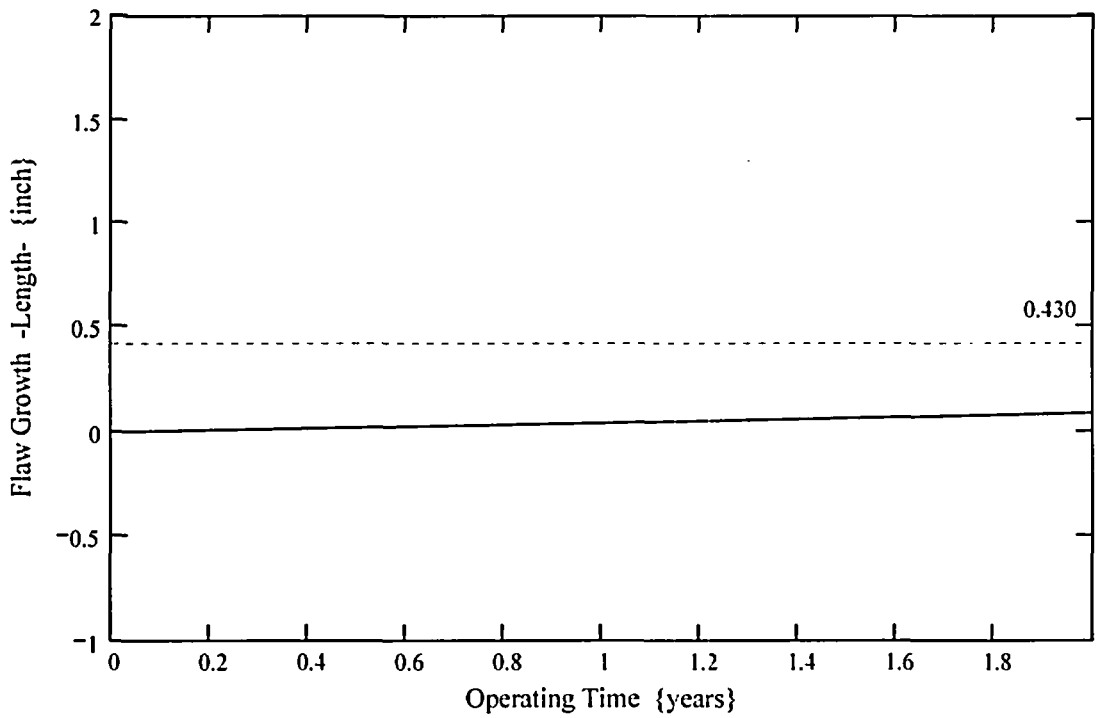
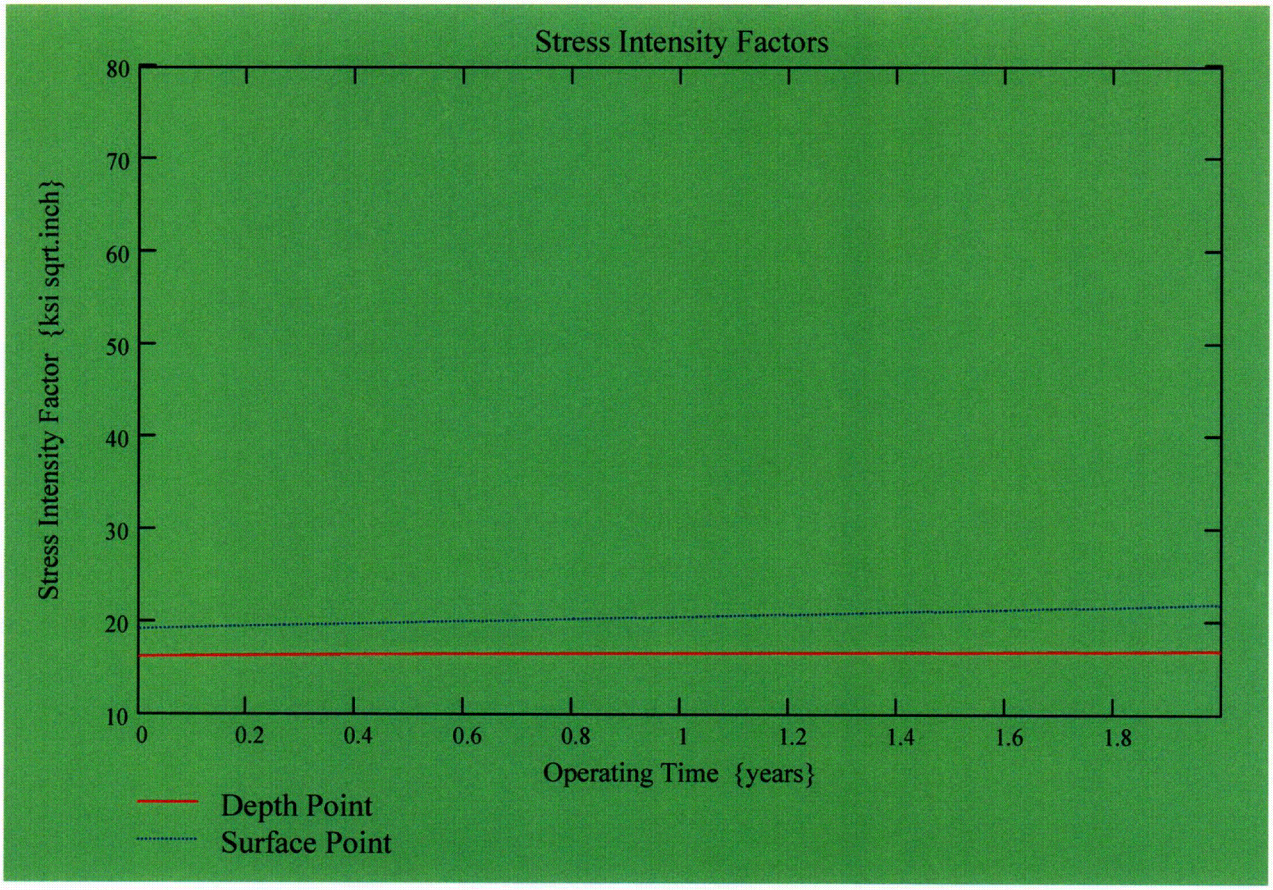
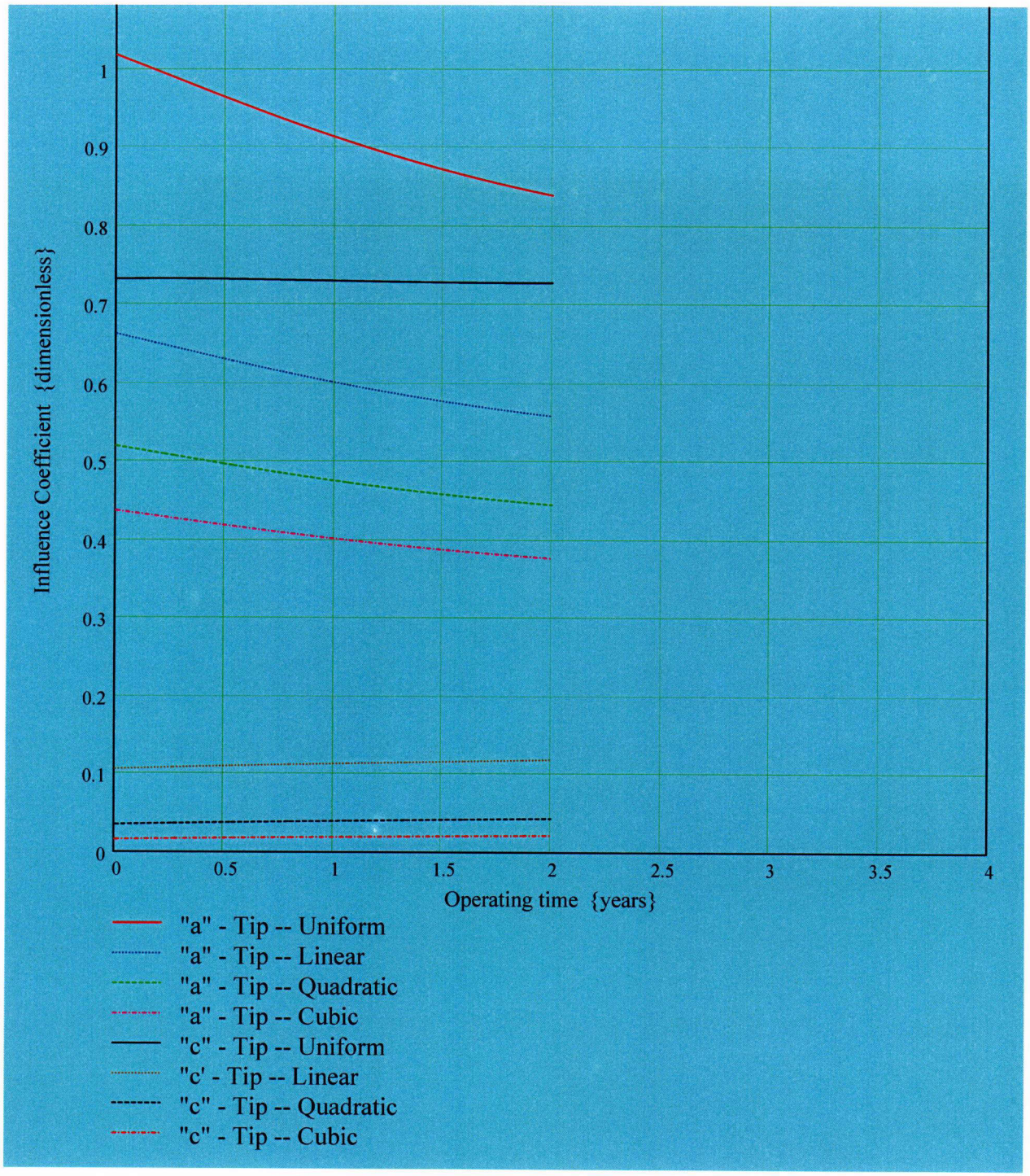
$$Prop_{Length} = 0.255$$


Flaw Growth in Depth Direction
Flaw Growth -Depth- {inch}
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Operating Time {years}


Flaw Growth -Length- {inch}
2
1.5
1
0.5
0
−0.5
−1
0.430
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Operating Time {years}


Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
70
60
50
40
30
20
10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Operating Time {years}
Depth Point
Surface Point

Influence Coefficients - Flaw
1.1


Influence Coefficient {dimensionless}
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

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

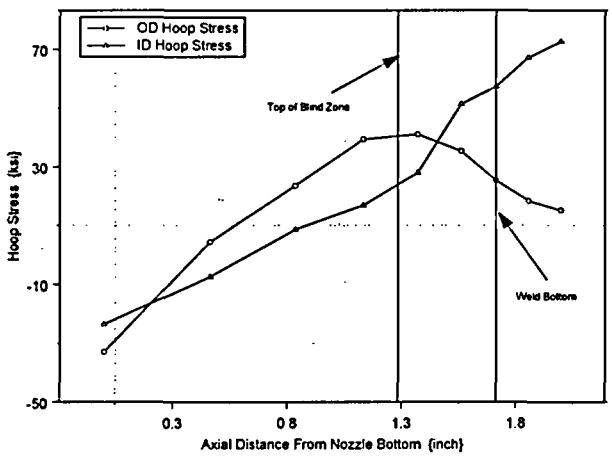
1.02
1.019
1.019
1.019
1.019
1.019
1.019
1.019
1.018
1.018
1.018
1.018
1.018
1.018
1.018
1.017

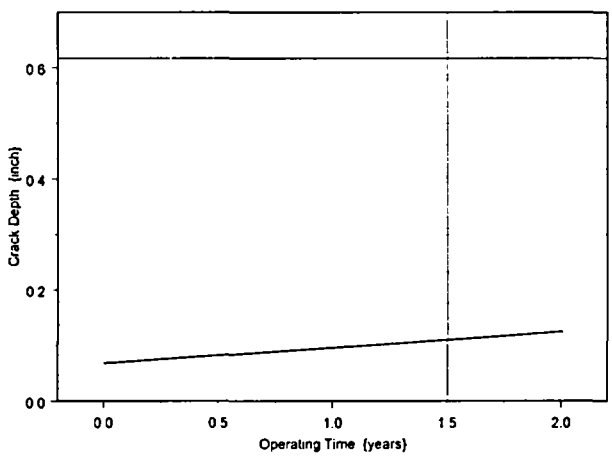
$CGR_{sambi_{(k,6)}}$ =

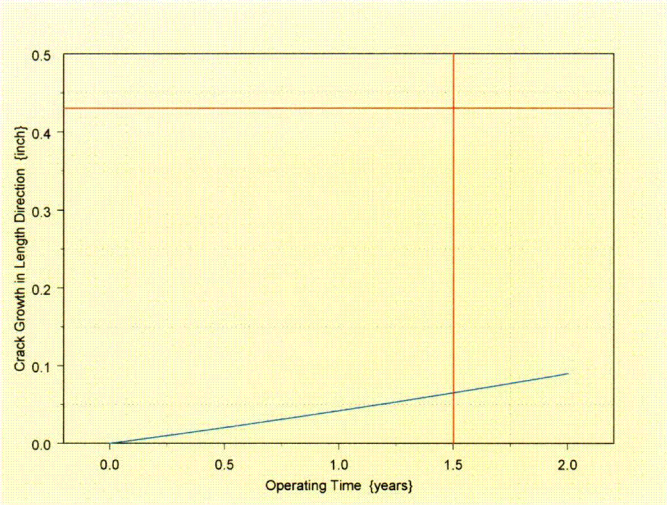
19.218
19.196
19.198
19.2
19.202
19.205
19.207
19.209
19.211
19.213
19.215
19.217
19.219
19.221
19.223
19.225

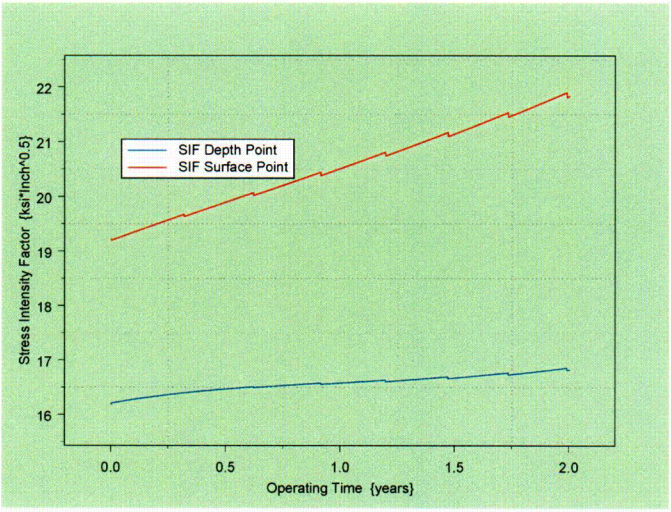
$CGR_{sambi_{(k,5)}}$ =

16.187
16.21
16.211
16.212
16.213
16.214
16.215
16.216
16.217
16.218
16.219
16.22
16.221
16.222
16.223
16.224


OD Hoop Stress
ID Hoop Stress
Top of Bend Zone
Weld Bottom
Hoop Stress (ksi)
70
30
-10
-50
0.3
0.8
1.3
1.8
Axial Distance From Nozzle Bottom (inch)


Crack Depth (inch)
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
Operating Time (years)


Crack Growth in Length Direction {inch}
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0
Operating Time {years}


Stress Intensity Factor {ksi*Inch^0.5}
16
17
18
19
20
21
22
SIF Depth Point
SIF Surface Point
0.0
0.5
1.0
1.5
2.0
Operating Time {years}

Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw

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

Arkansas Nuclear One Unit 1

Component : Reactor Vessel CRDM -"18.2" Degree Nozzle, "Downhill" Azimuth

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 the Freespan length from the NDE data sheet (Excel spread sheet)

$FS_{nde.data.sheet} := 0.430$

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).

$Val := 2$

Enter the Upper Extent of the Stress Distribution used for the analysis

$UL_{Strs.Dist} := 1.712$ Upper Axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom)

$Ref_{Point} := UL_{Strs.Dist} - FS_{nde.data.sheet}$

The regions highlighted below remain constant for ANO-1 analysis and should not be changed

Input Data :-

$L := 0.35$	Initial Flaw Length
$a_0 := 0.09872$	Initial Flaw Depth
$od := 4.00$	Tube OD
$id := 2.765$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 2$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 600$	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

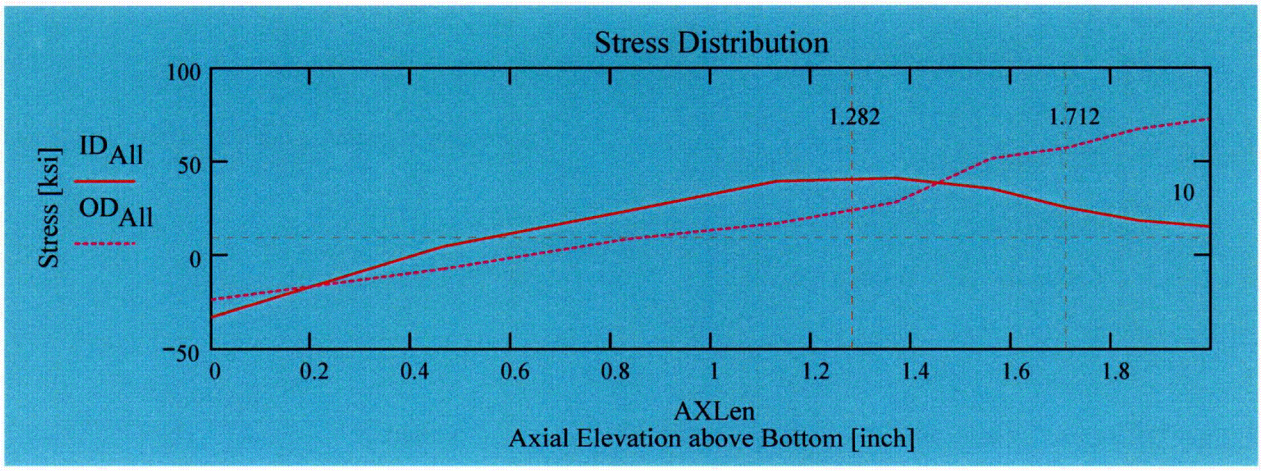
Stress Input Data

Import 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	-32.98	-29.55	-27.62	-25.63	-23.66
1	0.46	4.42	1.43	-2.62	-5.98	-7.49
2	0.83	23.6	20.13	17.47	13.58	8.56
3	1.13	39.38	33.76	28.59	23.55	16.9
4	1.37	41.08	35.6	32.56	29.09	28.07
5	1.56	35.47	35.03	34.72	41.39	51.48
6	1.71	25.31	30.93	36.76	48.63	57.32
7	1.85	18.48	26.76	37.58	49.67	67.27
8	2	15.18	24.43	37.51	53.17	72.59

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



$Ref_{Point} = 1.282$

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).

$$Data := \begin{pmatrix} 0 & -30.99 & -30.92 & -31.719 & -35.433 & -35.967 \\ 0.441 & -2.37 & -4.15 & -6.024 & -7.411 & -9.003 \\ 0.793 & 27.862 & 23.567 & 19.705 & 17.995 & 12.782 \\ 1.076 & 42.802 & 38.705 & 32.039 & 24.149 & 15.988 \\ 1.303 & 47.376 & 40.949 & 35.624 & 31.779 & 29.726 \\ 1.484 & 48.173 & 40.841 & 37.026 & 40.902 & 48.506 \\ 1.629 & 43.475 & 39.757 & 38.459 & 47.748 & 55.999 \\ 1.794 & 35.074 & 35.427 & 38.776 & 48.731 & 61.472 \\ 1.959 & 25.697 & 30.809 & 38.834 & 51.732 & 66.515 \end{pmatrix}$$

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

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

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

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

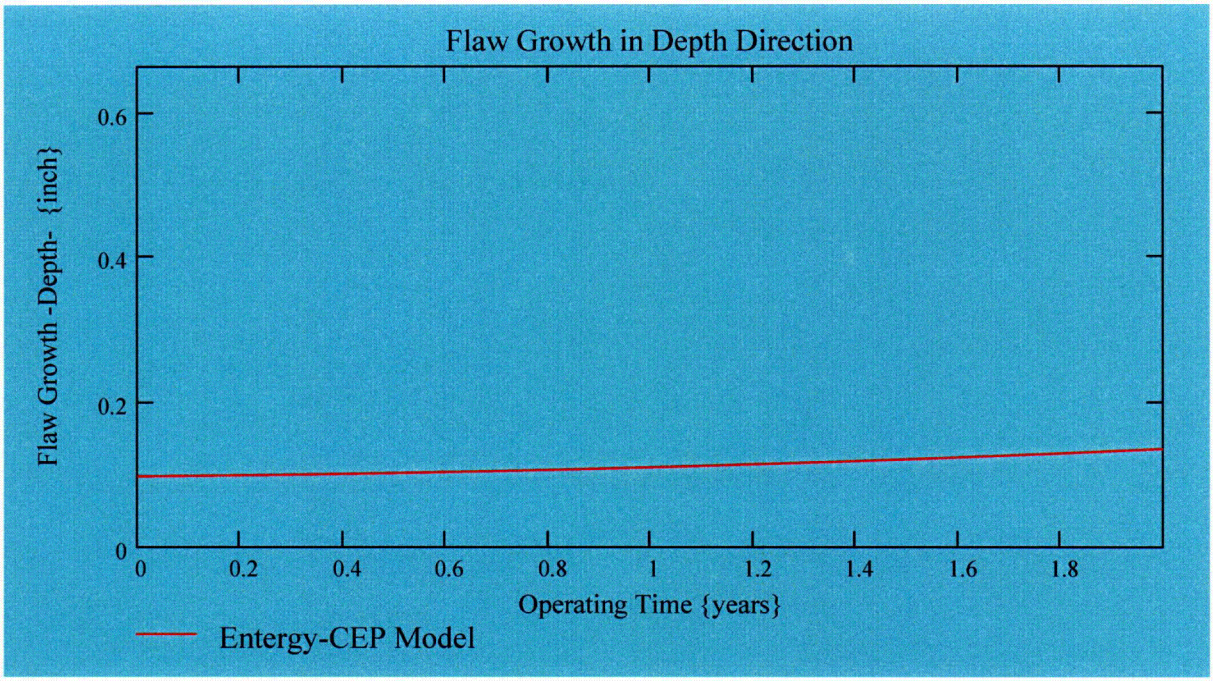
Flaw center Location Location above Nozzle Bottom

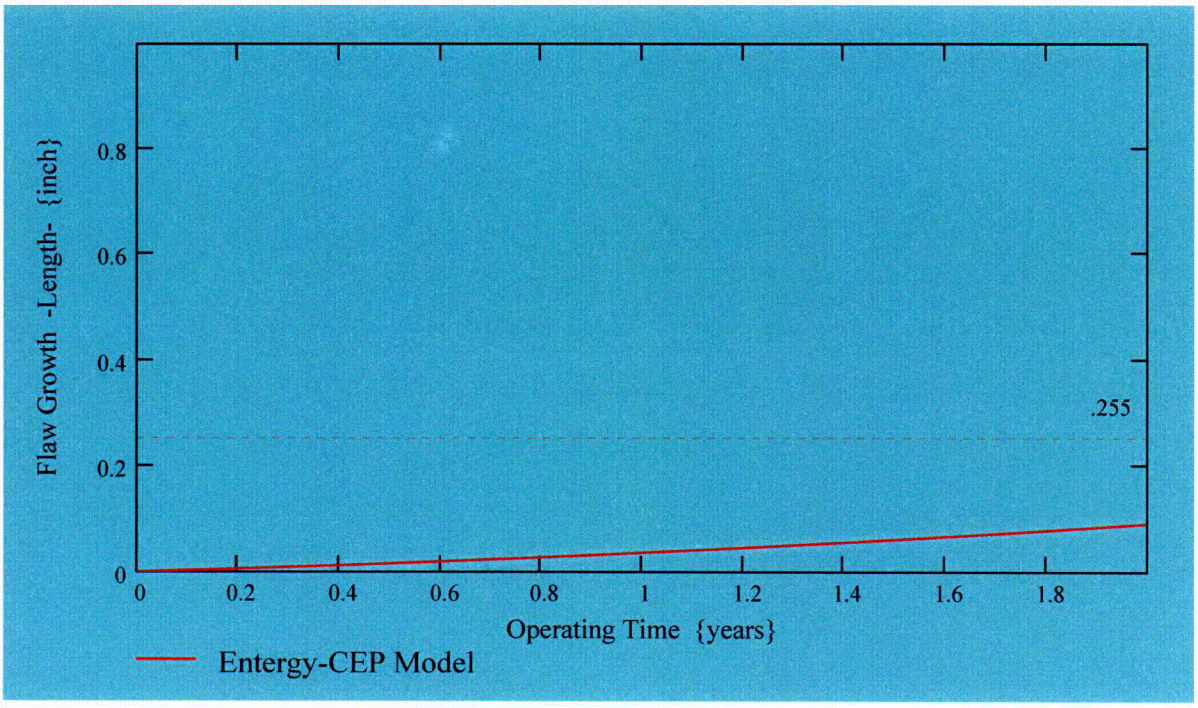
$U_{Tip} := FL_{Cntr} + c_0$

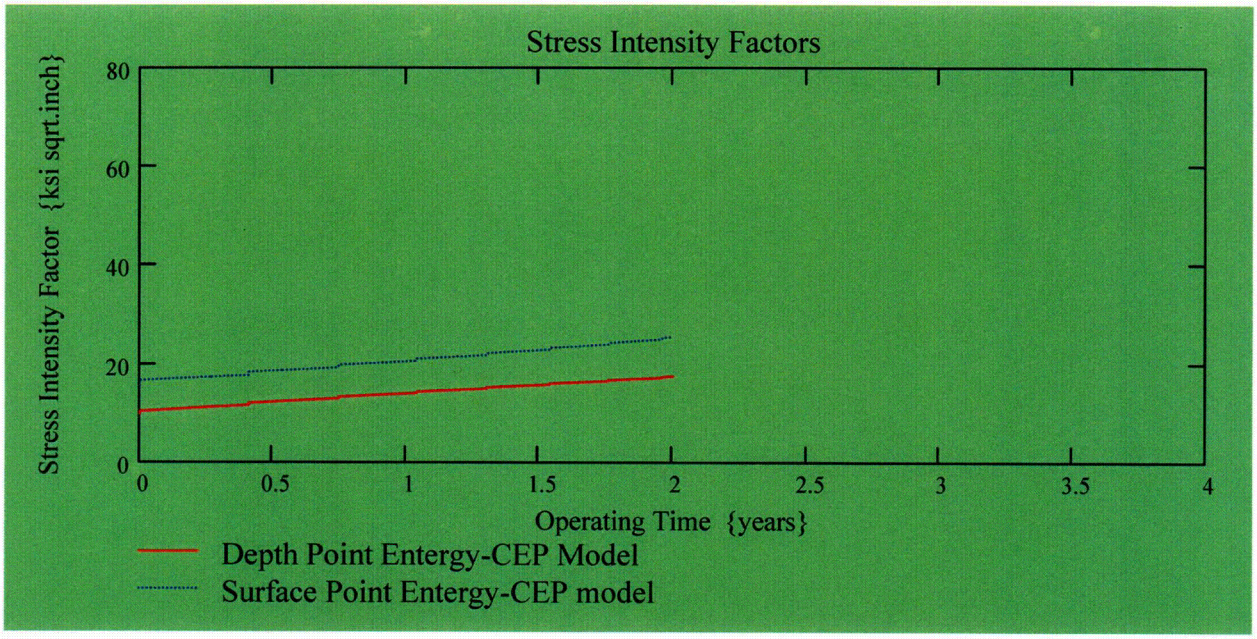
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

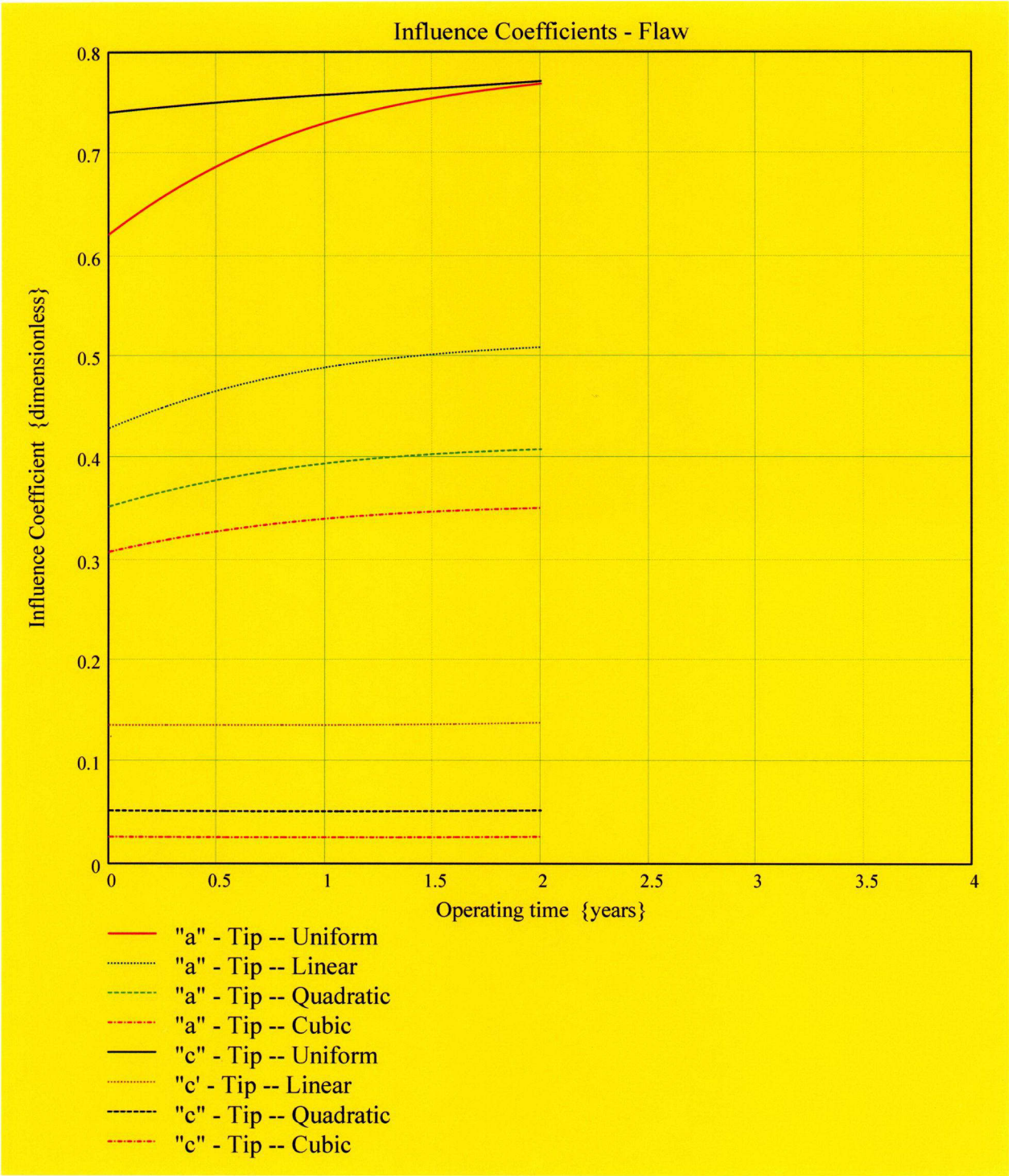
No User Input is required beyond this Point

$Prop_{Length} = 0.255$






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}
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

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

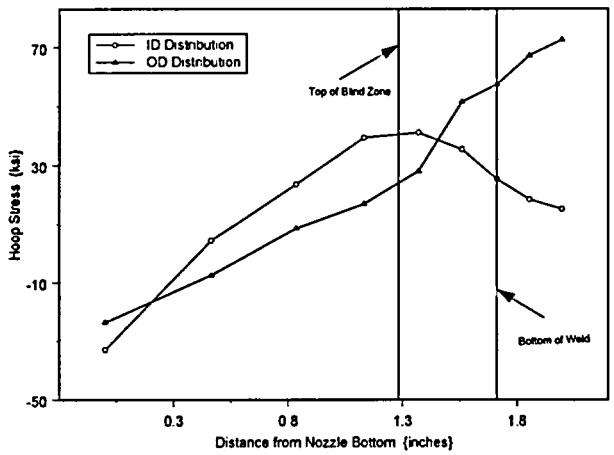
0.621
0.621
0.622
0.622
0.622
0.622
0.623
0.623
0.623
0.623
0.623
0.624
0.624
0.624
0.624
0.624

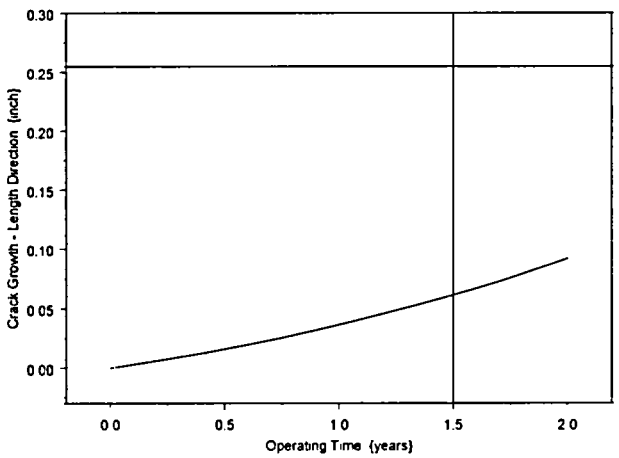
$CGR_{sambi_{(k,6)}}$ =

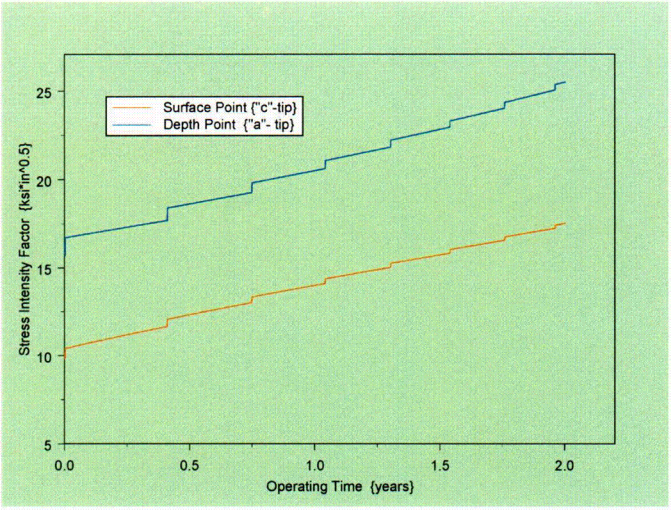
15.698
16.72
16.723
16.726
16.73
16.733
16.736
16.739
16.743
16.746
16.749
16.752
16.756
16.759
16.762
16.765

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

9.83
10.395
10.4
10.404
10.408
10.413
10.417
10.422
10.426
10.431
10.435
10.44
10.444
10.449
10.453
10.458


ID Distribution
OD Distribution
Top of Blind Zone
Bottom of Weld
Hoop Stress (ksi)
70
30
-10
-50
0.3
0.8
1.3
1.8
Distance from Nozzle Bottom (inches)


Crack Growth - Length Direction (inch)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
2.0
Operating Time (years)


Surface Point {"c"-tip}
Depth Point {"a"- tip}
Stress Intensity Factor {ksi*in^0.5}
25
20
15
10
5
0.0
0.5
1.0
1.5
2.0
Operating Time {years}

Stress Corrosion Crack Growth Analysis Through-wall flaw

Developed by Central Engineering Programs, Entergy Operations Inc.

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

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

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

Arkansas Nuclear One Unit 1

Component : Reactor Vessel CRDM -"18.2"degree Nozzle, "Downhill" Azimuth

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 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.

$UL_{Strs.Dist} := 1.712$ Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom to bottom of Fillet Weld)

The Second Input is needed 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 Length of the Freespan from NDE Data sheet

$FS_{nde.data.sheet} := 0.430$ Length of Freespan Obtained from NDE **Nozzle #18**

$BZ := UL_{Strs.Dist} - FS_{nde.data.sheet}$ Location of Blind Zone above nozzle bottom (inch)

The Highlighted Entries below remains constant for ANO-1 and should not be changed

Input Data :-

$L := 0.7$ Initial Crack Length TW axial Based on Stress Distribution. Bottom end of Crack to be set @ approximately 10ksi.

$od := 4.00$ Tube OD

$id := 2.765$ Tube ID

$P_{Int} := 2.235$ Design Operating Pressure (internal)

$Years := 2$ Number of Operating Years

$I_{lim} := 1500$ Iteration limit for Crack Growth loop

$T := 600$ Estimate of Operating Temperature

$\nu := 0.307$ Poissons ratio @ 600 F

$\alpha_{0c} := 2.67 \cdot 10^{-12}$ Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F

$Q_g := 31.0$ Thermal activation Energy for Crack Growth {MRP)

$T_{ref} := 617$ Reference Temperature for normalizing Data deg. F

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

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

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

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

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

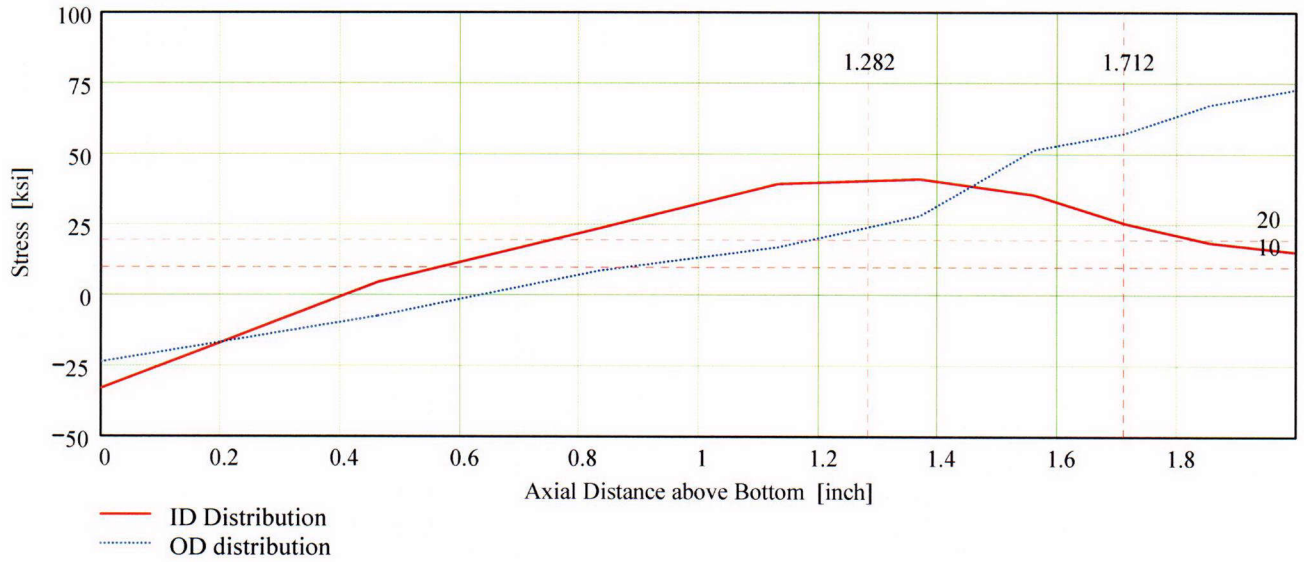
Stress Input Data

Import the Required data from applicable Excel spread Sheet. The column designations are as follows:
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	-32.98	-29.55	-27.62	-25.63	-23.66
1	0.46	4.42	1.43	-2.62	-5.98	-7.49
2	0.83	23.6	20.13	17.47	13.58	8.56
3	1.13	39.38	33.76	28.59	23.55	16.9
4	1.37	41.08	35.6	32.56	29.09	28.07
5	1.56	35.47	35.03	34.72	41.39	51.48
6	1.71	25.31	30.93	36.76	48.63	57.32
7	1.85	18.48	26.76	37.58	49.67	67.27
8	2	15.18	24.43	37.51	53.17	72.59

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



BZ = 1.282

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).

$$Data := \begin{pmatrix} 0 & -32.98 & -29.552 & -27.619 & -25.631 & -23.659 \\ 0.463 & 4.418 & 1.431 & -2.622 & -5.982 & -7.485 \\ 0.834 & 23.603 & 20.133 & 17.472 & 13.58 & 8.558 \\ 1.131 & 39.381 & 33.757 & 28.588 & 23.549 & 16.901 \\ 1.369 & 41.077 & 35.596 & 32.564 & 29.095 & 28.069 \\ 1.56 & 35.472 & 35.035 & 34.721 & 41.389 & 51.476 \\ 1.712 & 25.309 & 30.935 & 36.756 & 48.633 & 57.324 \\ 1.854 & 18.476 & 26.759 & 37.578 & 49.667 & 67.274 \end{pmatrix}$$

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

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

$FL_{Cntr} := BZ - l$ 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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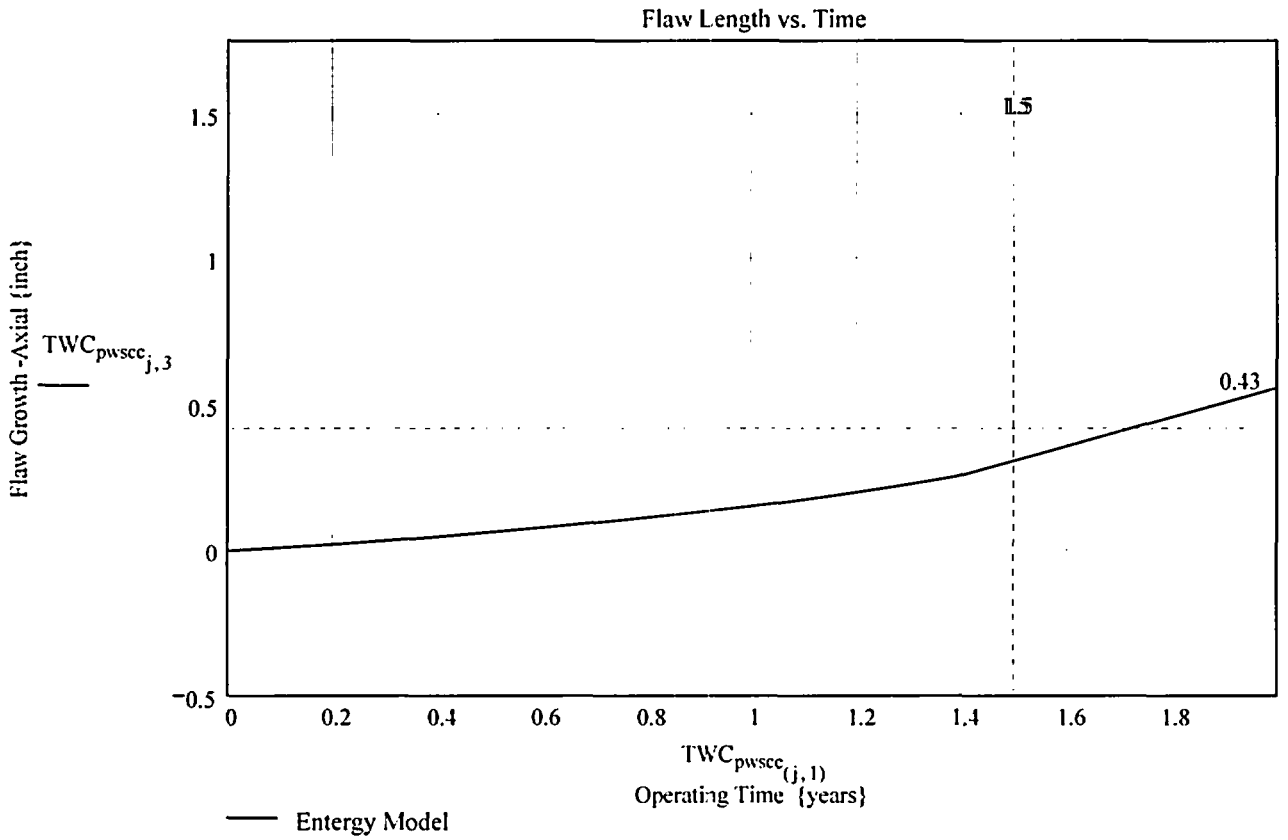
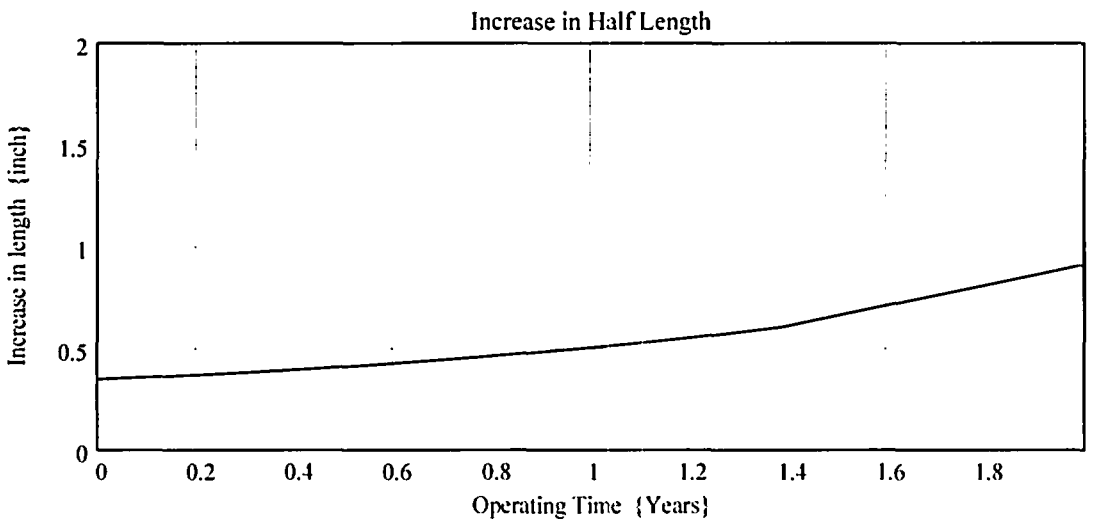
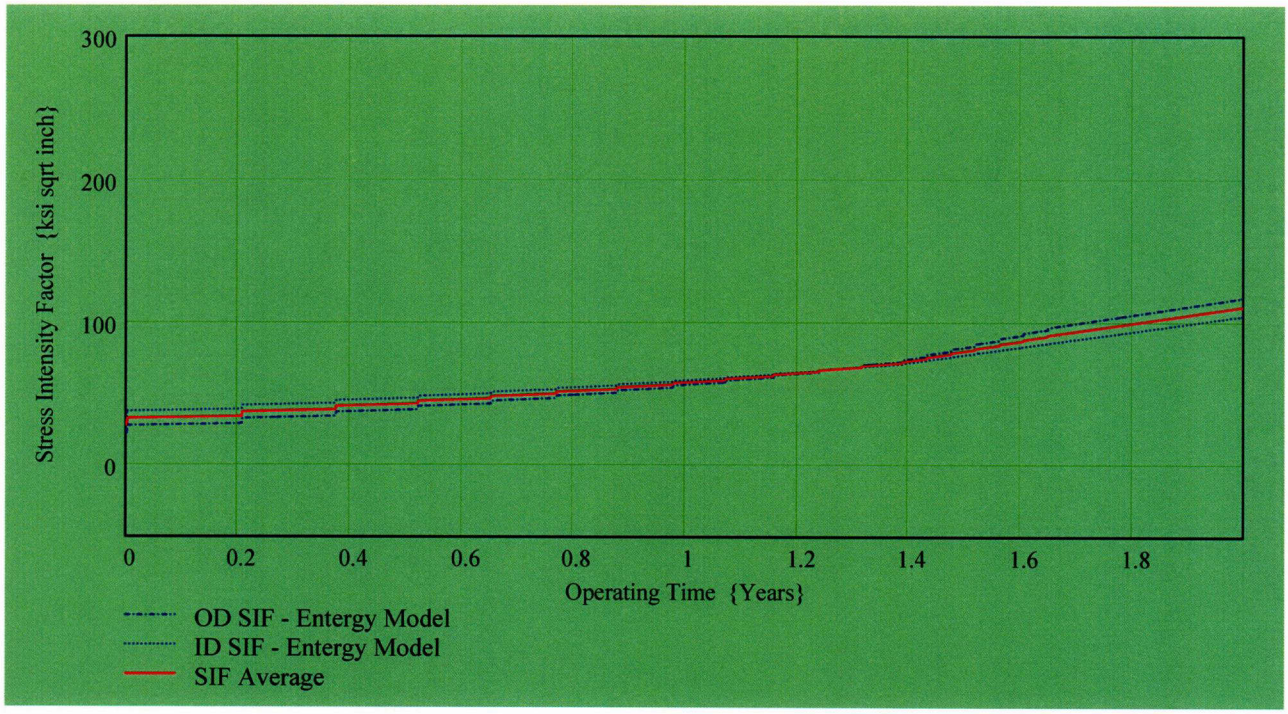
$Prop_{Length} = 0.43$






300
200
100
0
Stress Intensity Factor {ksi sqrt inch}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Operating Time {Years}
OD SIF - Entergy Model
ID SIF - Entergy Model
SIF Average

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

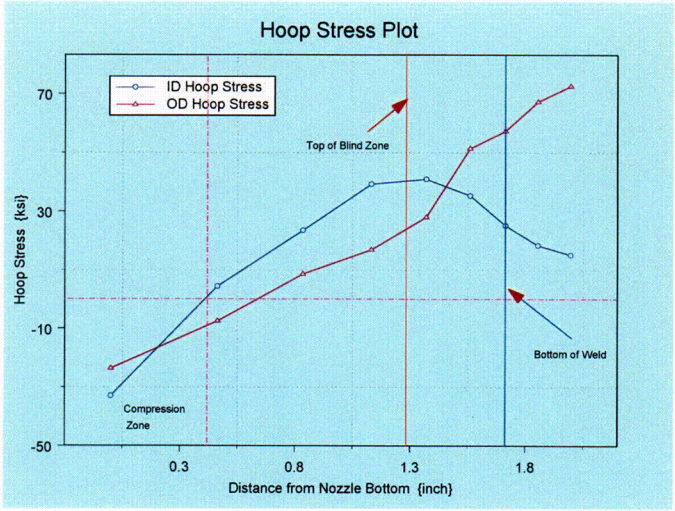
22.431
28.006
28.015
28.024
28.033
28.042
28.051
28.06
28.069
28.077
28.086
28.095
28.104
28.113
28.122
28.131

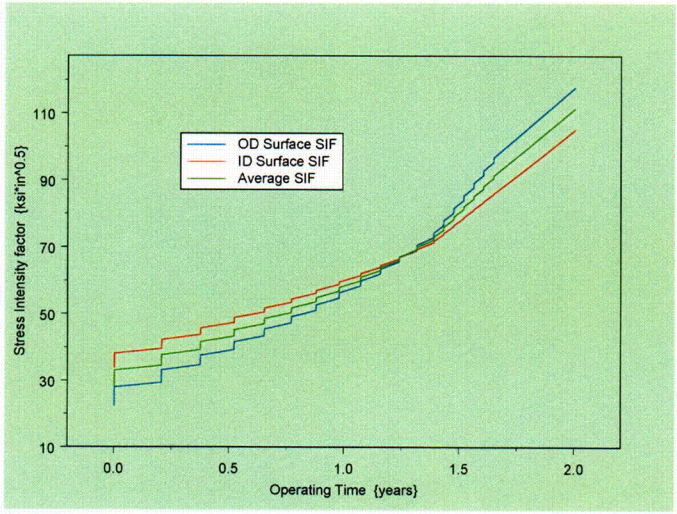
$TWC_{pwscc_{(j,7)}}$ =

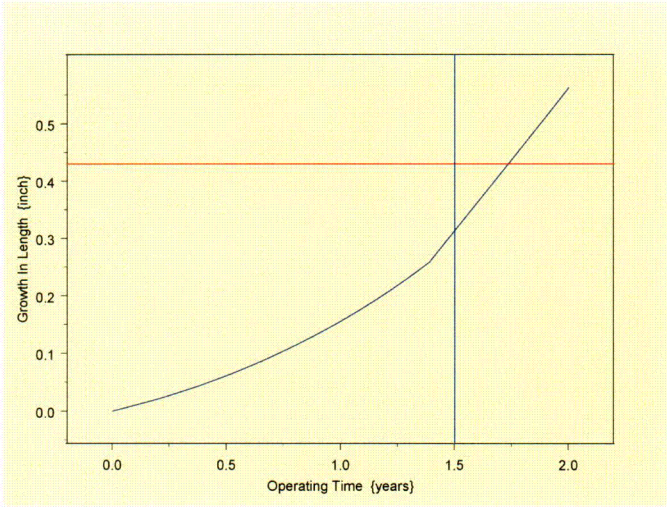
33.949
38.178
38.187
38.196
38.205
38.214
38.223
38.233
38.242
38.251
38.26
38.269
38.278
38.287
38.296
38.306

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

29.51
34.555
34.564
34.574
34.584
34.594
34.604
34.613
34.623
34.633
34.643
34.653
34.663
34.672
34.682
34.692


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Bottom of Weld
Compression Zone
Hoop Stress {ksi}
70
30
-10
-50
0.3
0.8
1.3
1.8
Distance from Nozzle Bottom {inch}


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor {ksi*in^0.5}
110
90
70
50
30
10
0.0
0.5
1.0
1.5
2.0
Operating Time {years}


Growth In Length {inch}
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0
Operating Time {years}