

Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw

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 2

Component : Reactor Vessel CEDM -"8" Degree Nozzle, Downhill Azimuth,
1.25" 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 necessary to evaluate the stress distribution on the flaw both for the initial flaw and for a growing flaw. This is defined as the reference point. Enter a number (inch) that represents the reference point elevation measured upward from the nozzle end.

Ref_{Point} := 1.25

This is the reduced blind zone providing a propagation length of
0.376 inch; freespan of 0.536

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

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

UL_{Strs.Dist} := 1.786

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

$$C_0 := C_{01}$$

75th percentile MRP-55 Revision 1

Stress Input Data

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

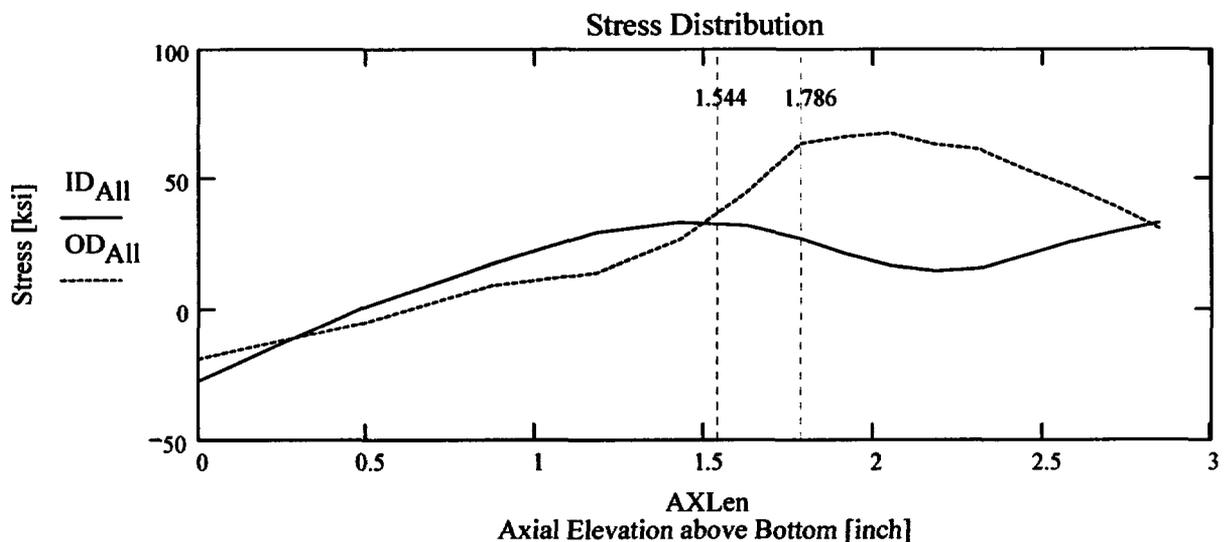
AllData :=

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

AXLen := AllData⁽⁰⁾

ID_{All} := AllData⁽¹⁾

OD_{All} := AllData⁽⁵⁾



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).

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

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

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

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

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

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

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

$$\text{FL}_{\text{Cntr}} := \begin{cases} \text{RefPoint} - c_0 & \text{if Val} = 1 \\ \text{RefPoint} & \text{if Val} = 2 \\ \text{RefPoint} + c_0 & \text{otherwise} \end{cases}$$

Flaw center Location Location above Nozzle Bottom

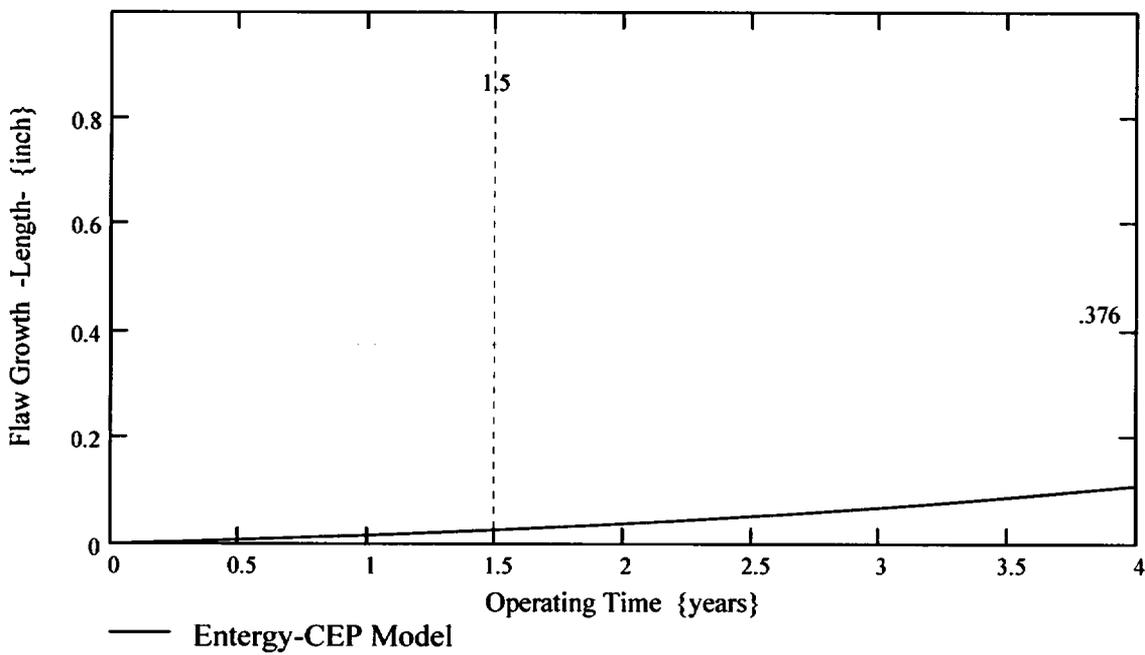
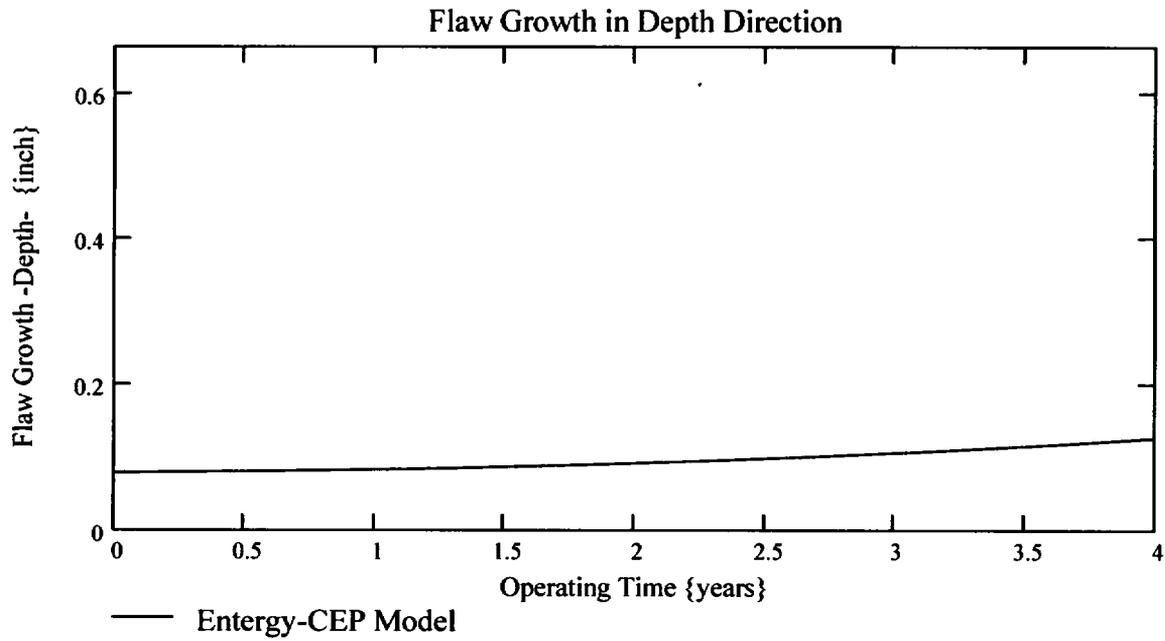
$$U_{\text{Tip}} := \text{FL}_{\text{Cntr}} + c_0$$

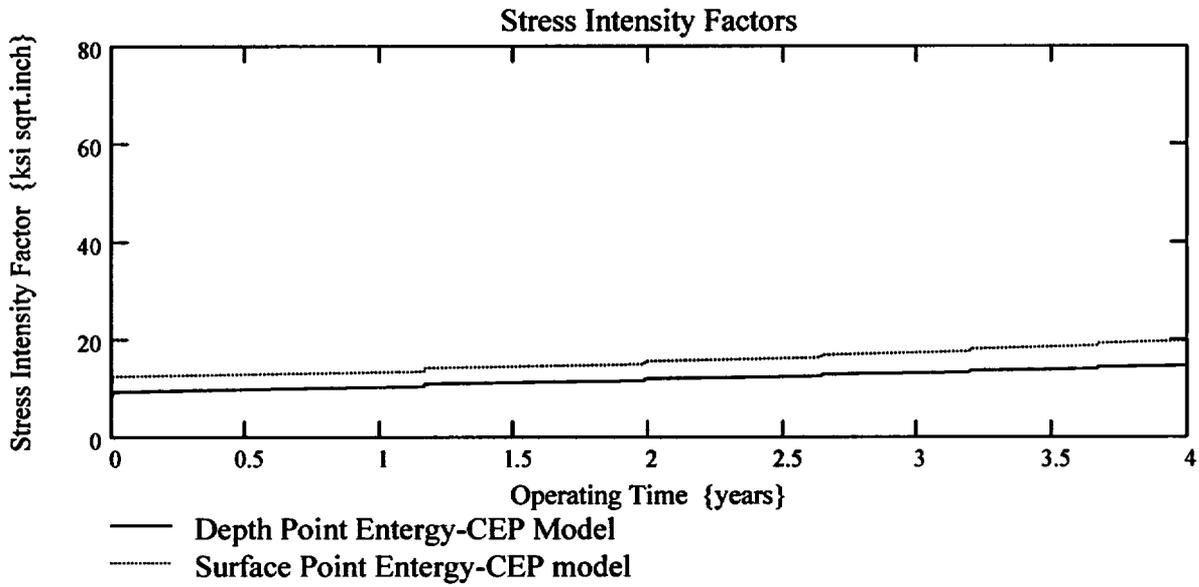
$$\text{IncStrs.avg} := \frac{\text{ULStrs.Dist} - U_{\text{Tip}}}{20}$$

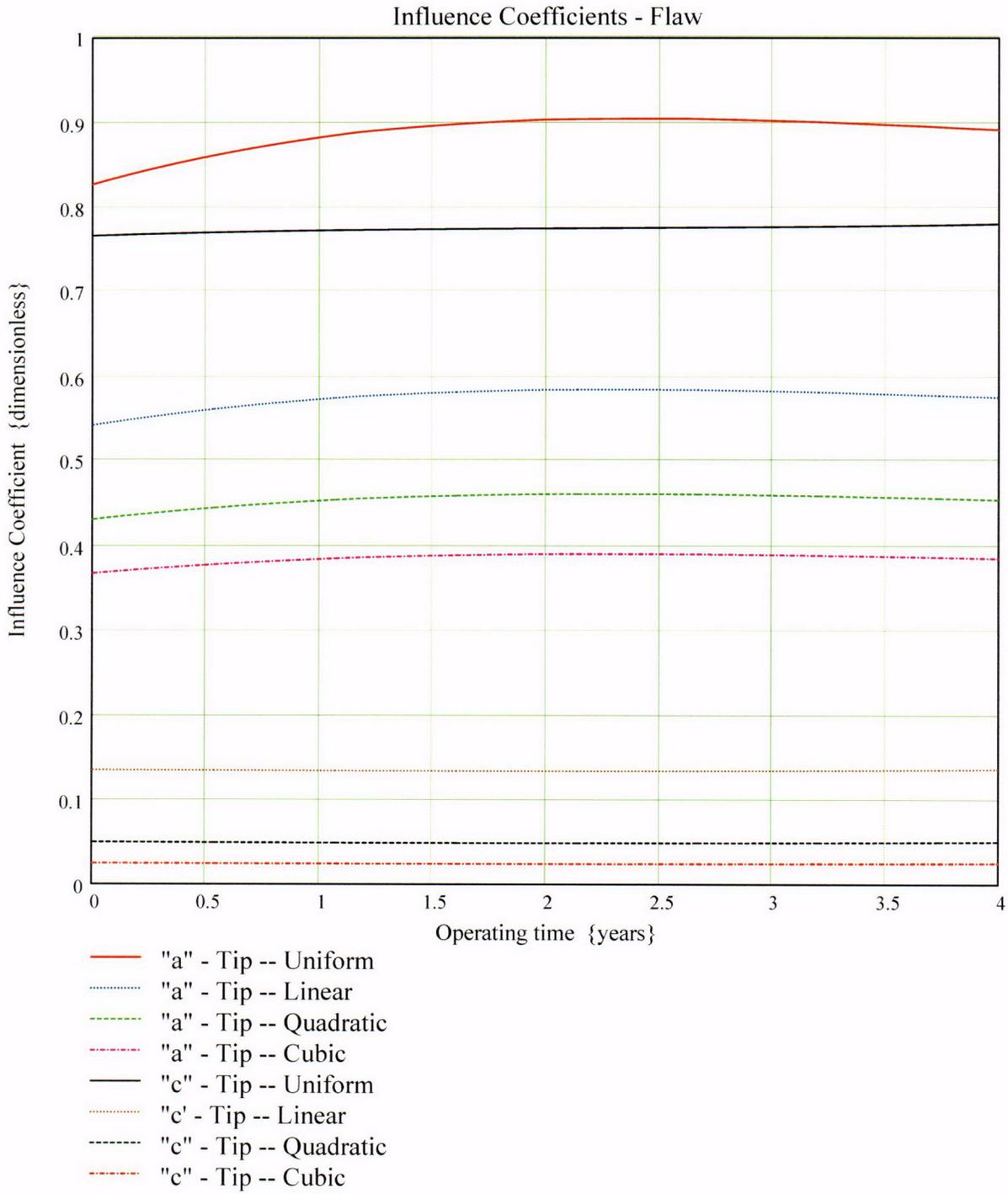
No User Input is required beyond this Point

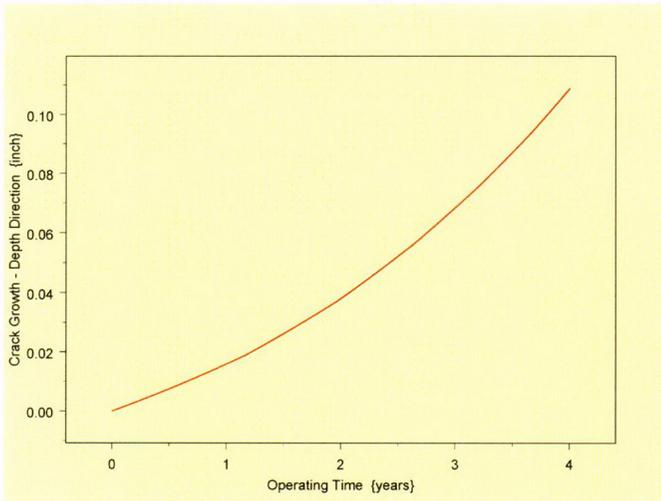
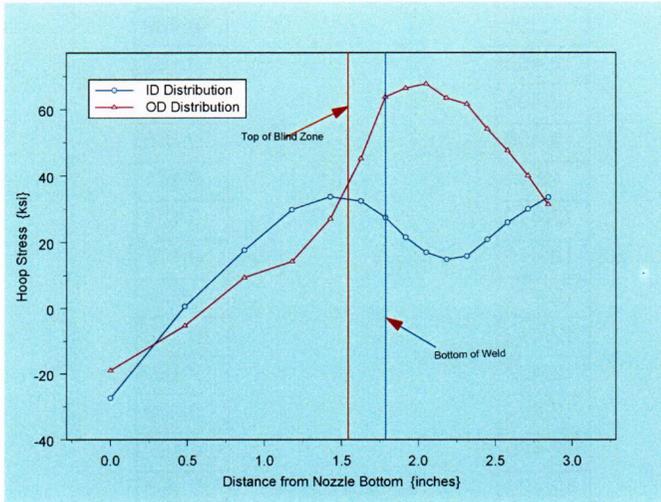
 Sat Aug 09 10:21:18 AM 2003

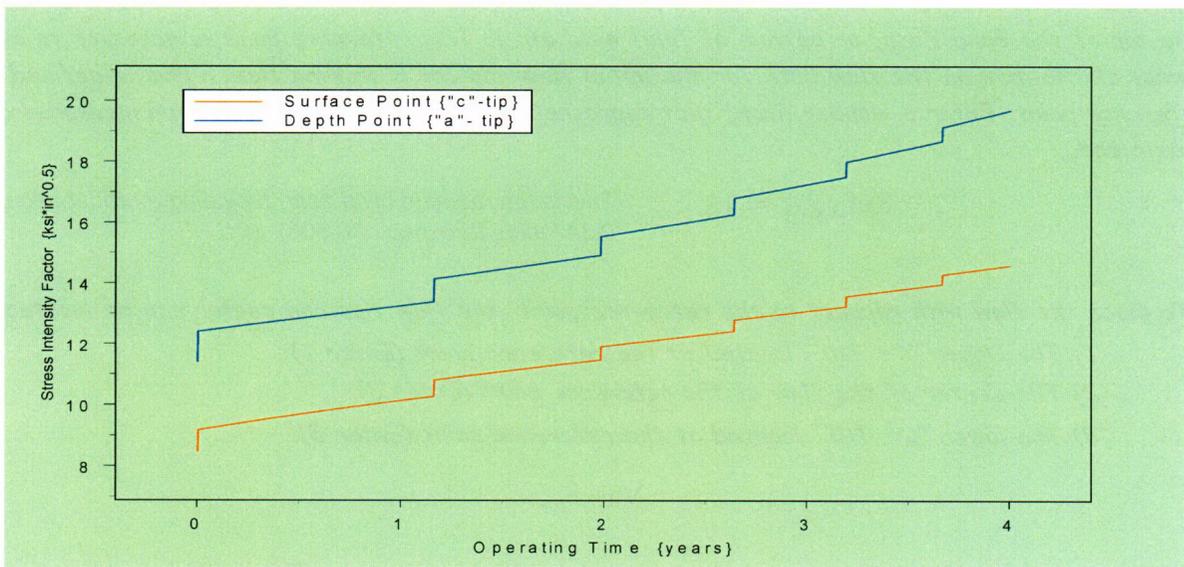
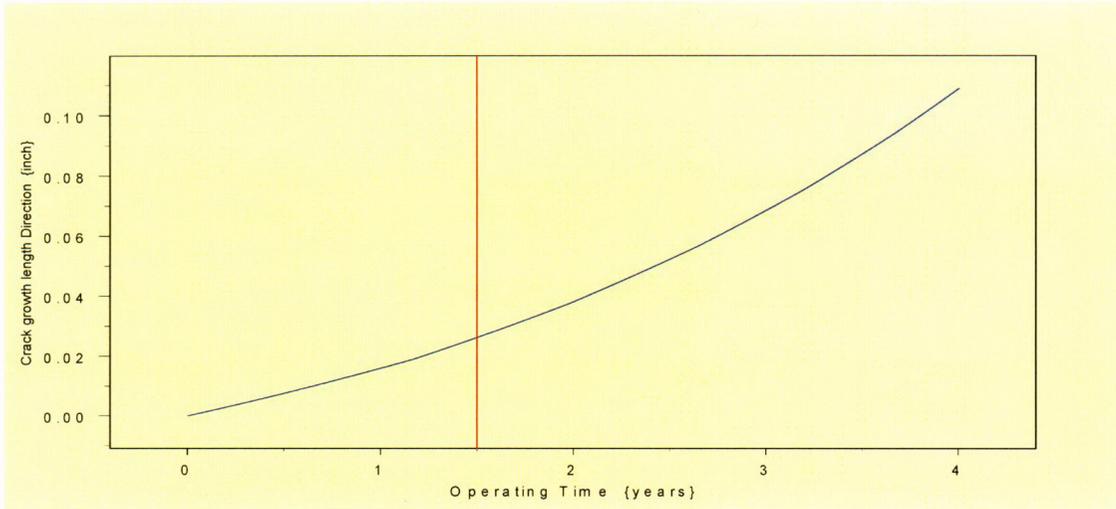
$$\text{Prop}_{\text{Length}} = 0.376$$











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Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8" Degree Nozzle, 22.5 degree from Downhill Azimuth, 1.30" 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 necessary to evaluate the stress distribution on the flaw both for the initial flaw and for a growing flaw. This is defined as the reference point. Enter a number (inch) that represents the reference point elevation measured upward from the nozzle end.

RefPoint := 1.3

This is the reduced blind zone providing a propagation length of 0.347 inch; freespan of 0.5067 inch

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

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

ULStrs.Dist := 1.8067

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

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

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

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

$$C_0 := C_{01}$$

75th 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)
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Column "3" = Mid Thickness Stress data at each Elevation (ksi)
Column "4" = Three Quarter Thickness Stress data at each Elevation (ksi)
Column "5" = OD Stress data at each Elevation (ksi)

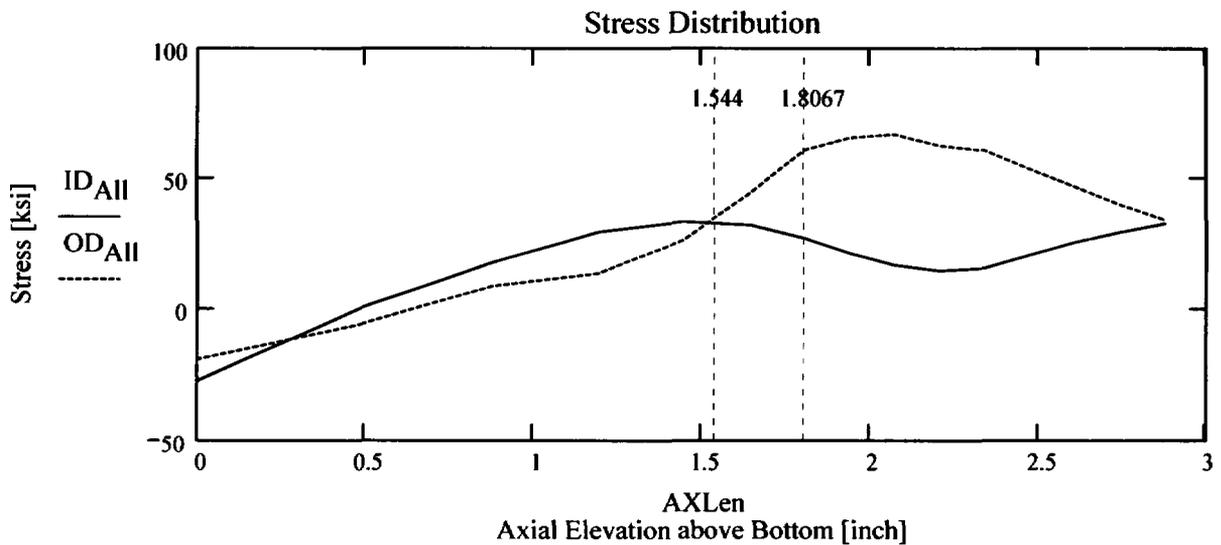
AllData :=

	0	1	2	3	4	5
0	0	-27.12	-24.15	-22.09	-20.36	-18.98
1	0.49	0.65	-1.53	-3.7	-4.6	-5.47
2	0.88	17.95	16.43	14.45	12.12	8.99
3	1.19	29.83	26.1	22.67	18.71	13.83
4	1.44	33.68	27.82	24.72	24.1	26.54
5	1.65	32.39	28.39	27.45	34.12	44.82
6	1.81	27.39	28.8	31.16	43.6	61.24
7	1.94	21.48	25.46	33.3	47.74	65.93
8	2.07	16.92	23.7	33.85	49.22	67.24
9	2.21	14.77	22.09	34.56	48.87	62.96

AXLen := AllData⁽⁰⁾

ID_{All} := AllData⁽¹⁾

OD_{All} := AllData⁽⁵⁾



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 :=	<table style="border-collapse: collapse; width: 100%; text-align: center;"> <tr><td>0</td><td>-27.118</td><td>-24.146</td><td>-22.087</td><td>-20.358</td><td>-18.981</td></tr> <tr><td>0.488</td><td>0.65</td><td>-1.526</td><td>-3.699</td><td>-4.599</td><td>-5.468</td></tr> <tr><td>0.88</td><td>17.955</td><td>16.435</td><td>14.447</td><td>12.118</td><td>8.995</td></tr> <tr><td>1.193</td><td>29.829</td><td>26.102</td><td>22.672</td><td>18.714</td><td>13.833</td></tr> <tr><td>1.444</td><td>33.679</td><td>27.823</td><td>24.722</td><td>24.104</td><td>26.541</td></tr> <tr><td>1.646</td><td>32.389</td><td>28.385</td><td>27.447</td><td>34.121</td><td>44.818</td></tr> <tr><td>1.807</td><td>27.386</td><td>28.803</td><td>31.156</td><td>43.603</td><td>61.245</td></tr> <tr><td>1.94</td><td>21.477</td><td>25.458</td><td>33.3</td><td>47.738</td><td>65.934</td></tr> <tr><td>2.074</td><td>16.919</td><td>23.701</td><td>33.846</td><td>49.217</td><td>67.244</td></tr> </table>	0	-27.118	-24.146	-22.087	-20.358	-18.981	0.488	0.65	-1.526	-3.699	-4.599	-5.468	0.88	17.955	16.435	14.447	12.118	8.995	1.193	29.829	26.102	22.672	18.714	13.833	1.444	33.679	27.823	24.722	24.104	26.541	1.646	32.389	28.385	27.447	34.121	44.818	1.807	27.386	28.803	31.156	43.603	61.245	1.94	21.477	25.458	33.3	47.738	65.934	2.074	16.919	23.701	33.846	49.217	67.244
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$$Axl := Data^{(0)} \quad MD := Data^{(3)} \quad ID := Data^{(1)} \quad TQ := Data^{(4)} \quad QT := Data^{(2)} \quad OD := Data^{(5)}$$

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

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

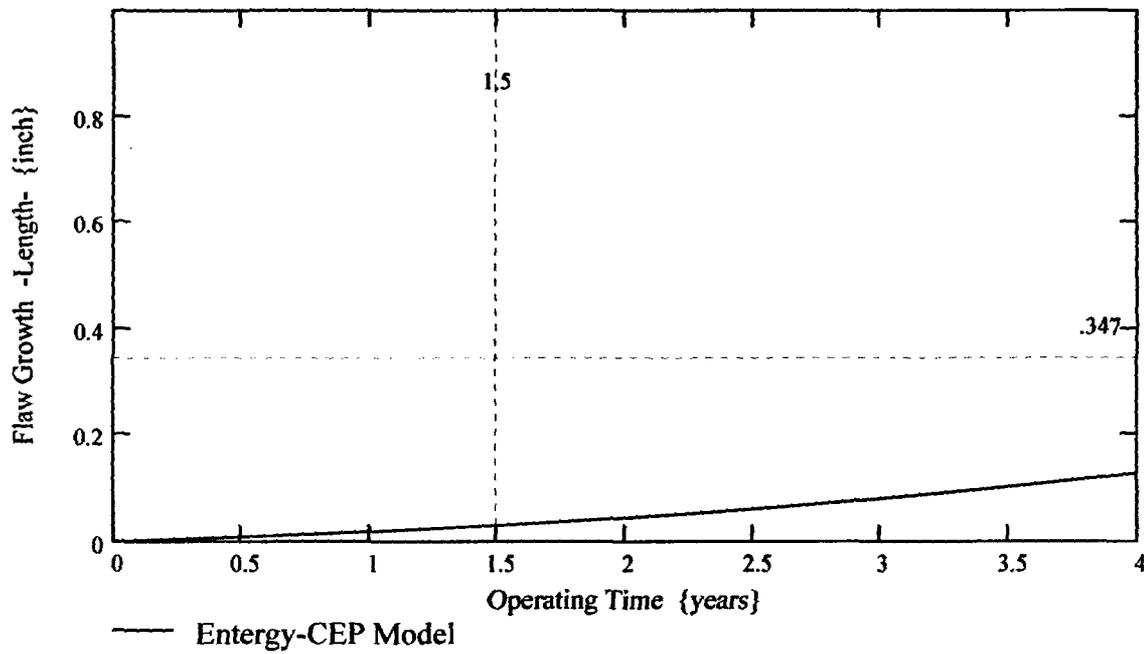
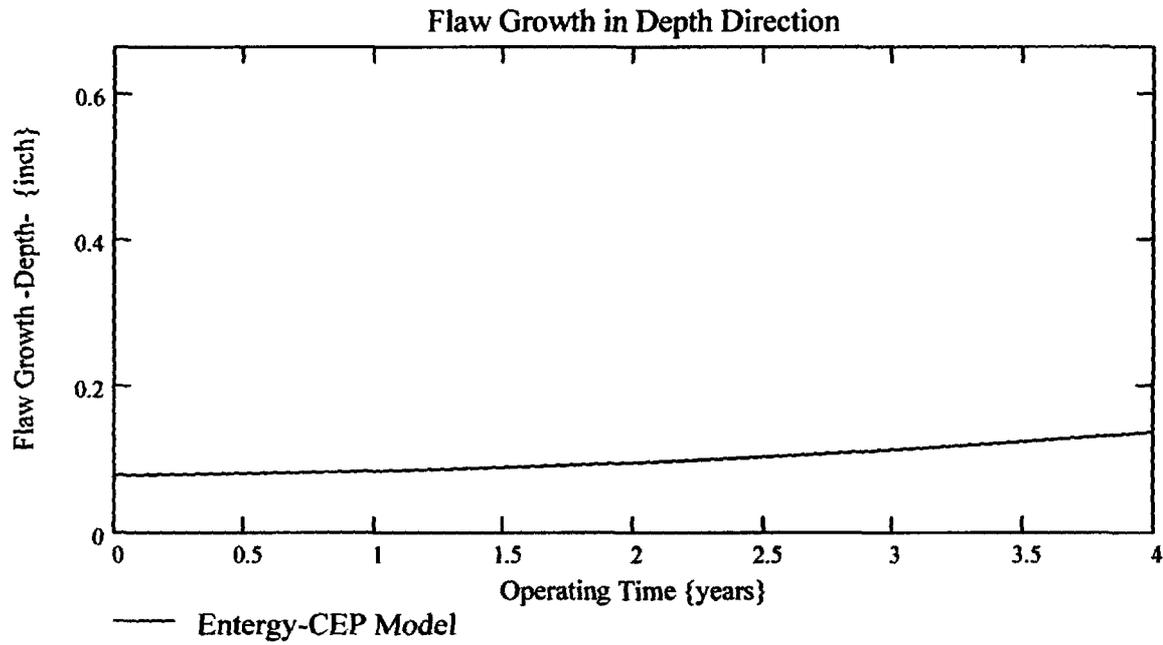
$$FL_{Cntr} := \begin{cases} RefPoint - c_0 & \text{if Val} = 1 \\ RefPoint & \text{if Val} = 2 \\ RefPoint + c_0 & \text{otherwise} \end{cases} \quad \text{Flaw center Location Location above Nozzle Bottom}$$

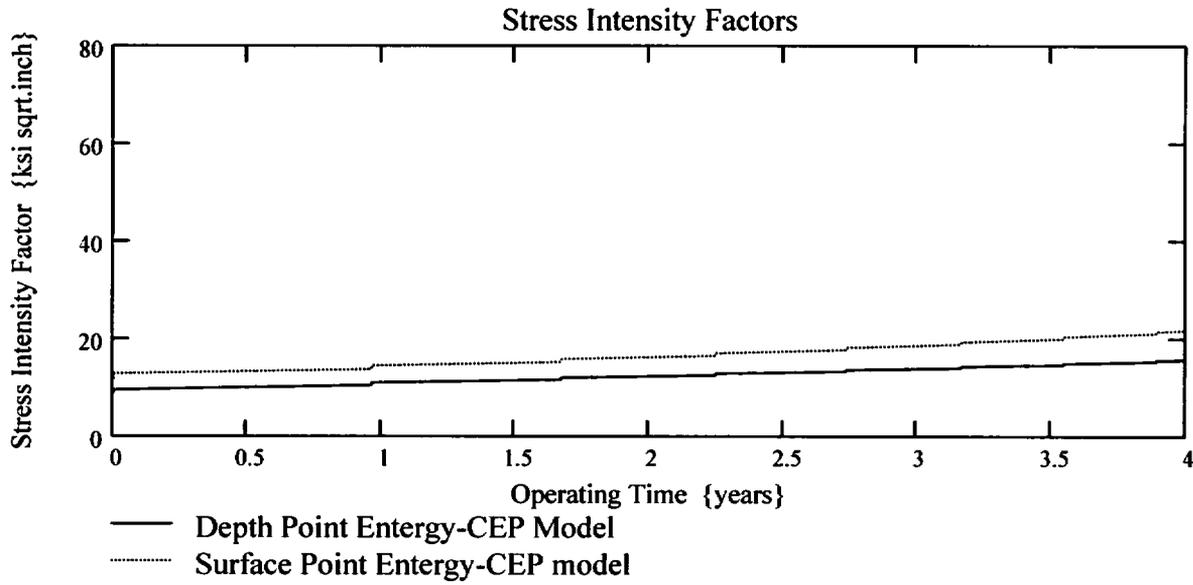
$$U_{Tip} := FL_{Cntr} + c_0 \quad IncStrs.avg := \frac{UL_{Strs}.Dist - U_{Tip}}{20}$$

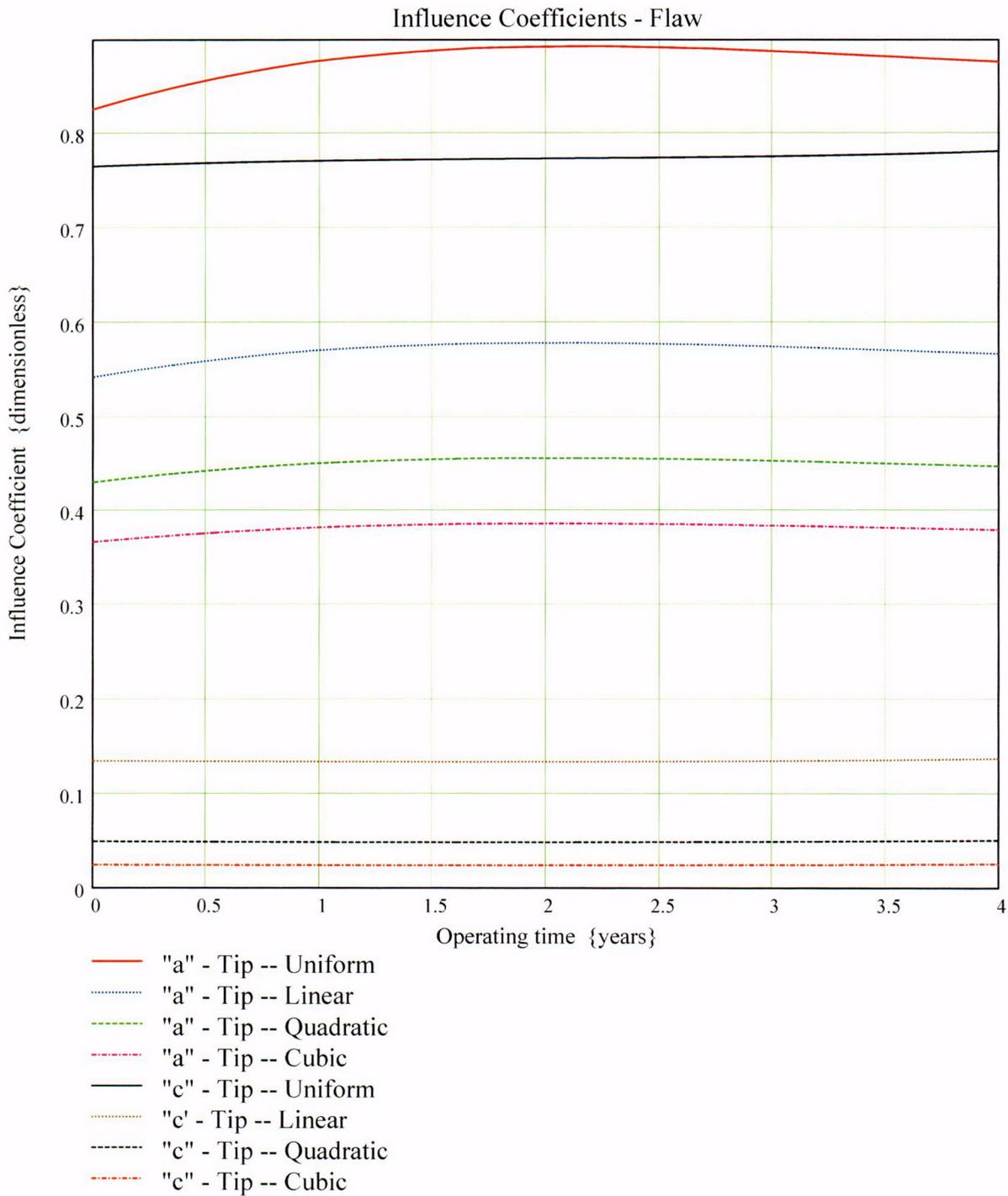
No User Input is required beyond this Point

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PropLength = 0.347







$$\text{CGR}_{\text{sambi}(k, 8)} =$$

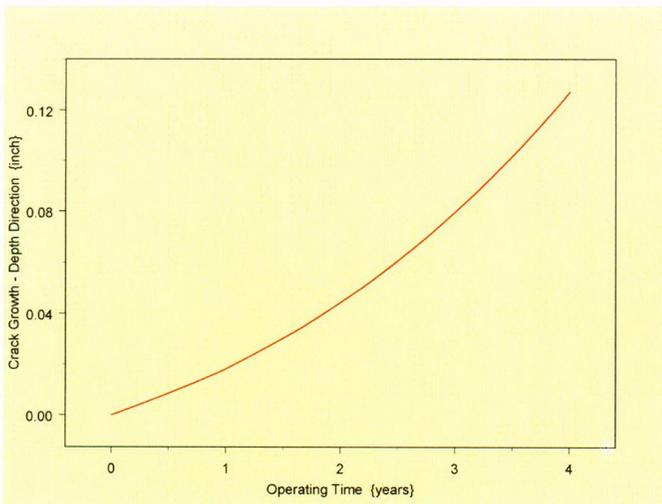
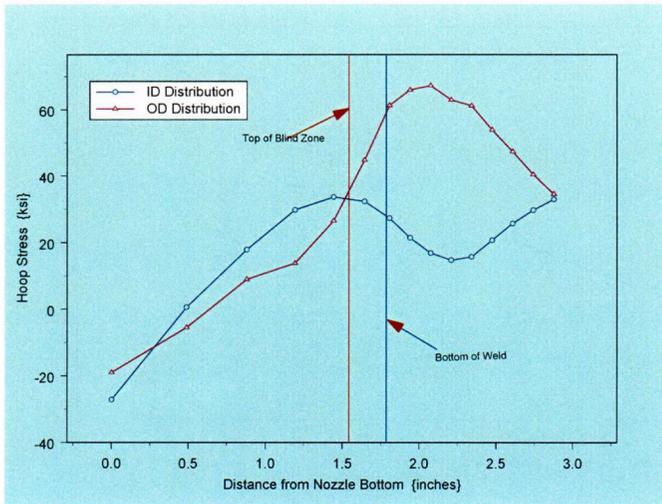
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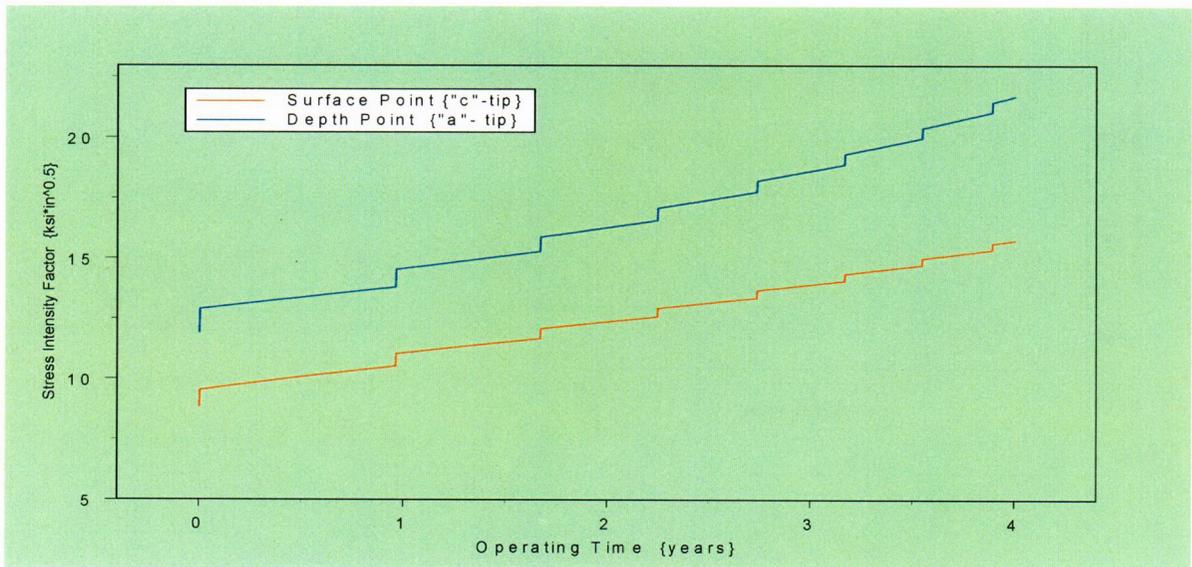
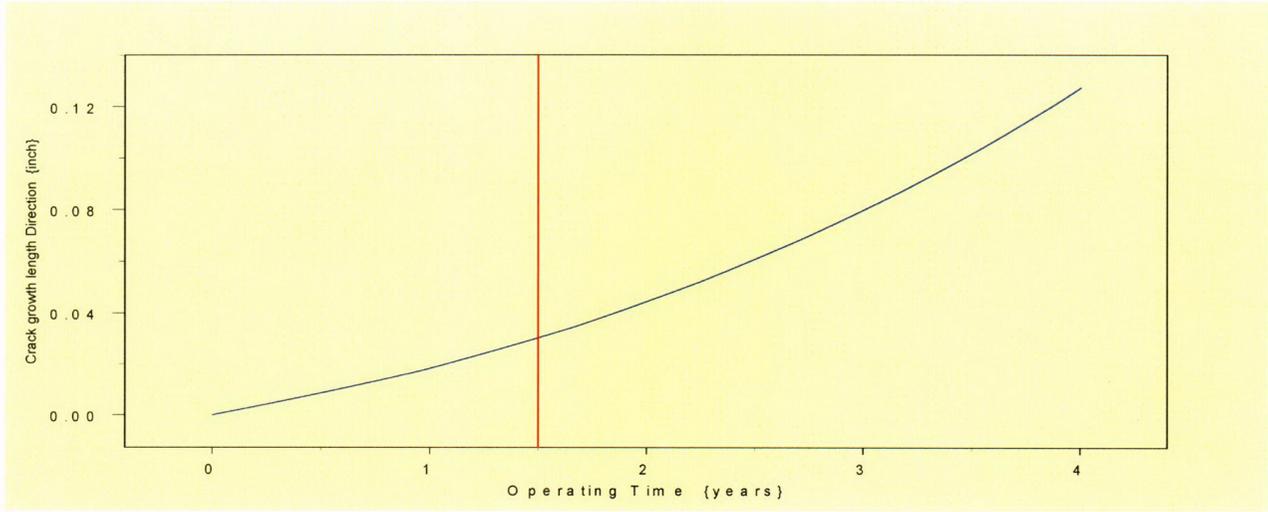
$$\text{CGR}_{\text{sambi}(k, 6)} =$$

11.9
12.895
12.897
12.9
12.903
12.905
12.908
12.91
12.913
12.916
12.918
12.921
12.923
12.926
12.929
12.931

$$\text{CGR}_{\text{sambi}(k, 5)} =$$

8.835
9.52
9.524
9.527
9.53
9.533
9.536
9.539
9.542
9.546
9.549
9.552
9.555
9.558
9.561
9.564





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Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8" Degree Nozzle, 45 degree from 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 .

OD Surface Flaw

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

Ref_{Point} := 1.544 This is the as-built blind zone providing a propagation length of
0.167 inch; freespan of 0.3274 inch

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

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

UL_{Strs.Dist} := 1.8714 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)
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$$CF_{inhr} := 1.417 \cdot 10^5 \quad C_{blk} := \frac{Tim_{opr}}{I_{lim}} \quad Prnt_{blk} := \left| \frac{I_{lim}}{50} \right| \quad c_0 := \frac{L}{2} \quad R_t := \frac{R_m}{t}$$

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

Temperature Correction for Coefficient Alpha

$$C_0 := C_{01}$$

75th 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)

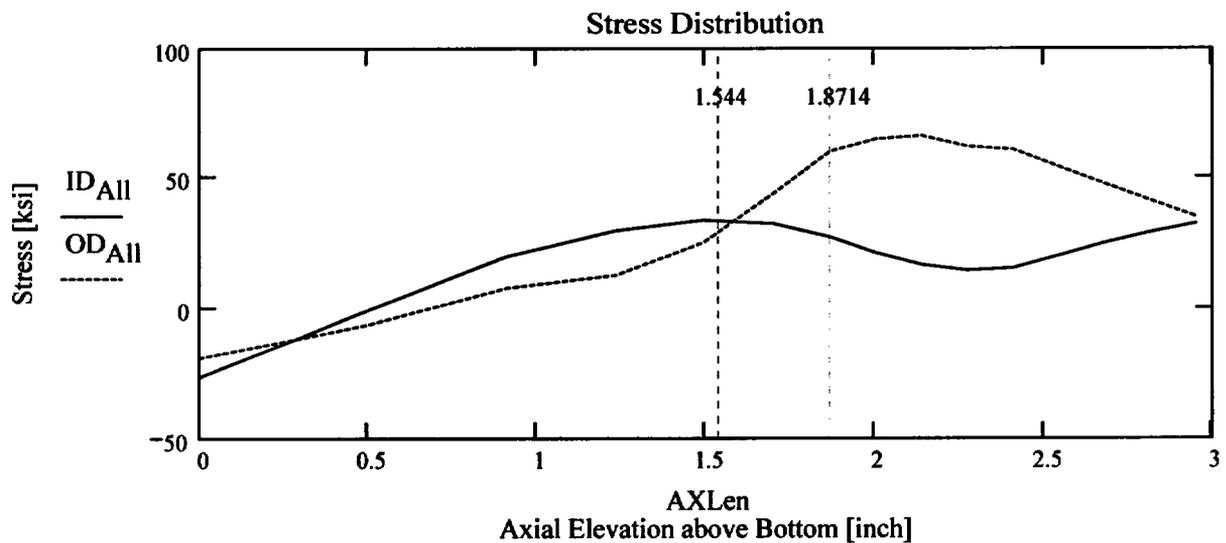
AllData :=

	0	1	2	3	4	5
0	0	-26.31	-23.54	-21.72	-20.18	-18.94
1	0.51	-0.38	-2.22	-3.97	-5.04	-6.03
2	0.91	20.09	16.85	14.02	11.34	7.92
3	1.24	29.93	26.24	22.49	18.07	12.79
4	1.5	33.83	27.91	24.53	23.55	25.42
5	1.7	32.49	28.21	27.05	33.58	44.17
6	1.87	27.43	28.6	30.66	42.95	60.21
7	2.01	21.43	25.17	32.65	46.97	64.95
8	2.14	16.79	23.32	33.24	48.59	66.19
9	2.28	14.56	21.63	33.98	48.34	62.07

AXLen := AllData⁽⁰⁾

ID_{All} := AllData⁽¹⁾

OD_{All} := AllData⁽⁵⁾



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).

$$\text{Data} := \begin{pmatrix} 0 & -26.311 & -23.544 & -21.718 & -20.18 & -18.943 \\ 0.506 & -0.377 & -2.222 & -3.968 & -5.036 & -6.028 \\ 0.911 & 20.089 & 16.851 & 14.017 & 11.337 & 7.917 \\ 1.236 & 29.934 & 26.239 & 22.486 & 18.067 & 12.788 \\ 1.496 & 33.829 & 27.906 & 24.526 & 23.554 & 25.421 \\ 1.704 & 32.487 & 28.206 & 27.053 & 33.58 & 44.169 \\ 1.871 & 27.432 & 28.598 & 30.659 & 42.946 & 60.214 \\ 2.006 & 21.433 & 25.168 & 32.645 & 46.971 & 64.949 \\ 2.141 & 16.793 & 23.322 & 33.237 & 48.59 & 66.19 \end{pmatrix}$$

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

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

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

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

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

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

$$\text{FL}_{\text{Cntr}} := \begin{cases} \text{RefPoint} - c_0 & \text{if Val} = 1 \\ \text{RefPoint} & \text{if Val} = 2 \\ \text{RefPoint} + c_0 & \text{otherwise} \end{cases}$$

Flaw center Location Location above Nozzle Bottom

$$U_{\text{Tip}} := \text{FL}_{\text{Cntr}} + c_0$$

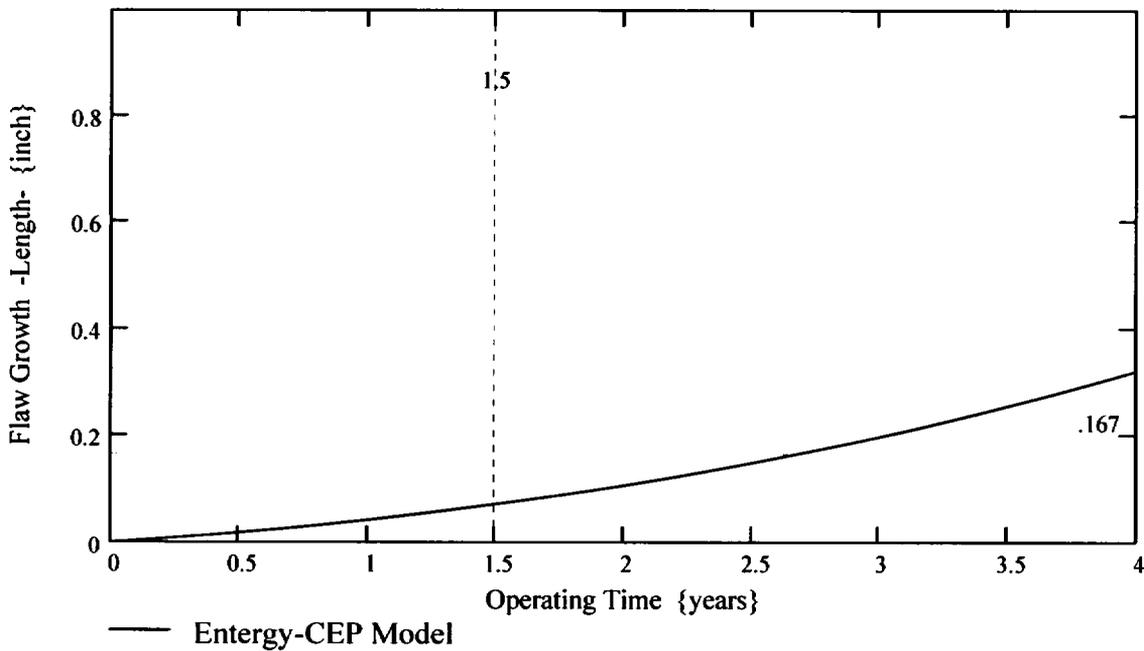
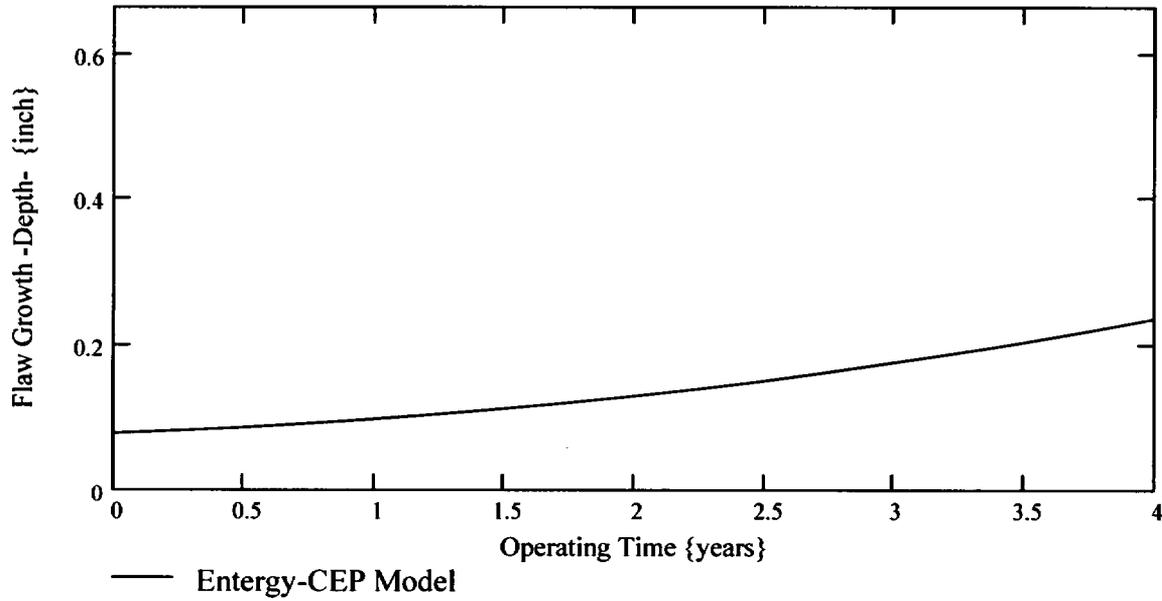
$$\text{IncStrs.avg} := \frac{UL_{\text{Strs.Dist}} - U_{\text{Tip}}}{20}$$

No User Input is required beyond this Point

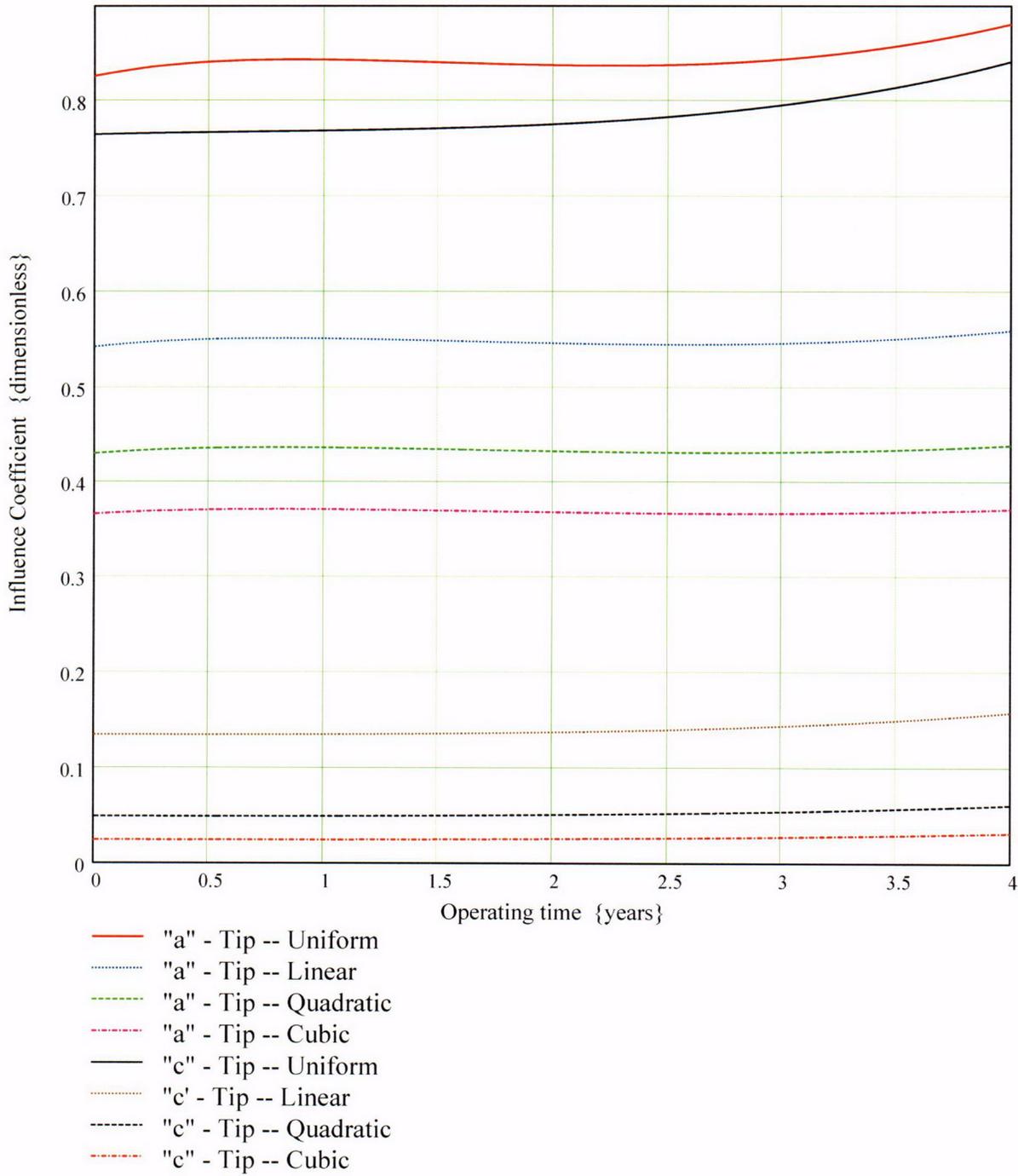
 Sat Aug 09 10:21:18 AM 2003

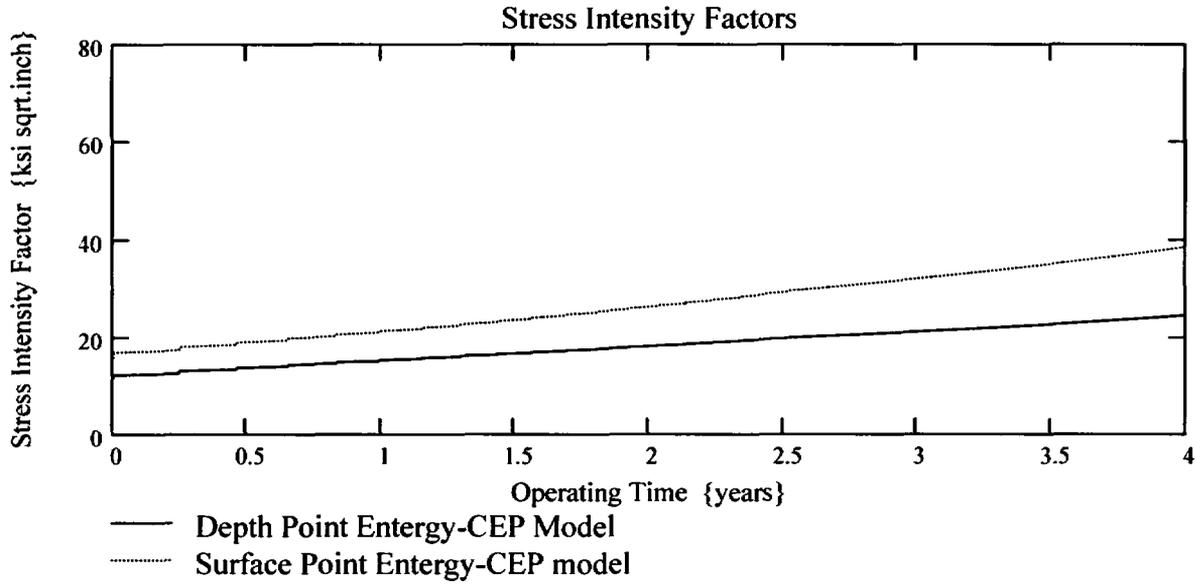
$Prop_{Length} = 0.167$

Flaw Growth in Depth Direction



Influence Coefficients - Flaw





$$\text{CGR}_{\text{sambi}(k,8)} =$$

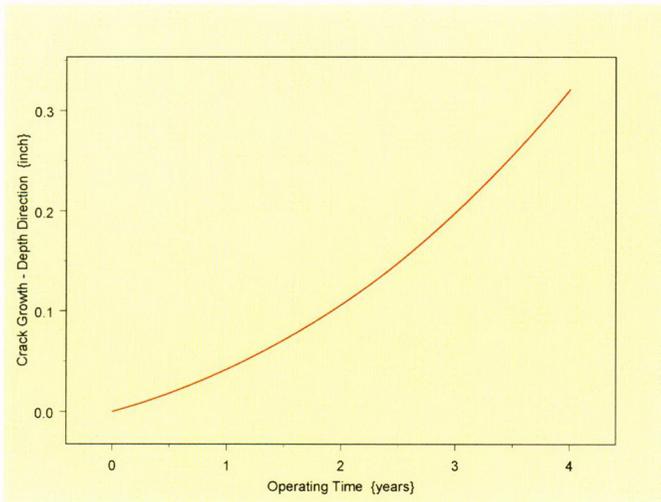
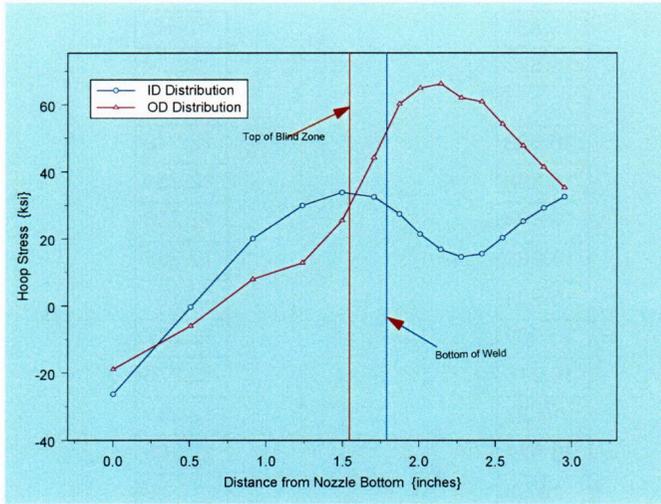
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.828
0.828
0.828
0.828
0.828
0.828
0.828
0.828

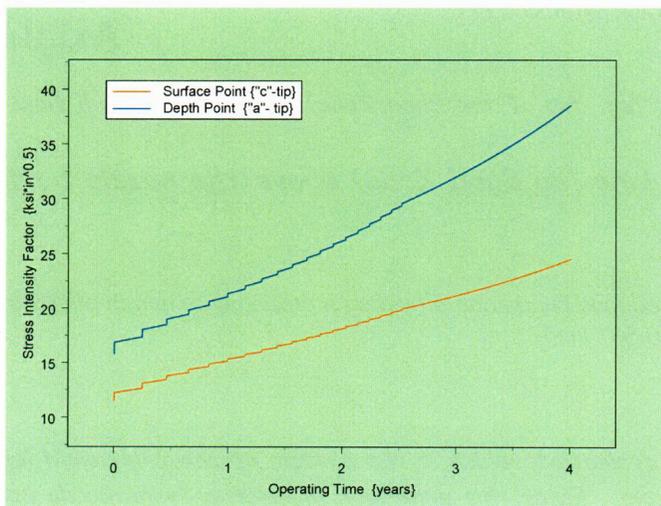
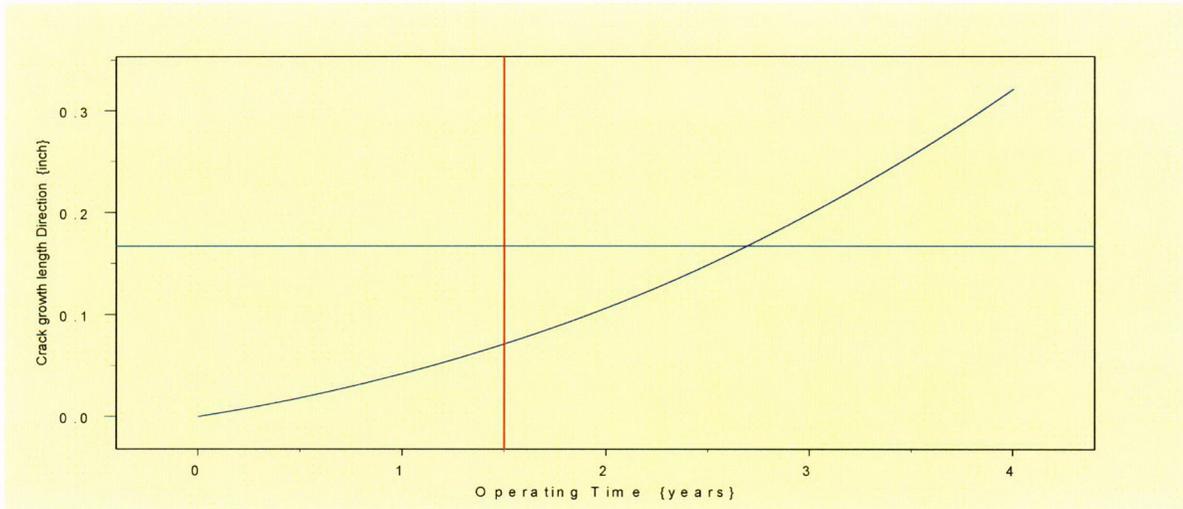
$$\text{CGR}_{\text{sambi}(k,6)} =$$

15.851
16.873
16.878
16.883
16.888
16.894
16.899
16.904
16.909
16.915
16.92
16.925
16.93
16.936
16.941
16.946

$$\text{CGR}_{\text{sambi}(k,5)} =$$

11.542
12.24
12.245
12.249
12.254
12.258
12.263
12.267
12.272
12.276
12.281
12.285
12.29
12.294
12.299
12.303





Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadേശam

Verified by: B. C. Gray

Note : Only for use when $R_{outside}/t$ is between 2.0 and 5.0 (Thickwall 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 2

Component : Reactor Vessel CEDM -"8"Degree Nozzle, 22.5 degree from Downhill Azimuth, Augmented Analysis
1.3 inch above Nozzle Bottom

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

Through Wall Axial Flaw

*The first Input is to locate the Reference Line (eg. top of the Blind Zone). The throughwall flaw "Upper Tip" is located at the Reference Line.
Enter the elevation of the Reference Line (eg. Blind Zone) above the nozzle bottom in inches.*

BZ := 1.3

*This is the reduced blind zone providing a propagation length of 507 inch ;
freespan is 0.507 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.

ULStrs.Dist := 1.8067

Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

Input Data :-

L := .794 Initial Flaw Length TW axial (Based on 10 Ksi average stress)

od := 4.05 Tube OD

id := 2.728 Tube ID

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

Years := 4 Number of Operating Years

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

T := 604 Estimate of Operating Temperature

v := 0.307 Poissons ratio @ 600 F

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

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

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

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

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

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

$$R_i := \frac{id}{2}$$

$$t := R_o - R_i$$

$$R_m := R_i + \frac{t}{2}$$

$$CF_{inhr} := 1.417 \cdot 10^5$$

$$C_{blk} := \frac{Tim_{opr}}{I_{lim}}$$

$$Prnt_{blk} := \left| \frac{I_{lim}}{50} \right|$$

$$l := \frac{L}{2}$$

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)

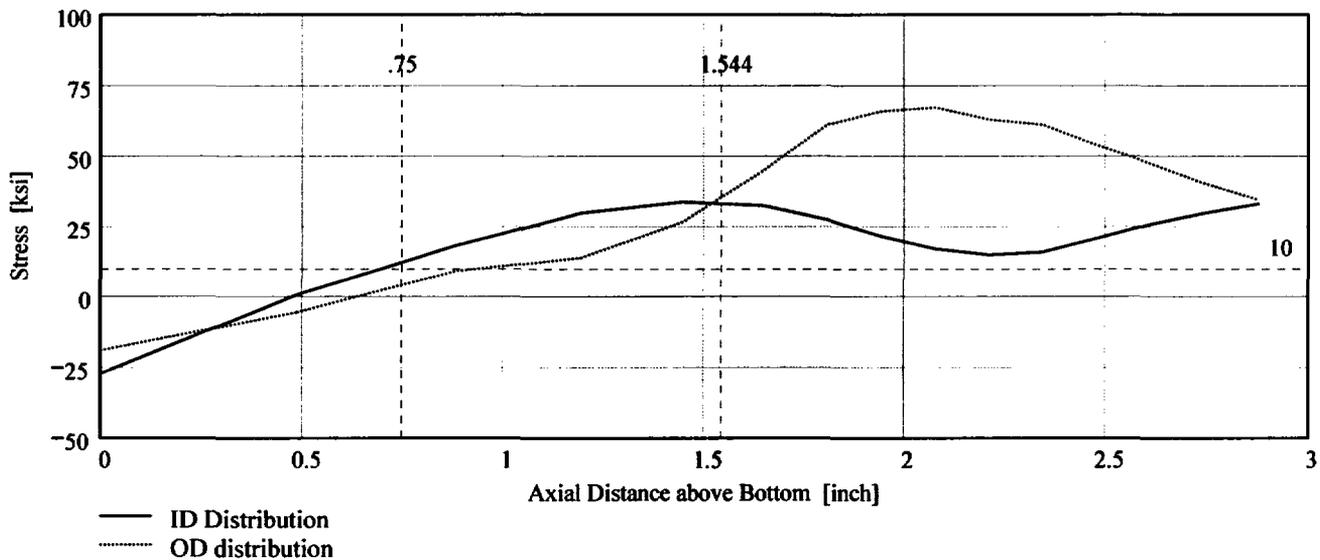
DataAll :=

	0	1	2	3	4	5
0	0	-27.12	-24.15	-22.09	-20.36	-18.98
1	0.49	0.65	-1.53	-3.7	-4.6	-5.47
2	0.88	17.95	16.43	14.45	12.12	8.99
3	1.19	29.83	26.1	22.67	18.71	13.83
4	1.44	33.68	27.82	24.72	24.1	26.54
5	1.65	32.39	28.39	27.45	34.12	44.82
6	1.81	27.39	28.8	31.16	43.6	61.24
7	1.94	21.48	25.46	33.3	47.74	65.93
8	2.07	16.92	23.7	33.85	49.22	67.24
9	2.21	14.77	22.09	34.56	48.87	62.96

AllAxI := DataAll^{<0>}

AllID := DataAll^{<1>}

AllOD := DataAll^{<5>}



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

Data :=

0	-27.118	-24.146	-22.087	-20.358	-18.981
0.488	0.65	-1.526	-3.699	-4.599	-5.468
0.88	17.955	16.435	14.447	12.118	8.995
1.193	29.829	26.102	22.672	18.714	13.833
1.444	33.679	27.823	24.722	24.104	26.541
1.646	32.389	28.385	27.447	34.121	44.818
1.807	27.386	28.803	31.156	43.603	61.245
1.94	21.477	25.458	33.3	47.738	65.934
2.074	16.919	23.701	33.846	49.217	67.244

Axl := Data⁽⁰⁾

ID := Data⁽¹⁾

OD := Data⁽⁵⁾

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

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

FL_{Cntr} := BZ - 1

Flaw Center above Nozzle Bottom

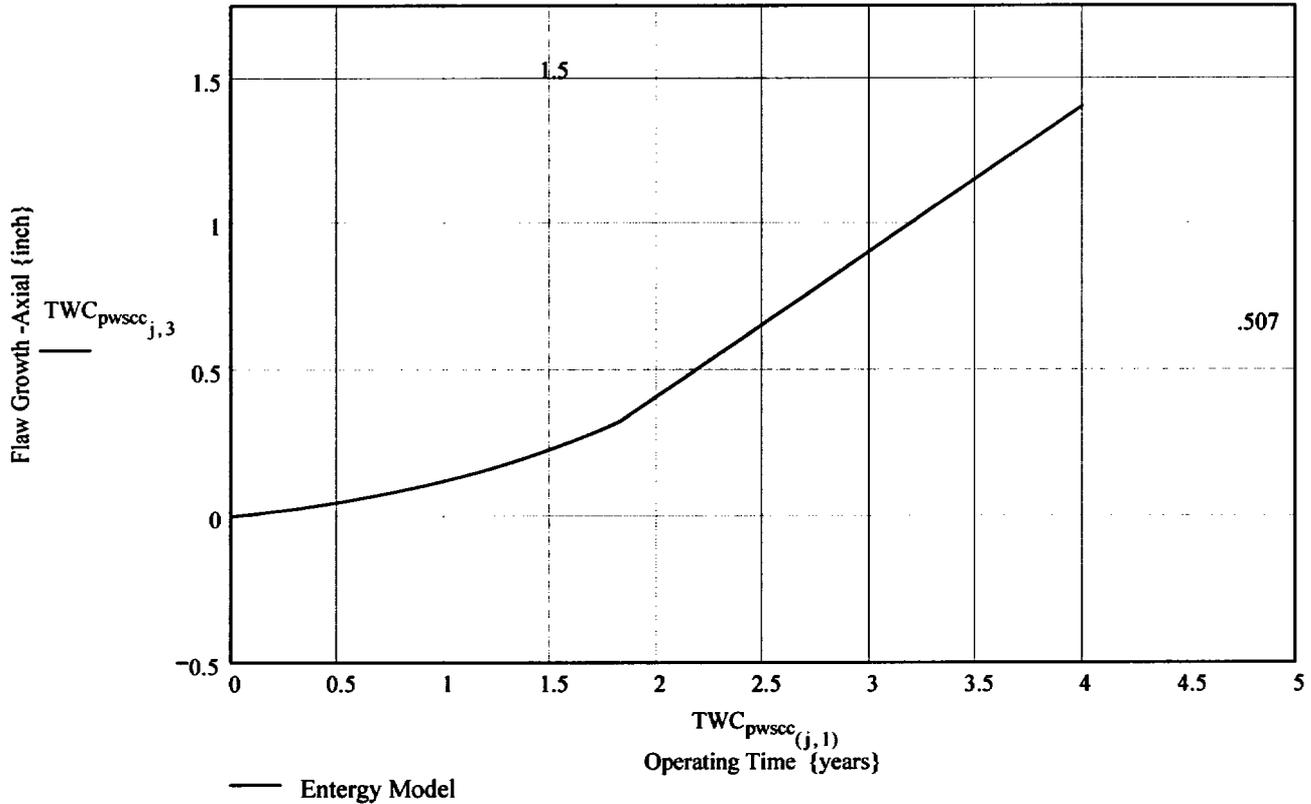
$$\text{IncStrs.avg} := \frac{\text{ULStrs.Dist} - \text{BZ}}{20}$$

No User Input required beyond this Point

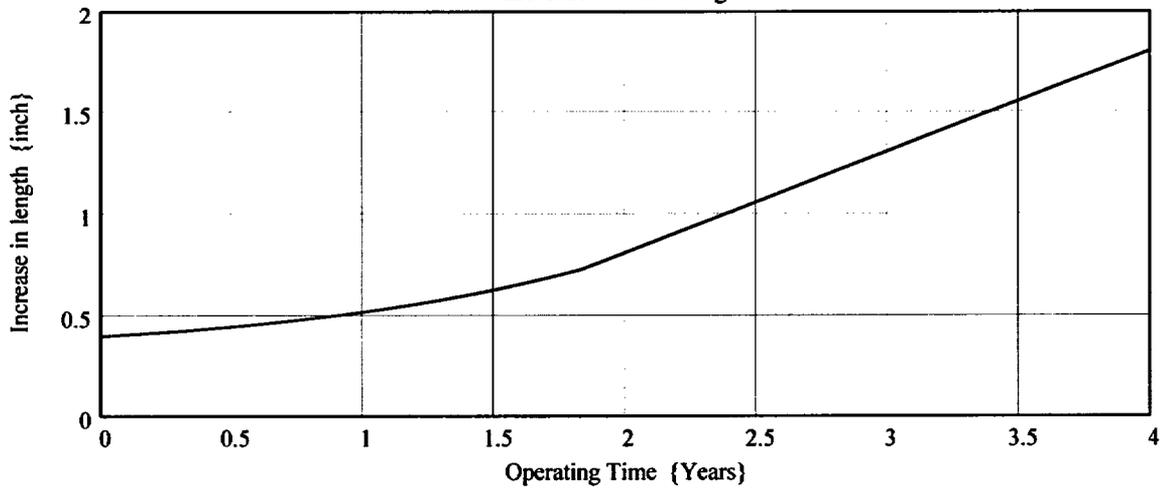
Sat Aug 09 11:44:49 AM 2003

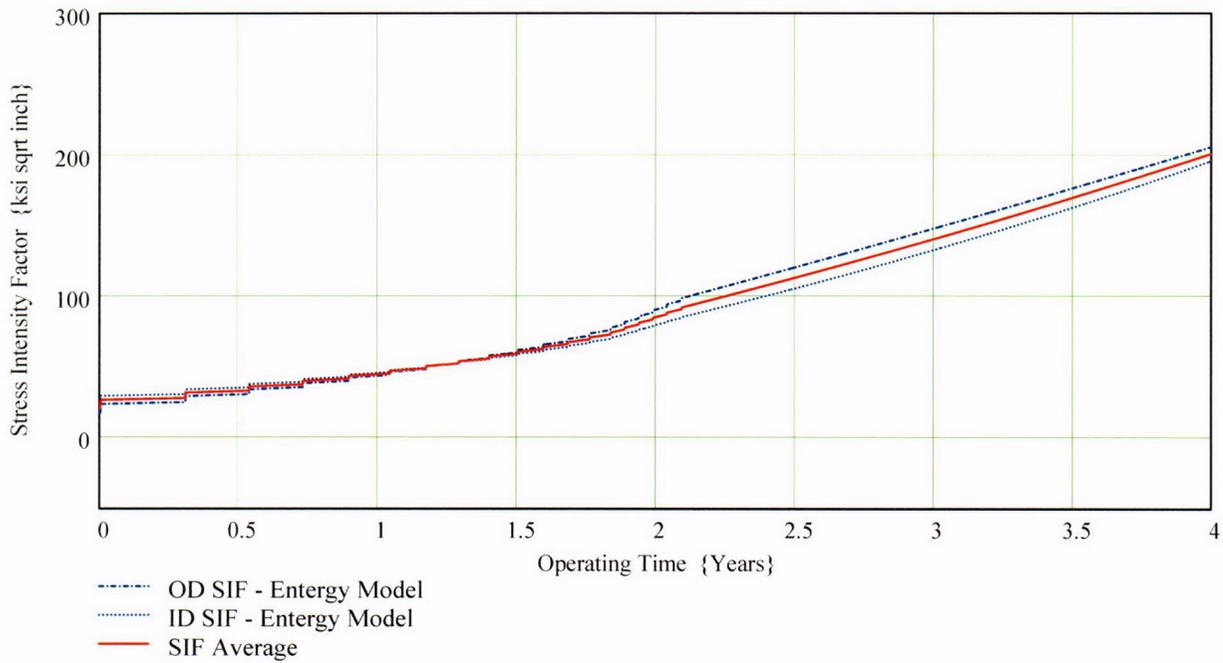
PropLength = 0.507

Flaw Length vs. Time



Increase in Half Length





Developed by:

Verified by:

C36

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

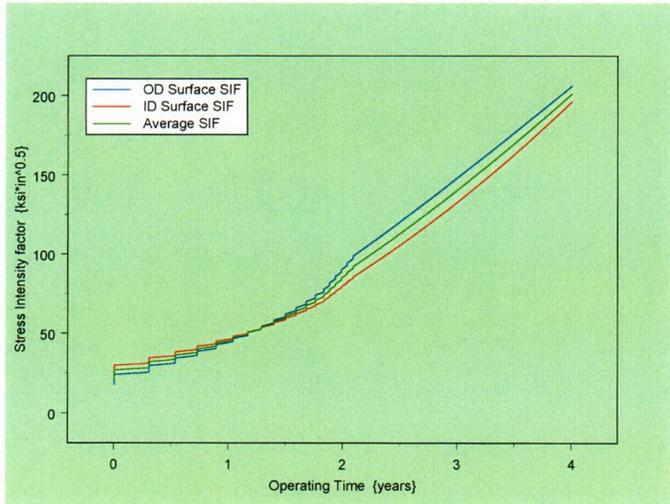
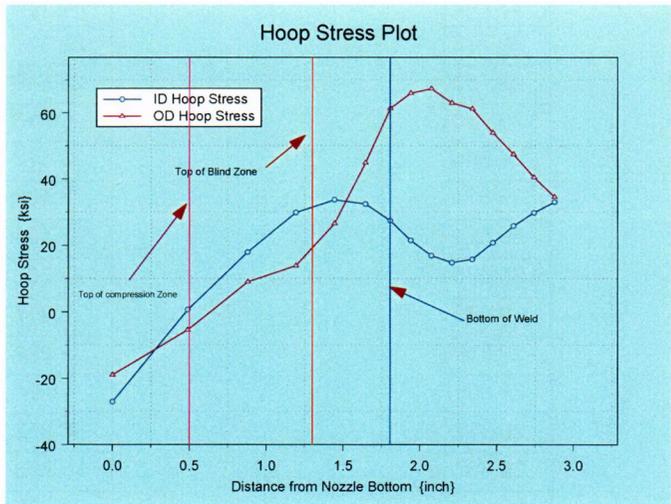
17.829
24.076
24.087
24.098
24.108
24.119
24.13
24.14
24.151
24.162
24.173
24.183
24.194
24.205
24.216
24.226

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

24.642
29.762
29.772
29.783
29.793
29.804
29.814
29.824
29.835
29.845
29.856
29.866
29.877
29.887
29.897
29.908

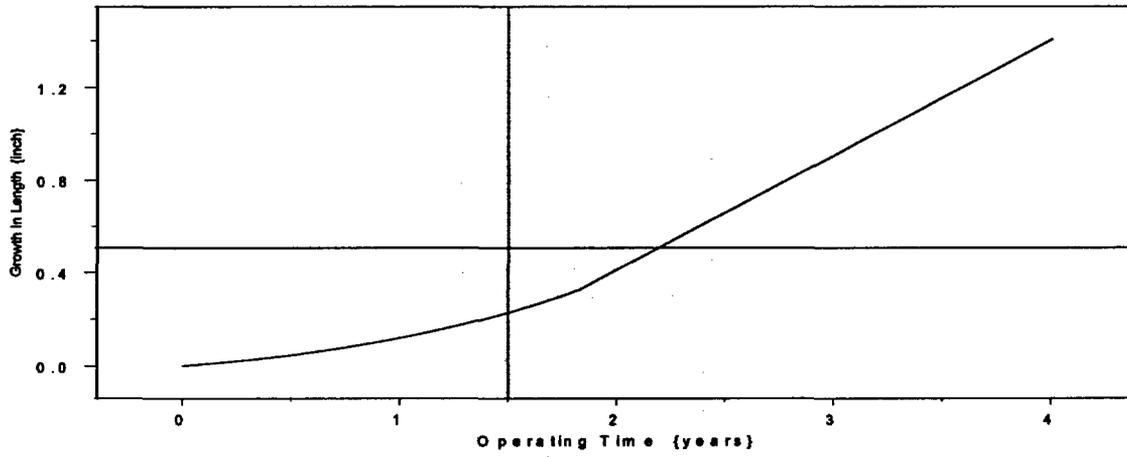
$TWC_{pwscc(j,8)} =$

22.253
28.126
28.137
28.149
28.16
28.172
28.183
28.194
28.206
28.217
28.229
28.24
28.252
28.263
28.275
28.286



Developed by:

Verified by:



Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadേശam

Verified by: B. C. Gray

Note : Only for use when $R_{outside}/t$ is between 2.0 and 5.0 (Thickwall 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 2

Component : Reactor Vessel CEDM -"8" Degree Nozzle, 45 degree from Downhill Azimuth, Augmented Analysis
1.544 inch above Nozzle Bottom

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

Through Wall Axial Flaw

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

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

BZ := 1.45

*This is the as-built blind zone providing a propagation length of .421 inch ;
freespan is 0.421 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.

ULStrs.Dist := 1.8714

Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

Input Data :-

L := .794 Initial Flaw Length TW axial (Based on 10 Ksi average stress)

od := 4.05 Tube OD

id := 2.728 Tube ID

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

Years := 4 Number of Operating Years

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

T := 604 Estimate of Operating Temperature

v := 0.307 Poissons ratio @ 600 F

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

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

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

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

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

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

$$R_i := \frac{id}{2}$$

$$t := R_o - R_i$$

$$R_m := R_i + \frac{t}{2}$$

$$CF_{inhr} := 1.417 \cdot 10^5$$

$$C_{blk} := \frac{Tim_{opr}}{I_{lim}}$$

$$Prnt_{blk} := \left| \frac{I_{lim}}{50} \right|$$

$$l := \frac{L}{2}$$

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)

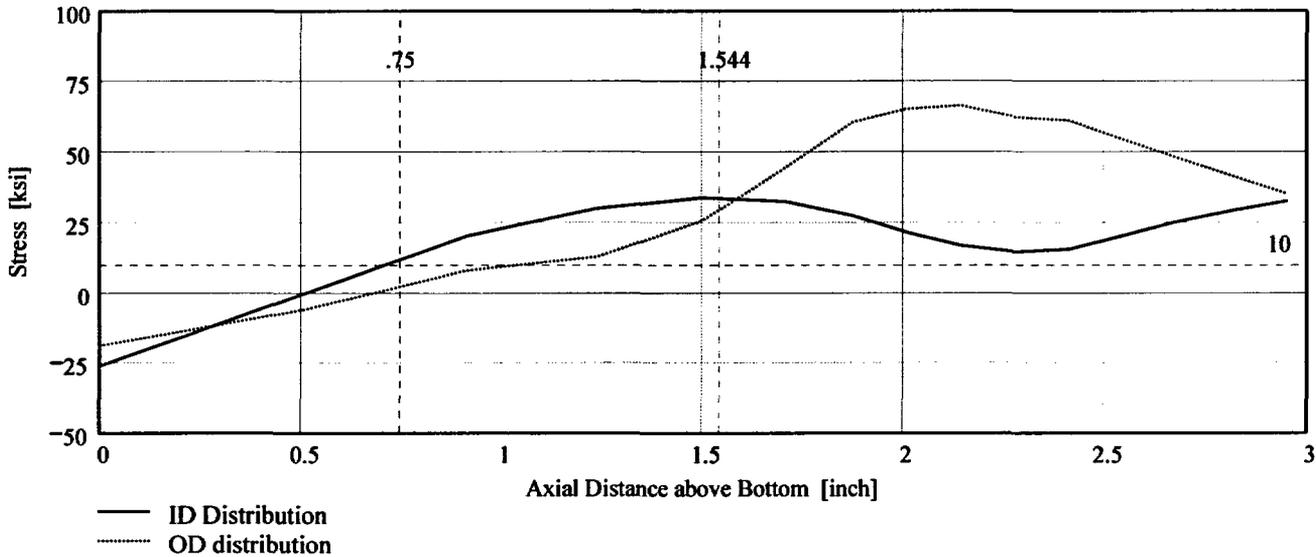
DataAll :=

	0	1	2	3	4	5
0	0	-26.31	-23.54	-21.72	-20.18	-18.94
1	0.51	-0.38	-2.22	-3.97	-5.04	-6.03
2	0.91	20.09	16.85	14.02	11.34	7.92
3	1.24	29.93	26.24	22.49	18.07	12.79
4	1.5	33.83	27.91	24.53	23.55	25.42
5	1.7	32.49	28.21	27.05	33.58	44.17
6	1.87	27.43	28.6	30.66	42.95	60.21
7	2.01	21.43	25.17	32.65	46.97	64.95
8	2.14	16.79	23.32	33.24	48.59	66.19
9	2.28	14.56	21.63	33.98	48.34	62.07

AllAxI := DataAll⁽⁰⁾

AllID := DataAll⁽¹⁾

AllOD := DataAll⁽⁵⁾



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	-26.311	-23.544	-21.718	-20.18	-18.943
0.506	-0.377	-2.222	-3.968	-5.036	-6.028
0.911	20.089	16.851	14.017	11.337	7.917
1.236	29.934	26.239	22.486	18.067	12.788
1.496	33.829	27.906	24.526	23.554	25.421
1.704	32.487	28.206	27.053	33.58	44.169
1.871	27.432	28.598	30.659	42.946	60.214
2.006	21.433	25.168	32.645	46.971	64.949
2.141	16.793	23.322	33.237	48.59	66.19

Axl := Data⁽⁰⁾

ID := Data⁽¹⁾

OD := Data⁽⁵⁾

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

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

FLCntr := BZ - 1

Flaw Center above Nozzle Bottom

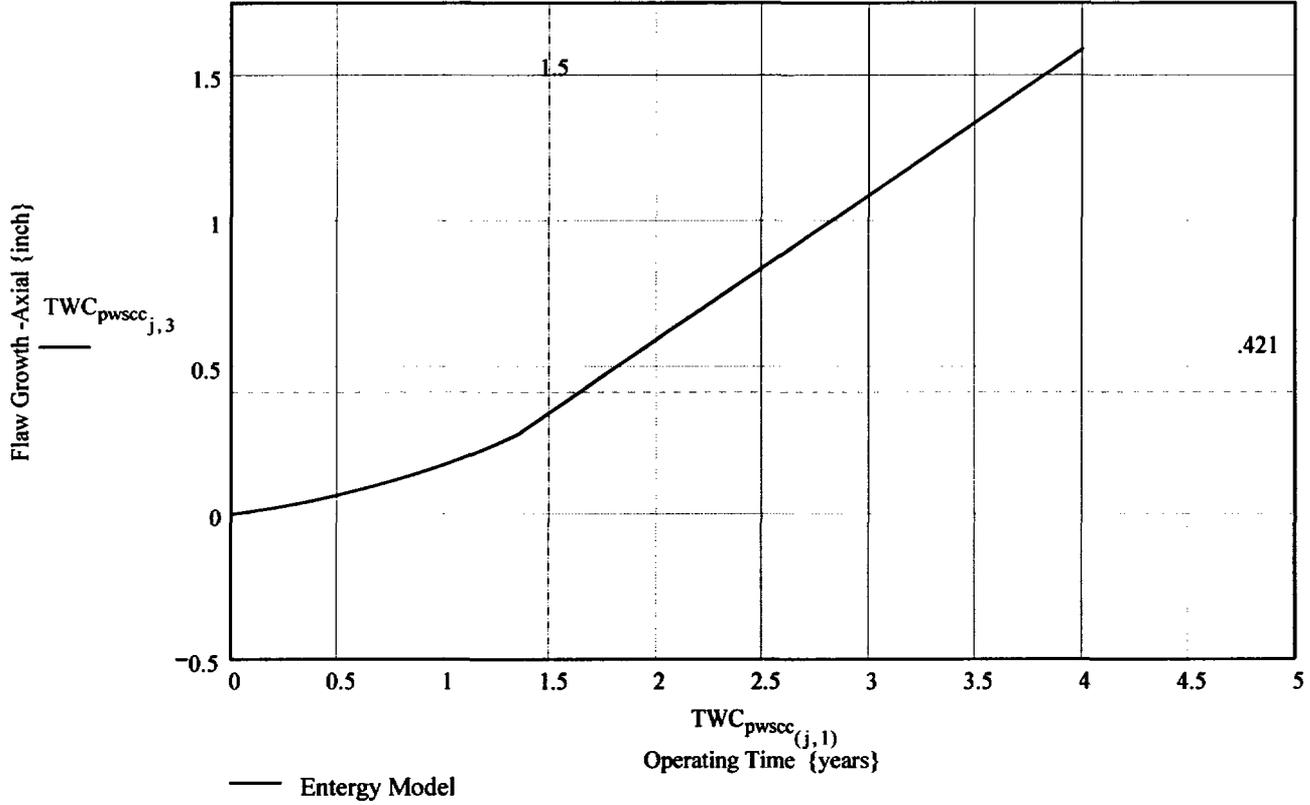
$$\text{IncStrs.avg} := \frac{\text{ULStrs.Dist} - \text{BZ}}{20}$$

No User Input required beyond this Point

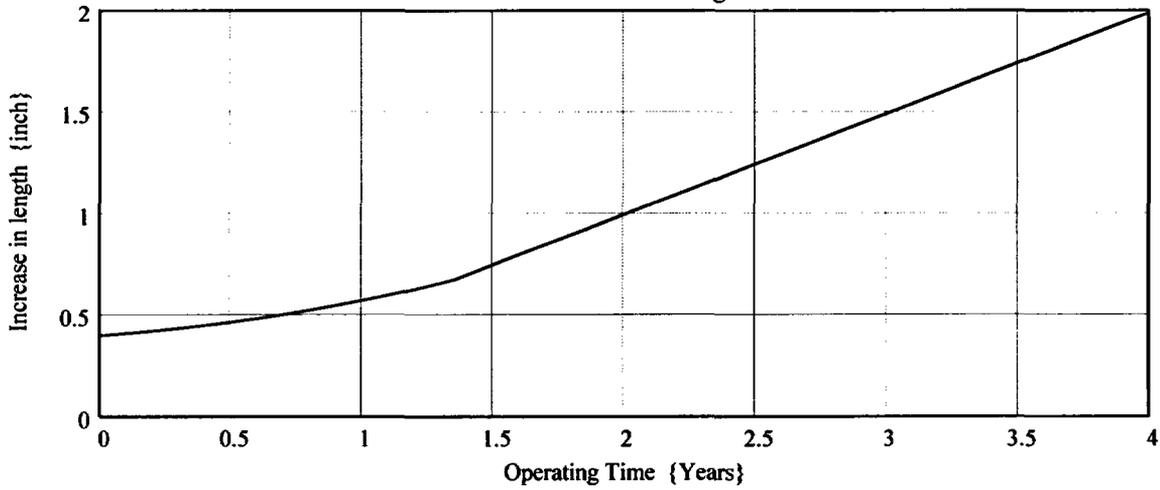
 Sat Aug 09 11:44:49 AM 2003

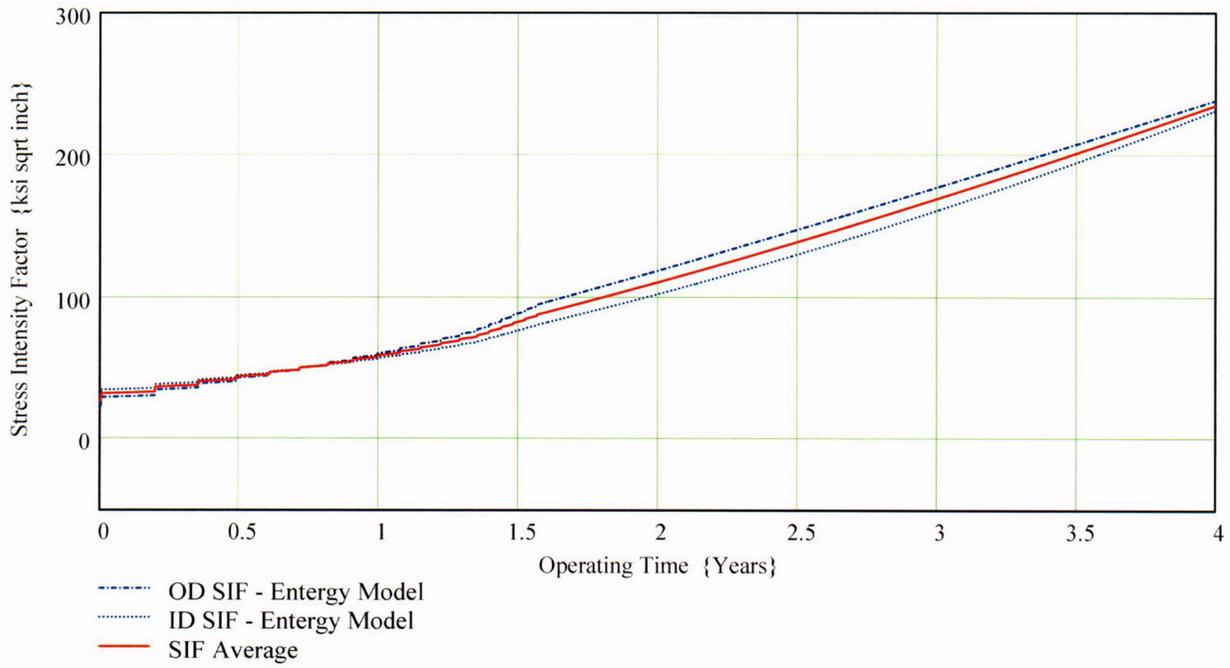
PropLength = 0.421

Flaw Length vs. Time



Increase in Half Length





Developed by:

Verified by:

C38

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

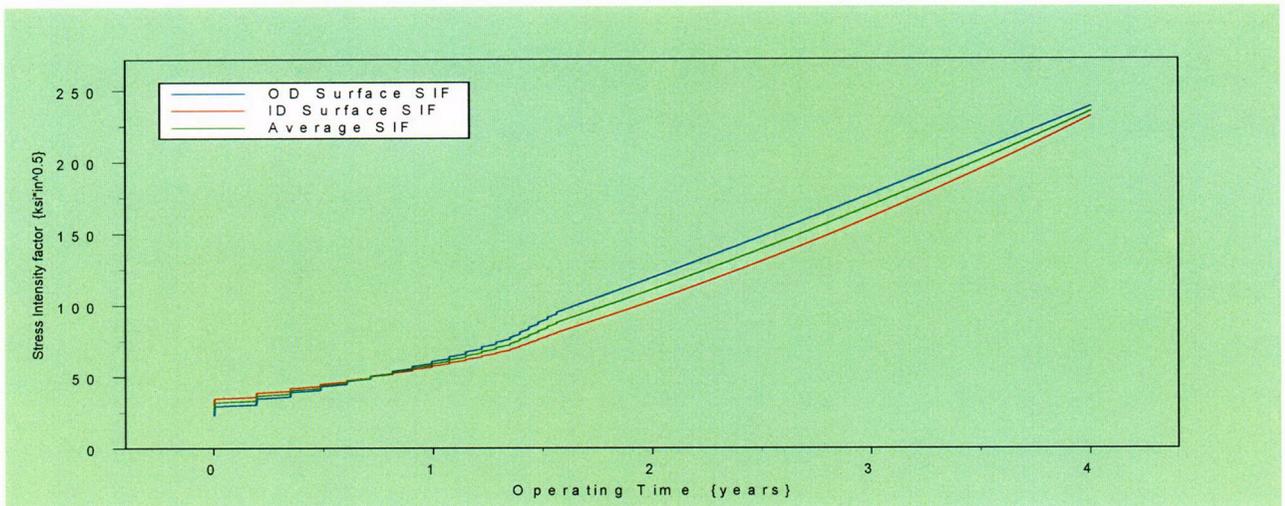
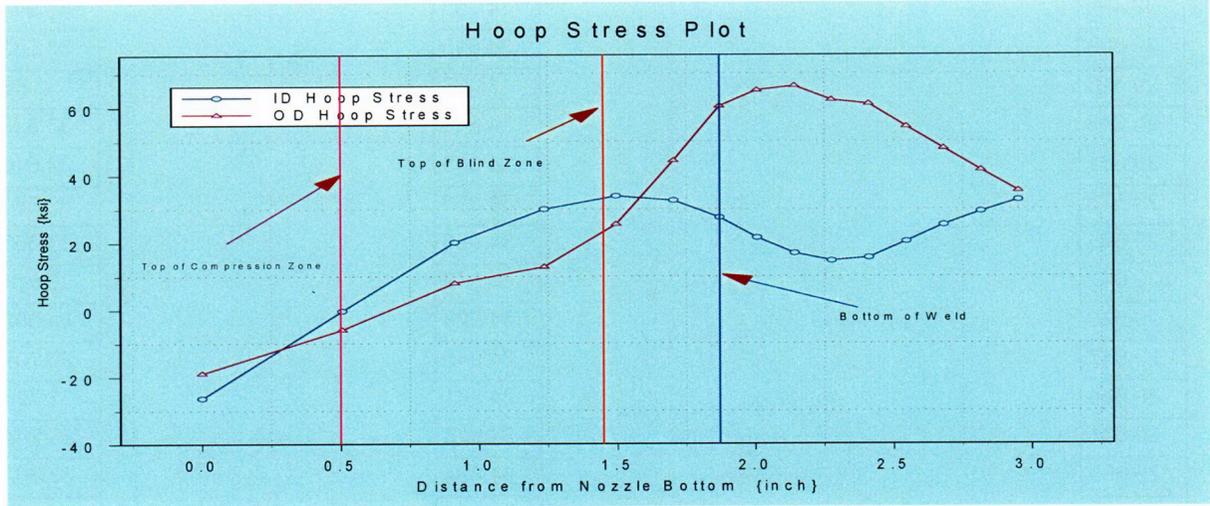
23.343
29.492
29.509
29.526
29.543
29.561
29.578
29.595
29.612
29.629
29.647
29.664
29.681
29.699
29.716
29.733

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

30.471
34.797
34.813
34.83
34.846
34.863
34.879
34.895
34.912
34.928
34.945
34.961
34.978
34.994
35.01
35.027

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

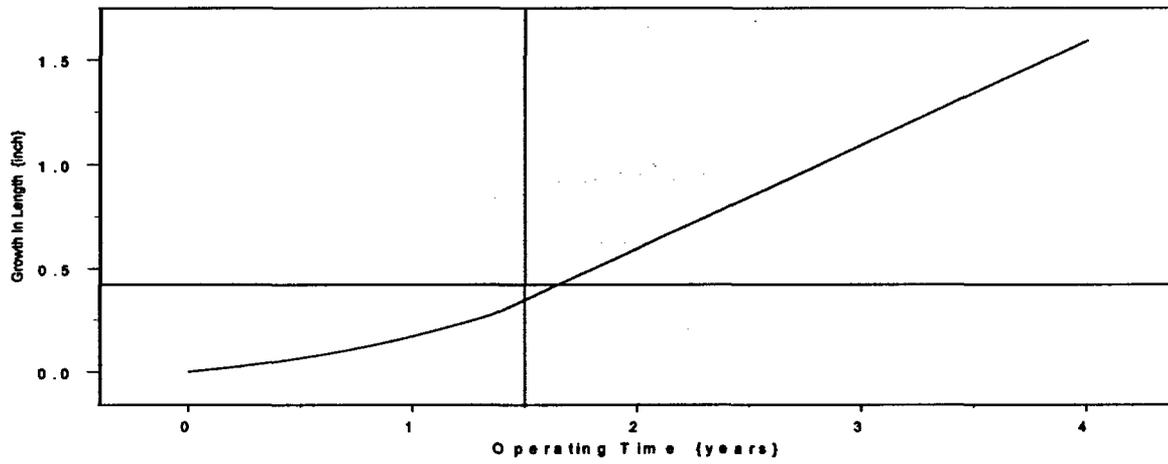
28.154
33.544
33.562
33.58
33.598
33.616
33.634
33.653
33.671
33.689
33.707
33.726
33.744
33.762
33.78
33.799



Developed by:

Verified by:

C39



Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadേശam

Verified by: B. C. Gray

Note : Only for use when $R_{outside}/t$ is between 2.0 and 5.0 (Thickwall 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 2

Component : Reactor Vessel CEDM -"8"Degree Nozzle, 67.5 degree from Downhill Azimuth, Augmented Analysis
1.544 inch above Nozzle Bottom

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

Through Wall Axial Flaw

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

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

BZ := 1.544

*This is the as-built blind zone providing a propagation length of .421 inch ;
freespan is 0.421 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.

ULStrs.Dist := 1.9699

Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

Input Data :-

L := .794 Initial Flaw Length TW axial (Based on 10 Ksi average stress)

od := 4.05 Tube OD

id := 2.728 Tube ID

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

Years := 4 Number of Operating Years

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

T := 604 Estimate of Operating Temperature

v := 0.307 Poissons ratio @ 600 F

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

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

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

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

Tim_{opr} := Years·365·24

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

$$R_i := \frac{id}{2}$$

$$t := R_o - R_i$$

$$R_m := R_i + \frac{t}{2}$$

$$CF_{inhr} := 1.417 \cdot 10^5$$

$$C_{blk} := \frac{Tim_{opr}}{I_{lim}}$$

$$Prnt_{blk} := \left| \frac{I_{lim}}{50} \right|$$

$$l := \frac{L}{2}$$

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)

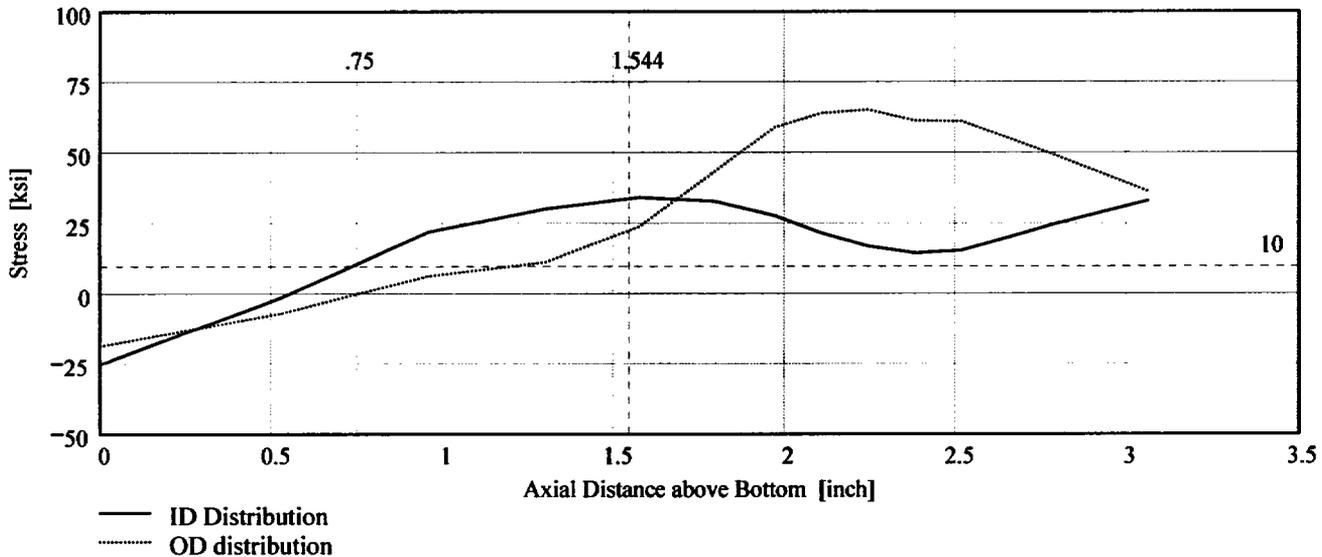
DataAll :=

	0	1	2	3	4	5
0	0	-25.24	-22.71	-21.18	-19.87	-18.8
1	0.53	-1.27	-2.96	-4.4	-5.69	-6.83
2	0.96	21.94	17.09	13.36	10.18	6.33
3	1.3	30.02	26.37	22.21	17.12	11.24
4	1.57	34.09	28.09	24.31	22.83	23.83
5	1.79	32.72	28.04	26.61	32.92	43.29
6	1.97	27.6	28.45	30.15	42.18	58.89
7	2.11	21.46	24.92	31.94	46.1	63.87
8	2.24	16.73	22.99	32.59	47.9	65.05
9	2.38	14.34	21.26	33.41	47.85	61.2

AllAxI := DataAll⁽⁰⁾

AllID := DataAll⁽¹⁾

AllOD := DataAll⁽⁵⁾



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	-25.236	-22.713	-21.175	-19.868	-18.802
	0.533	-1.267	-2.963	-4.403	-5.689	-6.833
	0.959	21.942	17.089	13.361	10.182	6.327
	1.301	30.023	26.373	22.21	17.121	11.241
	1.575	34.094	28.085	24.306	22.834	23.834
	1.794	32.716	28.035	26.605	32.916	43.289
	1.97	27.602	28.447	30.151	42.181	58.888
	2.106	21.457	24.92	31.944	46.103	63.871
	2.242	16.731	22.988	32.591	47.9	65.049

Axl := Data⁽⁰⁾

ID := Data⁽¹⁾

OD := Data⁽⁵⁾

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

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

FL_{Cntr} := BZ - 1

Flaw Center above Nozzle Bottom

$$\text{IncStrs.avg} := \frac{\text{ULStrs.Dist} - \text{BZ}}{20}$$

No User Input required beyond this Point

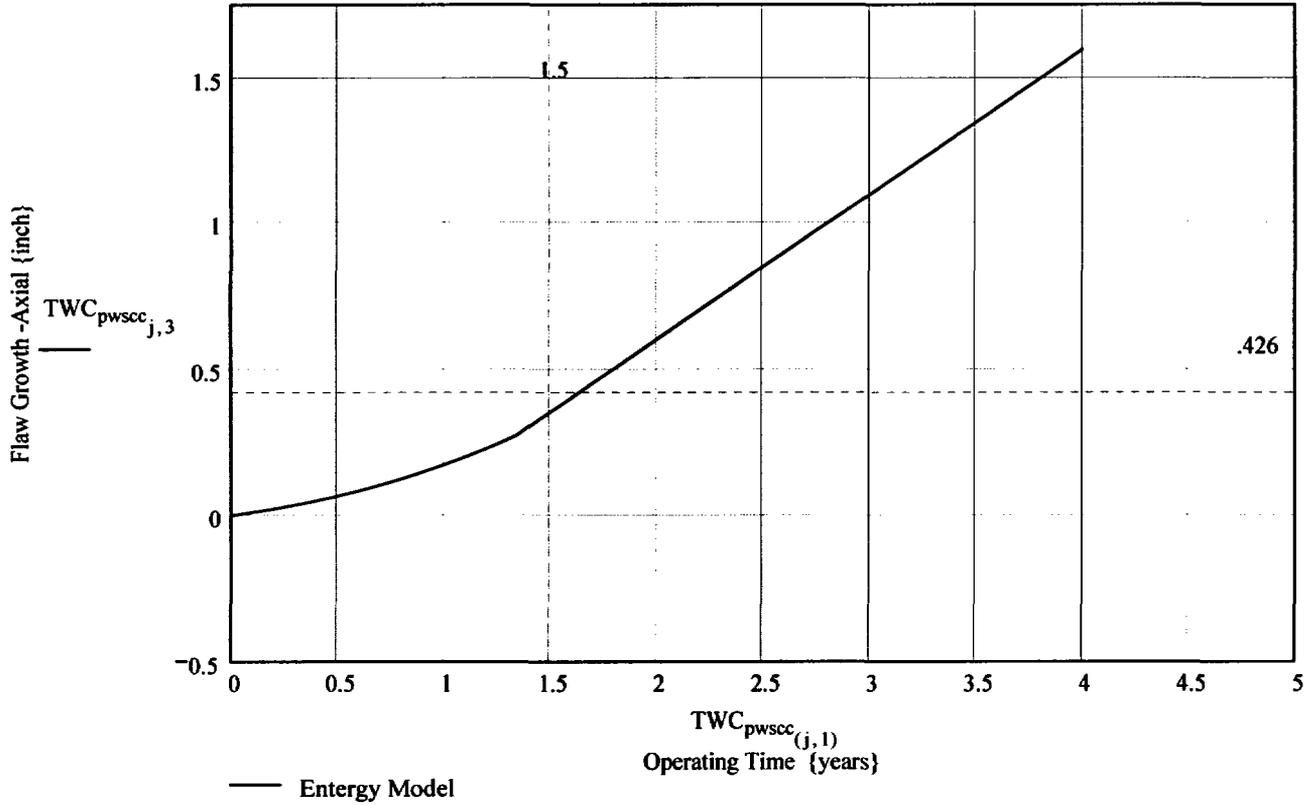
 Sat Aug 09 11:44:49 AM 2003

Developed by:

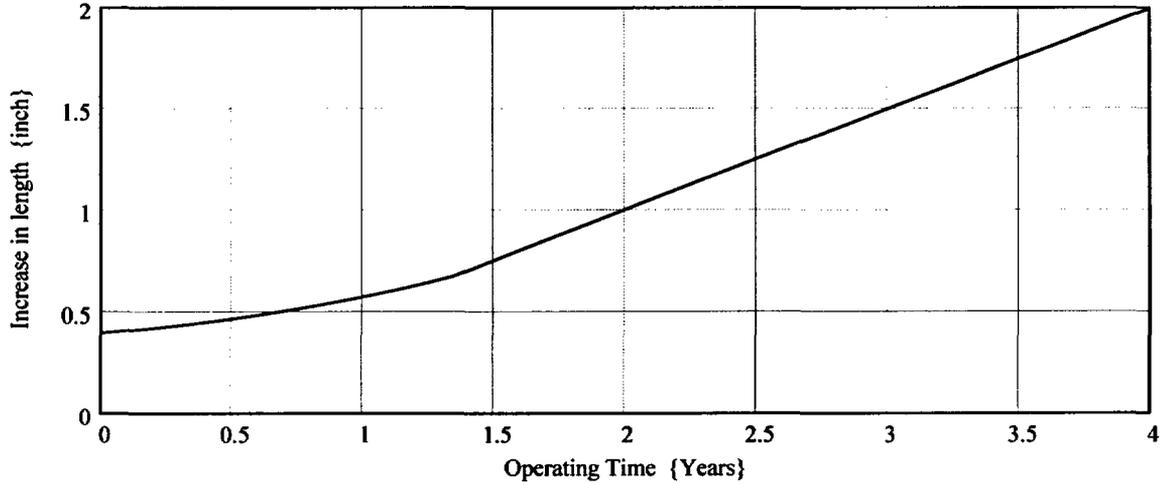
Verified by:

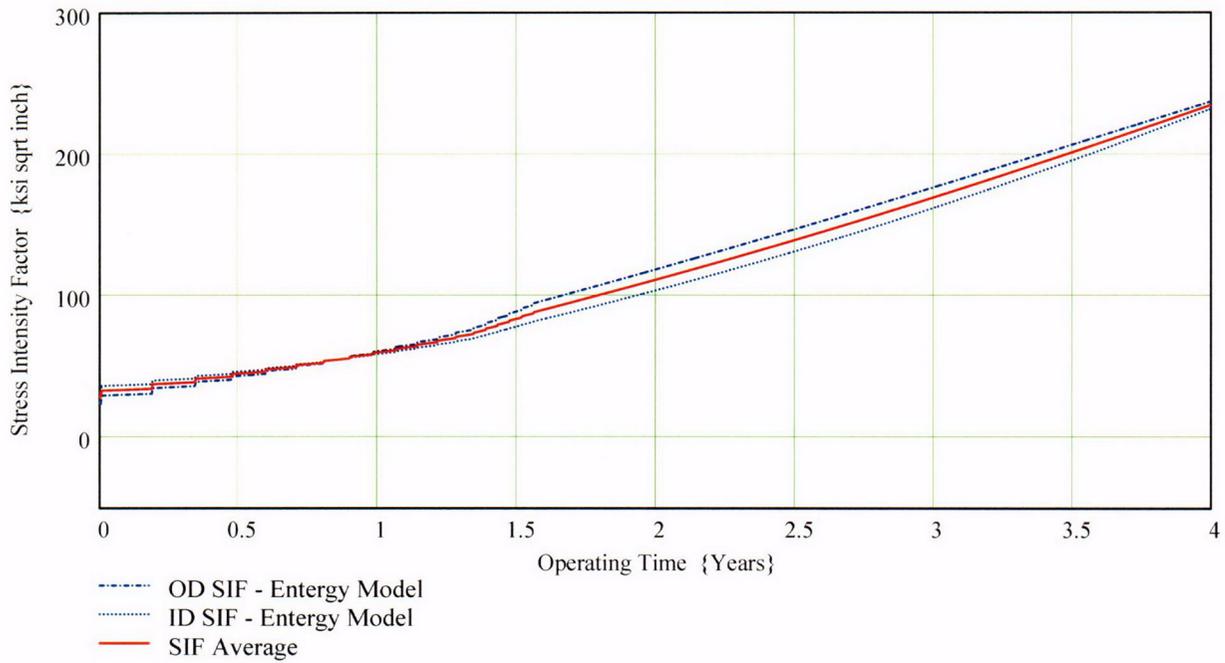
PropLength = 0.426

Flaw Length vs. Time



Increase in Half Length





Developed by:

Verified by:

C40

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

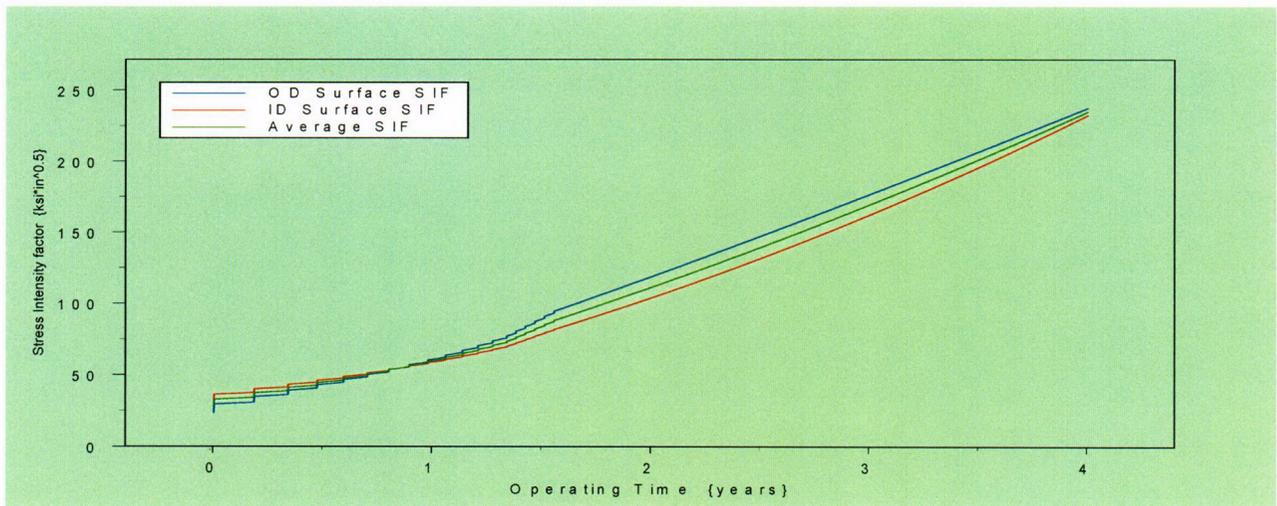
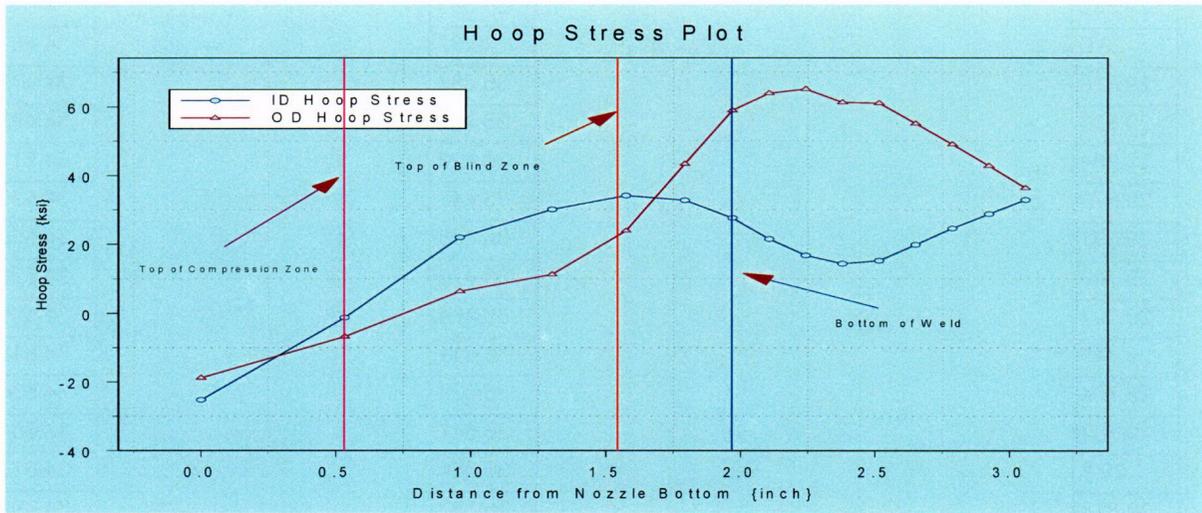
23.707
29.582
29.6
29.618
29.636
29.654
29.672
29.691
29.709
29.727
29.745
29.764
29.782
29.8
29.818
29.837

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

32.37
36.353
36.37
36.388
36.406
36.423
36.441
36.458
36.476
36.494
36.511
36.529
36.547
36.564
36.582
36.6

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

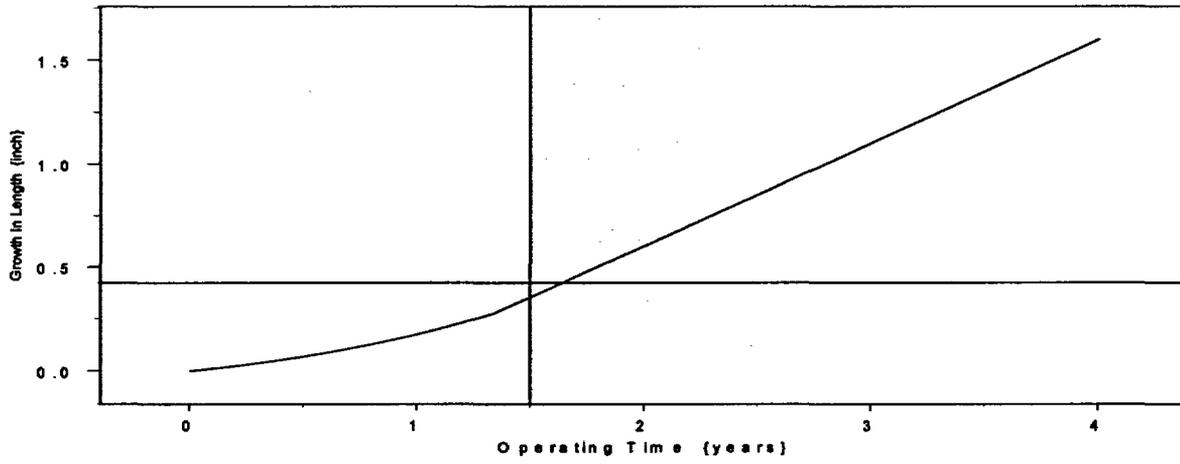
29.373
34.44
34.459
34.479
34.498
34.517
34.537
34.556
34.576
34.595
34.615
34.634
34.654
34.673
34.693
34.712



Developed by:

Verified by:

C41



Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw

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 2

Component : Reactor Vessel CEDM -"8" Degree Nozzle, 67.5 degree from 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 .

OD Surface Flaw

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

Ref_{Point} := 1.544 This is the as-built blind zone providing a propagation length of 0.167 inch; freespan of 0.3274 inch

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

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

UL_{Strs.Dist} := 1.9669 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

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

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

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

$$C_0 := C_{01}$$

75th 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)

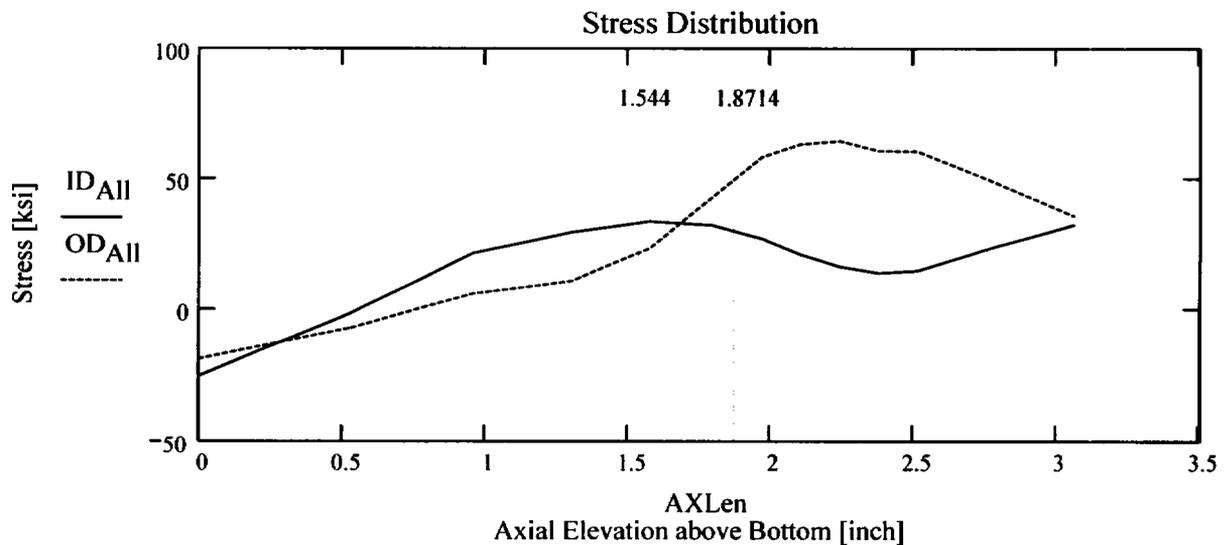
AllData :=

	0	1	2	3	4	5
0	0	-25.24	-22.71	-21.18	-19.87	-18.8
1	0.53	-1.27	-2.96	-4.4	-5.69	-6.83
2	0.96	21.94	17.09	13.36	10.18	6.33
3	1.3	30.02	26.37	22.21	17.12	11.24
4	1.57	34.09	28.09	24.31	22.83	23.83
5	1.79	32.72	28.04	26.61	32.92	43.29
6	1.97	27.6	28.45	30.15	42.18	58.89
7	2.11	21.46	24.92	31.94	46.1	63.87
8	2.24	16.73	22.99	32.59	47.9	65.05
9	2.38	14.34	21.26	33.41	47.85	61.2

AXLen := AllData⁽⁰⁾

ID_{All} := AllData⁽¹⁾

OD_{All} := AllData⁽⁵⁾



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).

$$\text{Data} := \begin{pmatrix} 0 & -25.236 & -22.713 & -21.175 & -19.868 & -18.802 \\ 0.533 & -1.267 & -2.963 & -4.403 & -5.689 & -6.833 \\ 0.959 & 21.942 & 17.089 & 13.361 & 10.182 & 6.327 \\ 1.301 & 30.023 & 26.373 & 22.21 & 17.121 & 11.241 \\ 1.575 & 34.094 & 28.085 & 24.306 & 22.834 & 23.834 \\ 1.794 & 32.716 & 28.035 & 26.605 & 32.916 & 43.289 \\ 1.97 & 27.602 & 28.447 & 30.151 & 42.181 & 58.888 \\ 2.106 & 21.457 & 24.92 & 31.944 & 46.103 & 63.871 \\ 2.242 & 16.731 & 22.988 & 32.591 & 47.9 & 65.049 \end{pmatrix}$$

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

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

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

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

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

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

$$\text{FL}_{\text{Cntr}} := \begin{cases} \text{RefPoint} - c_0 & \text{if Val} = 1 \\ \text{RefPoint} & \text{if Val} = 2 \\ \text{RefPoint} + c_0 & \text{otherwise} \end{cases}$$

Flaw center Location Location above Nozzle Bottom

$$U_{\text{Tip}} := \text{FL}_{\text{Cntr}} + c_0$$

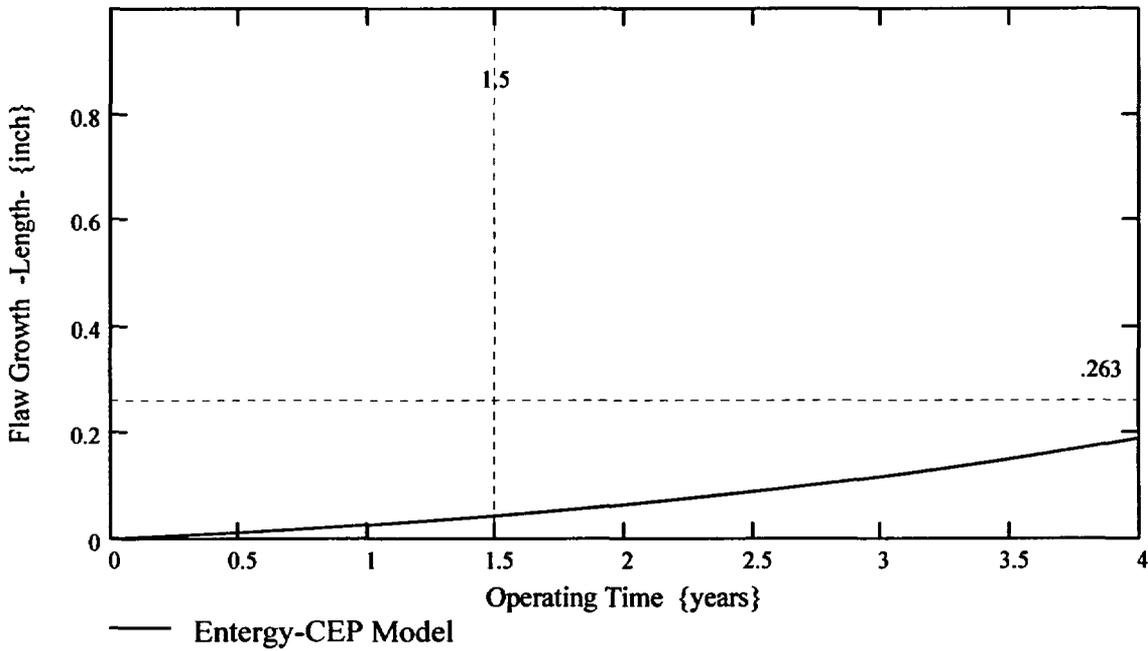
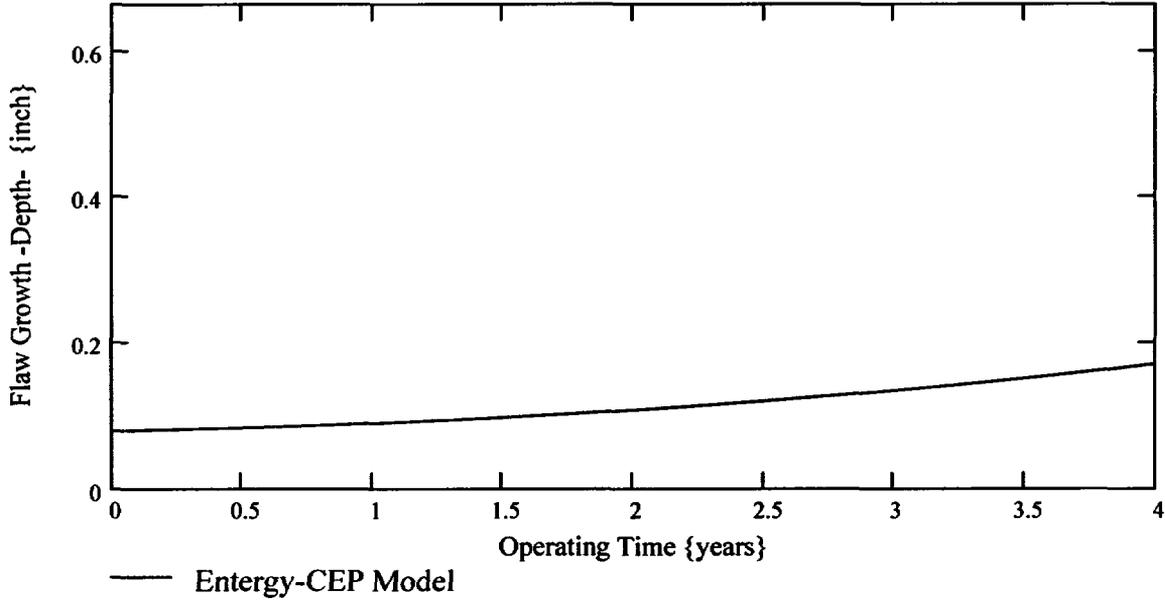
$$\text{IncStrs.avg} := \frac{\text{ULStrs.Dist} - U_{\text{Tip}}}{20}$$

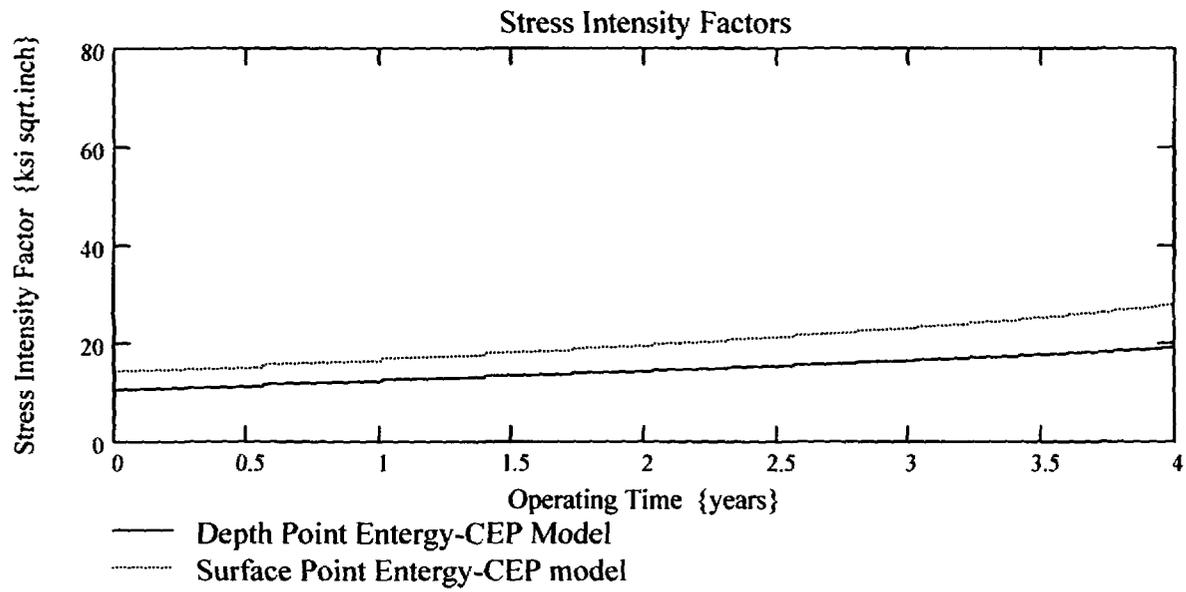
No User Input is required beyond this Point

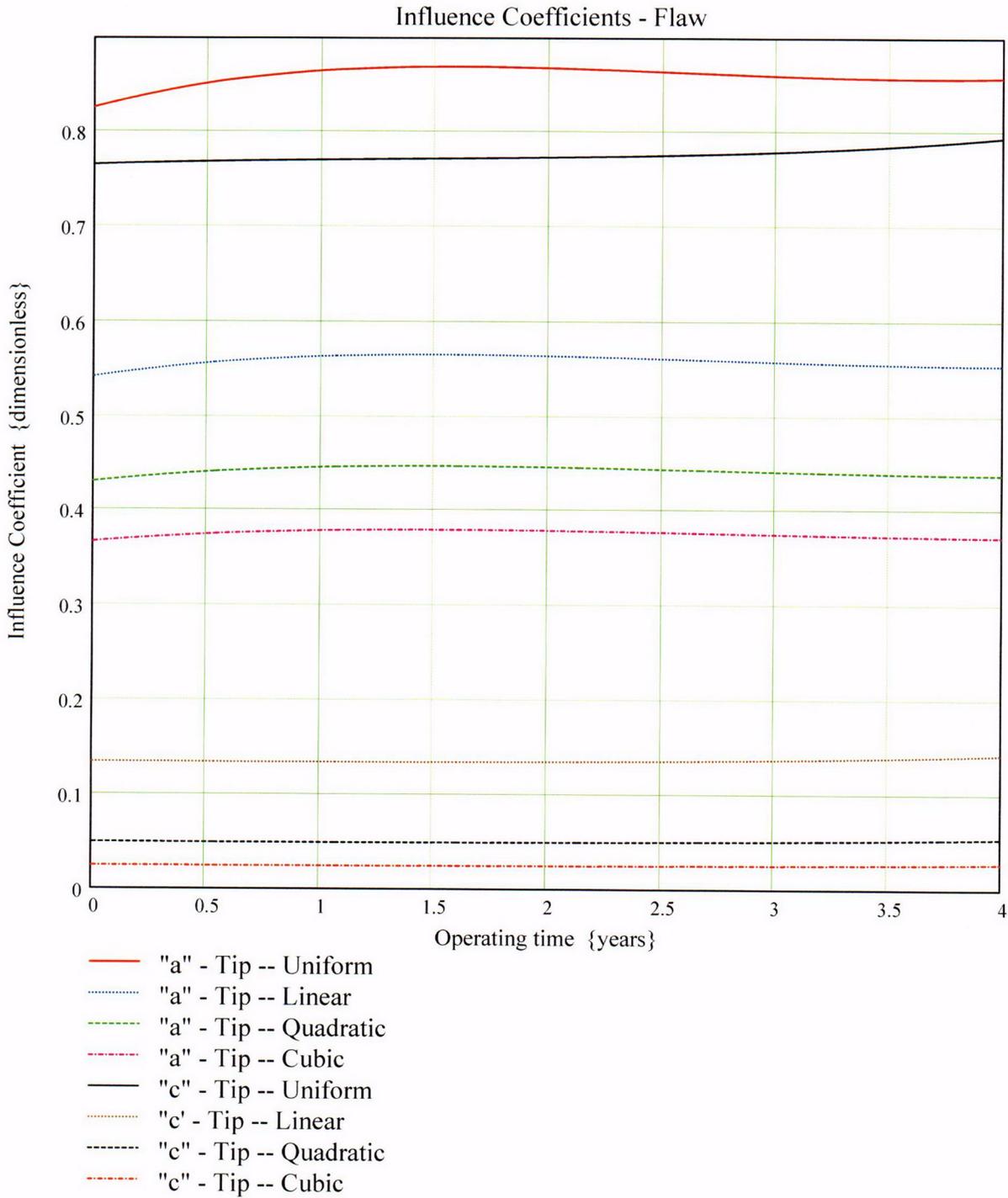
 Sat Aug 09 10:21:18 AM 2003

$$\text{PropLength} = 0.263$$

Flaw Growth in Depth Direction







$$CGR_{\text{sambi}}(k, 8) =$$

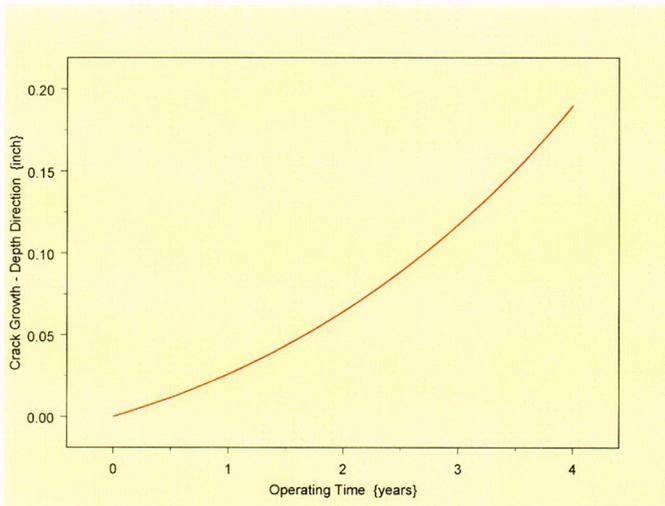
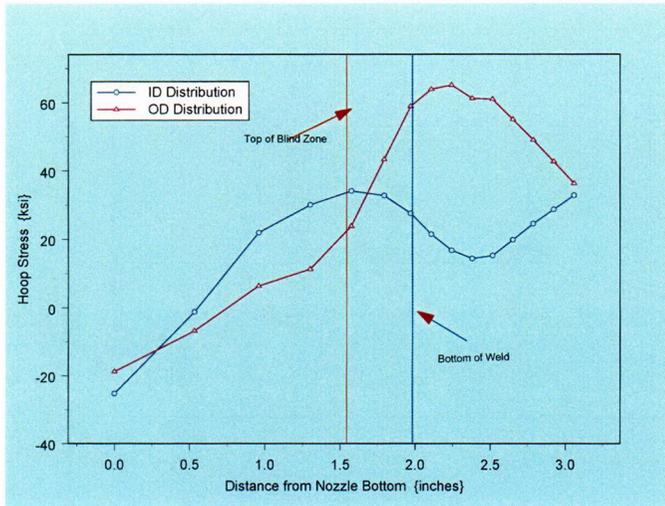
0.827
0.827
0.827
0.827
0.827
0.827
0.828
0.828
0.828
0.828
0.828
0.828
0.828
0.829
0.829
0.829
0.829

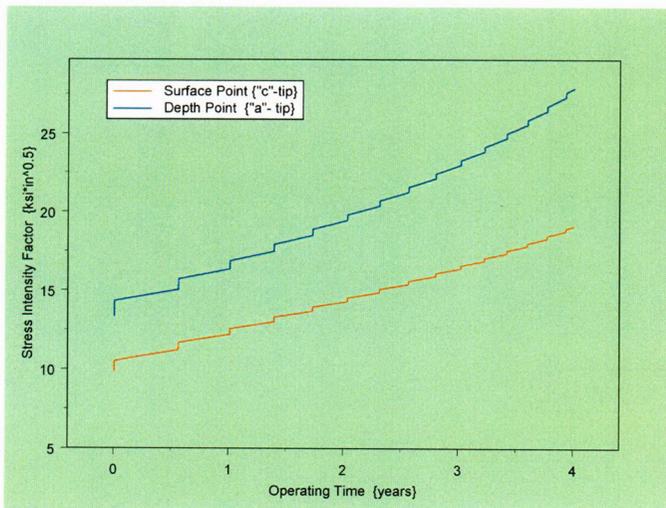
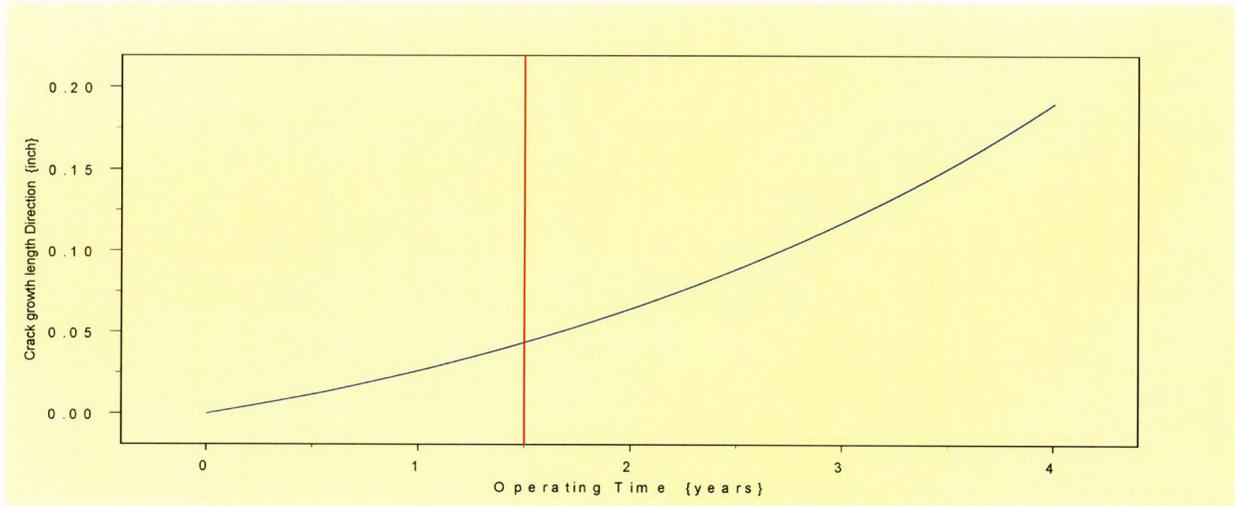
$$CGR_{\text{sambi}}(k, 6) =$$

13.362
14.331
14.334
14.338
14.341
14.345
14.348
14.351
14.355
14.358
14.362
14.365
14.369
14.372
14.376
14.379

$$CGR_{\text{sambi}}(k, 5) =$$

9.842
10.506
10.51
10.513
10.517
10.52
10.524
10.528
10.531
10.535
10.539
10.542
10.546
10.55
10.553
10.557





Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw

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 2

Component : Reactor Vessel CEDM -"28.8" Degree Nozzle, Downhill azimuth,
1.384" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

OD Surface Flaw

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

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

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

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

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

Input Data :-

$L := 0.32$	Initial Flaw Length
$a_0 := 0.661 \cdot 0.12$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth (MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

$$C_0 := C_{01}$$

75th 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)

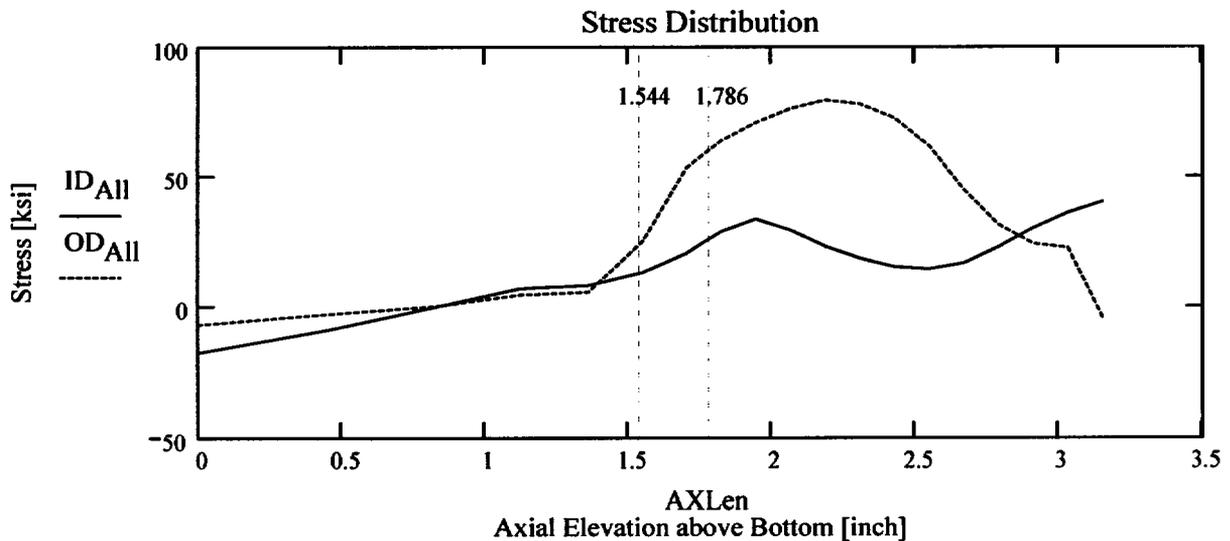
AllData :=

	0	1	2	3	4	5
0	0	-17.41	-13.55	-11.11	-8.88	-6.63
1	0.46	-8.49	-6.31	-4.92	-3.71	-2.54
2	0.83	0.09	0.18	0.11	0.19	0.28
3	1.13	7.03	6.95	6.31	5.21	4.65
4	1.36	8.22	10.95	10.85	9.51	5.65
5	1.55	13.27	16.41	16.06	17.13	25.26
6	1.7	20.63	22.24	25.41	43.58	53.78
7	1.83	29.04	28.83	31.29	53.55	64.08
8	1.95	33.95	30.93	36.41	61.6	71.01
9	2.07	29.59	31.79	40.54	64.61	76.42
10	2.19	23.26	29.74	41.2	64.19	79.63
11	2.31	18.69	27.73	41.29	61.78	78.12
12	2.43	15.39	26.1	40.67	58.6	72.78

AXLen := AllData⁽⁰⁾

ID_{All} := AllData⁽¹⁾

OD_{All} := AllData⁽⁵⁾



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

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

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

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

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

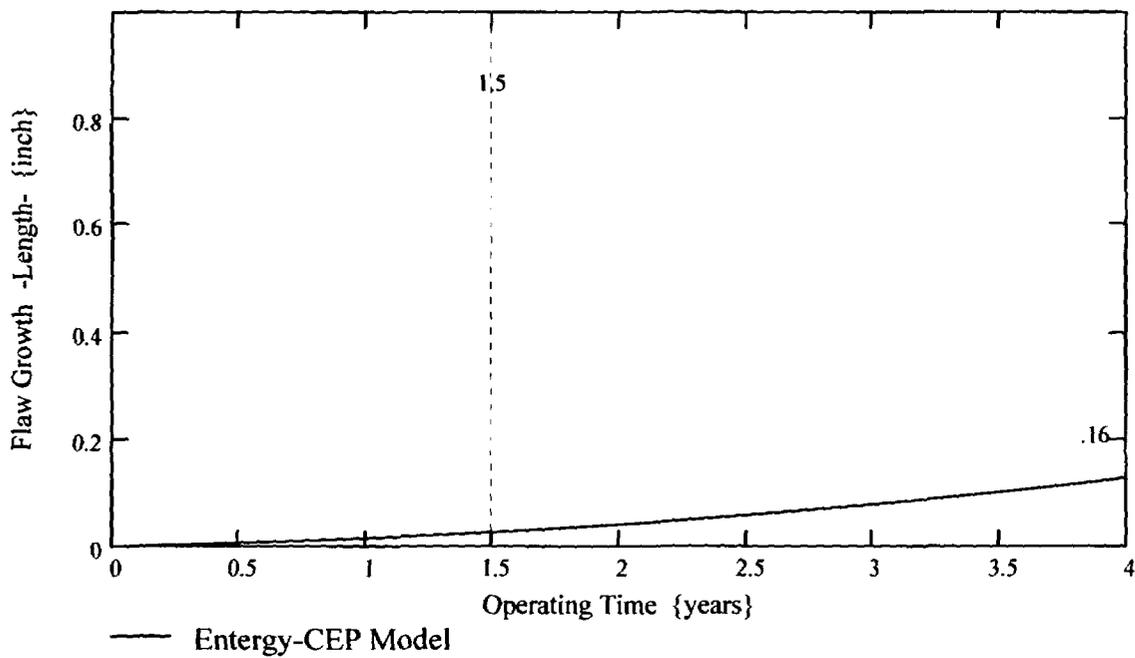
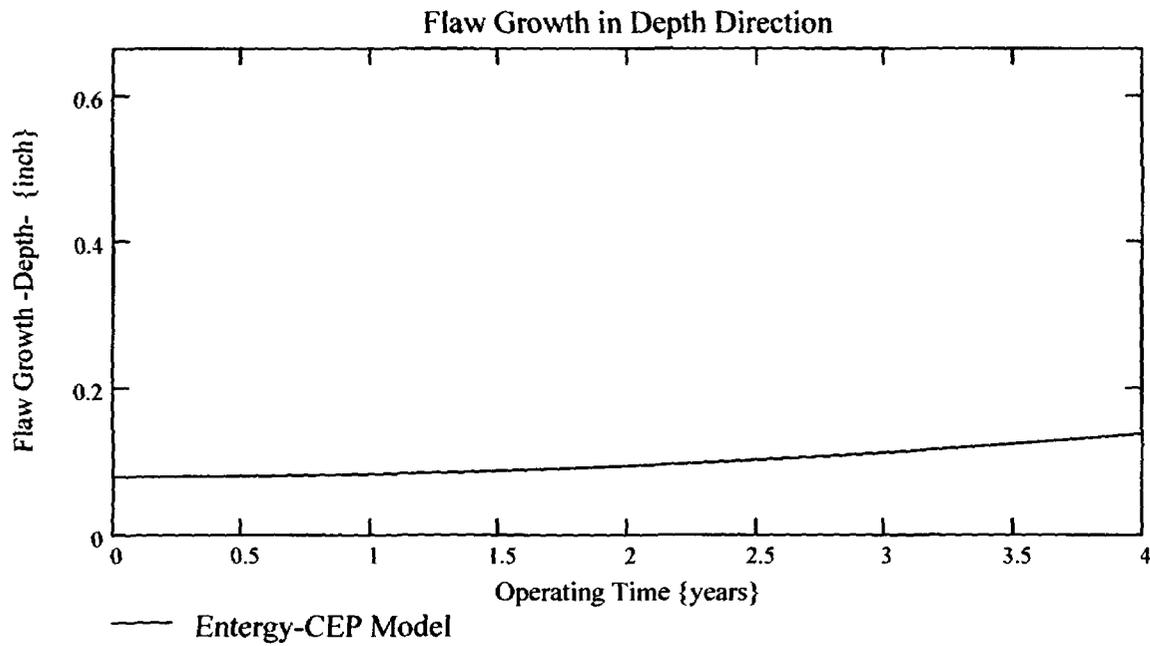
$$U_{Tip} := FL_{Cntr} + c_0$$

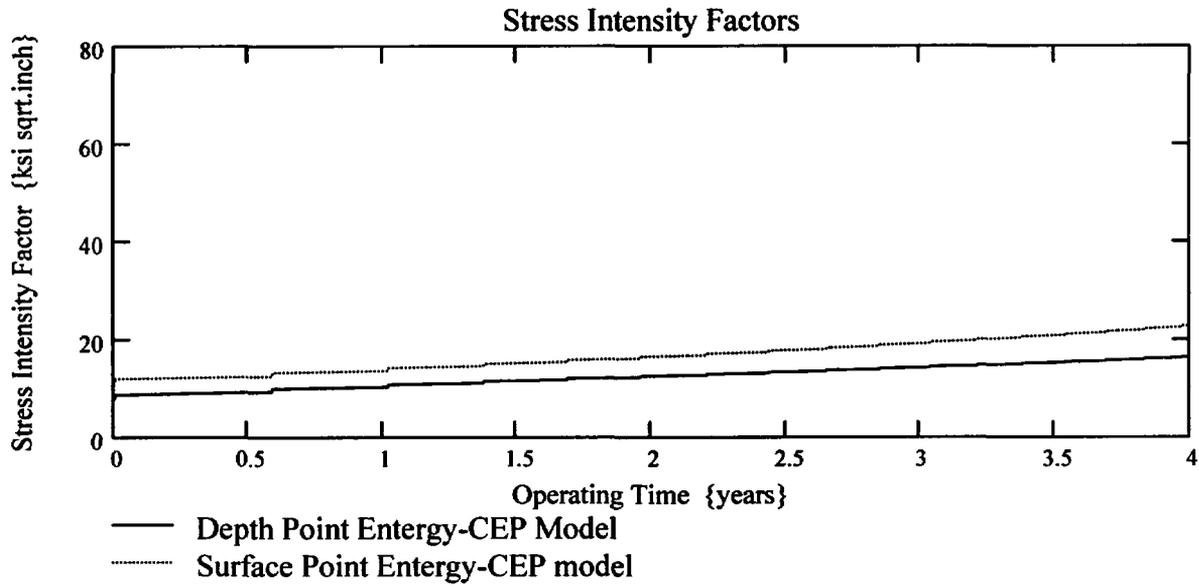
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

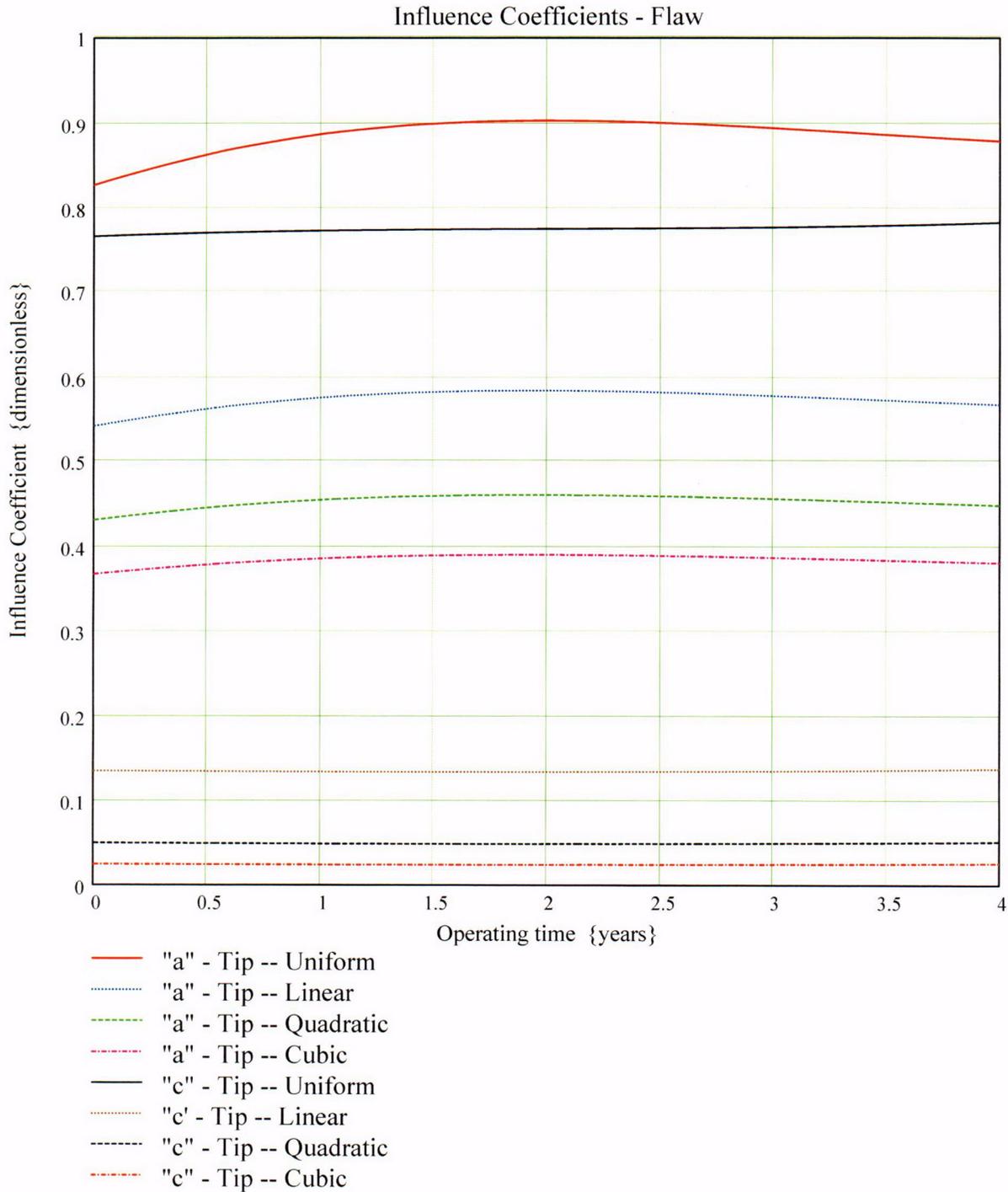
No User Input is required beyond this Point

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$PropLength = 0.16$







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

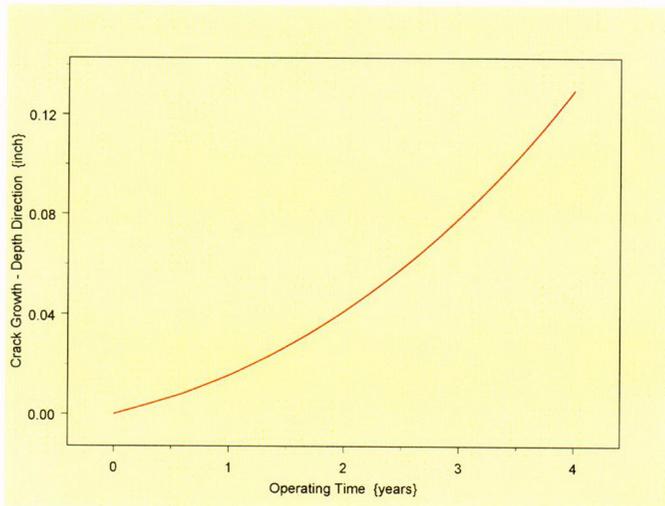
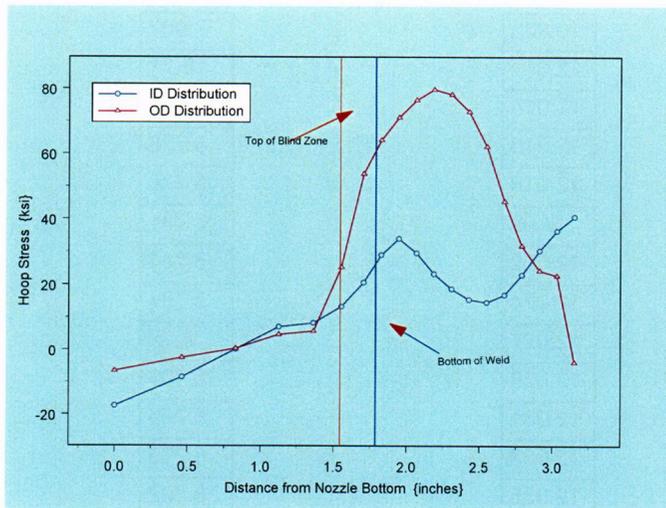
0.827
0.827
0.827
0.827
0.827
0.828
0.828
0.828
0.828
0.828
0.829
0.829
0.829
0.829
0.829
0.829
0.83
0.83

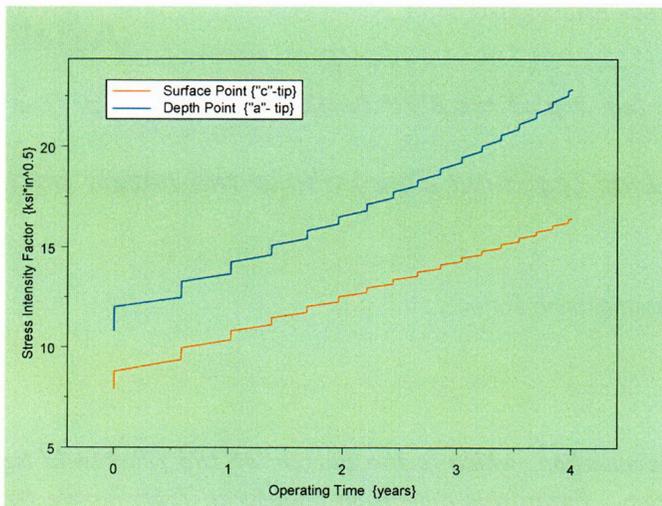
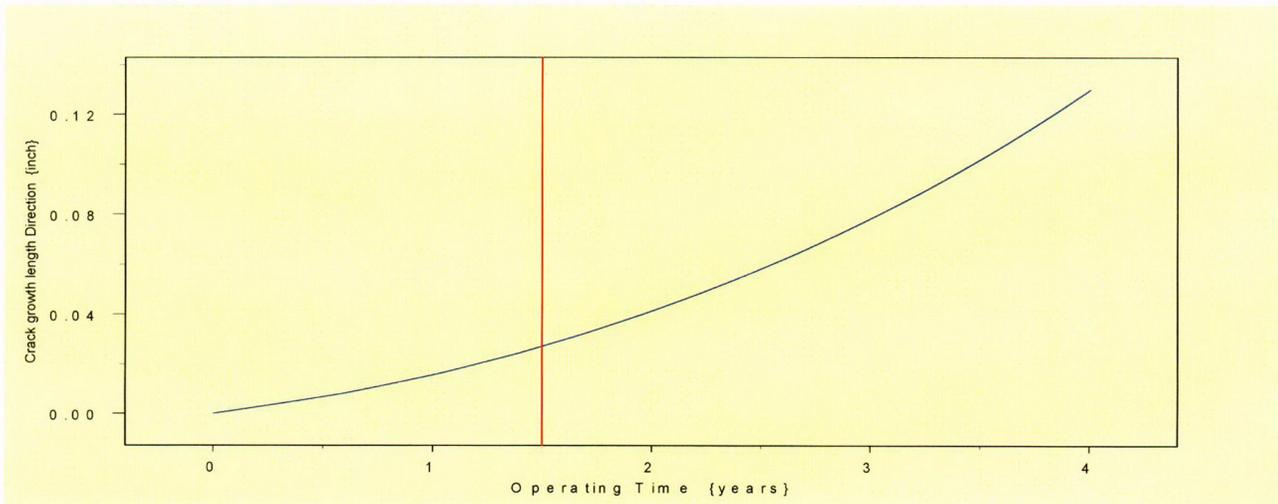
$CGR_{sambi(k,6)} =$

10.823
12.011
12.014
12.016
12.018
12.02
12.022
12.024
12.027
12.029
12.031
12.033
12.035
12.038
12.04
12.042

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

7.907
8.77
8.773
8.776
8.778
8.781
8.784
8.787
8.79
8.793
8.796
8.799
8.802
8.805
8.807
8.81





Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadേശam

Verified by: B. C. Gray

Note : Only for use when $R_{outside}/t$ is between 2.0 and 5.0 (Thickwall 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 2

Component : Reactor Vessel CEDM -"28.8" Degree Nozzle, 22.5 degree from Downhill Azimuth, Augmented
Analysis 1.544 inch above Nozzle Bottom

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

Through Wall Axial Flaw

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

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

BZ := 1.544

This is the normal blind zone

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

UL_{Strs}.Dist := 1.8317

Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance
above nozzle bottom)

Input Data :-

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

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

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

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

$$R_i := \frac{id}{2}$$

$$t := R_o - R_i$$

$$R_m := R_i + \frac{t}{2}$$

$$CF_{inhr} := 1.417 \cdot 10^5$$

$$C_{blk} := \frac{Tim_{opr}}{I_{lim}}$$

$$Prnt_{blk} := \left| \frac{I_{lim}}{50} \right|$$

$$l := \frac{L}{2}$$

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)

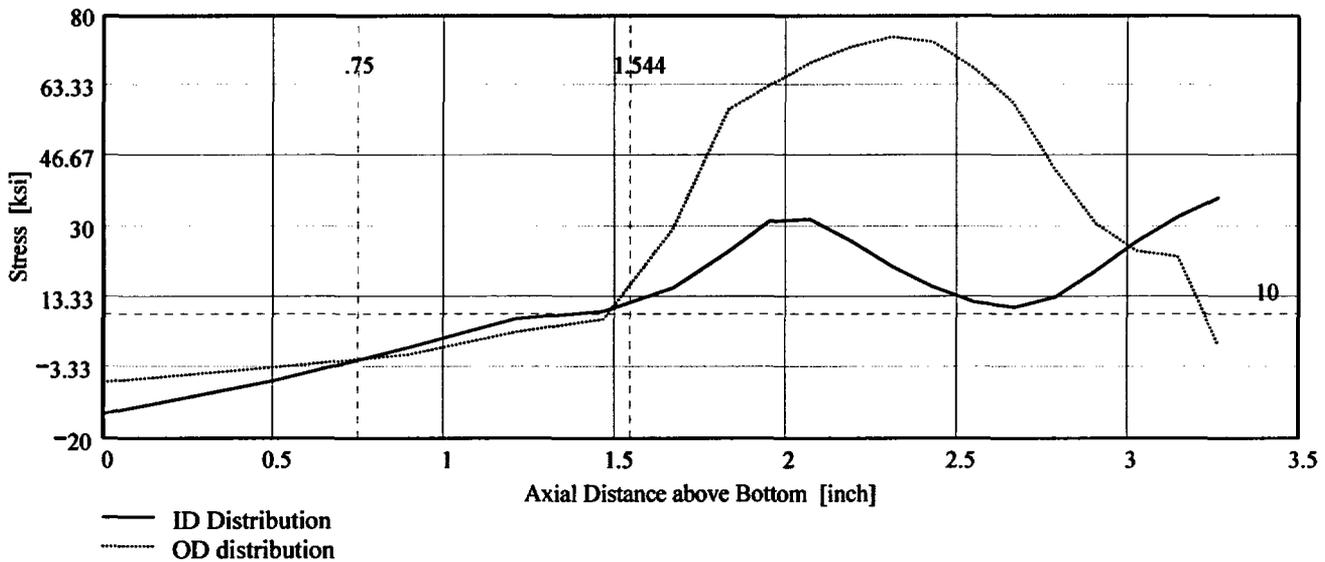
DataAll :=

	0	1	2	3	4	5
0	0	-14.21	-11.51	-9.79	-8.24	-6.72
1	0.5	-6.49	-5.19	-4.42	-3.8	-3.18
2	0.89	1.55	1.02	0.56	0.26	-0.08
3	1.21	8.43	7.98	7.2	6.19	5.29
4	1.46	10.25	12.71	12.22	11.35	8.36
5	1.67	15.66	18.34	18.7	20.84	29.7
6	1.83	24.32	24.53	26.71	44.52	57.73
7	1.95	31.5	28.7	31.23	53.02	63.55
8	2.07	31.98	30.11	35.63	59.45	69.03
9	2.19	26.83	29.95	38.37	61.12	72.69
10	2.31	20.84	27.29	38.5	59.95	75.04
11	2.43	15.99	24.67	38.16	58.17	73.85

AllAxI := DataAll⁽⁰⁾

AllID := DataAll⁽¹⁾

AllOD := DataAll⁽⁵⁾



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-Color) then insert the same to the right of the Mathcad Equals sign below (paste symbol).

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

Axl := Data⁽⁰⁾

ID := Data⁽¹⁾

OD := Data⁽⁵⁾

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

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

FL_{Cntr} := BZ - 1

Flaw Center above Nozzle Bottom

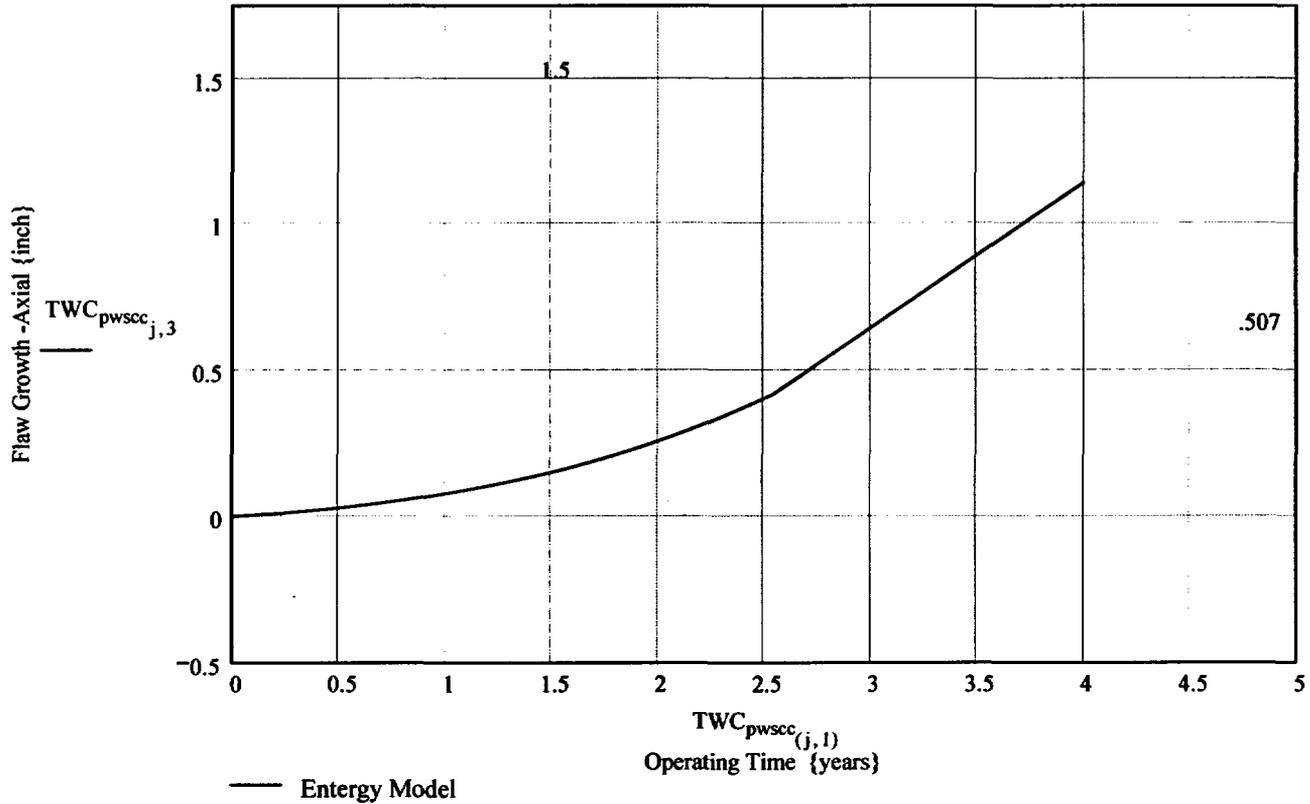
$$\text{IncStrs.avg} := \frac{\text{ULStrs.Dist} - \text{BZ}}{20}$$

No User Input required beyond this Point

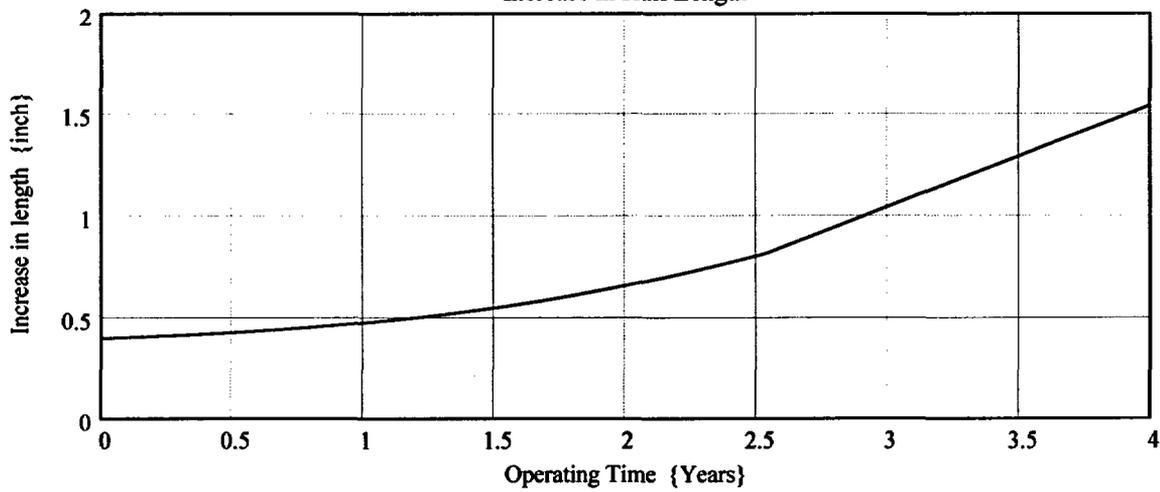
 Sat Aug 09 11:44:49 AM 2003

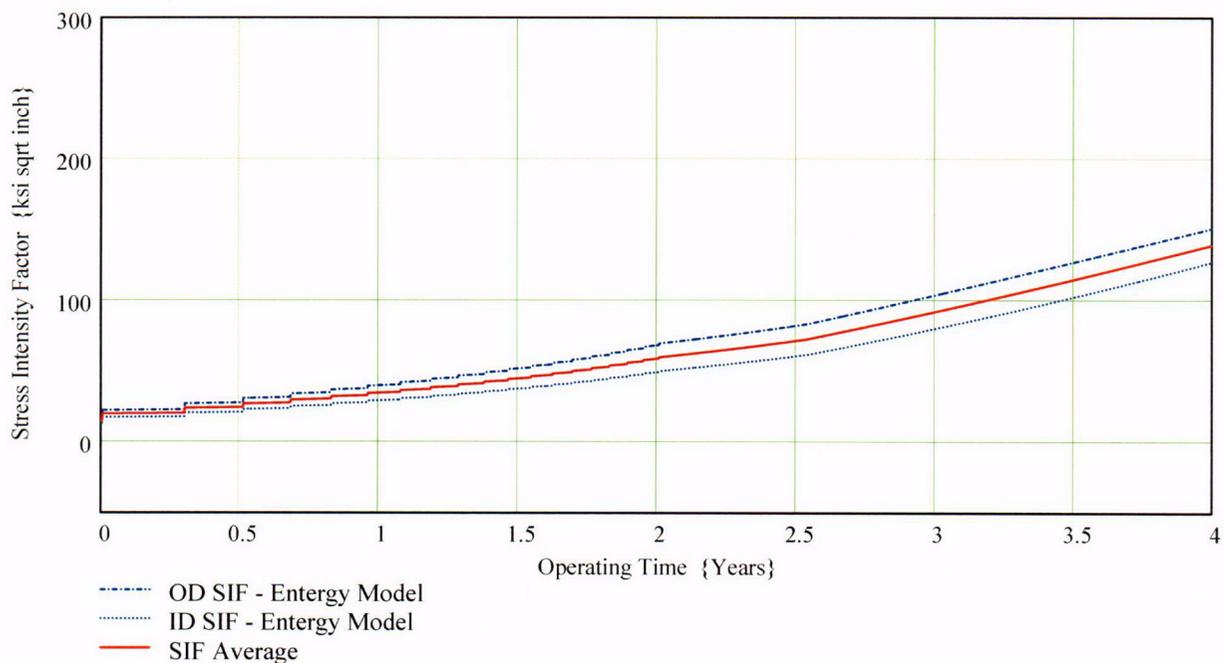
PropLength = 0.288

Flaw Length vs. Time



Increase in Half Length





Developed by:

Verified by:

C48

$TWC_{pwscc}_{(j,6)} =$

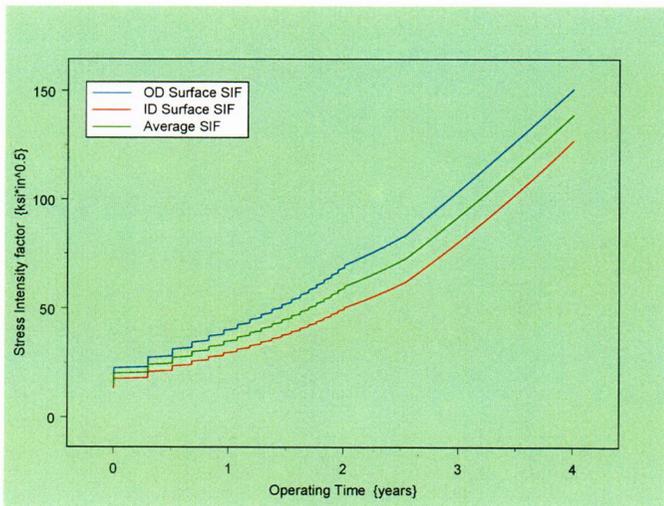
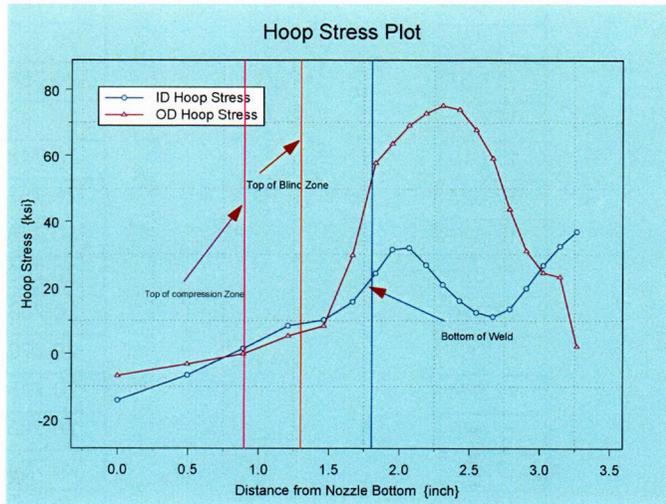
16.053
22.574
22.579
22.585
22.59
22.595
22.6
22.605
22.611
22.616
22.621
22.626
22.631
22.637
22.642
22.647

$TWC_{pwscc}_{(j,7)} =$

13.281
17.602
17.606
17.61
17.615
17.619
17.623
17.627
17.631
17.636
17.64
17.644
17.648
17.652
17.657
17.661

$TWC_{pwscc}_{(j,8)} =$

15.158
20.728
20.733
20.738
20.743
20.748
20.753
20.758
20.763
20.768
20.773
20.778
20.783
20.788
20.793
20.798



Developed by:

Verified by:

C49

