Through-Wall Axial Crack Model

Stress Corrosion Crack Growth Analysis Throughwall flaw

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

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

Refrences :

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

Arkansas Nuclear One Unit 2

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

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

Through Wall Axial Flaw

The same first part as the previous attachments. (see Attachment 1 of this Appendix)

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

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

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

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

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

Only two inputs one defining the location of the reference line {BZ} and the other the bottom of the weld {$UL_{Strs.Dist}$} are needed. The flaw description is not needed for this crack type, because the flaw upper tip is placed at the reference line (i.e. at the top of the blind zone)

Input Data :-

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

The input data is similar to that in Attachment 1, except that the crack (flaw) length is based on stress distribution consideration. The flaw length determination is made by locating the lower tip of the flaw at a location where the average stress ([ID + OD]/2} is about 10 ksi. In this manner the lower tip is at a location where no PWSCC growth towards the bottom of the nozzle is possible.

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

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

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

Determination of constants. Note the conversion for crack growth rate {da/dt} from metric (m/sec) to English units (inch/hr) is obtained by the factor defined as CF_{inhr}.

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

Stress Input Data

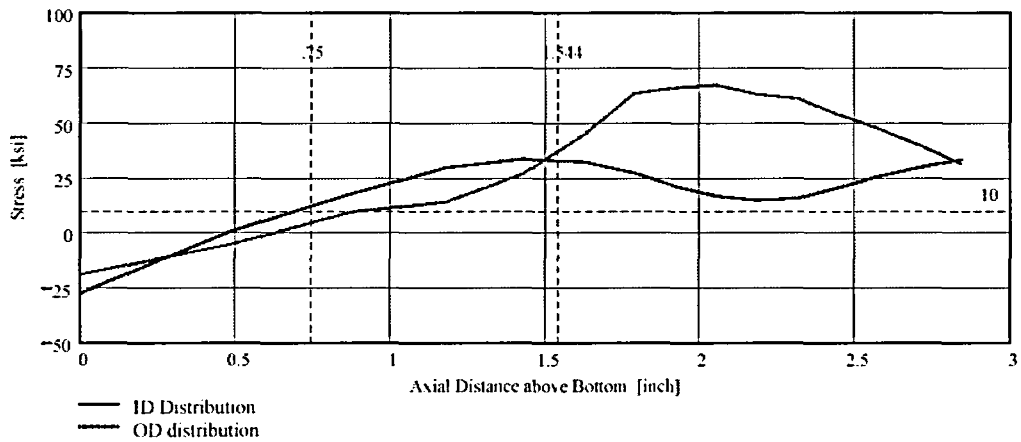
Import the Required data from applicable Excel spread Sheet. The column designations are as follo
Cloumn "0" = Axial distance from Minimum to Maximum recorded on the data sheet (inches)
Column "1" = ID Stress data at each Elevation (ksi)
Column "5" = OD Stress data at each Elevation (ksi)

$Data_{All} :=$

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

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

The nodal stress information is fully imported from the appropriate Excel spread sheet provided by Dominion Engineering. However, only the ID and OD distributions are required for this analysis. The stress input for this calculation uses the applied stress as defined by Membrane and bending components. These components are dependent on the stresses at the ID and OD surface. The model used uses the OD surface as the reference surface and the same method is followed in the calculation for this model.



The ID and OD distribution are plotted. The blind zone is located. The upper flaw tip is at the blind zone location and the lower flaw tip is located close to the region where the average stress (membrane) is about 10 ksi.

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

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

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

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

The Data matrix is obtained in a similar manner as described in Attachment 1 of this appendix. The regression is only performed on the ID and OD distributions as these are the only distributions required for the computation.

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

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

Location of the crack center and the segment height are defined. Once again twenty (20) segments are utilized.

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

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

$Loc_0 := FL_{Cntr} - L$

$i := 1 .. N + 3$

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

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

$SID_i := R_{ID_3} + R_{ID_4} \cdot Loc_i + R_{ID_5} \cdot (Loc_i)^2 + R_{ID_6} \cdot (Loc_i)^3$ $SOD_i := R_{OD_3} + R_{OD_4} \cdot Loc_i + R_{OD_5} \cdot (Loc_i)^2 + R_{OD_6} \cdot (Loc_i)^3$

In a similar manner to Attachment 1 of this appendix, the ID and OD stress profiles along the nozzle length are determined.

$j := 1 .. N$

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

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

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

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

The moving average stress, the membrane (σ_m) containing the internal pressure (P_{Int}) and the bending component (σ_b) are computed.

Membrane Stress: $\sigma_m =$

	0
0	0
1	23.795
2	27.339
3	29.561
4	31.121
5	32.304
6	33.253
7	34.044
8	34.727
9	35.33
10	35.875
11	36.374
12	36.839
13	37.276
14	37.69
15	38.086

Bending Stress: $\sigma_b =$

	0
0	0
1	-3.536
2	-1.932
3	-0.851
4	-0.028
5	0.649
6	1.238
7	1.771
8	2.266
9	2.735
10	3.186
11	3.626
12	4.058
13	4.485
14	4.91
15	5.333

OD Stress: $S_{od} =$

	0
0	0
1	18.023
2	23.172
3	26.475
4	28.858
5	30.719
6	32.256
7	33.58
8	34.757
9	35.83
10	36.826
11	37.766
12	38.662
13	39.526
14	40.365
15	41.185

ID Stress: $S_{id} =$

	0
0	0
1	25.096
2	27.036
3	28.176
4	28.914
5	29.42
6	29.779
7	30.039
8	30.226
9	30.361
10	30.453
11	30.513
12	30.546
13	30.555
14	30.545
15	30.518

Tabular display of the various stress components are printed to ensure that the regression and the moving average methods are functioning properly.

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

Allowable Propagation Length {$Prop_{Length}$}is defined as the difference between the bottom of weld elevation and the blind zone (upper flaw tip location) elevation. Since the Flaw Center {FL_{Cntr}} is located at half flaw length below the blind zone the second term within the parenthesis is the location of the blind zone.

$$TWC_{pwscc} := \left| \begin{array}{l} i \leftarrow 0 \\ l_0 \leftarrow l \\ NCB_0 \leftarrow C_{blk} \\ \text{while } i \le l_{lim} \end{array} \right.$$

Start and initialization of the recursive loop. The crack dimension used in the analysis is the half crack length defined as {*l*}. Therefore the initial crack size is set to the initial crack half length {l_0}.

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

Assignment of the applied stress component. This example shows the membrane component $\{\sigma_m\}$ for eleven segments. In the model all twenty (20) segments are considered and similar assignment is made for the bending component $\{\sigma_b\}$. The assignments are based on the current flaw location and the boundaries for the segment. This assignment is similar to the assignments described in Attachment 1 of this appendix.

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

Definition of the Crack parameter with respect to cylinder geometry (mean radius and thickness). This parameter accommodates the effect of cylinder geometry on the SIF.

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

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

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

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

Determination of the SICF for the two component stress loadings based on current crack half length and cylinder geometry (using the non dimensional flaw length λ.

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

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

Calculation of SIF for an equivalent flat plate geometry for the two applied stress conditions (membrane and bending).

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

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

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

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

Calculation of the SIF at the ID and OD for the two component stresses. Note the SICF factors are used as multipliers to the equivalent plate solutions determined above in calculating the SIF for the cylinder geometry.

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

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

The applied SIF at the ID and OD are determined by the sum of the sub-component SIF for the two conditions (membrane and bending).

$$\left| \begin{array}{l} K_{App_i} \leftarrow \dfrac{K_{AppOD_i} + K_{AppID_i}}{2} \\ K_{\alpha_i} \leftarrow K_{App_i} \cdot 1.099 \\ K_{\alpha_i} \leftarrow \left| \begin{array}{ll} 9.0 & \text{if } K_{\alpha_i} \le 9.0 \\ K_{\alpha_i} & \text{otherwise} \end{array} \right. \end{array} \right.$$

The applied SIF used for determining the crack growth is taken as the arithmetic average of the ID and OD SIF. The second statement converts the SIF from English units to metric units. The third statement ensures that the threshold criterion is appropriately satisfied. This conditional statement is used to prevent obtaining an imaginary value for the crack growth rate {da/dt} by a negative value for the ($SIF-SIF_{Threshold}$) term. Therefore this conditional statement ensures that the difference is zero (0) when the applied SIF is below the threshold value.

$$\left| \begin{array}{l} D_{len_i} \leftarrow C_0 \cdot \left(K_{\alpha_i} - 9.0\right)^{1.16} \\ D_{length_i} \leftarrow \left| \begin{array}{ll} D_{len_i} \cdot CF_{inhr} \cdot C_{blk} & \text{if } K_{\alpha_i} \le 80.0 \\ 4 \cdot 10^{-10} \cdot CF_{inhr} \cdot C_{blk} & \text{otherwise} \end{array} \right. \end{array} \right.$$

Calculation of crack growth rate {da/dt} and the crack growth within a time block. The crack growth rate is calculated in metric units (m/sec) and the crack growth in English units by use of the conversion factor {CF_{inhr}}

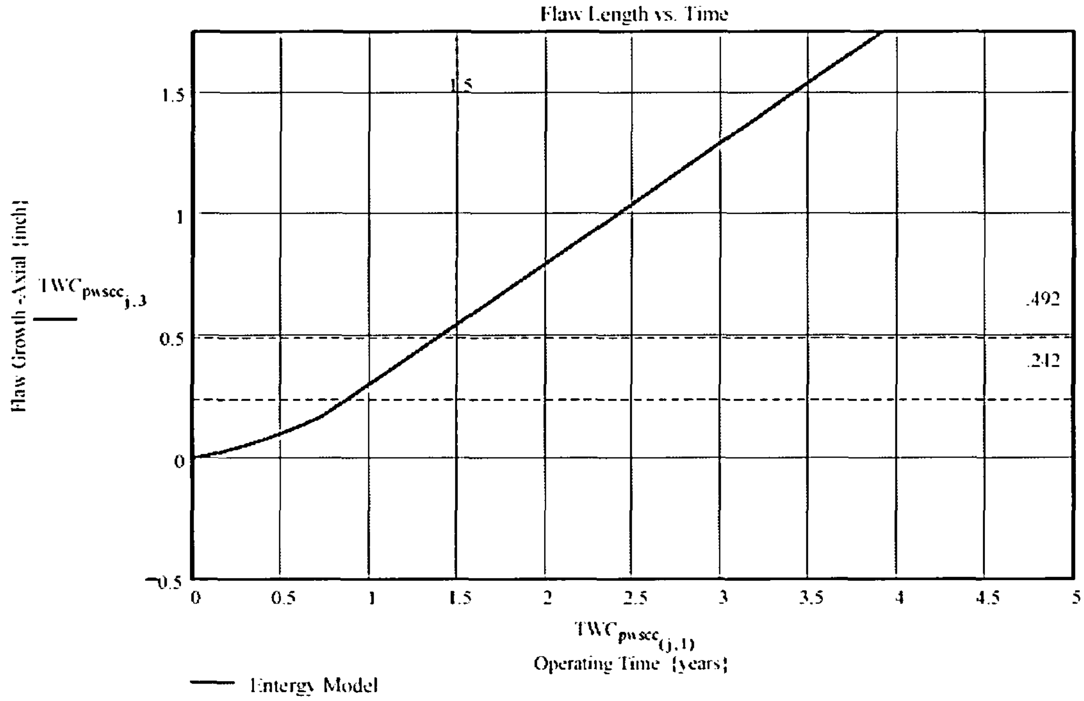
$$\left| \begin{array}{l} output_{(i,0)} \leftarrow i \\ output_{(i,1)} \leftarrow \dfrac{NCB_i}{365 \cdot 24} \\ output_{(i,2)} \leftarrow \lambda_i \end{array} \right.$$

Output statements to store variables required for loop operation and those for evaluation of time dependent crack growth. This part is similar to the same step described in Attachment 1 of this appendix.

$$\begin{array}{|l} i \leftarrow i + 1 \\ l_i \leftarrow l_{i-1} + D_{length_{i-1}} \\ NCB_i \leftarrow NCB_{i-1} + C_{blk} \end{array}$$

Loop increment and redefinition of parameters for the next recursive loop calculation.

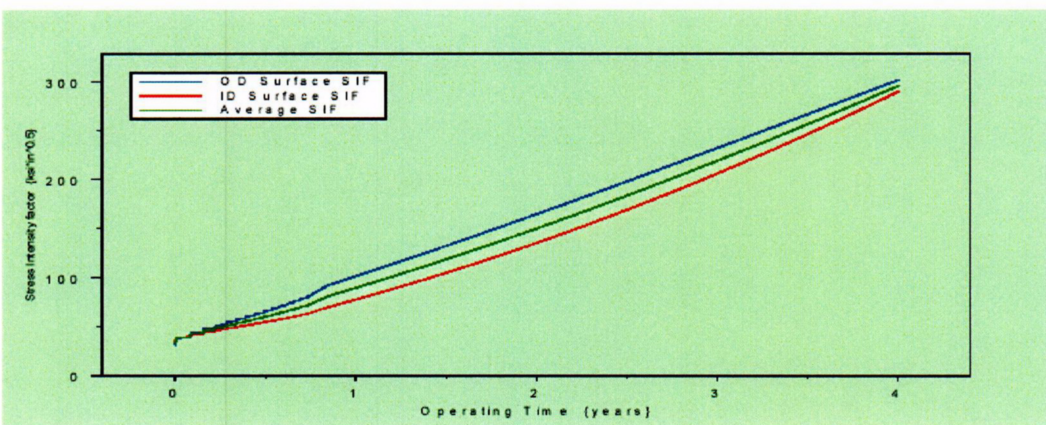
$PropLength = 0.242$



Typical Mathcad graphics used to compute the impact of crack growth. Note the allowable propagation length information in the top left corner. In this example the crack growth in one cycle exceeds the allowable propagation length, therefore the postulated flaw would reach the bottom of the weld within one operating cycle (1.5 years).

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

Typical tabular output to ensure proper functioning of the model.



Typical Axum plot for use in the report. This is similar to Attachment 1 of this appendix.

C01

Appendix C

Mathcad worksheet for CEDM Deterministic Fracture Mechanics Analyses

This Appendix has 33 Attachments. Attachment 31 to 33 contains the additional evaluations for the 49.7° nozzle at the nozzle bottom.

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

Waterford Steam Electric Station Unit 3

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

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

The first Required input is a location for a point on the tube elevation to define the point of interest (e.g. The top of the Blind Zone, or bottom of fillet weld etc.). This reference point is 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.

$Ref_{Point} \equiv 1.544$

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

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

$Val \equiv 2$

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.

$UL_{Strs.Dist} \equiv 2.573$ Upper axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom)

The highlighted region below remians constant for WSES-3 and should not be changed.

Input Data :-

$L := 32$	Initial Flaw Length
$a_0 := 0.04627$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth (MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg F

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

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

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

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

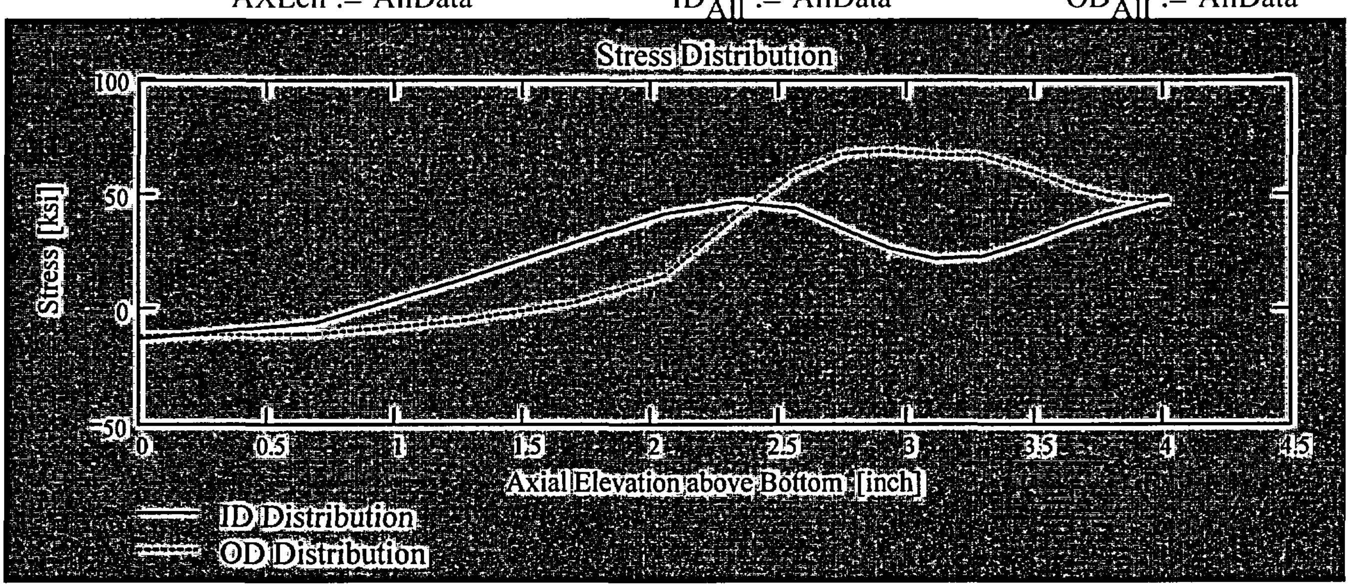
Stress Input Data

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

AllData :=

	0	1	2	3	4	5
0	0	-12.8	-11.86	-11.69	-11.59	-11.36
1	0.7	-5.76	-6.99	-8.36	-9.65	-10.65
2	1.25	12.52	6.55	0.3	-3.05	-5.05
3	1.7	28.96	26.39	19.22	11.6	2.76
4	2.06	41.81	37.11	30.32	22.64	14.56
5	2.34	46.95	39.38	33.87	34.26	41.31
6	2.57	44.29	40.27	38.75	48.68	59.98
7	2.75	35.28	36.13	40.48	54.52	68.35
8	2.94	26.74	32.32	40.93	56.86	69.51
9	3.12	22.01	29.24	40.65	55.17	67.67
10	3.3	23.06	28.56	39.67	53.42	67.54
11	3.48	29.39	30.62	38.89	49.24	61.16

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



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

$$Data := \begin{pmatrix} 0 & -12.796 & -11.857 & -11.688 & -11.588 & -11.36 \\ 0.696 & -5.757 & -6.987 & -8.359 & -9.647 & -10.654 \\ 1.253 & 12.517 & 6.554 & 0.301 & -3.045 & -5.052 \\ 1.699 & 28.961 & 26.385 & 19.217 & 11.596 & 2.764 \\ 2.057 & 41.814 & 37.112 & 30.325 & 22.635 & 14.562 \\ 2.343 & 46.95 & 39.385 & 33.873 & 34.257 & 41.315 \\ 2.572 & 44.292 & 40.273 & 38.751 & 48.684 & 59.975 \\ 2.754 & 35.285 & 36.135 & 40.478 & 54.515 & 68.35 \\ 2.935 & 26.742 & 32.322 & 40.928 & 56.857 & 69.509 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location above Nozzle Bottom

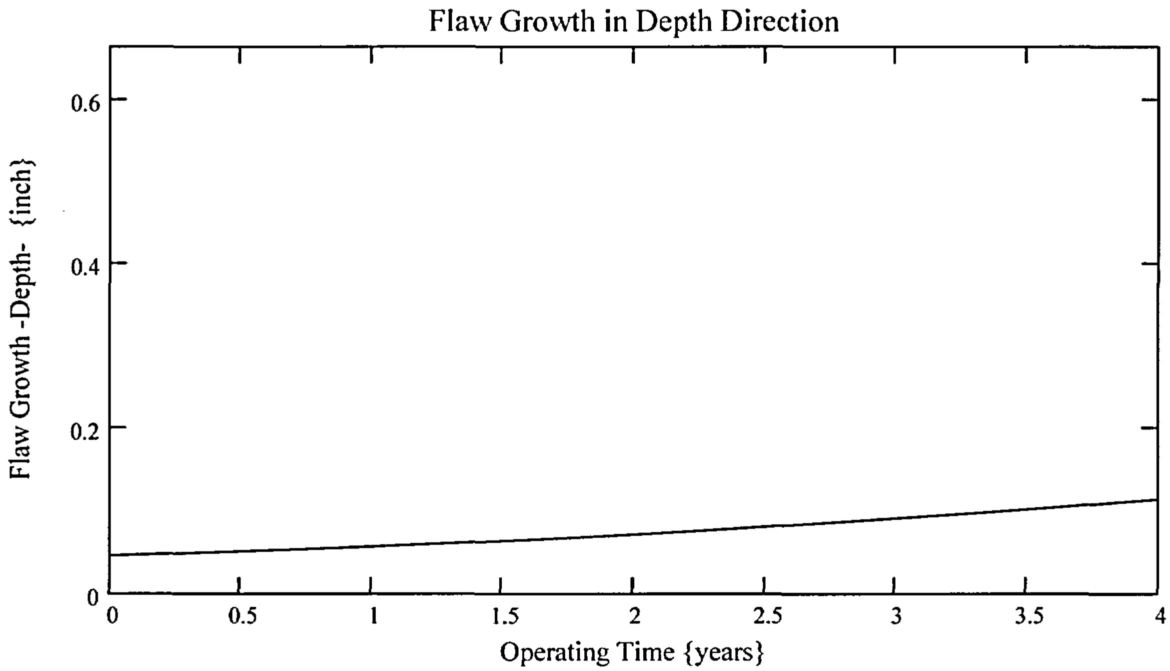
$$U_{Tip} := FL_{Cntr} + c_0$$

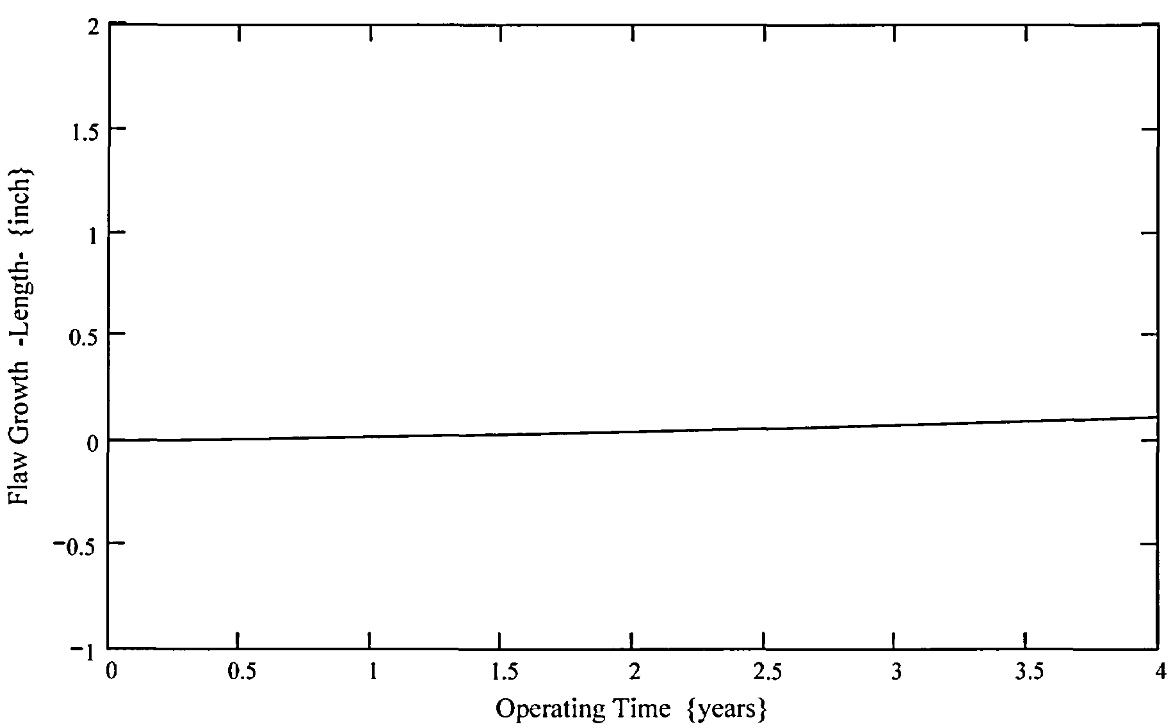
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

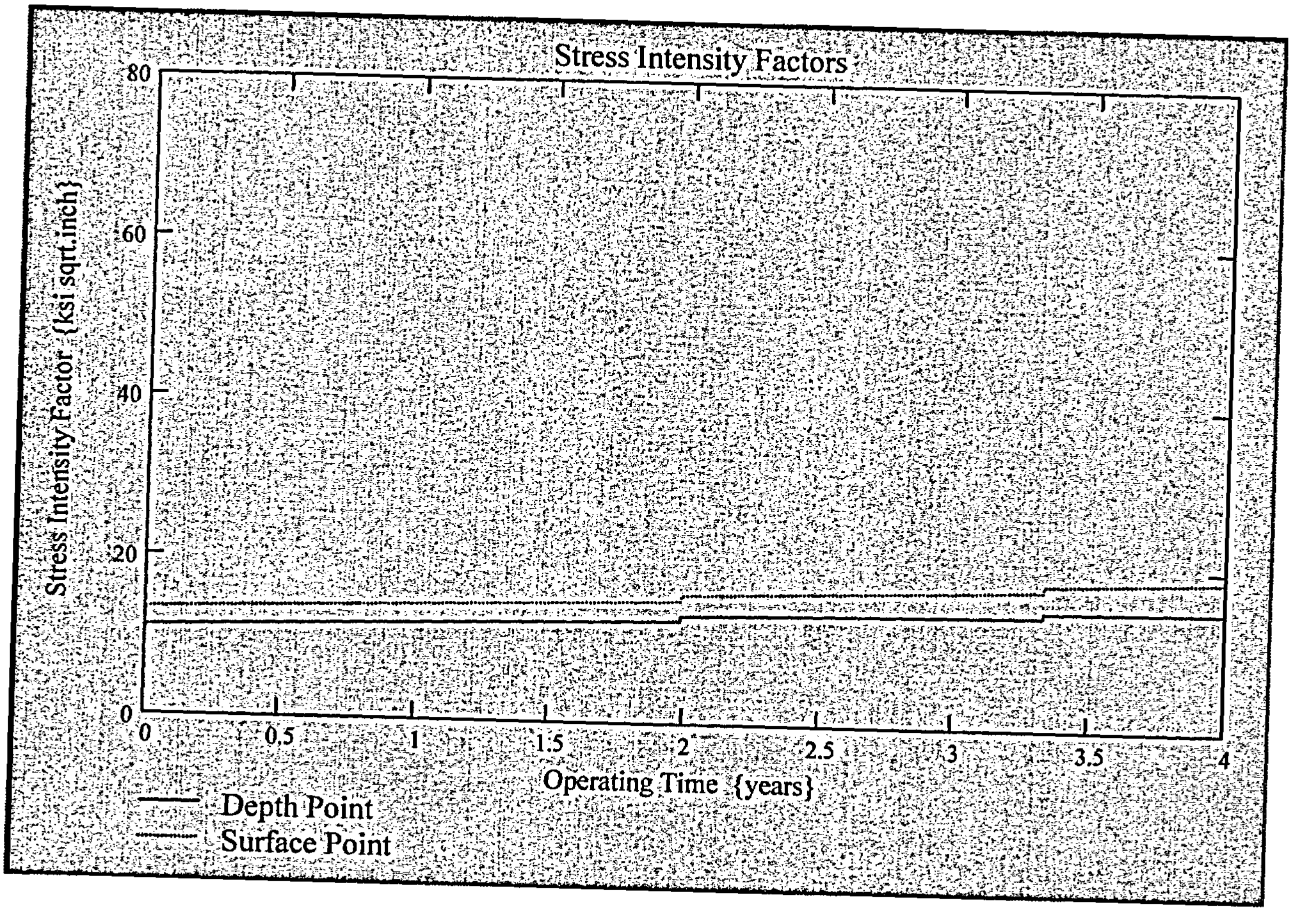
No User Input is required beyond this Point

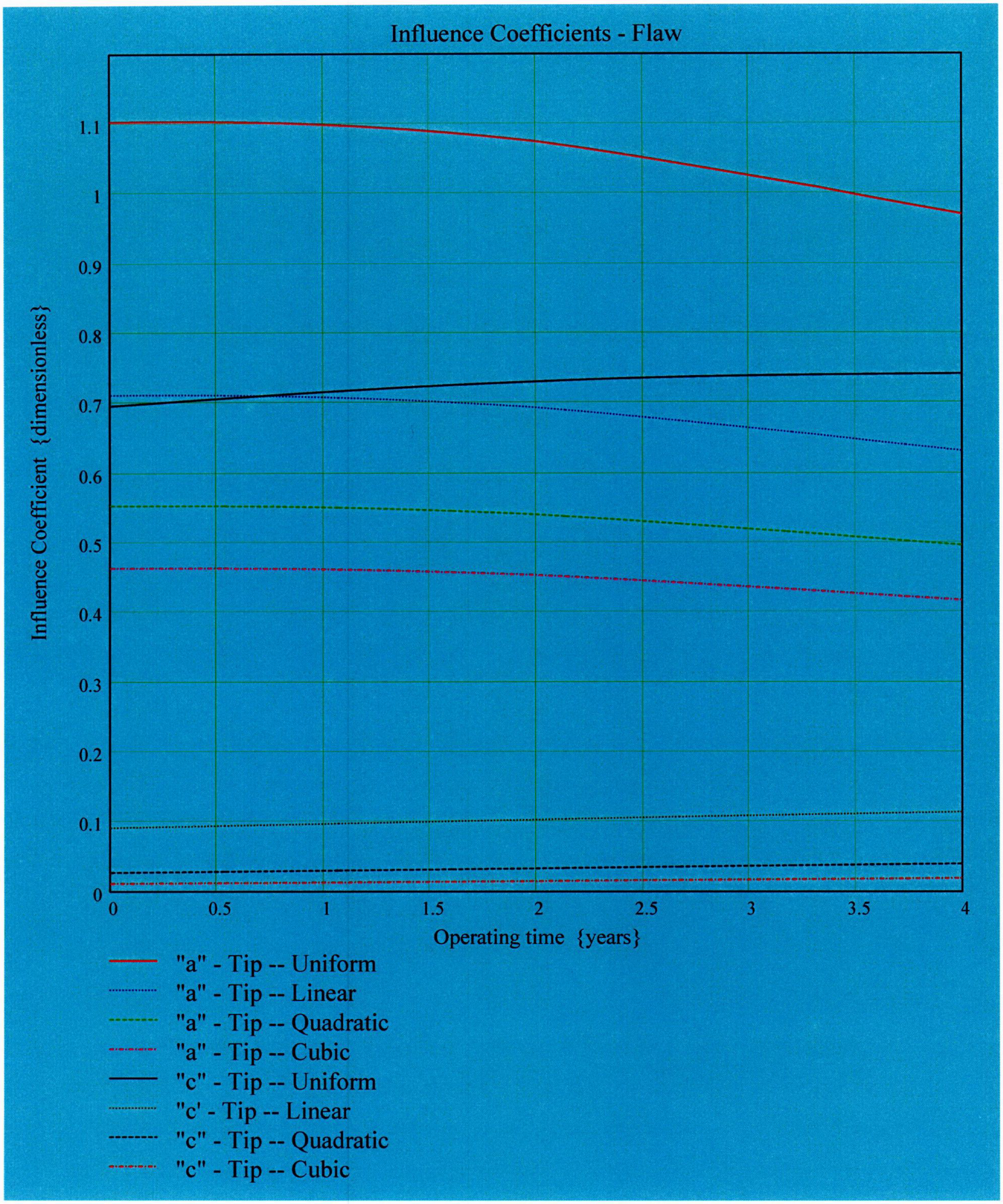
Sat Aug 09 10:59:39 AM 2003

$Prop_{Length} = 0.869$



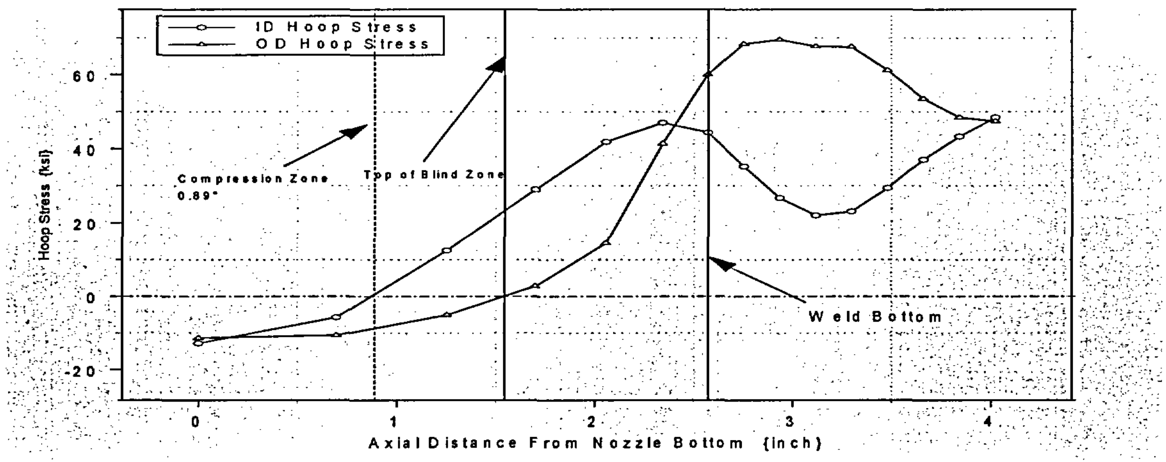


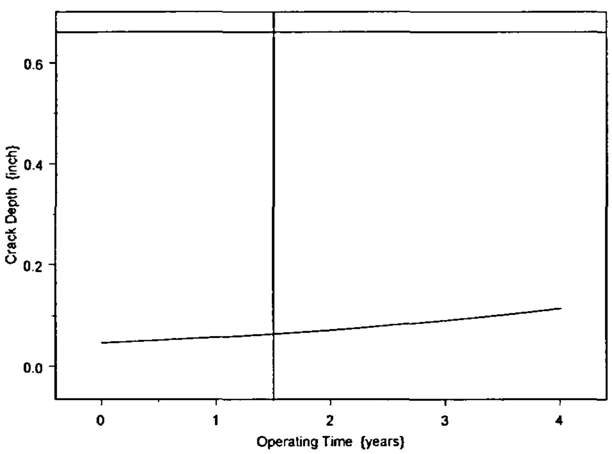

Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point
Surface Point

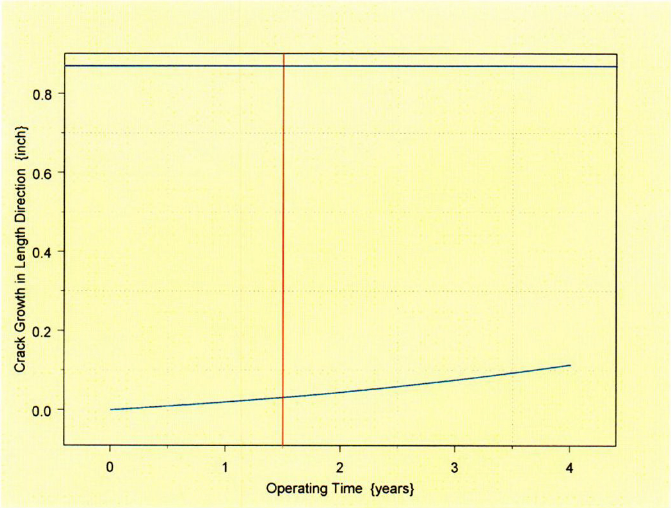

Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic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

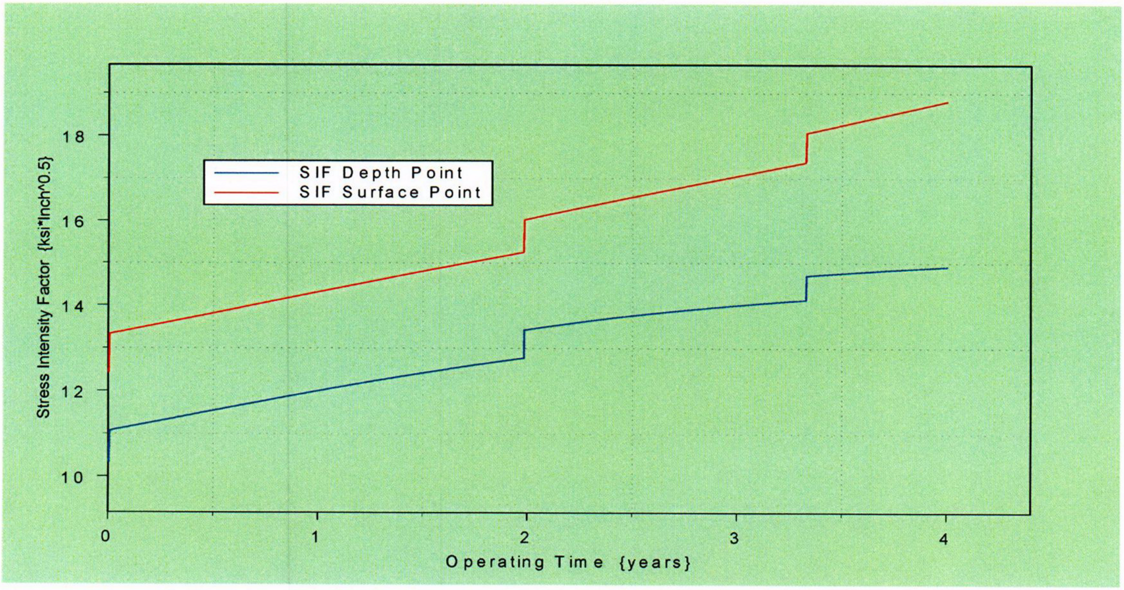
C02

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(k,5)}} =$
1.103	12.434	10.325
1.103	13.325	11.073
1.103	13.327	11.076
1.103	13.33	11.078
1.103	13.333	11.081
1.103	13.335	11.083
1.103	13.338	11.086
1.103	13.34	11.088
1.103	13.343	11.091
1.103	13.346	11.093
1.103	13.348	11.096
1.103	13.351	11.098
1.103	13.353	11.101
1.103	13.356	11.103
1.103	13.359	11.106
1.103	13.361	11.108


ID Hoop Stress
OD Hoop Stress
Compression Zone
0.89"
Top of Blind Zone
Weld Bottom
Hoop Stress (ksi)
60
40
20
0
-20
0
1
2
3
4
Axial Distance From Nozzle Bottom (inch)


Crack Depth (inch)
0.6
0.4
0.2
0.0
0
1
2
3
4
Operating Time (years)


Crack Growth in Length Direction {inch}
0.0
0.2
0.4
0.6
0.8
0
1
2
3
4
Operating Time {years}


Stress Intensity Factor {ksi*Inch^0.5}
10
12
14
16
18
SIF Depth Point
SIF Surface Point
0
1
2
3
4
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

Waterford Steam Electric Station Unit 3

Component : Reactor Vessel CEDM -"0" Degree Nozzle, "All" 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.

$Ref_{Point} := 1.544$

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

$UL_{Strs.Dist} := 2.573$

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

The regions highlighted below remain constant for WSES-3 analysis and should not be changed

Input Data :-

$L := 0.32$	Initial Flaw Length
$a_0 := 0.07932$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth (MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

Temperature Correction for Coefficient Alpha

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

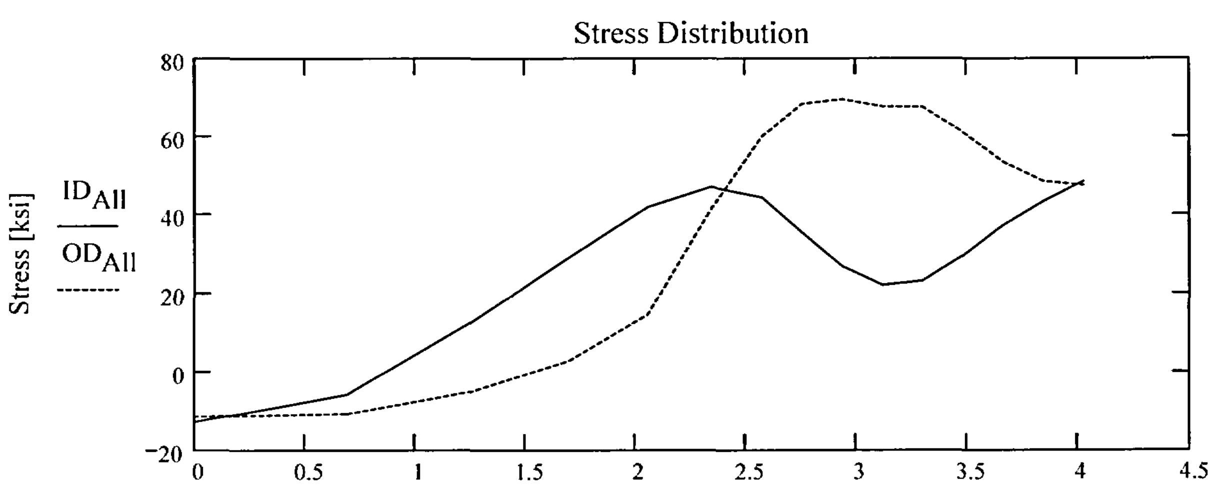
Stress Input Data

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	-12.8	-11.86	-11.69	-11.59	-11.36
1	0.7	-5.76	-6.99	-8.36	-9.65	-10.65
2	1.25	12.52	6.55	0.3	-3.05	-5.05
3	1.7	28.96	26.39	19.22	11.6	2.76
4	2.06	41.81	37.11	30.32	22.64	14.56
5	2.34	46.95	39.38	33.87	34.26	41.31
6	2.57	44.29	40.27	38.75	48.68	59.98
7	2.75	35.28	36.13	40.48	54.52	68.35
8	2.94	26.74	32.32	40.93	56.86	69.51
9	3.12	22.01	29.24	40.65	55.17	67.67

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



AXLen
Axial Elevation above Bottom [inch]

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).

$$Data := \begin{pmatrix} 0 & -12.796 & -11.857 & -11.688 & -11.588 & -11.36 \\ 0.696 & -5.757 & -6.987 & -8.359 & -9.647 & -10.654 \\ 1.253 & 12.517 & 6.554 & 0.301 & -3.045 & -5.052 \\ 1.699 & 28.961 & 26.385 & 19.217 & 11.596 & 2.764 \\ 2.057 & 41.814 & 37.112 & 30.325 & 22.635 & 14.562 \\ 2.343 & 46.95 & 39.385 & 33.873 & 34.257 & 41.315 \\ 2.572 & 44.292 & 40.273 & 38.751 & 48.684 & 59.975 \\ 2.754 & 35.285 & 36.135 & 40.478 & 54.515 & 68.35 \\ 2.935 & 26.742 & 32.322 & 40.928 & 56.857 & 69.509 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

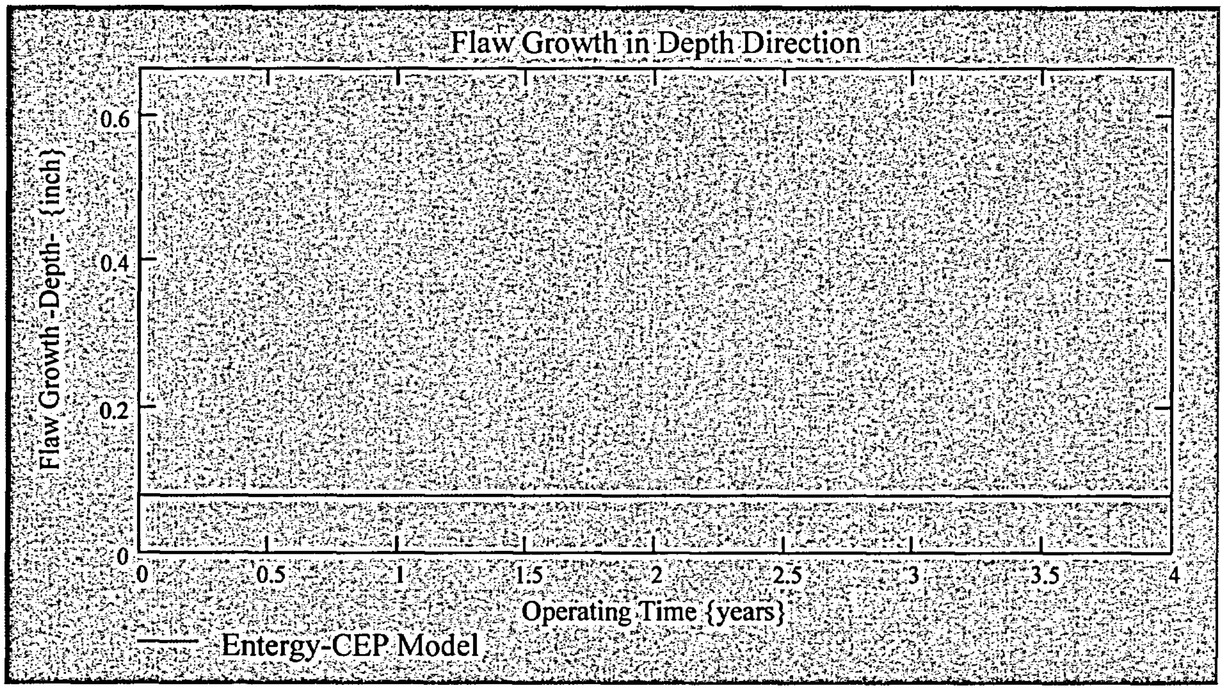
$U_{Tip} := FL_{Cntr} + c_0$

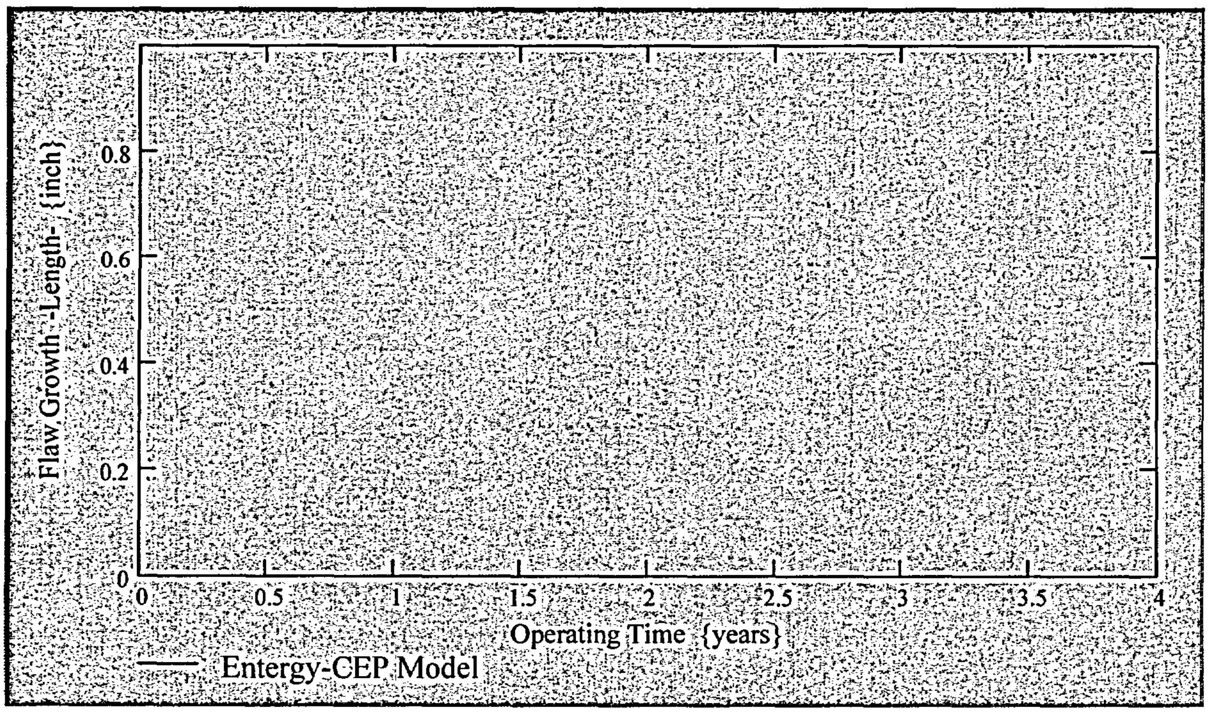
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

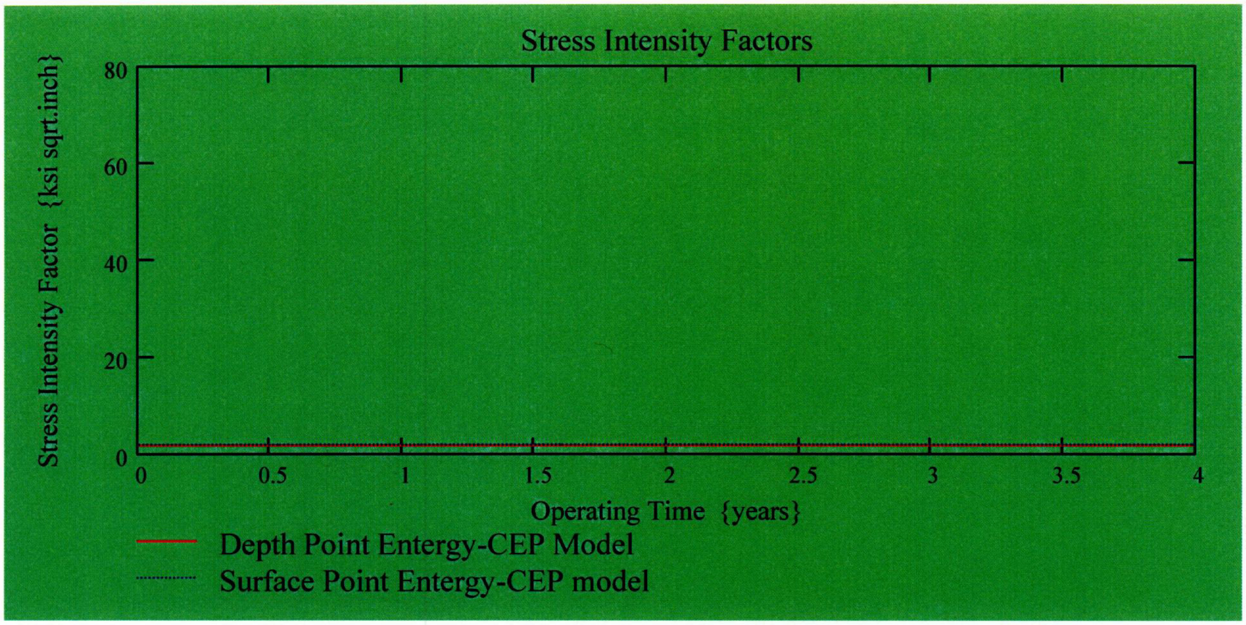
No User Input is required beyond this Point

Sat Aug 09 10:21:18 AM 2003

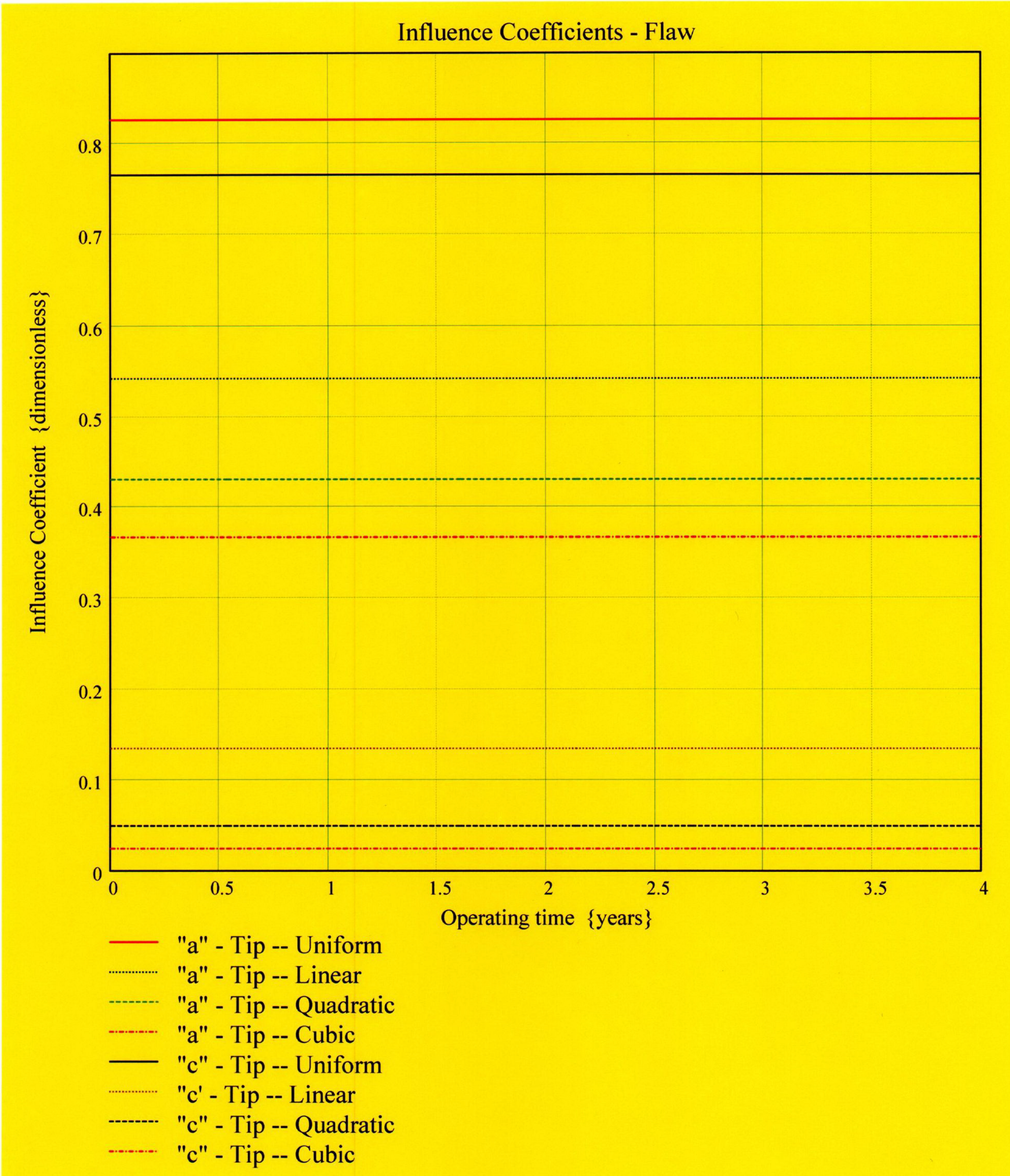
$Prop_{Length} = 0.869$






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

C04


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

C05

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

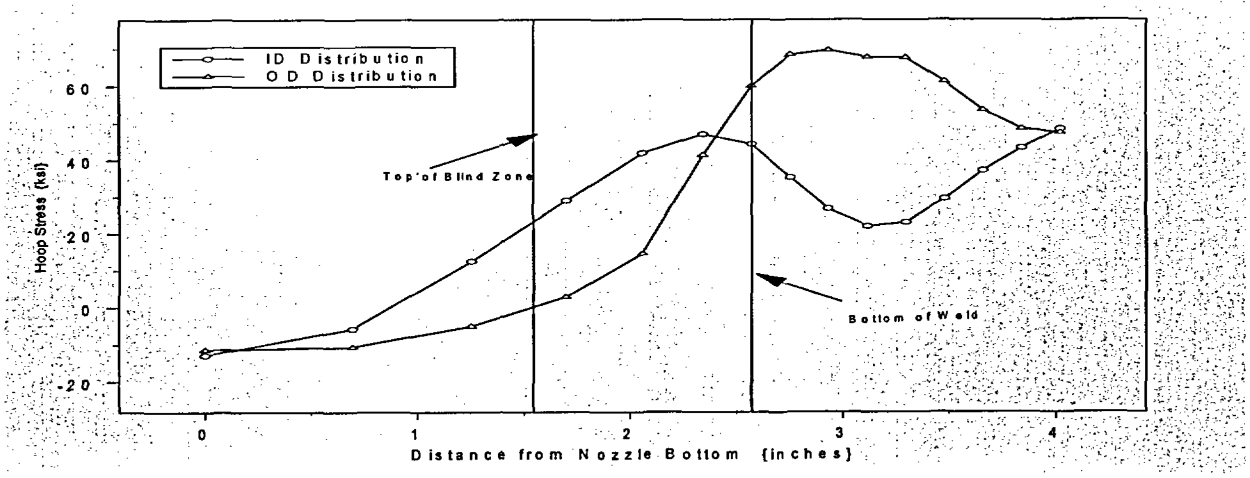
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827

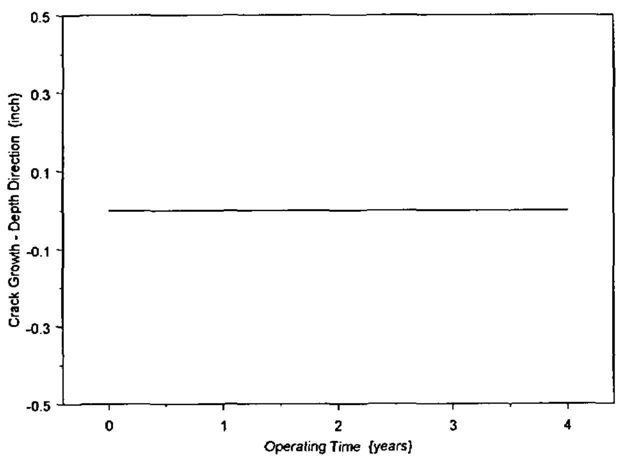
$CGR_{sambi_{(k,6)}} =$

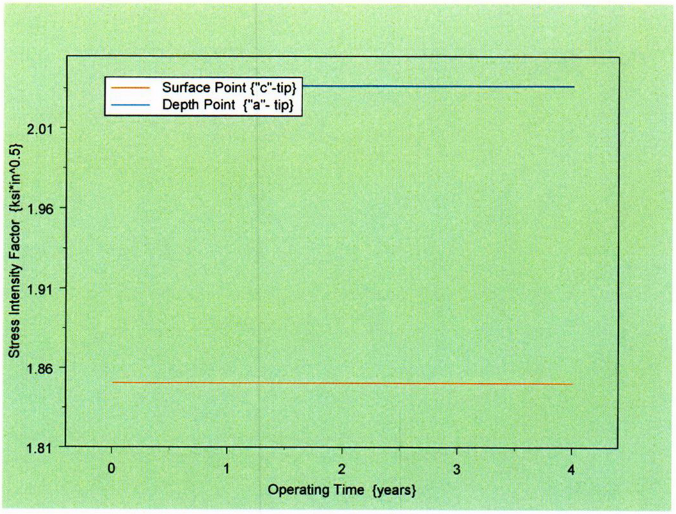
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037
2.037

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

1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851
1.851


ID Distribution
OD Distribution
Top of Blind Zone
Bottom of Weld
Hoop Stress (ksi)
Distance from Nozzle Bottom (inches)


Crack Growth - Depth Direction (inch)
Operating Time (years)


Surface Point {"c"-tip}
Depth Point {"a"- tip}
Stress Intensity Factor {ksi*in^0.5}
2.01
1.96
1.91
1.86
1.81
0
1
2
3
4
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

Waterford Steam Electric Station Unit 3

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

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

Through Wall Axial Flaw

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

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

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

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

$UL_{StrsDist}$:= 2.573 Upper axial Extent for Stress Distribution to be used in the analysis (Axial distance above nozzle bottom)

The Highlighted Entries below remains constant for WSES-3 and should not be changed

Input Data :-

$L := 0.3$ — Initial Crack Length TW axial Based on Stress Distribution. Bottom end of Crack to be set @ approximately 10ksi.

$od := 4.05$ — Tube OD

$id := 2.728$ — Tube ID

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

$Years := 4$ — Number of Operating Years

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

$T := 604$ — Estimate of Operating Temperature

$v := 0.307$ — Poissons ratio @ 600 F

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

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

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

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

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

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

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

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

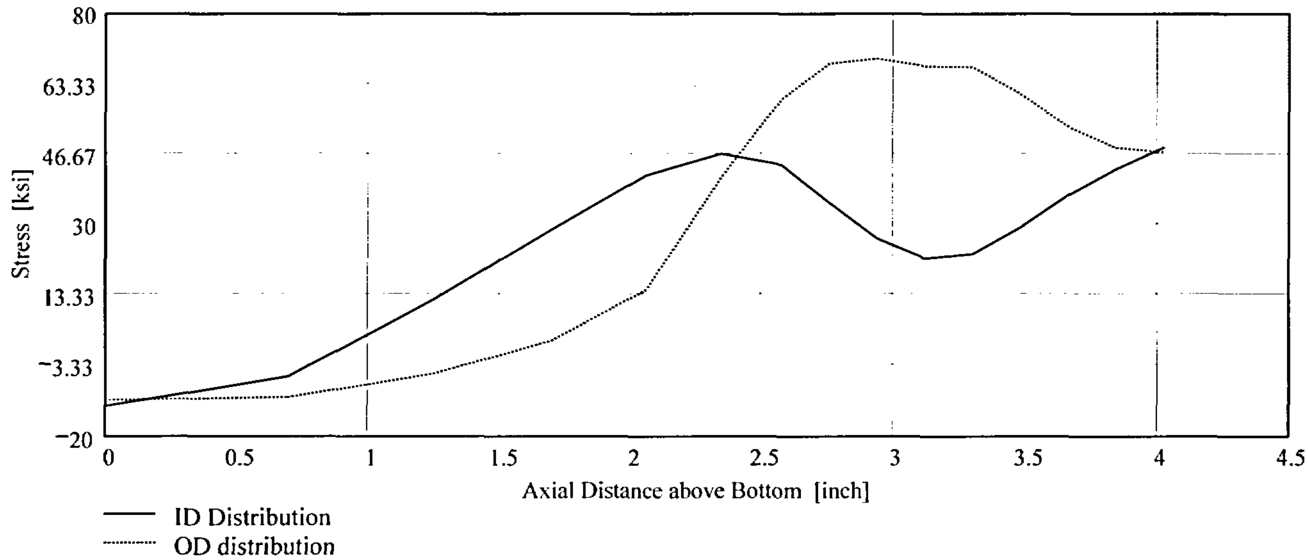
Stress Input Data

mport 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	-12.8	-11.86	-11.69	-11.59	-11.36
1	0.7	-5.76	-6.99	-8.36	-9.65	-10.65
2	1.25	12.52	6.55	0.3	-3.05	-5.05
3	1.7	28.96	26.39	19.22	11.6	2.76
4	2.06	41.81	37.11	30.32	22.64	14.56
5	2.34	46.95	39.38	33.87	34.26	41.31
6	2.57	44.29	40.27	38.75	48.68	59.98
7	2.75	35.28	36.13	40.48	54.52	68.35
8	2.94	26.74	32.32	40.93	56.86	69.51
9	3.12	22.01	29.24	40.65	55.17	67.67

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



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

$$Data := \begin{pmatrix} 0 & -12.796 & -11.857 & -11.688 & -11.588 & -11.36 \\ 0.696 & -5.757 & -6.987 & -8.359 & -9.647 & -10.654 \\ 1.253 & 12.517 & 6.554 & 0.301 & -3.045 & -5.052 \\ 1.699 & 28.961 & 26.385 & 19.217 & 11.596 & 2.764 \\ 2.057 & 41.814 & 37.112 & 30.325 & 22.635 & 14.562 \\ 2.343 & 46.95 & 39.385 & 33.873 & 34.257 & 41.315 \\ 2.572 & 44.292 & 40.273 & 38.751 & 48.684 & 59.975 \\ 2.754 & 35.285 & 36.135 & 40.478 & 54.515 & 68.35 \\ 2.935 & 26.742 & 32.322 & 40.928 & 56.857 & 69.509 \end{pmatrix}$$

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

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

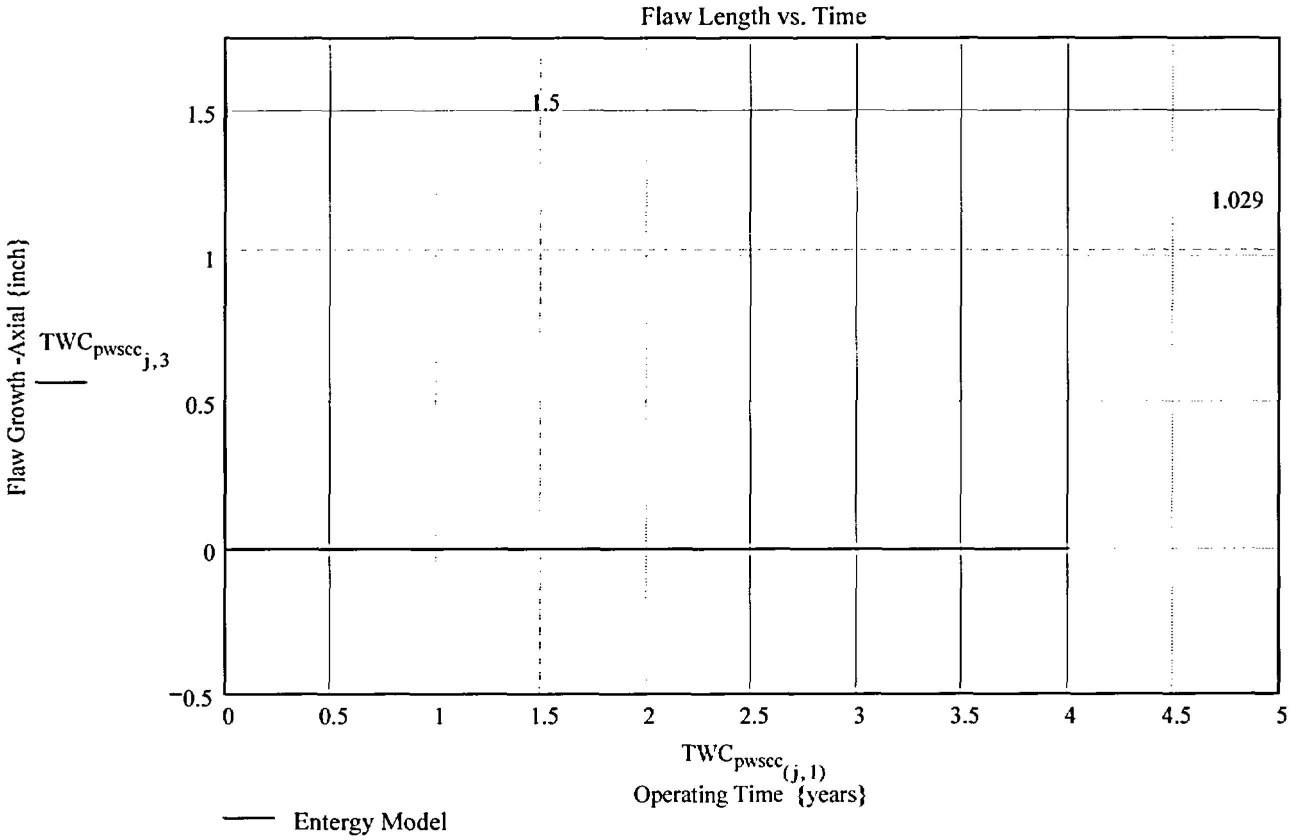
$FL_{Cntr} := BZ - l$ Flaw Center above Nozzle Bottom

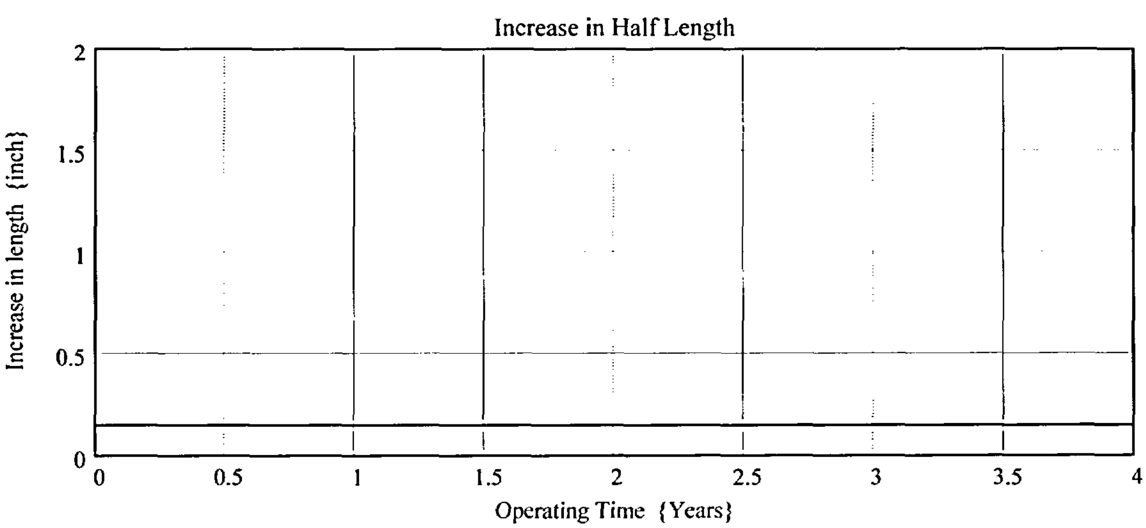
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - BZ}{20}$$

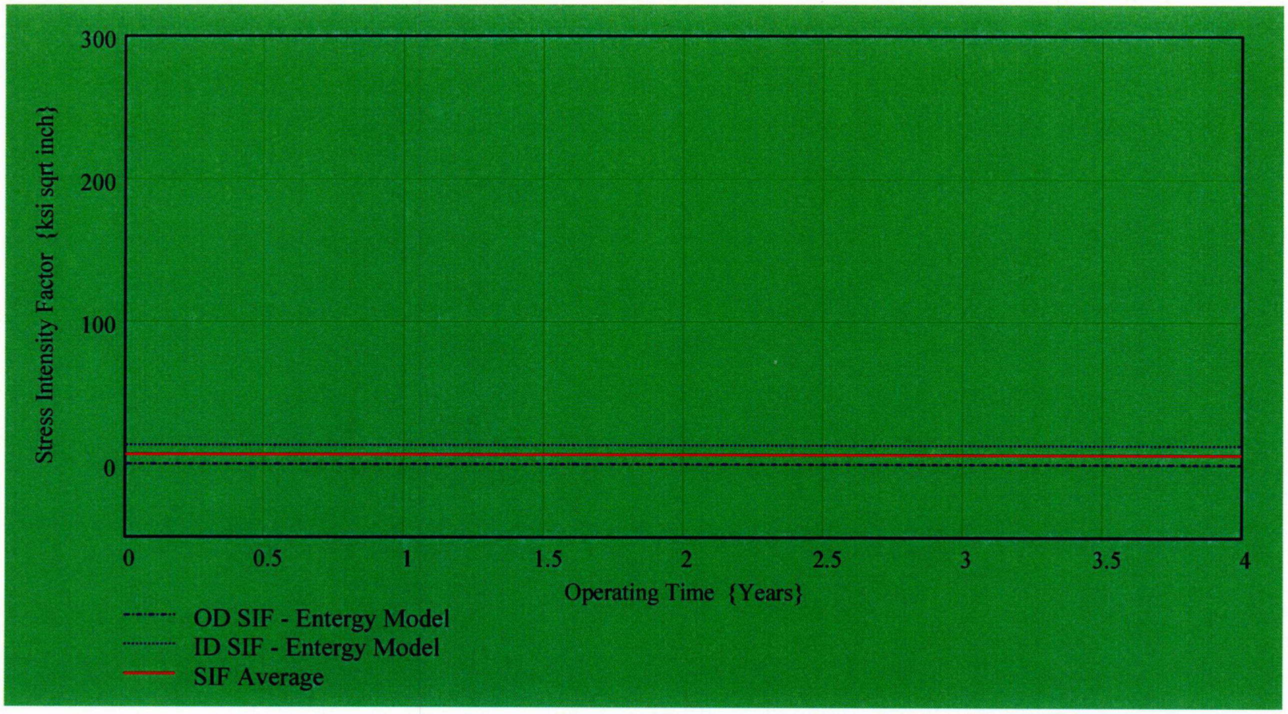
No User Input required beyond this Point

Sat Aug 09 11:44:49 AM 2003

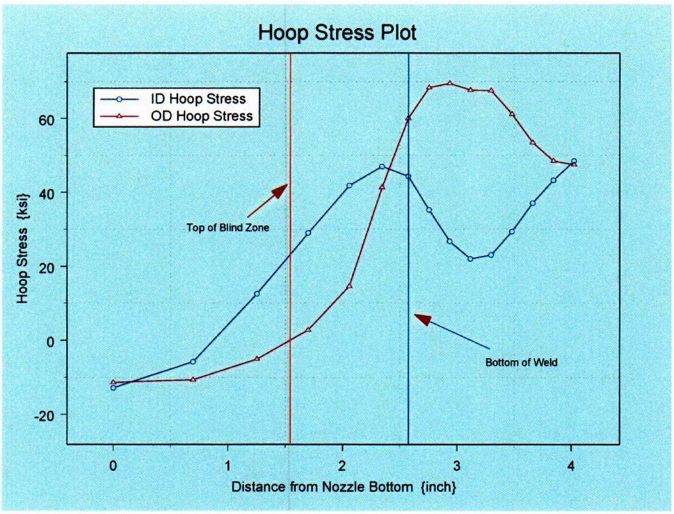
$Prop_{Length} = 1.029$

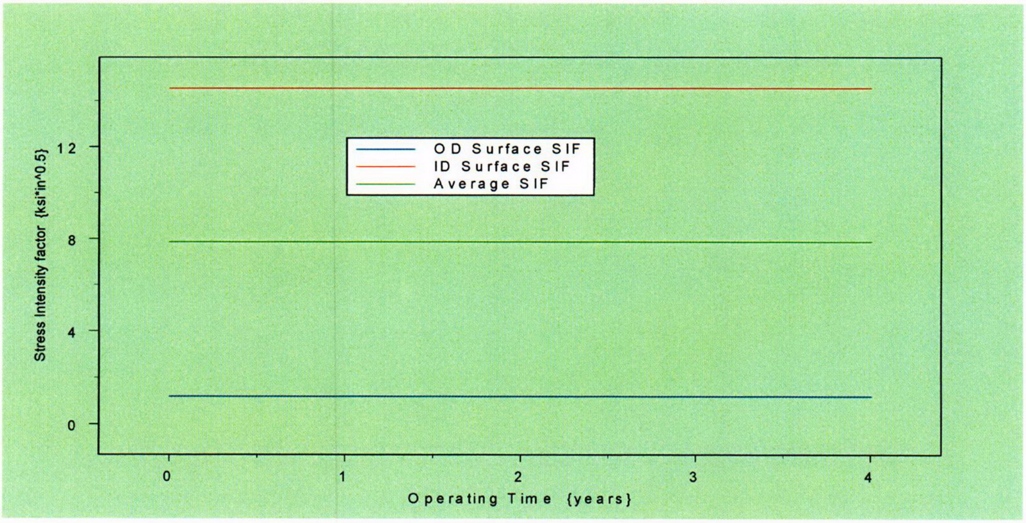


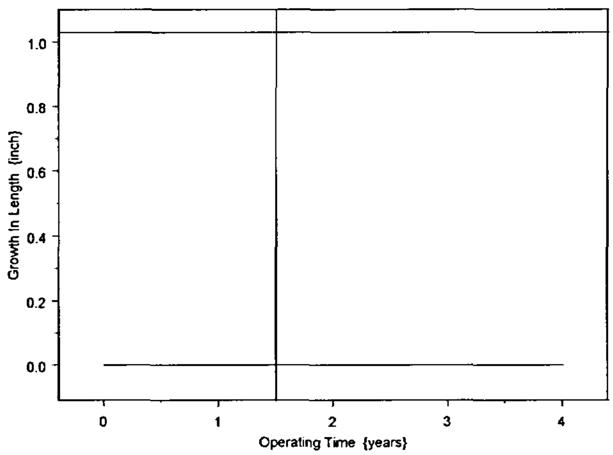



300
200
100
0
Stress Intensity Factor {ksi sqrt inch}
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {Years}
OD SIF - Entergy Model
ID SIF - Entergy Model
SIF Average

$TWC_{pwscc_{(j,6)}}$ =	$TWC_{pwscc_{(j,7)}}$ =	$TWC_{pwscc_{(j,8)}}$ =
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139
1.198	14.548	8.139


Hoop Stress Plot
ID Hoop Stress
OD Hoop Stress
Top of Blind Zone
Bottom of Weld
Hoop Stress {ksi}
Distance from Nozzle Bottom {inch}
-20
0
20
40
60
0
1
2
3
4


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor {ksi*in^0.5}
Operating Time {years}
0
4
8
12
0
1
2
3
4


Growth In Length {inch}
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
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

Waterford Steam Electric Station Unit 3

Component : Reactor Vessel CEDM -"7.8" Degree Nozzle, "0" Degree Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

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

$Ref_{Point} := 1.544$

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

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

$Val := 2$

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

$UL_{Strs.Dist} := 2.546$ Upper axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom)

The highlighted region below remians constant for WSES-3 and should not be changed

Input Data :

$L := 0.32$	Initial Flaw Length
$a_0 := 0.04627$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth (MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg F

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

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

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

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

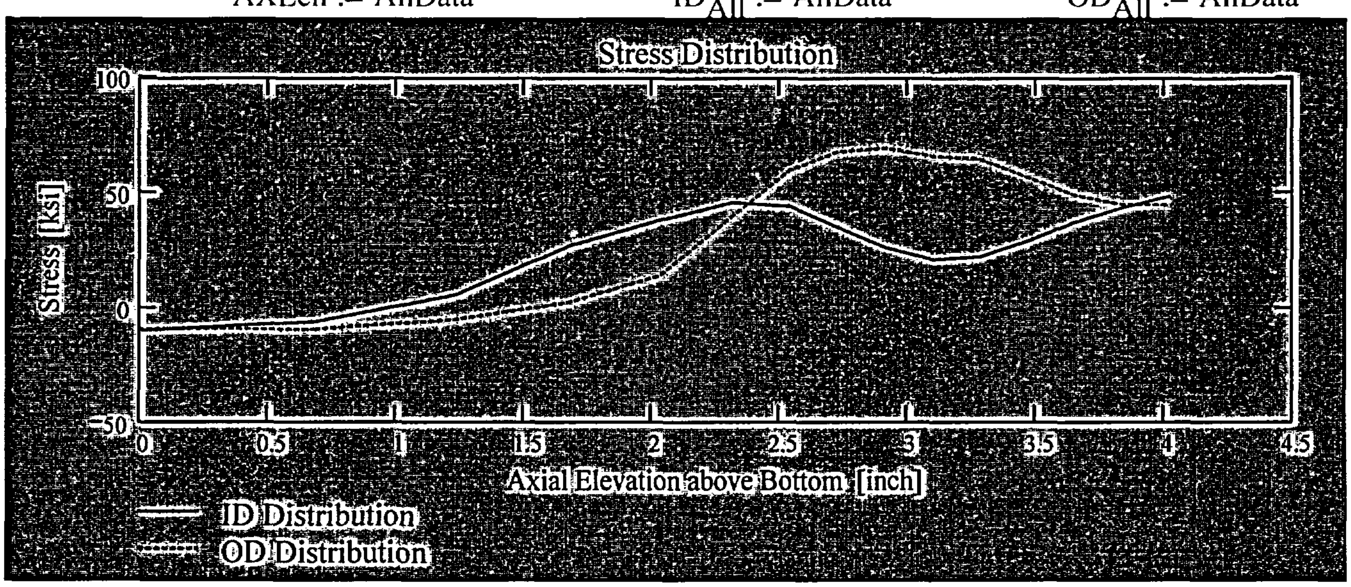
Stress Input Data

Input all available Nodal stress data in the table below. The column designations are as follows:
Column "0" = Axial distance from minimum to maximum recorded on data sheet (inches)
Column "1" = ID Stress data at each Elevation (ksi)
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	-9.81	-9.21	-9.15	-9.11	-9.01
1	0.69	-5.96	-6.67	-7.6	-8.5	-9.17
2	1.24	5.97	1.89	-1.41	-3.64	-4.89
3	1.68	27.3	20.8	14.76	9.07	2.76
4	2.04	38.32	34.26	28.39	21.56	14.2
5	2.32	46.03	38.24	33.08	32.77	40.16
6	2.55	44.34	40.22	38.94	48.67	60.18
7	2.73	35.38	36.51	40.84	54.4	68.18
8	2.92	26.51	32.53	41.33	56.35	69.72
9	3.1	21.36	29.6	40.6	53.91	66.27

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



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

$$Data := \begin{pmatrix} 0 & -9.806 & -9.211 & -9.151 & -9.105 & -9.007 \\ 0.688 & -5.963 & -6.674 & -7.601 & -8.5 & -9.173 \\ 1.24 & 5.968 & 1.891 & -1.405 & -3.639 & -4.887 \\ 1.681 & 27.297 & 20.8 & 14.757 & 9.074 & 2.762 \\ 2.035 & 38.318 & 34.255 & 28.387 & 21.562 & 14.198 \\ 2.319 & 46.033 & 38.236 & 33.079 & 32.77 & 40.164 \\ 2.546 & 44.342 & 40.223 & 38.935 & 48.672 & 60.179 \\ 2.731 & 35.382 & 36.514 & 40.837 & 54.397 & 68.177 \\ 2.916 & 26.506 & 32.532 & 41.33 & 56.353 & 69.718 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location above Nozzle Bottom

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

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

No User Input is required beyond this Point

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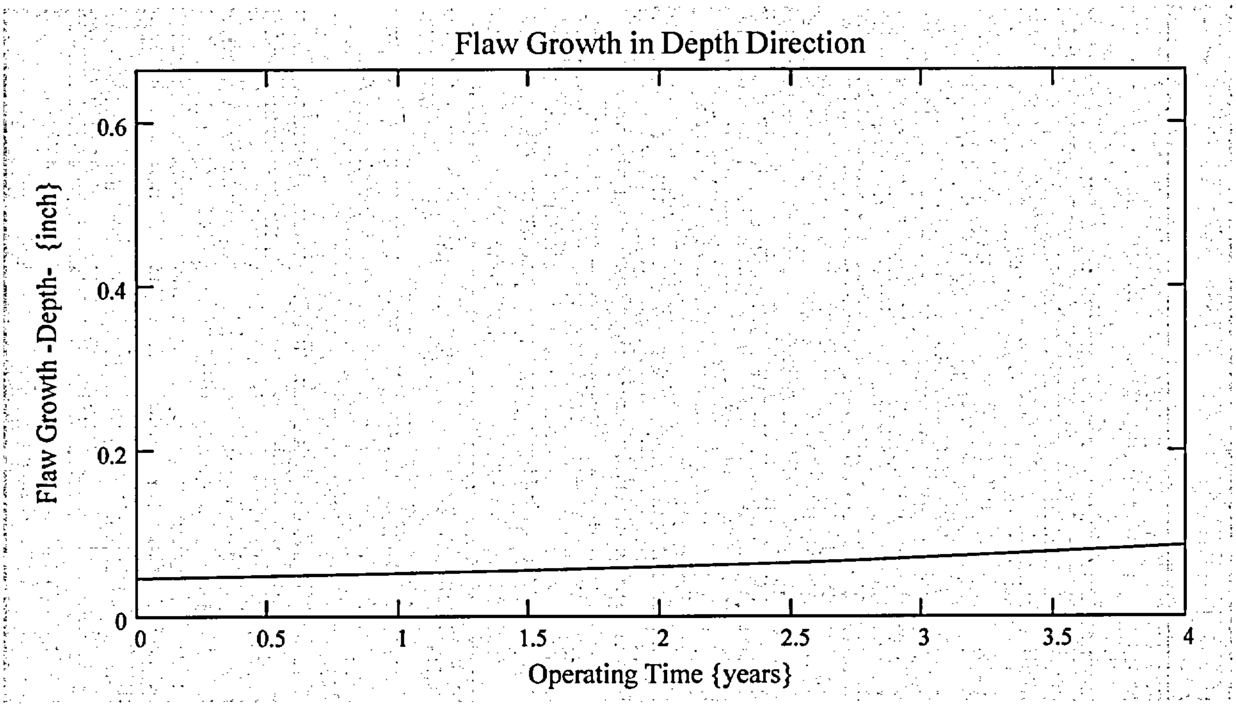
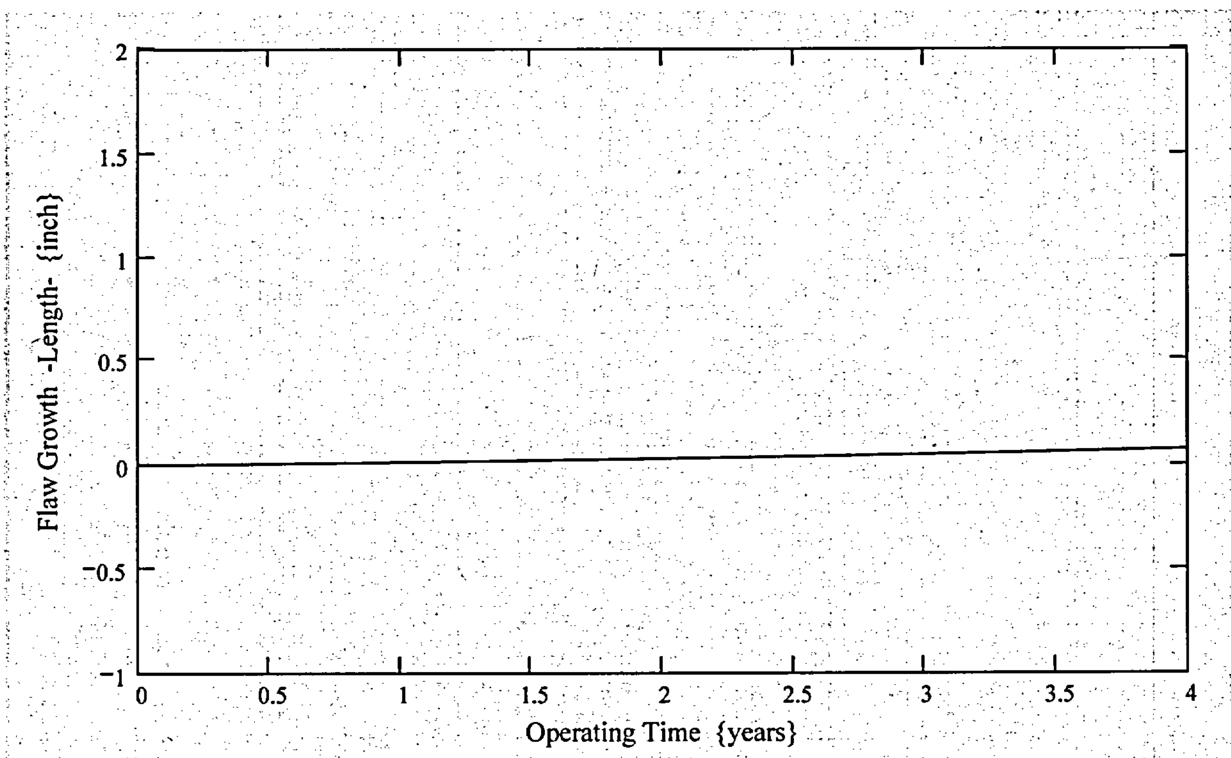
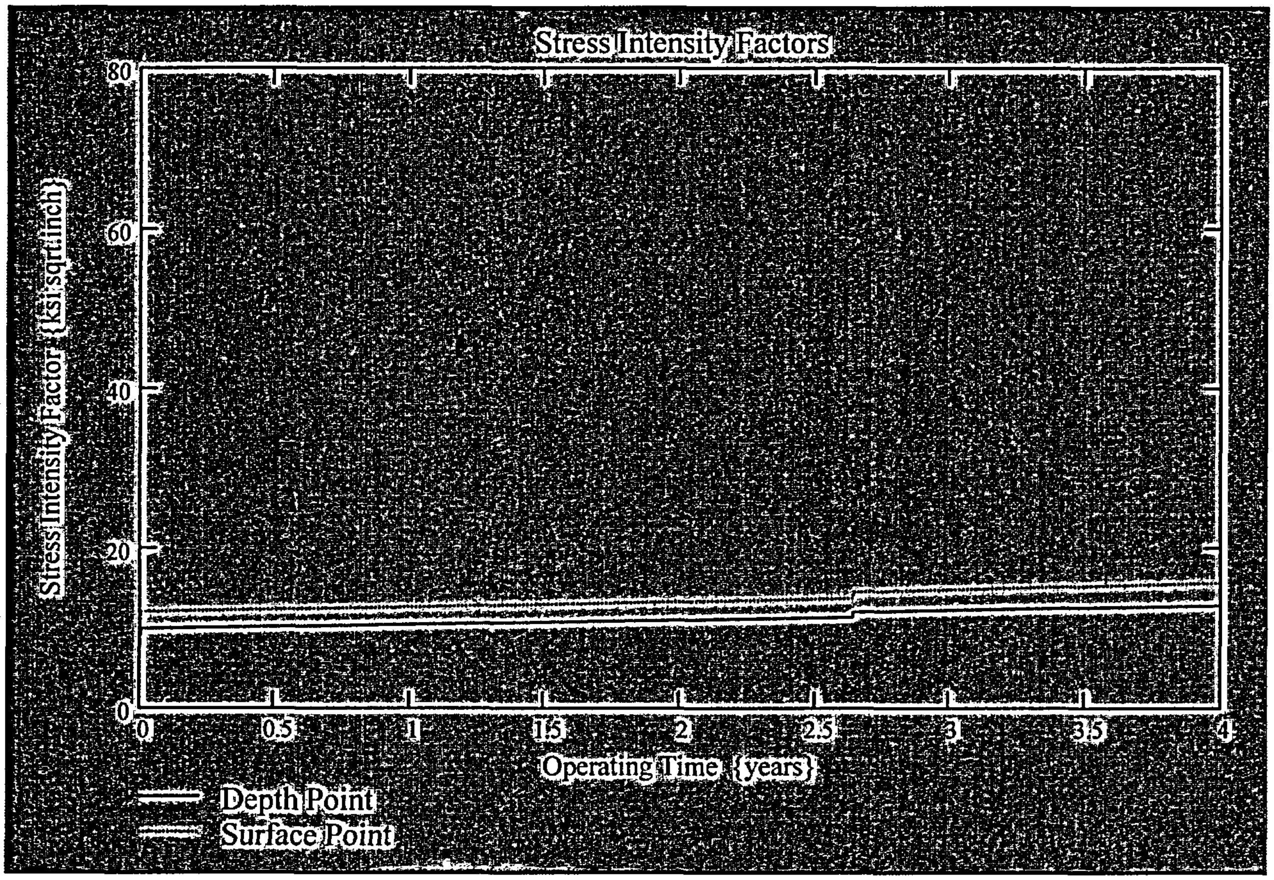
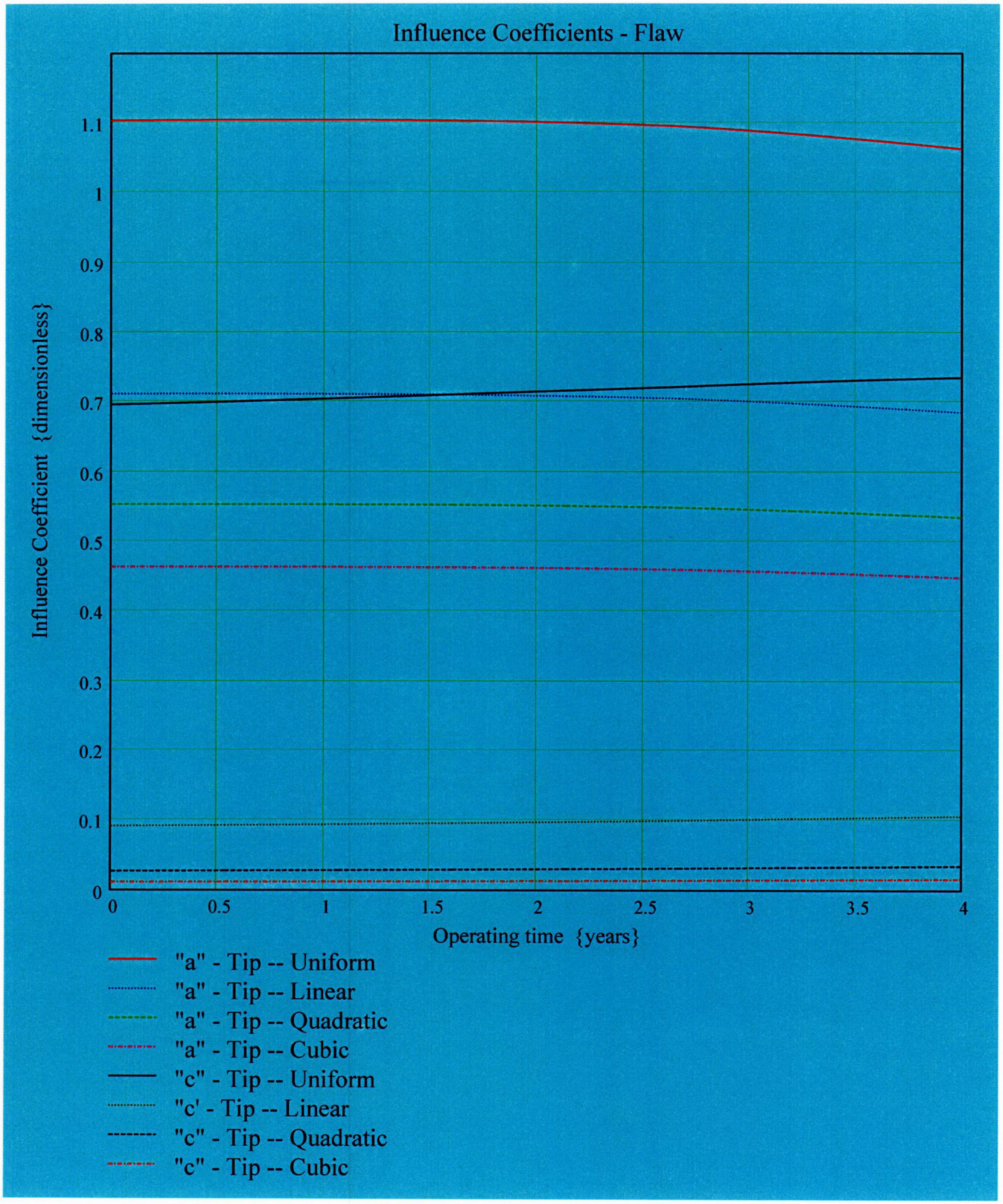
$Prop_{Length} = 0.842$






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


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

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

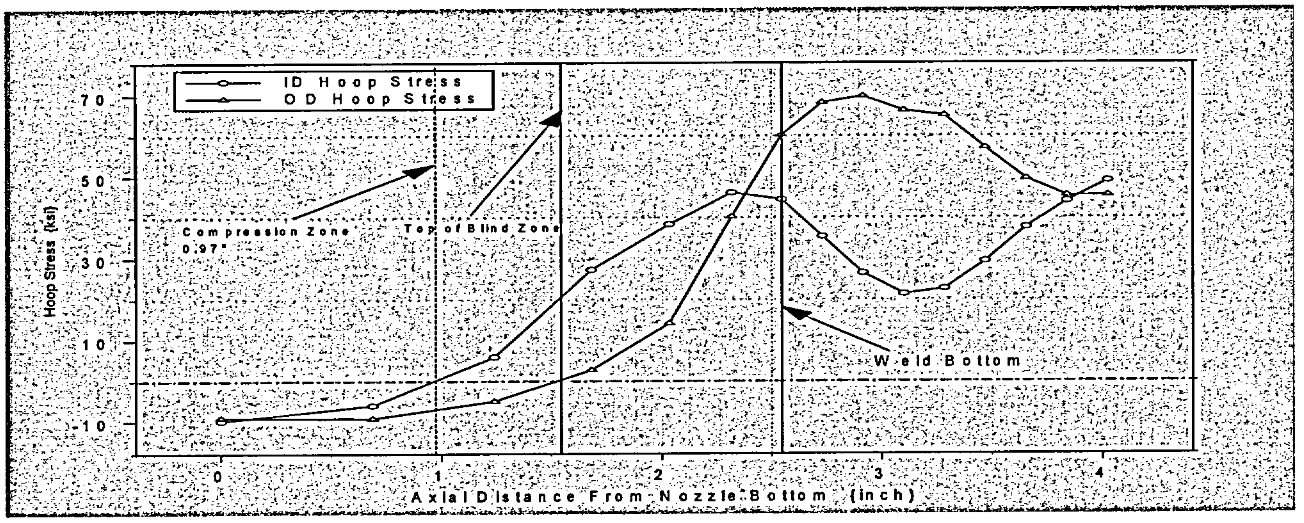
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103
1.103

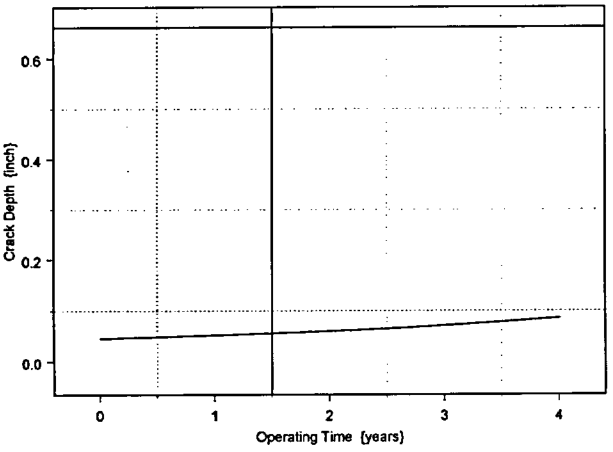
$CGR_{sambi_{(k,6)}} =$

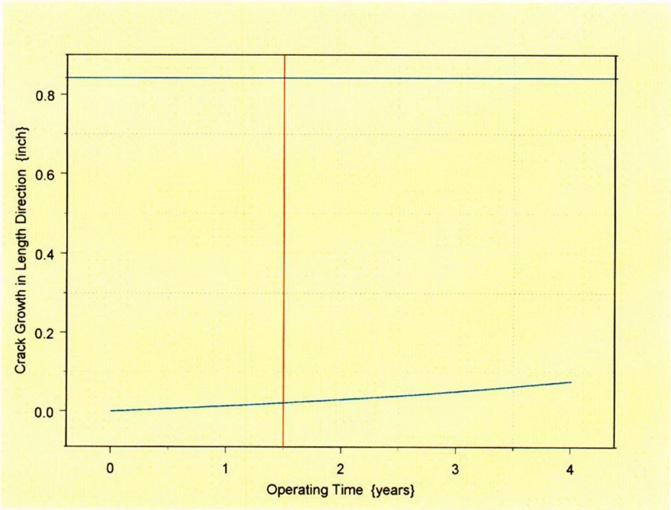
11.109
12.024
12.026
12.027
12.029
12.03
12.031
12.033
12.034
12.036
12.037
12.039
12.04
12.042
12.043
12.045

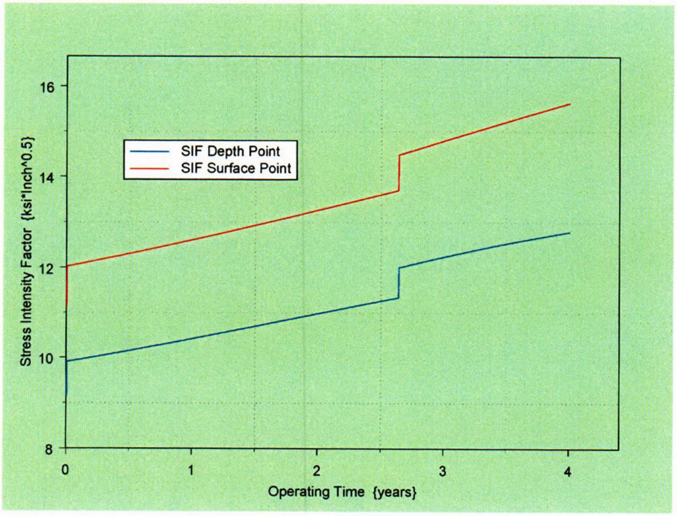
$CGR_{sambi_{(k,5)}} =$

9.147
9.912
9.913
9.914
9.916
9.917
9.918
9.92
9.921
9.922
9.923
9.925
9.926
9.927
9.928
9.93


ID Hoop Stress
OD Hoop Stress
Hoop Stress (ksi)
Compression Zone
0.97"
Top of Blind Zone
Weld Bottom
Axial Distance From Nozzle Bottom (inch)


Crack Depth (inch)
Operating Time (years)


Crack Growth in Length Direction {inch}
0.0
0.2
0.4
0.6
0.8
0
1
2
3
4
Operating Time {years}


Stress Intensity Factor {ksi*inch^0.5}
8
10
12
14
16
SIF Depth Point
SIF Surface Point
0
1
2
3
4
Operating Time {years}