Appendix B

Explanation of Mathcad worksheet used in the deterministic Fracture Mechanics Analyses.

This Appendix has three (3) Attachments.

ID Surface Flaws

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

Developed by: J. S. Brihmadesam

Verified by: B. C. Gray

Refrences :

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

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8.8" 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

General information containing the Component Identification for analysis. Note the information for Nozzle group , Location, and Elevation at which the analysis is being performed. This information is not critical to the analyses; it is general information but it is important for cataloging the analyses files.

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 1$$

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

$UL_{Strs.Dist} := 2.05$ Upper axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom).

Three critical information are required in the three entries on page one.

1) the first entry required {Ref_{Point}} is the "Reference Location"; this entry defines the reference line (e.g. the blind zone elevation) with respect to the nozzle bottom.
2) The second entry {Val} defines the location of the Crack. In the current analysis a value of two (2) is selected. This value locates the center of the flaw at the reference line described above.
3) The third required input is the upper limit, elevation above nozzle bottom, to be used for the stress distribution that will be used in the analyses. This location for the current analyses is chosen to be slightly above the bottom of the weld such that the appropriate stress profiles are incorporated into the analyses.

Input Data :-

$L := .35$	Initial Flaw Length
$a_0 := 0.035$	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

1) General Input data for tube and flaw geometry. In addition other parameters required for the analyses are defined. These inputs remain unchanged for this set of analyses.
2) The input for internal pressure P_{Int} is used to add the internal pressure to the flaw face.
3) The operating time Years is set to four (4) such that proper analysis for one cycle of operation is obtained.
4) The iteration limit I_{Lim} is prescribed as a large number (1500) such that small time increments for crack growth are used in the crack growth analysis.
5) The remainder of the inputs are for crack growth model, which is based on MRP-55 at the seventy-fifth percentile.

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

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

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

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

General calculations to develop the constants needed for the analyses.

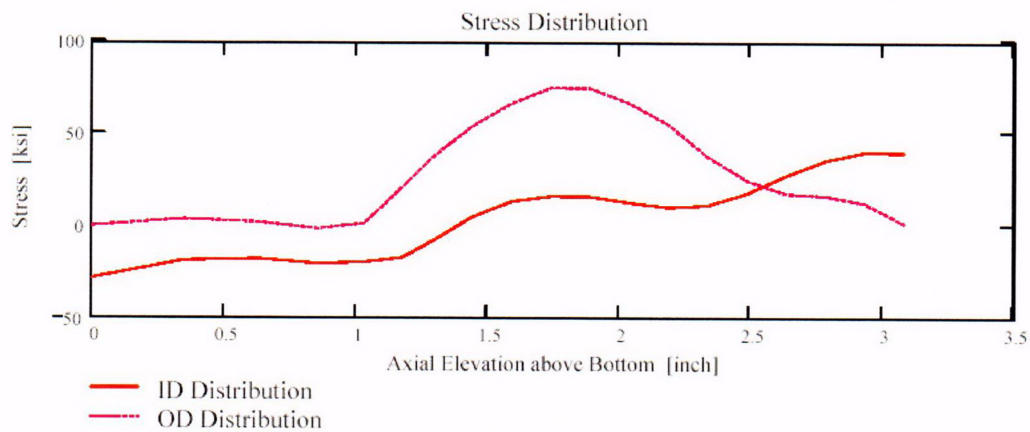
Stress Input Data

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

AllData :=

	0	1	2	3	4	5
0	0	-28.32	-18.3	-12.16	-6.2	-0.02
1	0.35	-18.79	-12.49	-6.61	-1.37	3.65
2	0.63	-17.84	-10.52	-4.41	-0.48	2.08
3	0.85	-20.52	-12.97	-5.9	-0.87	-1.54
4	1.03	-19.66	-11.83	-5.29	0.23	1.46
5	1.18	-17.2	-10.59	-0.52	16.33	21.02
6	1.29	-8.02	-2.2	10.46	32.66	37.29
7	1.44	4.78	9.56	24.9	38.18	54.09
8	1.59	13.25	18.57	35.28	52.81	66.52
9	1.74	16	22.02	39.19	62.95	75
10	1.89	15.86	23.14	40.23	64.33	74.87
11	2.04	12.63	23.76	41.26	58.67	66.78

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



1) the nodal stress data is imported from an Excel spread sheet provided by Dominion Engineering. The appropriate data set in the spread sheet is provided in the import command in Mathcad. It is important not to import the node number column.
2) The data imported is plotted for the ID and OD distribution along the length of the nozzle.
3) The plot presents all the nodal stress data imported. This plot is used to define the region of interest for analysis and to select the sub-set of stress distribution data pertinent to the analysis.

C01

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

$$Data := \begin{pmatrix} 0 & -28.324 & -18.299 & -12.16 & -6.201 & -0.021 \\ 0.35 & -18.794 & -12.495 & -6.607 & -1.366 & 3.655 \\ 0.63 & -17.838 & -10.518 & -4.407 & -0.477 & 2.08 \\ 0.854 & -20.517 & -12.968 & -5.902 & -0.874 & -1.536 \\ 1.034 & -19.663 & -11.831 & -5.288 & 0.227 & 1.46 \\ 1.178 & -17.203 & -10.587 & -0.515 & 16.326 & 21.019 \\ 1.293 & -8.023 & -2.205 & 10.461 & 32.658 & 37.289 \\ 1.442 & 4.778 & 9.557 & 24.903 & 38.177 & 54.089 \\ 1.591 & 13.252 & 18.569 & 35.278 & 52.808 & 66.517 \\ 1.74 & 16.001 & 22.017 & 39.194 & 62.945 & 75.001 \\ 1.889 & 15.857 & 23.14 & 40.235 & 64.335 & 74.874 \\ 2.038 & 12.629 & 23.76 & 41.263 & 58.673 & 66.777 \end{pmatrix}$$

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

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

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

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

1) Shows the incorporation of the selected data into a Data matrix that will be used in the analysis.
2) The definiton of the axial distribution at the five locations through the wall thickness are defined.
3) A third-order polynomial regression is performed at each of the five through-wall locations to define the curve used to develop the through-wall distributions.

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

Flaw center Location above Nozzle Bottom

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

1) defines the upper tip of the flaw based on reference line and flaw location (Val) inputs provided in the first sheet.
2) Determination of segment length above the initial crack upper tip location. Twenty (20) segments are used.

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

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

$$i := 1..N+3 \qquad Incr_i := \begin{vmatrix} c_0 & \text{if } i < 4 \\ Inc_{Strs.avg} & \text{otherwise} \end{vmatrix}$$

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

1) Setting of the iterative loop to develop the through-wall stress distribution.
2) Initialization of the loop to define axial elevation and segment length required to obtain the through-wall stress profiles at defined locations.

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

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

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

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

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

Determination of stresses at the five locations through the thickness and at defined elevations. This structure develops the matrix for the through-wall stress distributions for the defined locations that will be used in the moving average method for developing the stress profiles.

$j := 1..N$

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

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

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

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

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

Loop structure to perform the calculations for stress profiles at the defined locations along the nozzle height.

1) All five locations through the thickness are similar.
2) The first conditional statement defines the average stress at the initial flaw location, which is the average of the stress at the lower tip, the flaw center, and the upper tip. These stresses are used to calculate the applied stress for the initial flaw.
3) The second conditional statement performs the moving average at each segment location. Thus the moving average accounts for the changing stress field as the crack progresses towards the bottom of the weld. In the current analyses the stress field increases in magnitude as the crack progresses towards the weld bottom.

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

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

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

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

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

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

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

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

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

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

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

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

Setting of a column matrix for the stresses at each segment for the five through-wall location.

$IDRG_1 := regress(Y, SIG_1, 3)$

$IDRG_2 := regress(Y, SIG_2, 3)$

$IDRG_3 := regress(Y, SIG_3, 3)$

$IDRG_4 := regress(Y, SIG_4, 3)$

$IDRG_5 := regress(Y, SIG_5, 3)$

$IDRG_6 := regress(Y, SIG_6, 3)$

$IDRG_7 := regress(Y, SIG_7, 3)$

$IDRG_8 := regress(Y, SIG_8, 3)$

$IDRG_9 := regress(Y, SIG_9, 3)$

$IDRG_{10} := regress(Y, SIG_{10}, 3)$

$IDRG_{11} := regress(Y, SIG_{11}, 3)$

$IDRG_{12} := regress(Y, SIG_{12}, 3)$

$IDRG_{13} := regress(Y, SIG_{13}, 3)$

$IDRG_{14} := regress(Y, SIG_{14}, 3)$

$IDRG_{15} := regress(Y, SIG_{15}, 3)$

$IDRG_{16} := regress(Y, SIG_{16}, 3)$

$IDRG_{17} := regress(Y, SIG_{17}, 3)$

$IDRG_{18} := regress(Y, SIG_{18}, 3)$

$IDRG_{19} := regress(Y, SIG_{19}, 3)$

$IDRG_{20} := regress(Y, SIG_{20}, 3)$

Third-order polynomial regression to determine the coefficients that describe the stress distribution through the wall at the defined locations.

SICF Coefficient Determination

Jsb :=

	0	1	2
0	1.000	0.200	0.000
1	1.000	0.200	0.200
2	1.000	0.200	0.500
3	1.000	0.200	0.800
4	1.000	0.200	1.000
5	1.000	0.400	0.000
6	1.000	0.400	0.200
7	1.000	0.400	0.500
8	1.000	0.400	0.800
9	1.000	0.400	1.000
10	1.000	1.000	0.000
11	1.000	1.000	0.200
12	1.000	1.000	0.500
13	1.000	1.000	0.800
14	1.000	1.000	1.000
15	2.000	0.200	0.000
16	2.000	0.200	0.200
17	2.000	0.200	0.500
18	2.000	0.200	0.800
19	2.000	0.200	1.000
20	2.000	0.400	0.000
21	2.000	0.400	0.200
22	2.000	0.400	0.500

Partial data table for the SICF determination.

1) Column 0 is the R_m/t ratio.
2) Column 1 is the a/c ratio (crack aspect ratio)
3) Column 2 is the a/t ratio (normalized crack depth)

This table in conjunction with the table in the following page together is used to determine the particular SICF

ambi :=

	0	1	2	3	4	5	6	7
0	1.076	0.693	0.531	0.434	0.608	0.083	0.023	0.009
1	1.056	0.647	0.495	0.408	0.615	0.085	0.027	0.013
2	1.395	0.767	0.557	0.446	0.871	0.171	0.069	0.038
3	2.53	1.174	0.772	0.58	1.554	0.363	0.155	0.085
4	3.846	1.615	0.995	0.716	2.277	0.544	0.233	0.127
5	1.051	0.689	0.536	0.444	0.74	0.112	0.035	0.015
6	1.011	0.646	0.504	0.421	0.745	0.119	0.041	0.02
7	1.149	0.694	0.529	0.435	0.916	0.181	0.073	0.04
8	1.6	0.889	0.642	0.51	1.334	0.307	0.132	0.073
9	2.087	1.093	0.761	0.589	1.752	0.421	0.183	0.101
10	0.992	0.704	0.534	0.506	1.044	0.169	0.064	0.032
11	0.987	0.701	0.554	0.491	1.08	0.182	0.067	0.034
12	1.01	0.709	0.577	0.493	1.116	0.2	0.078	0.041
13	1.07	0.73	0.623	0.523	1.132	0.218	0.095	0.051
14	1.128	0.75	0.675	0.556	1.131	0.229	0.11	0.06
15	1.049	0.673	0.519	0.427	0.6	0.078	0.021	0.008
16	1.091	0.661	0.502	0.413	0.614	0.083	0.025	0.012

Partial table of the influence coefficients (SICF) as described below:

1) Column 0 is the uniform coefficient for the a-tip.
2) Column 1 is the linear coefficient for the a-tip.
3) Column 2 is the quadratic coefficient for the a-tip.
4) Column 3 is the cubic coefficient for the a-tip.
5) Column 4 is the uniform coefficient for the c-tip.
6) Column 5 is the linear coefficient for the c-tip.
7) Column 6 is the quadratic coefficient for the c-tip.
8) Column 7 is the cubic coefficient for the c-tip.

Both tables, (labeled Jsb and sambi), have the same number of rows.

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

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

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

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

"a-Tip" Uniform Term

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

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

$f_{aU}(4, .4, .8) = 1.424$ *Check Calculation*

Programming steps shown for determining the SICF.

1) First is the definition of the column matrix defined with respect to the tables above.
2) Second is the conditional statement that defines the polynomial order based on cylinder property (R_m/t ratio). For thick cylinder the polynomial order is cubic (3) whereas for thin cylinder it is quadratic (2).
3) Third the M_{aU} statement assembles the matrix required for regression and interpolation for the uniform a-tip SICF.
4) Fourth the R_{aU} statement performs the nonlinear regression on the assembled matrix to determine the regression coefficients needed for the interpolation routine. This is for the uniform a-tip term.
5) Fifth the f_{aU} statement defines the interpolation function. This is for the uniform a-tip term.
6) Sixth the $f_{aU}(4,.4,.8)$ statement is the check calculation for $R_m/t = 4$, $a/c = 0.4$ and $a/t = 0.8$. The calculated value of 1.424 compares favorably with the text value of 1.443.
7) Similar structure is followed for all the other SICF entries.

Recursive Loop for Calculation of PWSCC Crack Growth

$$
CGR_{sambi} := \left|
\begin{array}{l}
j \leftarrow 0 \\
a_0 \leftarrow a_0 \\
c_0 \leftarrow c_0 \\
NCB_0 \leftarrow C_{blk} \\
\text{while } j \le I_{lim}
\end{array}
\right.
$$

Start of the recursive loop showing the loop initialization.

1) Index "j" is set to zero (0).
2) Initial crack depth and half length are defined.
3) The Time for corrosion interval is initialized.
4) The internal loop for each corrosion time span is initiated.

$$\sigma_0 \leftarrow \begin{array}{|l} IDRG1_{3} \text{ if } c_j \le c_0 \\ IDRG2_{3} \text{ if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\ IDRG3_{3} \text{ if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg} \\ IDRG4_{3} \text{ if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg} \\ IDRG5_{3} \text{ if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg} \\ IDRG6_{3} \text{ if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg} \\ IDRG7_{3} \text{ if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg} \\ IDRG8_{3} \text{ if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg} \\ IDRG9_{3} \text{ if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg} \\ IDRG10_{3} \text{ if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg} \end{array}$$

Partial statement showing assignment of the uniform stress coefficient. The assignment considers all twenty (20) segments. Similar assignment statements cover the other three stress coefficients (viz. linear – σ_1, quadratic- σ_2 , and cubic - σ_3). The assignment is based on the current flaw upper c-tip location. The conditional statement is based on current location "c_j" as compared to the upper and lower limit for each segment.

$$
\begin{aligned}
&\xi_0 \leftarrow \sigma_0 \\
&\xi_1 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.25 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.25 \cdot a_j}{t}\right)^3 \\
&\xi_2 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.5 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.5 \cdot a_j}{t}\right)^3 \\
&\xi_3 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{0.75 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{0.75 \cdot a_j}{t}\right)^3 \\
&\xi_4 \leftarrow \sigma_0 + \sigma_1 \cdot \left(\frac{1.0 \cdot a_j}{t}\right) + \sigma_2 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^2 + \sigma_3 \cdot \left(\frac{1.0 \cdot a_j}{t}\right)^3
\end{aligned}
$$

Using the stress coefficients for the through-wall stress distribution, this step determines the stress distribution across the crack face in the depth direction. The crack depth is divided into five equal segments. The stress distribution across the crack face is calculated for each current crack location.

$$
\begin{aligned}
&x_0 \leftarrow 0.0 \\
&x_1 \leftarrow 0.25 \\
&x_2 \leftarrow 0.5 \\
&x_3 \leftarrow 0.75 \\
&x_4 \leftarrow 1.0 \\
&X \leftarrow \text{stack}(x_0, x_1, x_2, x_3, x_4) \\
&ST \leftarrow \text{stack}(\xi_0, \xi_1, \xi_2, \xi_3, \xi_4) \\
&RG \leftarrow \text{regress}(X, ST, 3)
\end{aligned}
$$

Developing the appropriate matrix and performing a third-order polynomial regression to determine the stress coefficients for the stress distribution across the crack face. These stress coefficients are used in the SIF dteremination.

$$\sigma_{00} \leftarrow RG_3 + P_{Int}$$
$$\sigma_{10} \leftarrow RG_4$$
$$\sigma_{20} \leftarrow RG_5$$
$$\sigma_{30} \leftarrow RG_6$$

Assignment of the stress coefficients. The stress coefficient for the uniform term σ_{00} contains the coefficient for the uniform stress (operating+residual) and the addition of the internal pressure (P_{Int}). This is the step where the internal pressure is added to the calculation. This step ensures that the crack faces are pressurized.

$$AR_j \leftarrow \frac{a_j}{c_j}$$
$$AT_j \leftarrow \frac{a_j}{t}$$
$$G_{au_j} \leftarrow f_{aU}(R_t, AR_j, AT_j)$$
$$G_{al_j} \leftarrow f_{aL}(R_t, AR_j, AT_j)$$
$$G_{aq_j} \leftarrow f_{aQ}(R_t, AR_j, AT_j)$$
$$G_{ac_j} \leftarrow f_{aC}(R_t, AR_j, AT_j)$$
$$G_{cu_j} \leftarrow f_{cU}(R_t, AR_j, AT_j)$$
$$G_{cl_j} \leftarrow f_{cL}(R_t, AR_j, AT_j)$$
$$G_{cq_j} \leftarrow f_{cQ}(R_t, AR_j, AT_j)$$
$$G_{cc_j} \leftarrow f_{cC}(R_t, AR_j, AT_j)$$

Step showing calculation of current crack aspect ratio (a/c), the current crack normalized depth (a/t) and the function call {G_{xx}; e.g.(G_{au_j})} for the eight SICF associated with the current crack dimensions.

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

Determination of the crack shape factor depending on the current crack aspect ratio.

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

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

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

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

Determination of the SIF at the two crack tips (a-tip and c-tip) in English units and conversion to metric units.

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

Conditional statement to test for the threshold value for the SIF. This is needed for PWSCC crack growth analysis. Done for both the a-tip and c-tip. Only the a-tip is shown.

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

Calculation of the crack growth rate {da/dt} in metric units (m/sec). Shown for the a-tip but sthe same calculation is performed for the c-tip.

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

Calculation for crack growth in one time block. This block for the current analysis is about twenty-four hours (24 hrs.). The crack growth is in English units (inch) because the conversion factor {CF_{inhr}} is used. The first statement is set when the SIF is below the upper asymptote and the second statement is used when the SIF is greater than the upper asymptote. When the SIF is greater than the upper asymptote, the SIF independent crack growth is about 0.5 inch per year.

$$output_{(j,0)} \leftarrow j$$
$$output_{(j,1)} \leftarrow a_j$$
$$output_{(j,2)} \leftarrow c_j - c_0$$
$$output_{(j,3)} \leftarrow D_{ag_j}$$
$$output_{(j,4)} \leftarrow D_{cg_j}$$
$$output_{(j,5)} \leftarrow K_{a_j}$$
$$output_{(j,6)} \leftarrow K_{c_j}$$
$$output_{(j,7)} \leftarrow \frac{NCB_j}{365 \cdot 24}$$

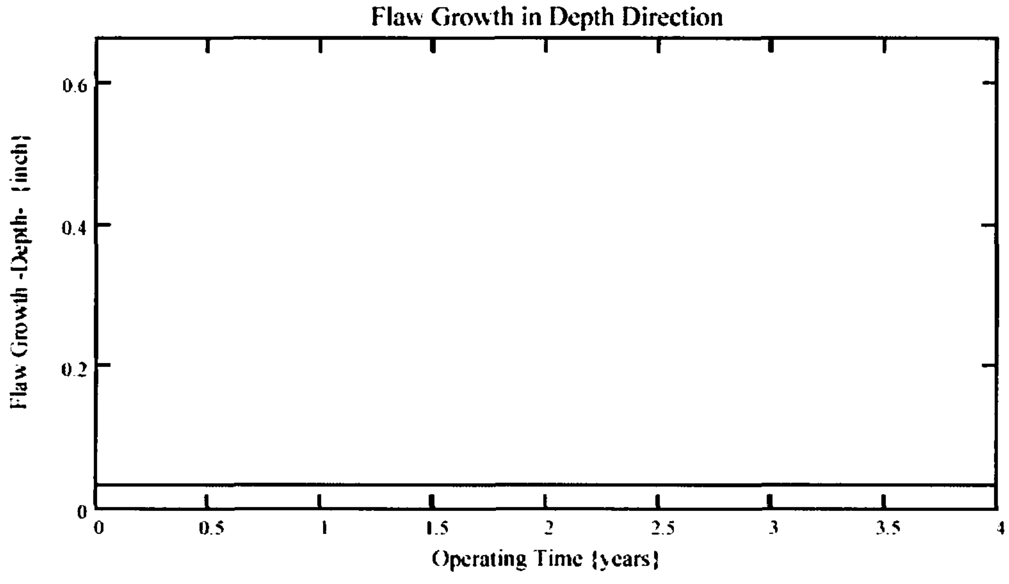
Typical output statements within the recursive loop showing the storing of variables that are required for loop operation and those of interest in displaying the time dependent trend.

$$j \leftarrow j + 1$$
$$a_j \leftarrow a_{j-1} + D_{ag_{j-1}}$$
$$c_j \leftarrow c_{j-1} + D_{cg_{j-1}}$$
$$a_j \leftarrow \begin{cases} t & \text{if } a_j \geq t \\ a_j & \text{otherwise} \end{cases}$$
$$NCB_j \leftarrow NCB_{j-1} + C_{blk}$$

output

The recursive loop is incremented and the required variables (crack depth, crack length, and the time variable are updated for the start of the next recursive loop operation. The last statement is a dummy statement to terminate the recursive loop.

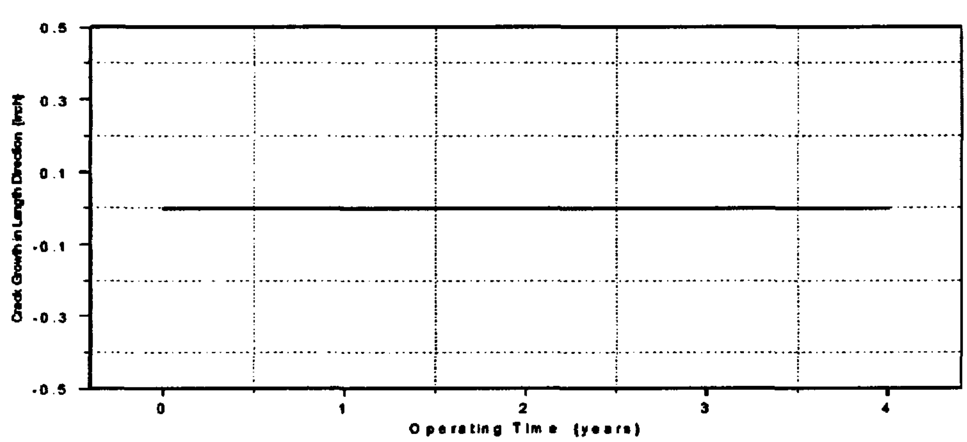
$Prop_{Length} = 0.506$



Typical Mathcad graphical display used to evaluate the important parameters. The $Prop_{Length}$ in the upper left corner is used to ascertain the growth to the weld. This number is calculated internally before the recursive loop is started. This is the difference between the weld bottom location ($UL_{Strs.Dist}$) and the Crack Upper Tip location (U_{Tip}).

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(1}}$
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111
1	0.163	0.111

Typical numerical output in tabular form used to ensure proper functioning of the model.



Typical Axum graphics for use in the report.

End of the Mathcad worksheet Description

Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw

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

Refrences :

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

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8.8" 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 .

OD Surface Flaw

Note :- The two differences between this model and the ID surface flaw model are:
1) Use of SICF tables from Reference1 for External flaws (pages 9 - 12).
2) The stress distribution is from the OD to the ID (pages 6 - 8).
These diffetences are noted (in bold red print) at the appropriate locations.

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

$$Ref_{Point} := 1.544$$

To place the flaw with repsect to the reference point, the flaw tips and center can be located as follows:
1) The Upper "c- tip" located at the reference point (Enter 1)
2) The Center of the flaw at the reference point (Enter 2)
3) The lower "c- tip" located at the reference point (Enter 3).

$$Val := 1$$

Input Data :-

$L := 0.3966$ Initial Flaw Length

$a_0 := 0.0661$ Initial Flaw Depth

$od := 4.05$ Tube OD

$id := 2.728$ Tube ID

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

$Years := 4$ Number of Operating Years

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

$T := 604$ Estimate of Operating Temperature

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

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

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

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

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

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

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

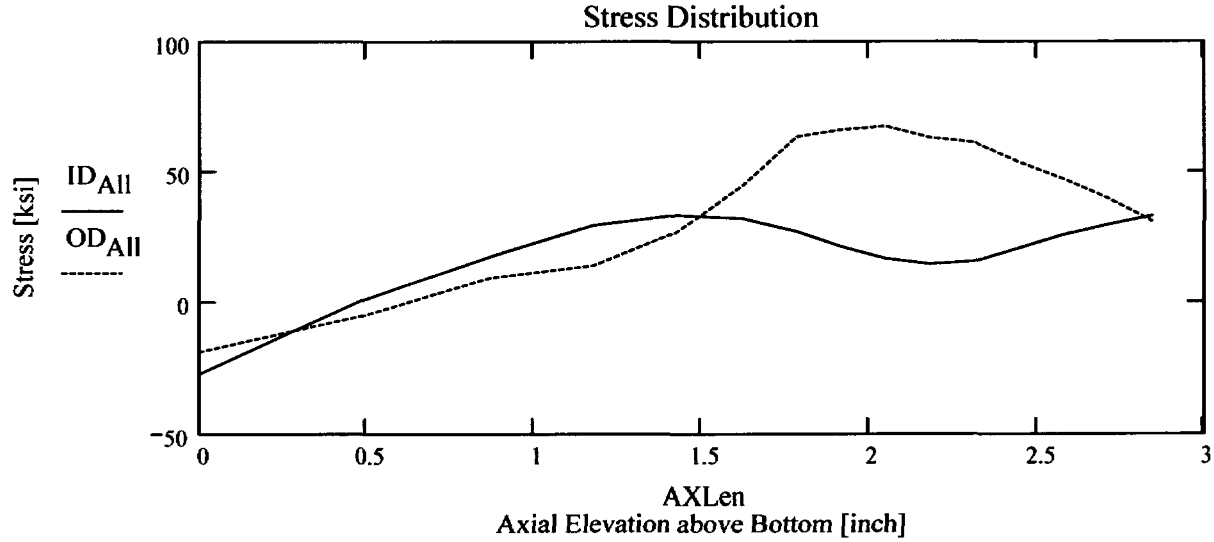
Stress Input Data

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

AllData :=

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

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



Observing the stress distribution select the region in the table above labeled Data$_{All}$ that represents the

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

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

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

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

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

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

No User Input is required beyond this Point

Calculation to Develop Hoop Stress Profiles in the Axial Direction for Fracture Mechanics Analysis

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

$Loc_0 := FL_{Cntr} - L$

$i := 1 .. N + 3$

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

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

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

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

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

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

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

Development of Elevation-Averaged stresses at 20 elevations along the tube for use in Fracture Mechanics Model

$j := 1 .. N$

$| \; SID_j + SID_{j+1} + SID_{j+2} \; ...$ $| \; SQT_j + SQT_{j+1} + SQT_{j+2} \; ...$

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

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

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

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

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

Note the Change here to develop stress distribution form OD to ID

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

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

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

$$SIG_1 := \text{stack}(S_{od_1}, S_{tq_1}, S_{md_1}, S_{qt_1}, S_{id_1})$$

$$SIG_2 := \text{stack}(S_{od_2}, S_{tq_2}, S_{md_2}, S_{qt_2}, S_{id_2})$$

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

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

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

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

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

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

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

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

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

Regression of Throughwall Stress distribution to obtain Stress Coefficients throughwall using a Third Order polynomial

$ODRG_1 := regress\left(Y, SIG_1, 3\right)$ $ODRG_2 := regress\left(Y, SIG_2, 3\right)$

$ODRG_3 := regress(Y, SIG_3, 3)$

$ODRG_4 := regress(Y, SIG_4, 3)$

$ODRG_5 := regress(Y, SIG_5, 3)$

$ODRG_6 := regress(Y, SIG_6, 3)$

$ODRG_7 := regress(Y, SIG_7, 3)$

$ODRG_8 := regress(Y, SIG_8, 3)$

$ODRG_9 := regress(Y, SIG_9, 3)$

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

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

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

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

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

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

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

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

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

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

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

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

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

$Prop_{Length} = 0.242$

Data Files for Flaw Shape Factors from NASA (NASA-TM-111707-SC04 Model) {NO INPUT Required}

Data Tables for External falws from Reference 1

Mettu Raju Newman Sivakumar Forman Solution of ID Part throughwall Flaw in Cyinder

Jsb :=

	0	1	2
0	1.000	0.200	0.000
1	1.000	0.200	0.200
2	1.000	0.200	0.500
3	1.000	0.200	0.800
4	1.000	0.200	1.000
5	1.000	0.400	0.000
6	1.000	0.400	0.200
7	1.000	0.400	0.500
8	1.000	0.400	0.800
9	1.000	0.400	1.000
10	1.000	1.000	0.000
11	1.000	1.000	0.200
12	1.000	1.000	0.500
13	1.000	1.000	0.800
14	1.000	1.000	1.000
15	2.000	0.200	0.000
16	2.000	0.200	0.200
17	2.000	0.200	0.500
18	2.000	0.200	0.800
19	2.000	0.200	1.000
20	2.000	0.400	0.000
21	2.000	0.400	0.200
22	2.000	0.400	0.500
23	2.000	0.400	0.800
24	2.000	0.400	1.000
25	2.000	1.000	0.000
26	2.000	1.000	0.200
27	2.000	1.000	0.500
28	2.000	1.000	0.800
29	2.000	1.000	1.000
30	4.000	0.200	0.000
31	4.000	0.200	0.200
32	4.000	0.200	0.500
33	4.000	0.200	0.800
34	4.000	0.200	1.000
35	4.000	0.400	0.000

36	4.000	0.400	0.200
37	4.000	0.400	0.500
38	4.000	0.400	0.800
39	4.000	0.400	1.000
40	4.000	1.000	0.000
41	4.000	1.000	0.200
42	4.000	1.000	0.500
43	4.000	1.000	0.800
44	4.000	1.000	1.000
45	10.000	0.200	0.000
46	10.000	0.200	0.200
47	10.000	0.200	0.500
48	10.000	0.200	0.800
49	10.000	0.200	1.000
50	10.000	0.400	0.000
51	10.000	0.400	0.200
52	10.000	0.400	0.500
53	10.000	0.400	0.800
54	10.000	0.400	1.000
55	10.000	1.000	0.000
56	10.000	1.000	0.200
57	10.000	1.000	0.500
58	10.000	1.000	0.800
59	10.000	1.000	1.000
60	300.000	0.200	0.000
61	300.000	0.200	0.200
62	300.000	0.200	0.500
63	300.000	0.200	0.800
64	300.000	0.200	1.000
65	300.000	0.400	0.000
66	300.000	0.400	0.200
67	300.000	0.400	0.500
68	300.000	0.400	0.800
69	300.000	0.400	1.000
70	300.000	1.000	0.000
71	300.000	1.000	0.200
72	300.000	1.000	0.500
73	300.000	1.000	0.800
74	300.000	1.000	1.000

Sambi :=

	0	1	2	3	4	5	6	7
0	1.244	0.754	0.564	0.454	0.755	0.153	0.06	0.032
1	1.237	0.719	0.536	0.435	0.594	0.076	0.021	0.009
2	1.641	0.867	0.615	0.486	0.648	0.089	0.026	0.011
3	2.965	1.336	0.858	0.635	1.293	0.271	0.109	0.058
4	4.498	1.839	1.107	0.783	2.129	0.481	0.202	0.11
5	1.146	0.716	0.546	0.448	0.889	0.17	0.064	0.032
6	1.175	0.709	0.539	0.444	0.809	0.132	0.046	0.023
7	1.452	0.806	0.589	0.474	0.934	0.17	0.064	0.033
8	2.119	1.046	0.714	0.55	1.492	0.329	0.136	0.073
9	2.8	1.279	0.833	0.621	2.143	0.497	0.21	0.114
10	1.03	0.715	0.577	0.49	1.148	0.202	0.076	0.039
11	1.054	0.725	0.586	0.499	1.202	0.214	0.081	0.042
12	1.146	0.76	0.606	0.513	1.354	0.256	0.1	0.053
13	1.305	0.817	0.634	0.527	1.594	0.327	0.133	0.071
14	1.412	0.866	0.657	0.537	1.796	0.387	0.161	0.087
15	1.111	0.688	0.522	0.426	0.72	0.121	0.041	0.02
16	1.193	0.7	0.524	0.427	0.611	0.079	0.022	0.01
17	1.655	0.868	0.614	0.484	0.693	0.105	0.035	0.017
18	2.732	1.255	0.817	0.609	1.207	0.245	0.097	0.051
19	3.842	1.634	1.009	0.726	1.826	0.395	0.162	0.086
20	1.077	0.685	0.528	0.436	0.817	0.14	0.049	0.023
21	1.136	0.692	0.528	0.436	0.796	0.13	0.046	0.022
22	1.403	0.785	0.576	0.465	0.959	0.182	0.071	0.037
23	1.942	0.984	0.682	0.53	1.425	0.315	0.131	0.071
24	2.454	1.168	0.78	0.591	1.915	0.443	0.188	0.102
25	1.02	0.72	0.585	0.498	1.152	0.196	0.072	0.036
26	1.044	0.722	0.584	0.498	1.185	0.209	0.079	0.041
27	1.117	0.746	0.597	0.505	1.318	0.25	0.098	0.052
28	1.236	0.797	0.625	0.523	1.56	0.315	0.127	0.068
29	1.335	0.844	0.652	0.538	1.775	0.37	0.151	0.08
30	1.009	0.65	0.507	0.427	0.589	0.073	0.018	0.006
31	1.162	0.691	0.524	0.434	0.612	0.08	0.023	0.01
32	1.64	0.861	0.613	0.488	0.786	0.134	0.049	0.025
33	2.51	1.178	0.782	0.596	1.16	0.242	0.097	0.051
34	3.313	1.464	0.932	0.693	1.517	0.339	0.139	0.073
35	1	0.655	0.518	0.44	0.754	0.118	0.036	0.017
36	1.109	0.685	0.53	0.445	0.793	0.13	0.045	0.022
37	1.36	0.773	0.575	0.472	0.994	0.195	0.078	0.041
38	1.727	0.914	0.653	0.523	1.4	0.318	0.134	0.073
39	2.025	1.032	0.72	0.568	1.781	0.427	0.181	0.1
40	0.986	0.711	0.589	0.513	1.127	0.189	0.068	0.034

41	1.03	0.72	0.591	0.513	1.163	0.204	0.077	0.04
42	1.094	0.743	0.603	0.52	1.286	0.243	0.096	0.051
43	1.156	0.777	0.625	0.536	1.498	0.302	0.122	0.064
44	1.194	0.804	0.644	0.551	1.681	0.35	0.142	0.073
45	0.981	0.636	0.501	0.422	0.598	0.078	0.02	0.007
46	1.147	0.685	0.521	0.432	0.612	0.08	0.023	0.01
47	1.584	0.839	0.6	0.48	0.806	0.142	0.053	0.028
48	2.298	1.099	0.739	0.568	1.262	0.277	0.114	0.062
49	2.921	1.323	0.859	0.645	1.715	0.402	0.169	0.092
50	0.975	0.645	0.516	0.439	0.75	0.114	0.036	0.017
51	1.096	0.68	0.528	0.444	0.788	0.128	0.045	0.022
52	1.31	0.755	0.565	0.466	0.984	0.192	0.076	0.04
53	1.565	0.858	0.625	0.505	1.378	0.309	0.129	0.07
54	1.749	0.938	0.675	0.539	1.747	0.411	0.174	0.095
55	0.982	0.709	0.588	0.515	1.123	0.188	0.068	0.034
56	1.025	0.718	0.59	0.513	1.156	0.202	0.076	0.039
57	1.078	0.738	0.6	0.518	1.266	0.236	0.092	0.048
58	1.118	0.765	0.619	0.533	1.453	0.286	0.113	0.059
59	1.137	0.786	0.636	0.548	1.613	0.326	0.129	0.067
60	0.936	0.62	0.486	0.405	0.582	0.068	0.015	0.005
61	1.145	0.681	0.514	0.42	0.613	0.081	0.024	0.011
62	1.459	0.79	0.569	0.454	0.79	0.138	0.051	0.026
63	1.774	0.917	0.641	0.501	1.148	0.239	0.096	0.051
64	1.974	1.008	0.696	0.537	1.482	0.328	0.134	0.07
65	0.982	0.651	0.512	0.427	0.721	0.103	0.031	0.013
66	1.095	0.677	0.52	0.431	0.782	0.127	0.045	0.022
67	1.244	0.727	0.546	0.446	0.946	0.18	0.071	0.037
68	1.37	0.791	0.585	0.473	1.201	0.253	0.102	0.054
69	1.438	0.838	0.618	0.496	1.413	0.31	0.126	0.066

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

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

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

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

"a-Tip" Uniform Term

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

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

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

Linear Term

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

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

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

Quadratic Term

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

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

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

Cubic Term

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

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

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

"C" Tip Coefficients

Uniform Term

$M_{cU} := \text{augment}(W, X, Y)$ $\quad V_{cU} := c_U$ $\quad R_{cU} := \text{regress}(M_{cU}, V_{cU}, n)$

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

$f_{cU}(4, .4, .8) = 1.371$ *Check Calculation*

Linear Term

$M_{cL} := \text{augment}(W, X, Y)$ $\quad V_{cL} := c_L$ $\quad R_{cL} := \text{regress}(M_{cL}, V_{cL}, n)$

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

$f_{cL}(2, .4, .8) = 0.319$ *Check Calculation*

Quadratic Term

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

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

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

Cubic Term

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

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

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

Calculations : Recursive calculations to estimate flaw growth

Calculations : Recursive calculations to estimate flaw growth.

Recursive Loop for Calculation of PWSCC Crack Growth Entergy Model

$CGR_{sambi} :=$

$j \leftarrow 0$

$a_0 \leftarrow a_0$

$c_0 \leftarrow c_0$

$NCB_0 \leftarrow C_{blk}$

while $j \le I_{lim}$

$\sigma_0 \leftarrow$
- $ODRG_{1_3}$ if $c_j \le c_0$
- $ODRG_{2_3}$ if $c_0 < c_j \le c_0 + Inc_{Strs.avg}$
- $ODRG_{3_3}$ if $c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$
- $ODRG_{4_3}$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$
- $ODRG_{5_3}$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$
- $ODRG_{6_3}$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$
- $ODRG_{7_3}$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$
- $ODRG_{8_3}$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$
- $ODRG_{9_3}$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$
- $ODRG_{10_3}$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$
- $ODRG_{11_3}$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$
- $ODRG_{12_3}$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$
- $ODRG_{13_3}$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$
- $ODRG_{14_3}$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$
- ODRG ... if $c_0 + 13 \cdot Inc$ ... $< c_j \le c_0 + 14 \cdot Inc$ ...

$ODRG_{15_3}$ if $c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$

$ODRG_{16_3}$ if $c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$

$ODRG_{17_3}$ if $c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$

$ODRG_{18_3}$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$ODRG_{19_3}$ if $c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$

$ODRG_{20_3}$ otherwise

$\sigma_1 \leftarrow$ $ODRG_{1_4}$ if $c_j \le c_0$

$ODRG_{2_4}$ if $c_0 < c_j \le c_0 + Inc_{Strs.avg}$

$ODRG_{3_4}$ if $c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$

$ODRG_{4_4}$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$

$ODRG_{5_4}$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$

$ODRG_{6_4}$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$

$ODRG_{7_4}$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$

$ODRG_{8_4}$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$

$ODRG_{9_4}$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$

$ODRG_{10_4}$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$

$ODRG_{11_4}$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$

$ODRG_{12_4}$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$

$ODRG_{13_4}$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$

$ODRG_{14_4}$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$

$ODRG_{15_4}$ if $c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$

$ODRG_{16_4}$ if $c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$

$ODRG_{17_4}$ if $c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$

$ODRG_{18_4}$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$ODRG_{19_4}$ if $c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$

$ODRG_{20_4}$ otherwise

$\sigma_2 \leftarrow$ $ODRG_{1_5}$ if $c_j \le c_0$

$ODRG_{2_5}$ if $c_0 < c_j \le c_0 + Inc_{Strs.avg}$

$ODRG_{3_5}$ if $c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$

$ODRG_{4_5}$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$

$ODRG_{5_5}$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$

$ODRG_{6_5}$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$

$ODRG_{7_5}$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$

$ODRG_{8_5}$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$

$ODRG_{9_5}$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$

$ODRG_{10_5}$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$

$ODRG_{11_5}$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$

$ODRG_{12_5}$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$

$ODRG_{13_5}$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$

$ODRG_{14_5}$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$

$ODRG_{15_5}$ if $c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$

$ODRG_{16_5}$ if $c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$

$ODRG_{17_5}$ if $c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$

$ODRG_{18}$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$$\ldots 18_5 \quad \ldots \, \text{Strs.avg} \ldots j \ldots \text{Strs.avg}$$

$$\text{ODRG}_{19_5} \quad \text{if } c_0 + 17 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 18 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{20_5} \quad \text{otherwise}$$

$$\sigma_3 \leftarrow \text{ODRG}_{1_6} \quad \text{if } c_j \le c_0$$

$$\text{ODRG}_{2_6} \quad \text{if } c_0 < c_j \le c_0 + \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{3_6} \quad \text{if } c_0 + \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 2 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{4_6} \quad \text{if } c_0 + 2 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 3 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{5_6} \quad \text{if } c_0 + 3 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 4 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{6_6} \quad \text{if } c_0 + 4 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 5 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{7_6} \quad \text{if } c_0 + 5 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 6 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{8_6} \quad \text{if } c_0 + 6 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 7 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{9_6} \quad \text{if } c_0 + 7 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 8 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{10_6} \quad \text{if } c_0 + 8 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 9 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{11_6} \quad \text{if } c_0 + 9 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 10 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{12_6} \quad \text{if } c_0 + 10 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 11 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{13_6} \quad \text{if } c_0 + 11 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 12 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{14_6} \quad \text{if } c_0 + 12 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 13 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{15_6} \quad \text{if } c_0 + 13 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 14 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{16_6} \quad \text{if } c_0 + 14 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 15 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{17_6} \quad \text{if } c_0 + 15 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 16 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{18_6} \quad \text{if } c_0 + 16 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 17 \cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{19_6} \quad \text{if } c_0 + 17 \cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 18 \cdot \text{Inc}_{\text{Strs.avg}}$$

$ODRG20_6$ otherwise

$\xi_0 \leftarrow \sigma_0$

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

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

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

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

$x_0 \leftarrow 0.0$

$x_1 \leftarrow 0.25$

$x_2 \leftarrow 0.5$

$x_3 \leftarrow 0.75$

$x_4 \leftarrow 1.0$

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

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

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

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

$\sigma_{10} \leftarrow RG_4$

$\sigma_{20} \leftarrow RG_5$

$\sigma_{30} \leftarrow RG_6$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$\quad 4\cdot 10^{-10}\cdot CF_{inhr}\cdot C_{blk}$ otherwise

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$j \leftarrow j + 1$

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

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

$$\cdots + cg_{j-1}$$

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

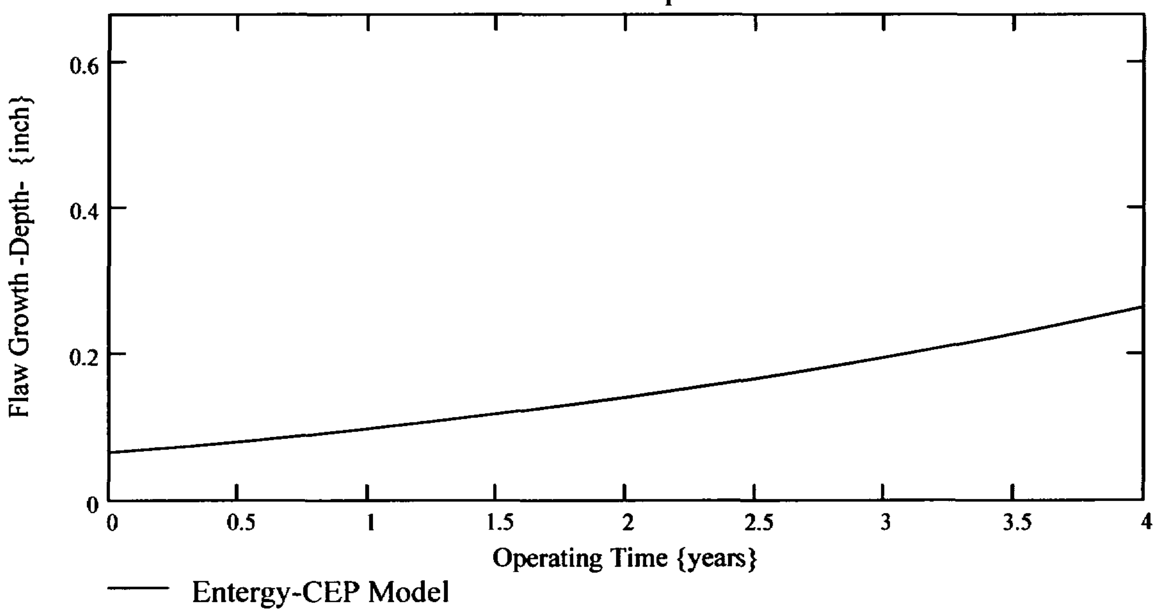
$$NCB_j \leftarrow NCB_{j-1} + C_{blk}$$

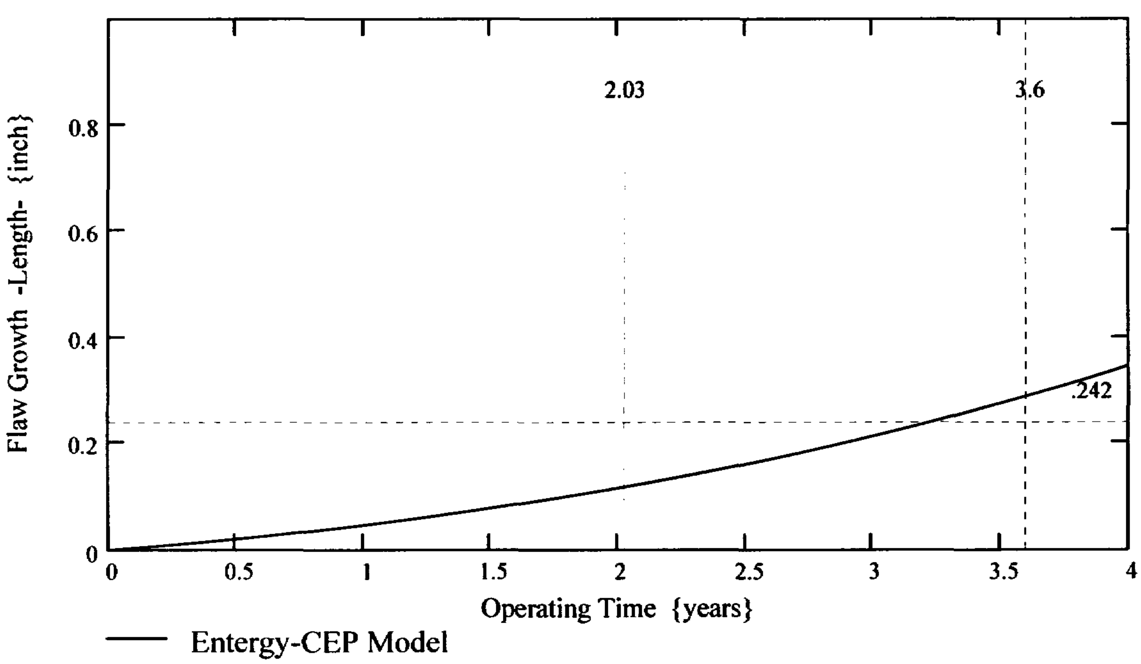
output

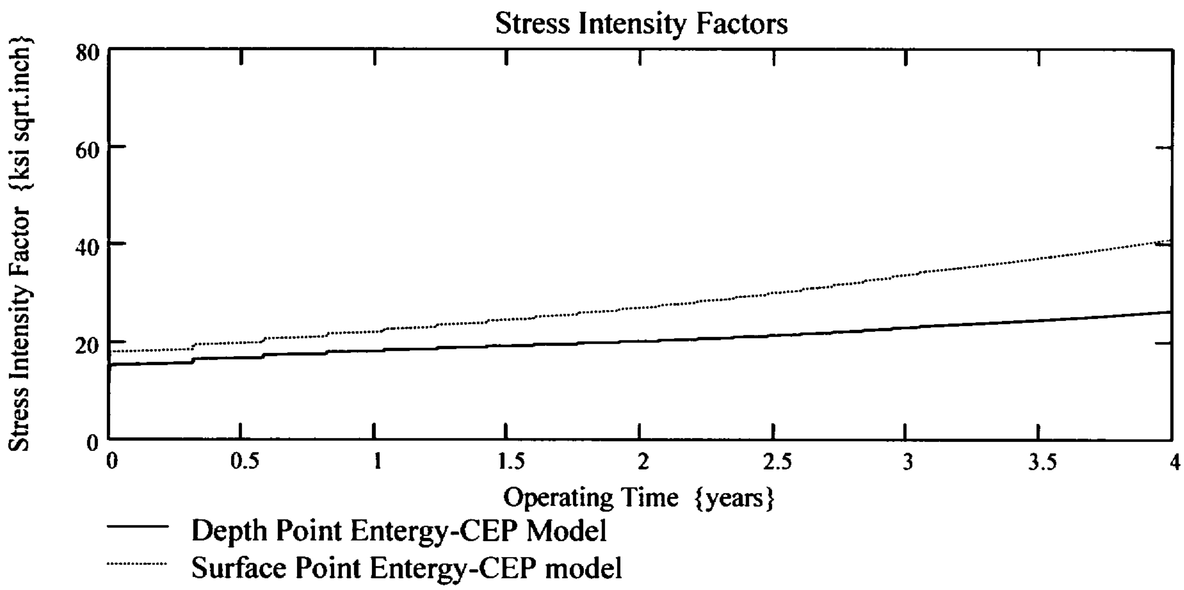
$$k := 0 .. I_{lim}$$

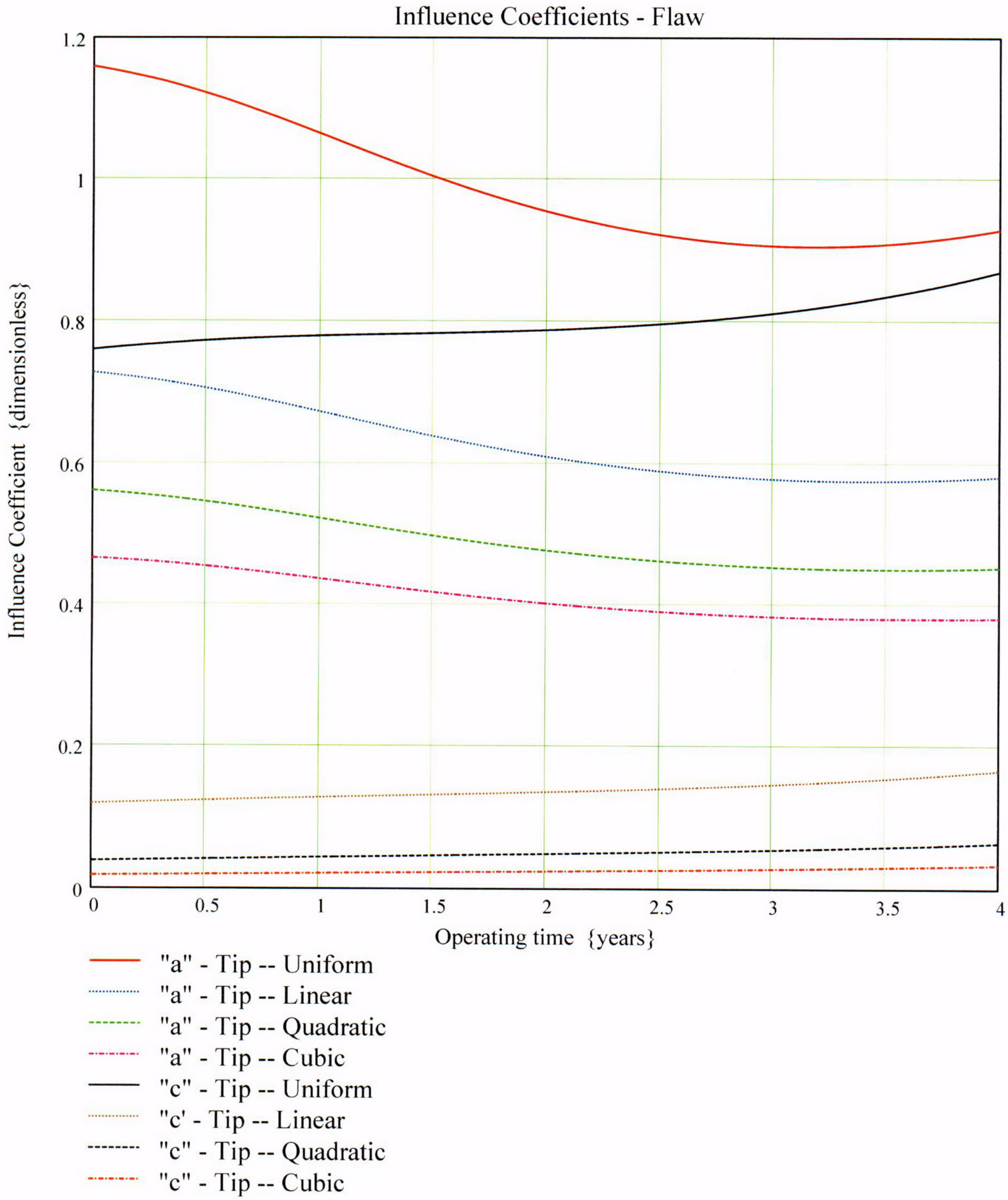
$Prop_{Length} = 0.242$

Flaw Growth in Depth Direction






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


Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
Operating time {years}
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
3.5
4
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic
"c" - Tip -- Cubic

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

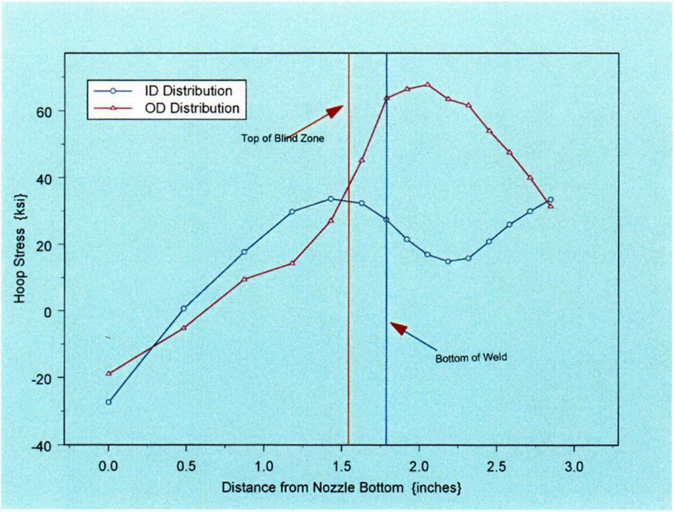
1.158
1.158
1.158
1.158
1.158
1.158
1.158
1.157
1.157
1.157
1.157
1.157
1.157
1.156
1.156
1.156

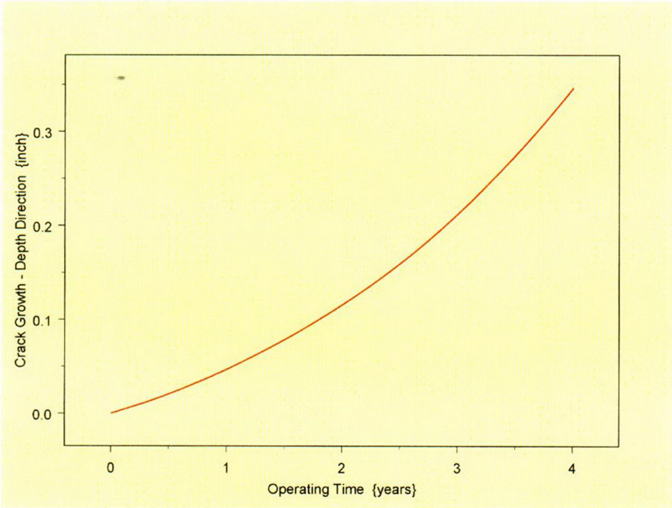
$CGR_{sambi_{(k,6)}} =$

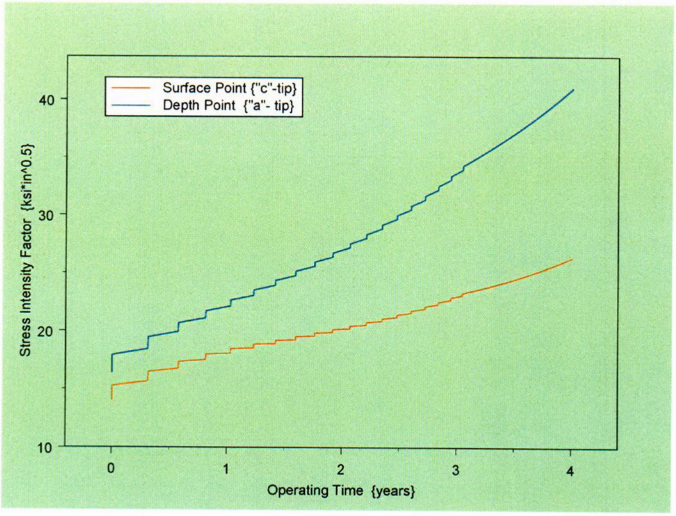
16.383
17.9
17.905
17.91
17.915
17.919
17.924
17.929
17.934
17.939
17.943
17.948
17.953
17.958
17.962
17.967

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

14
15.225
15.229
15.233
15.237
15.241
15.245
15.249
15.253
15.257
15.261
15.265
15.269
15.273
15.277
15.281


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


Crack Growth - Depth Direction {inch}
0.3
0.2
0.1
0.0
0
1
2
3
4
Operating Time {years}


Surface Point {"c"-tip}
Depth Point {"a"- tip}
Stress Intensity Factor {ksi*in^0.5}
10
20
30
40
0
1
2
3
4
Operating Time {years}

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.

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

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

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

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

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

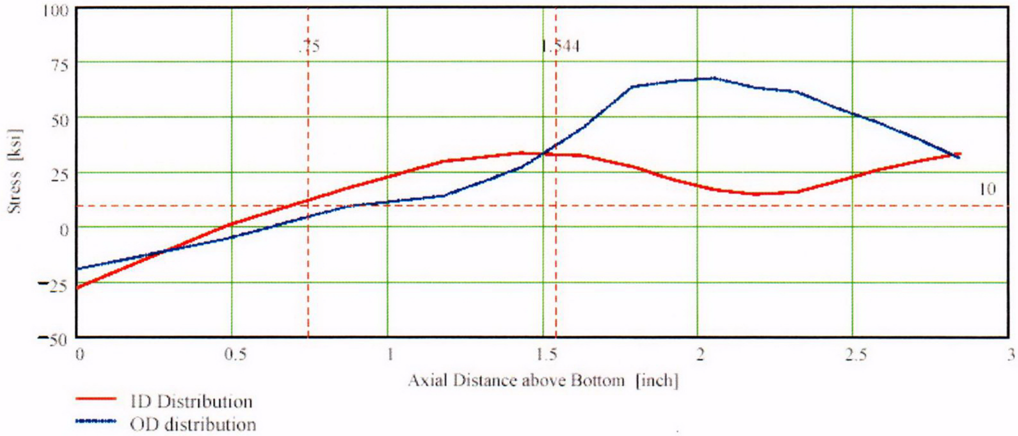
Import the Required data from applicable Excel spread Sheet. The column designations are as follo
Cloumn "0" = Axial distance from Minimum to Maximum recorded on the data sheet (inches)
Column "1" = ID Stress data at each Elevation (ksi)
Column "5" = OD Stress data at each Elevation (ksi)

$Data_{All} :=$

	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.

C04

$FL_{Cntr} := BZ - l$ **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.

$j := 1..N$

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

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

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

	Membrane Stress σ_m =	Bending Stress σ_b =	OD Stress S_{od} =	ID Stress S_{id} =
	0	0	0	0
0	0	0	0	0
1	23.795	-3.536	18.023	25.096
2	27.339	-1.932	23.172	27.036
3	29.561	-0.851	26.475	28.176
4	31.121	-0.028	28.858	28.914
5	32.304	0.649	30.719	29.42
6	33.253	1.238	32.256	29.779
7	34.044	1.771	33.58	30.039
8	34.727	2.266	34.757	30.226
9	35.33	2.735	35.83	30.361
10	35.875	3.186	36.826	30.453
11	36.374	3.626	37.766	30.513
12	36.839	4.058	38.662	30.546
13	37.276	4.485	39.526	30.555
14	37.69	4.91	40.365	30.545
15	38.086	5.333	41.185	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 $\{l_0\}$.

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

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).

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

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

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

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 ($SIF\text{-}SIF_{Threshold}$) term. Therefore this conditional statement ensures that the difference is zero (0) when the applied SIF is below the threshold value.

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

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

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}}

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

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

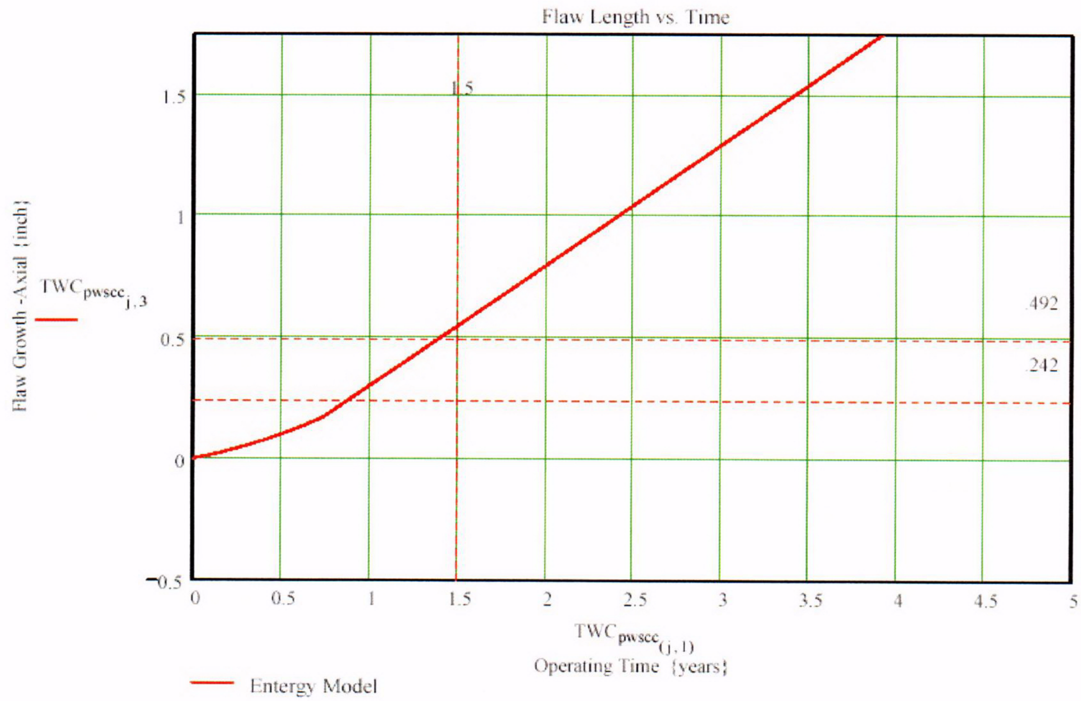
$$output \leftarrow \lambda_i$$

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.

$$\begin{aligned} & i \leftarrow i + 1 \\ & l_i \leftarrow l_{i-1} + D_{lengrth_{i-1}} \\ & NCB_i \leftarrow NCB_{i-1} + C_{blk} \end{aligned}$$

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

$Prop_{Length} = 0.242$

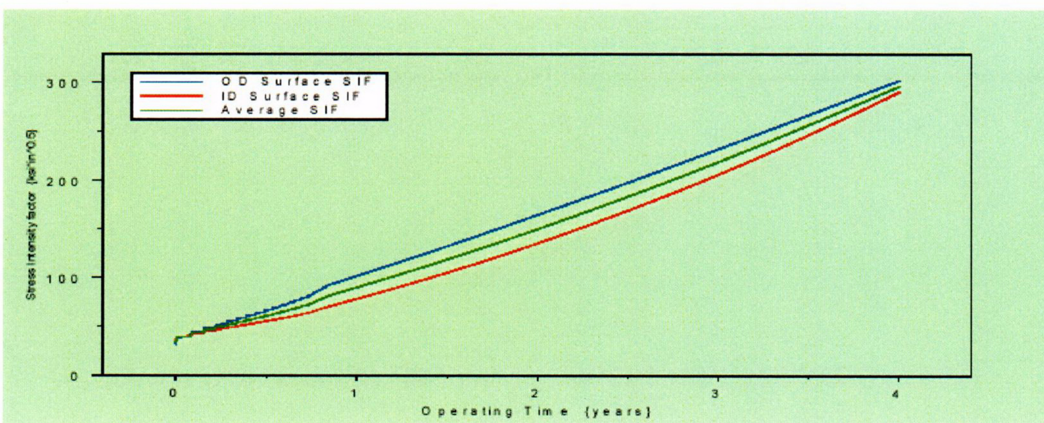


Typical Mathcad graphics used to compute the impact of crack growth. Note the allowable propagation length information in the top left corner. In this example the crack growth in one cycle exceeds the allowable propagation length, therefore the postulated flaw would reach the bottom of the weld within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

C05

$TWC_{pwscc_{(j,6)}}$ =	$TWC_{pwscc_{(j,7)}}$ =	$TWC_{pwscc_{(j,8)}}$ =
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.

C06

Appendix C

Mathcad worksheet for CEDM Deterministic Fracture Mechanics Analyses

This Appendix has 48 Attachments. Attachment 32 is Intentionally Blank

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

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

Refrences :

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

Arkansas Nuclear One Unit 2

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

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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

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

Input Data :-

$L := 0.32$	Initial Flaw Length (Twice detectable length)
$a_0 := 0.661 \cdot 0.07$	Initial Flaw Depth (Minimum Detecteble Depth was 5% TW)
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

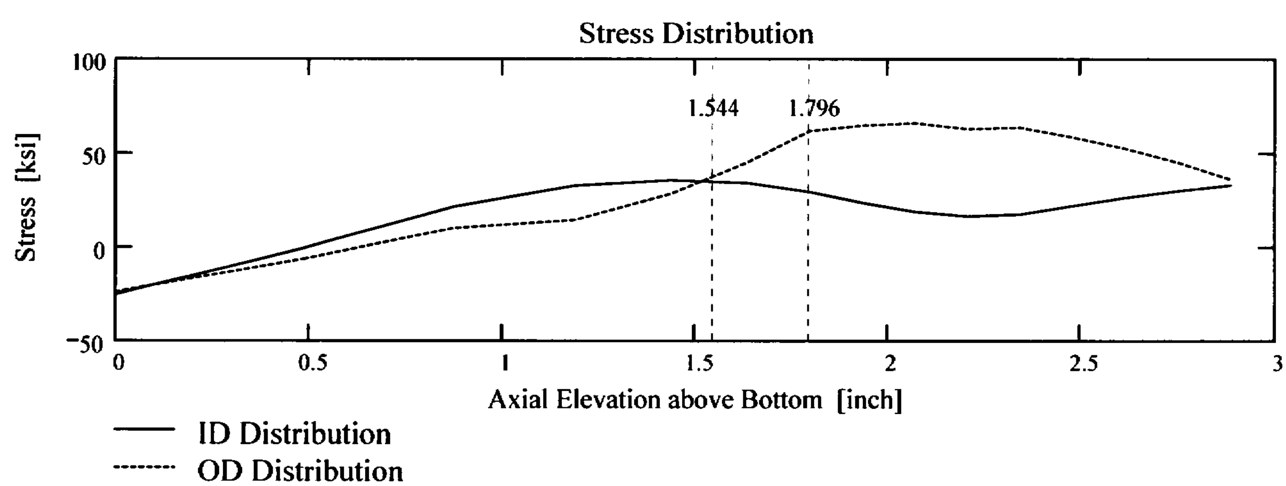
Stress Input Data

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

AllData :=

	0	1	2	3	4	5
0	0	-25.09	-27.55	-27.79	-25.62	-23.76
1	0.49	-0.56	-0.54	-2.11	-4.85	-6.16
2	0.87	21.52	18.64	17.12	14.84	10.09
3	1.19	32.75	28.49	24.14	19.64	14.45
4	1.44	35.67	29.6	26.17	25.59	28.42
5	1.64	34.24	29.57	28.29	35.41	45.38
6	1.8	29.45	29.81	31.39	43.34	61.71
7	1.93	23.67	26.5	33.26	47.61	64.65
8	2.07	18.93	24.56	33.97	49.07	65.88
9	2.2	16.54	22.85	34.79	49.52	62.8

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



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

$$Data := \begin{pmatrix} 0 & -25.088 & -27.546 & -27.787 & -25.624 & -23.763 \\ 0.485 & -0.563 & -0.539 & -2.111 & -4.851 & -6.157 \\ 0.874 & 21.515 & 18.635 & 17.122 & 14.843 & 10.089 \\ 1.186 & 32.751 & 28.494 & 24.136 & 19.645 & 14.45 \\ 1.436 & 35.667 & 29.598 & 26.166 & 25.589 & 28.417 \\ 1.635 & 34.244 & 29.574 & 28.286 & 35.408 & 45.379 \\ 1.796 & 29.45 & 29.814 & 31.385 & 43.337 & 61.713 \\ 1.932 & 23.674 & 26.502 & 33.261 & 47.609 & 64.65 \\ 2.068 & 18.928 & 24.564 & 33.968 & 49.071 & 65.876 \end{pmatrix}$$

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

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

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

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

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

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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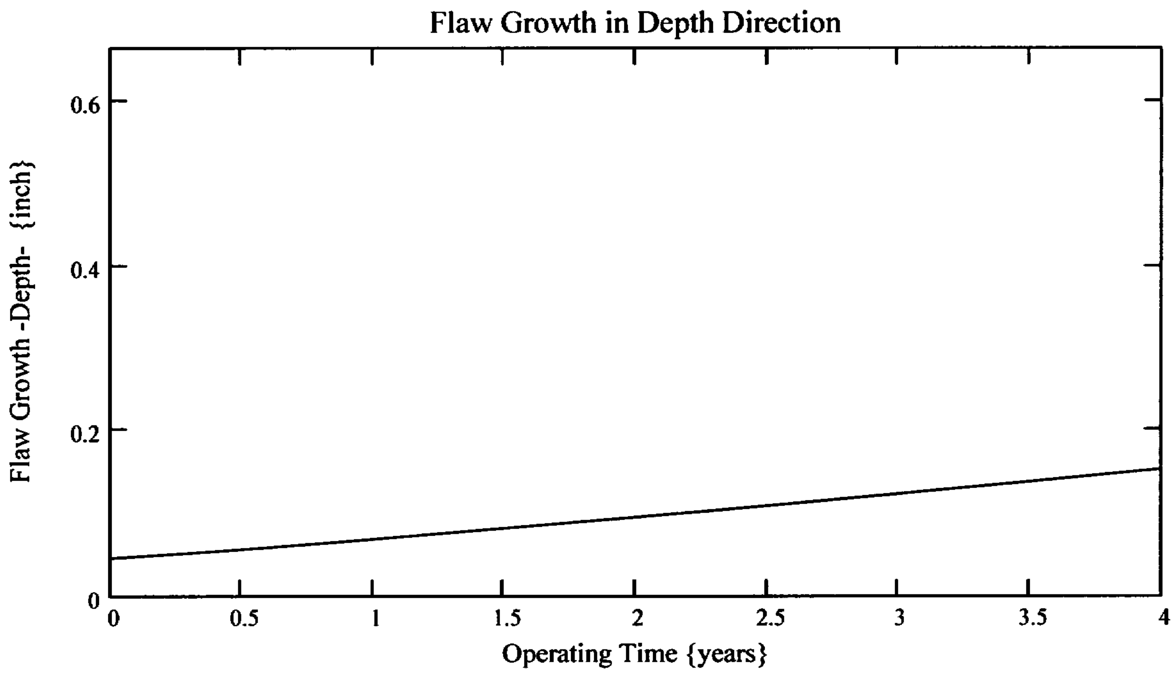
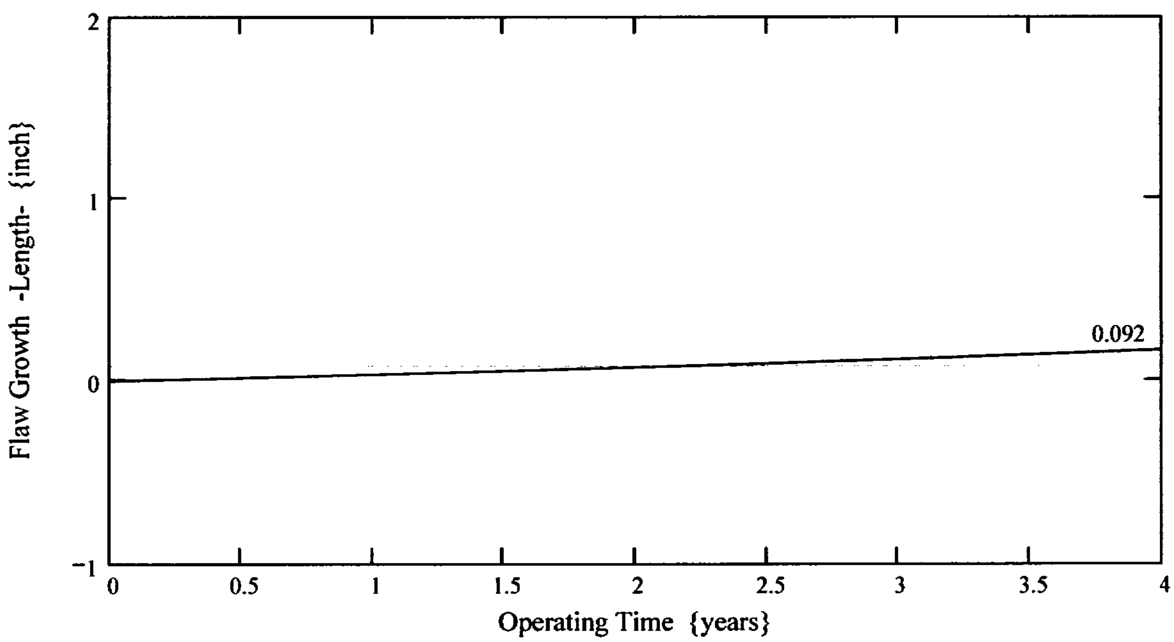
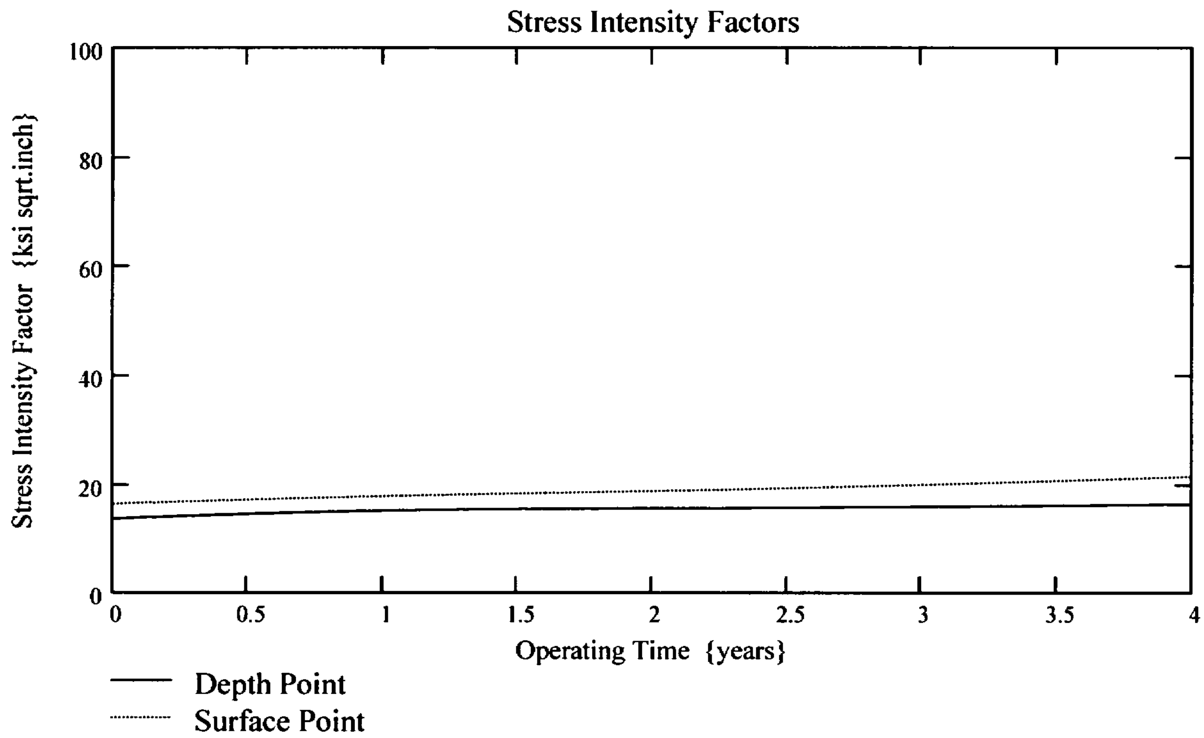
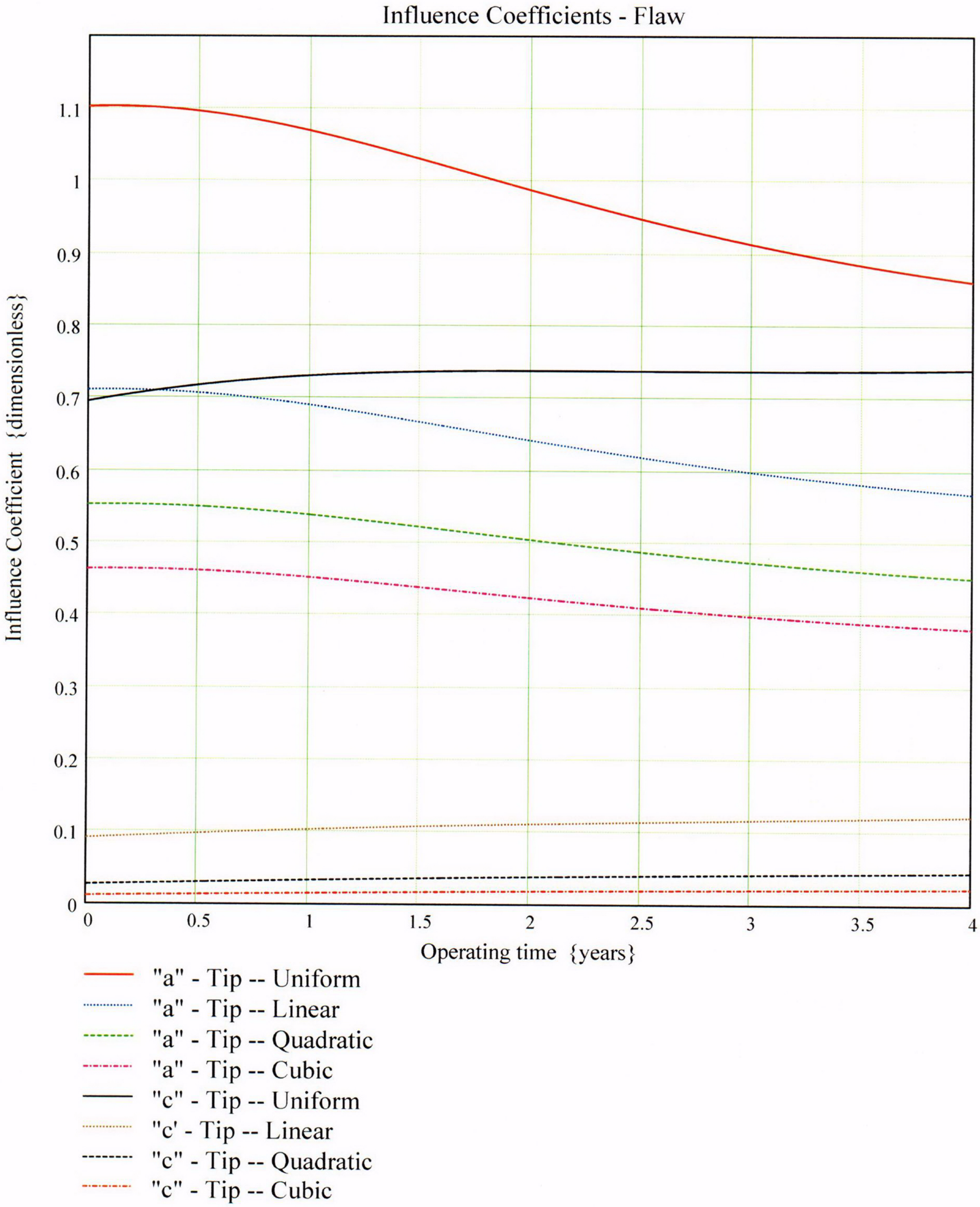
$Prop_{Length} = 0.092$

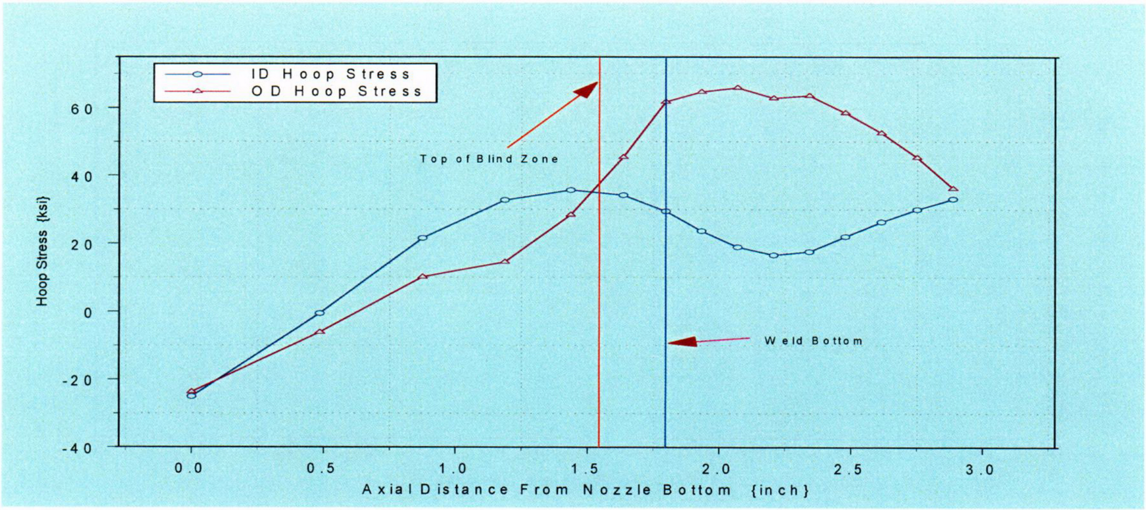


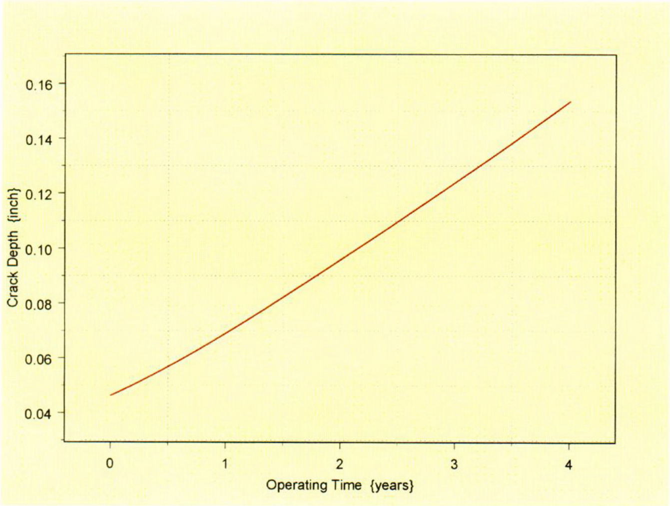


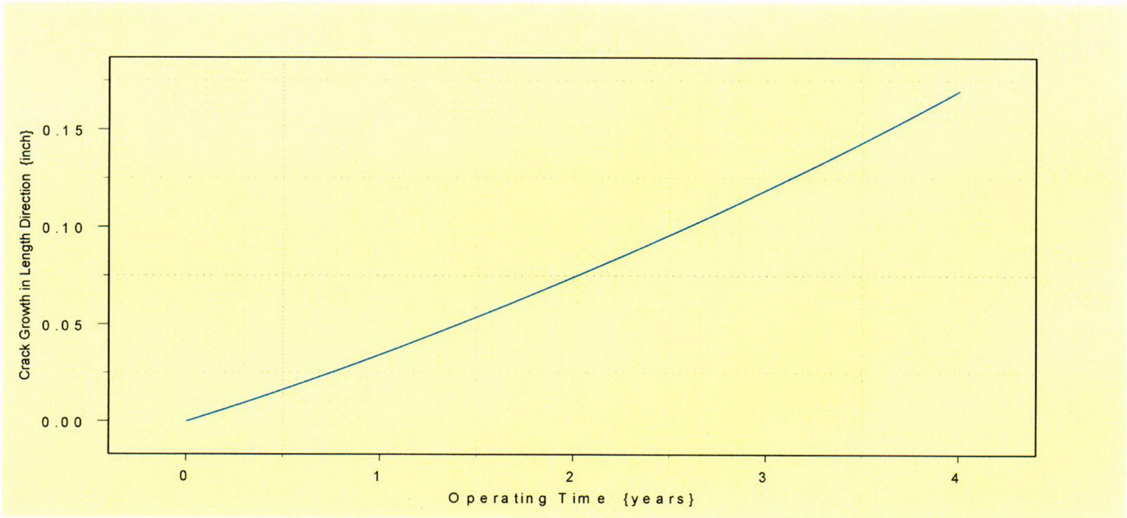

Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point
Surface Point

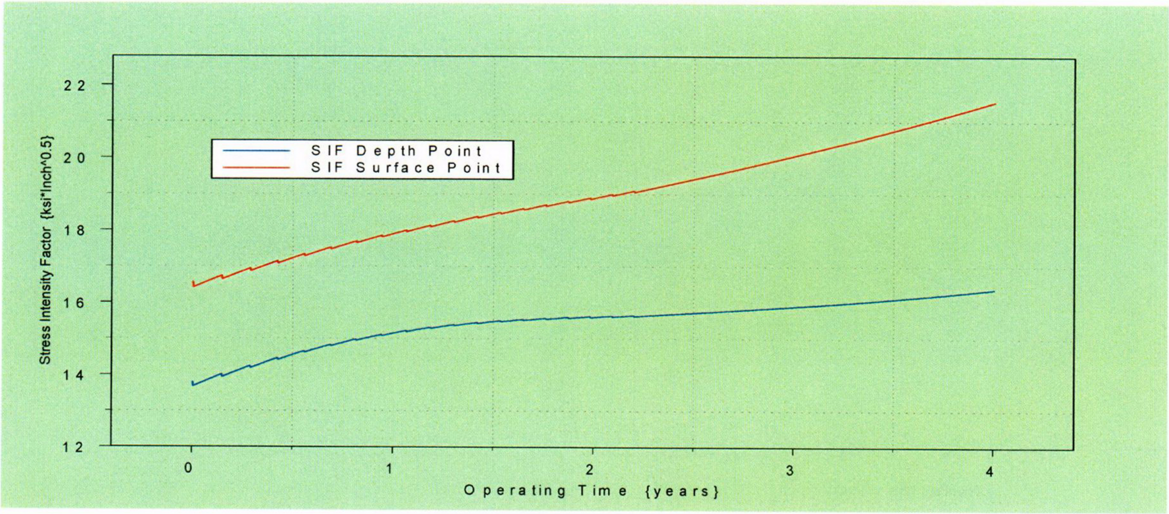

Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic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

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(k,5)}} =$
1.103	16.561	13.786
1.103	16.414	13.676
1.103	16.42	13.682
1.103	16.426	13.688
1.103	16.433	13.695
1.103	16.439	13.701
1.103	16.445	13.708
1.103	16.451	13.714
1.103	16.457	13.721
1.103	16.463	13.727
1.103	16.469	13.733
1.103	16.475	13.74
1.103	16.482	13.746
1.103	16.488	13.753
1.103	16.494	13.759
1.103	16.5	13.765


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


Crack Depth {inch}
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0
1
2
3
4
Operating Time {years}


Crack Growth in Length Direction {inch}
0.15
0.10
0.05
0.00
0
1
2
3
4
Operating Time {years}


Stress Intensity Factor {ksi*Inch^0.5}
22
20
18
16
14
12
SIF Depth Point
SIF Surface Point
0
1
2
3
4
Operating Time {years}

Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw

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

Refrences :

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

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"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 necessar to evaluate the stress distribution on the flaw both for the initial flaw and for a growing flaw. This is defined as the reference point. Enter a number (inch) that represnets the reference point elevation measured upward from the nozzle end.

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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

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

Input Data :-

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

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

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

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

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

Stress Input Data

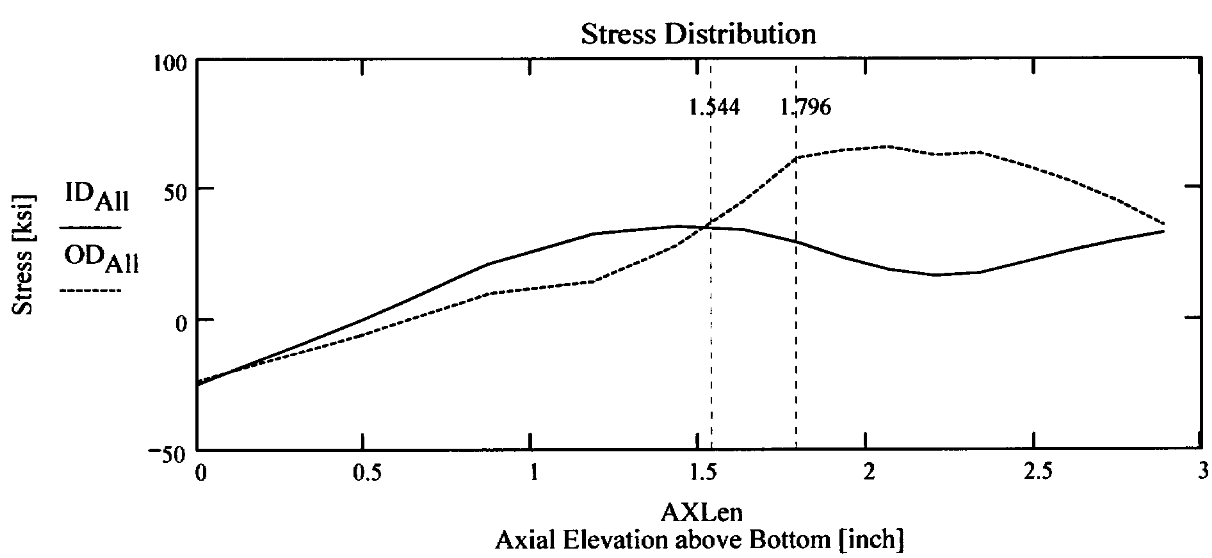
Input all available Nodal stress data in the table below. The column designations are as follows:

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

AllData :=

	0	1	2	3	4	5
0	0	-25.09	-27.55	-27.79	-25.62	-23.76
1	0.49	-0.56	-0.54	-2.11	-4.85	-6.16
2	0.87	21.52	18.64	17.12	14.84	10.09
3	1.19	32.75	28.49	24.14	19.64	14.45
4	1.44	35.67	29.6	26.17	25.59	28.42
5	1.64	34.24	29.57	28.29	35.41	45.38
6	1.8	29.45	29.81	31.39	43.34	61.71
7	1.93	23.67	26.5	33.26	47.61	64.65
8	2.07	18.93	24.56	33.97	49.07	65.88
9	2.2	16.54	22.85	34.79	49.52	62.8

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



Observing the stress distribution select the region in the table above labeled DataAll 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).

$$Data := \begin{pmatrix} 0 & -25.088 & -27.546 & -27.787 & -25.624 & -23.763 \\ 0.485 & -0.563 & -0.539 & -2.111 & -4.851 & -6.157 \\ 0.874 & 21.515 & 18.635 & 17.122 & 14.843 & 10.089 \\ 1.186 & 32.751 & 28.494 & 24.136 & 19.645 & 14.45 \\ 1.436 & 35.667 & 29.598 & 26.166 & 25.589 & 28.417 \\ 1.635 & 34.244 & 29.574 & 28.286 & 35.408 & 45.379 \\ 1.796 & 29.45 & 29.814 & 31.385 & 43.337 & 61.713 \\ 1.932 & 23.674 & 26.502 & 33.261 & 47.609 & 64.65 \\ 2.068 & 18.928 & 24.564 & 33.968 & 49.071 & 65.876 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

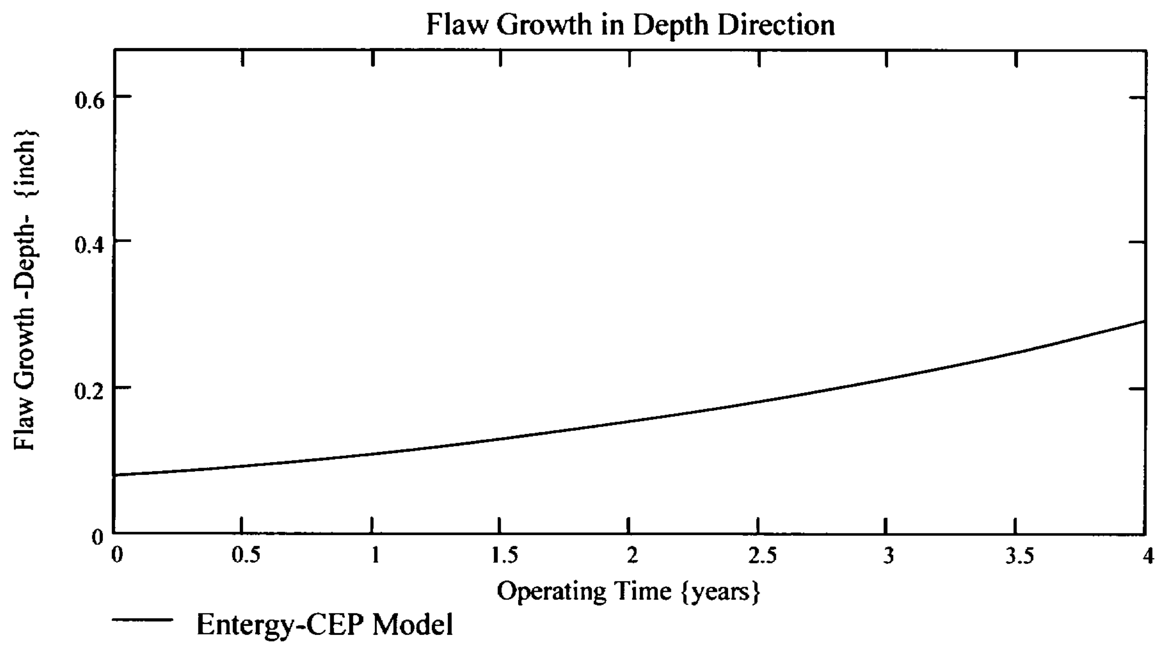
$U_{Tip} := FL_{Cntr} + c_0$

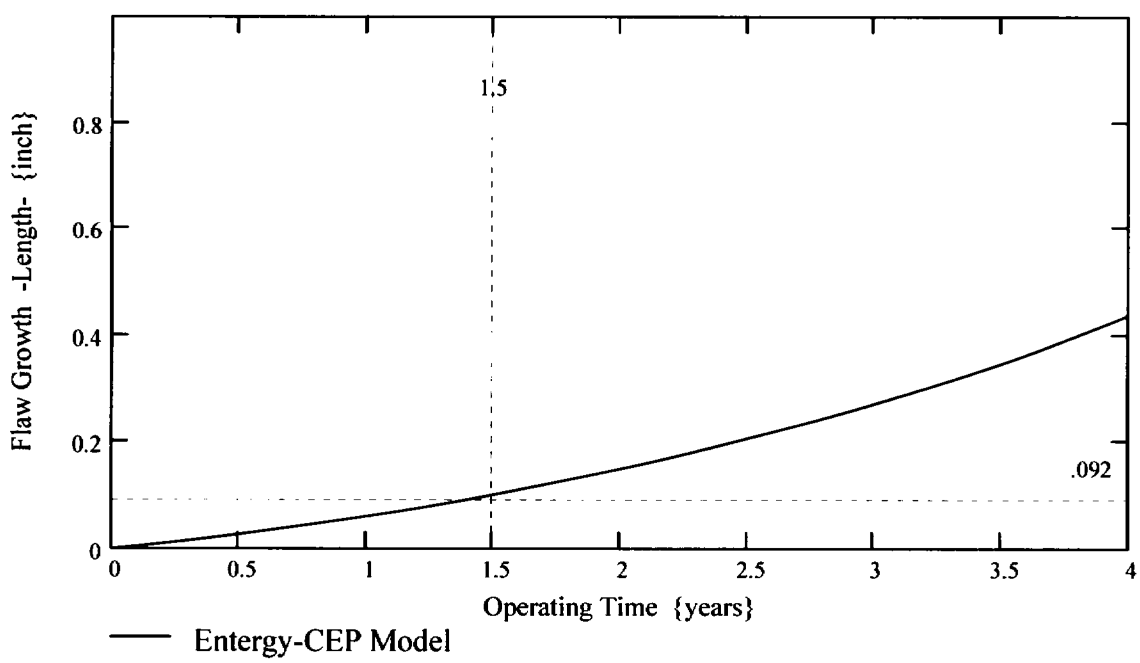
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

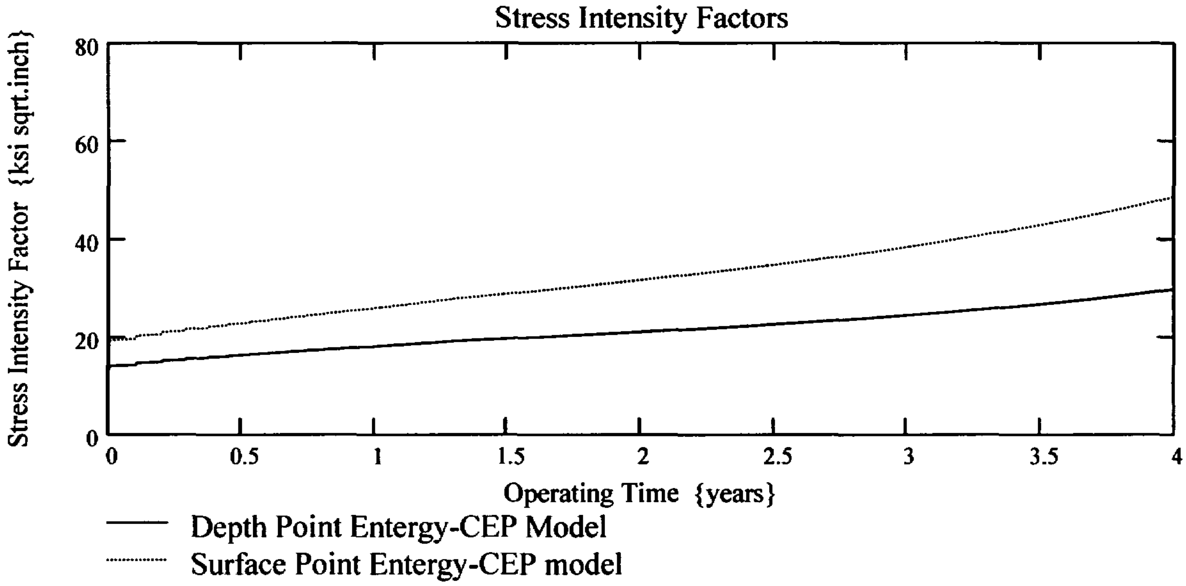
No User Input is required beyond this Point

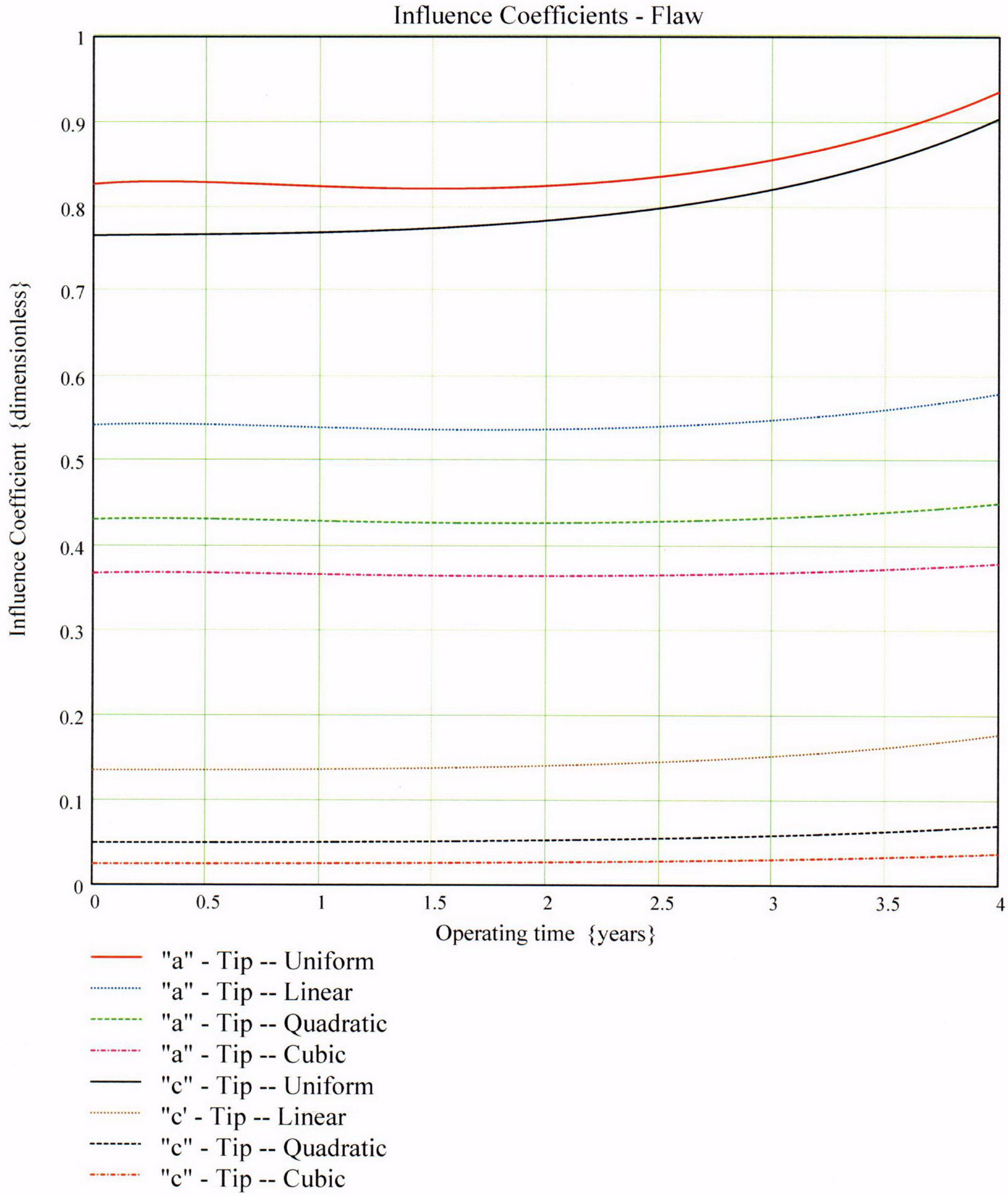
Sat Aug 09 10:21:18 AM 2003

$Prop_{Length} = 0.092$






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


Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
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

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

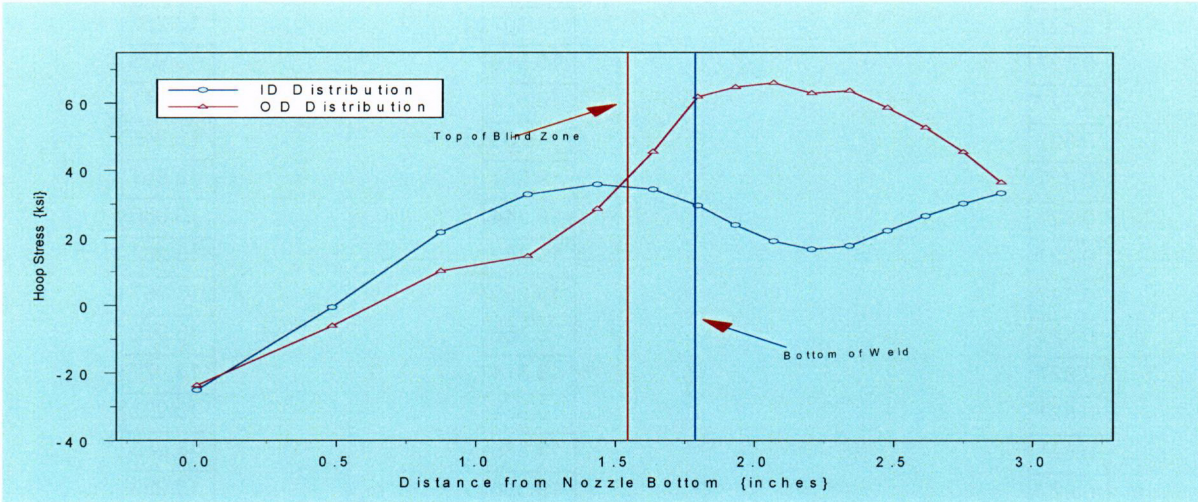
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827

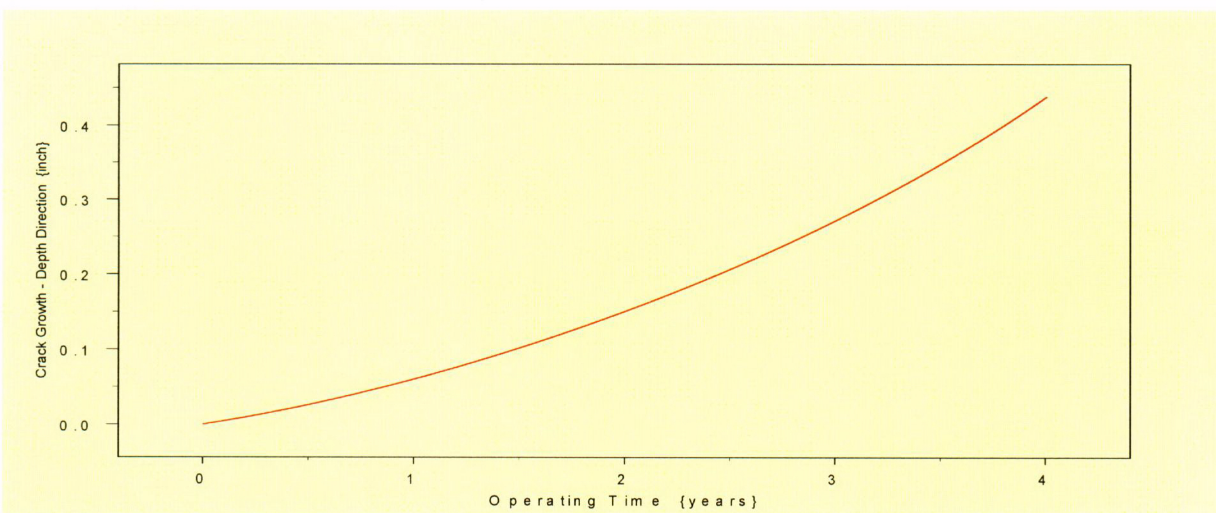
$CGR_{sambi_{(k,6)}} =$

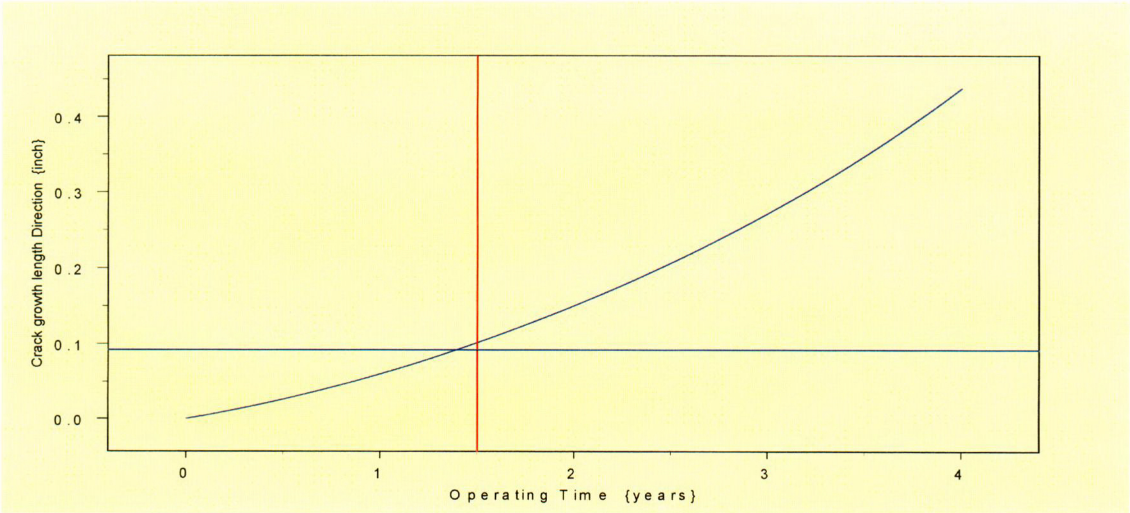
18.307
19.315
19.322
19.33
19.337
19.344
19.352
19.359
19.366
19.374
19.381
19.388
19.396
19.403
19.41
19.417

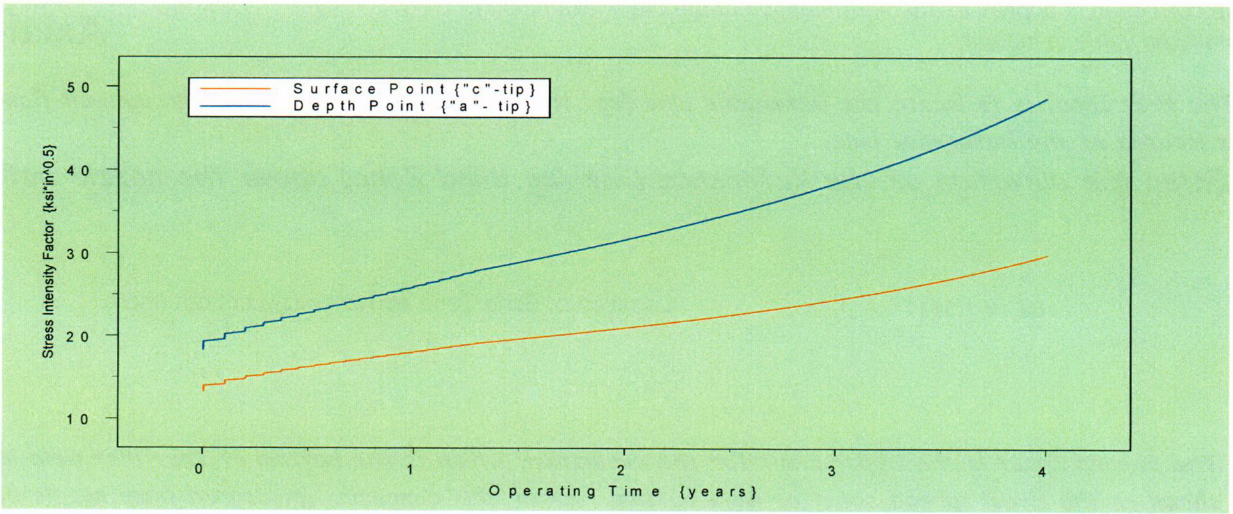
$CGR_{sambi_{(k,5)}} =$

13.252
13.936
13.941
13.946
13.951
13.956
13.962
13.967
13.972
13.977
13.982
13.988
13.993
13.998
14.003
14.008


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


Crack Growth - Depth Direction {inch}
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
Operating Time {years}


Crack growth length Direction {inch}
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
Operating Time {years}


Surface Point {"c"-tip}
Depth Point {"a"- tip}
Stress Intensity Factor {ksi*in^0.5}
50
40
30
20
10
0
1
2
3
4
Operating Time {years}

Stress Corrosion Crack Growth Analysis Throughwall flaw

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

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

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

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"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 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.

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

Input Data :-

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

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

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

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

Developed by: *Verified by:*

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

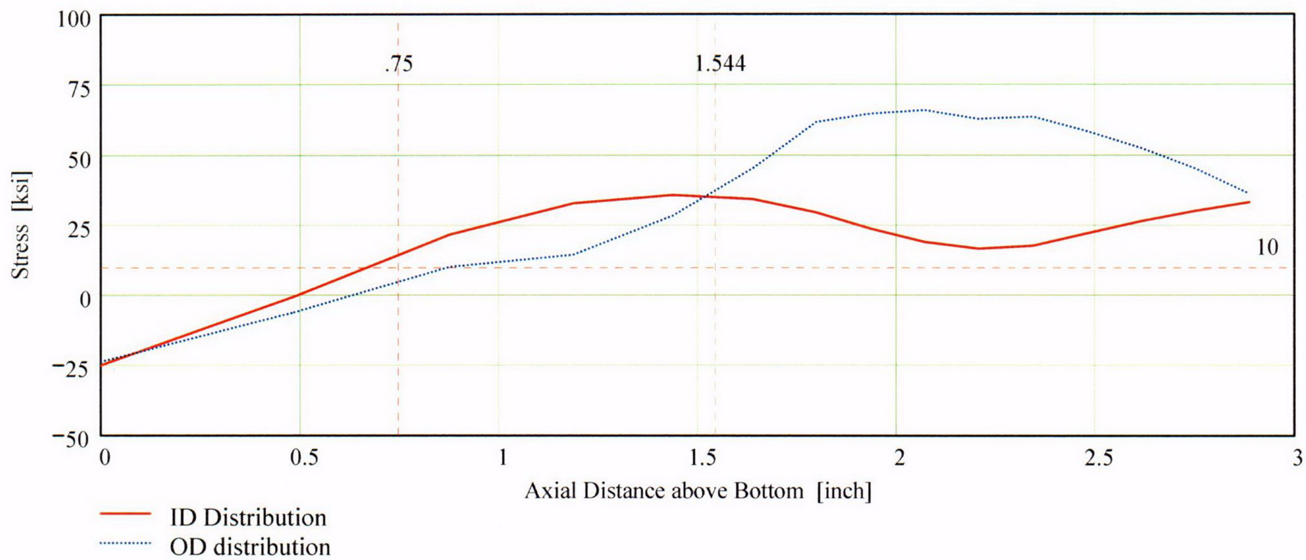
Stress Input Data

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

$Data_{All} :=$

	0	1	2	3	4	5
0	0	-25.09	-27.55	-27.79	-25.62	-23.76
1	0.49	-0.56	-0.54	-2.11	-4.85	-6.16
2	0.87	21.52	18.64	17.12	14.84	10.09
3	1.19	32.75	28.49	24.14	19.64	14.45
4	1.44	35.67	29.6	26.17	25.59	28.42
5	1.64	34.24	29.57	28.29	35.41	45.38
6	1.8	29.45	29.81	31.39	43.34	61.71
7	1.93	23.67	26.5	33.26	47.61	64.65
8	2.07	18.93	24.56	33.97	49.07	65.88
9	2.2	16.54	22.85	34.79	49.52	62.8
10	2.34	17.56	22.68	33.81	47.49	63.56

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



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

Data :=

0	−25.088	−27.546	−27.787	−25.624	−23.763
0.485	−0.563	−0.539	−2.111	−4.851	−6.157
0.874	21.515	18.635	17.122	14.843	10.089
1.186	32.751	28.494	24.136	19.645	14.45
1.436	35.667	29.598	26.166	25.589	28.417
1.635	34.244	29.574	28.286	35.408	45.379
1.796	29.45	29.814	31.385	43.337	61.713
1.932	23.674	26.502	33.261	47.609	64.65
2.068	18.928	24.564	33.968	49.071	65.876
2.204	16.541	22.854	34.789	49.525	62.795

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

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

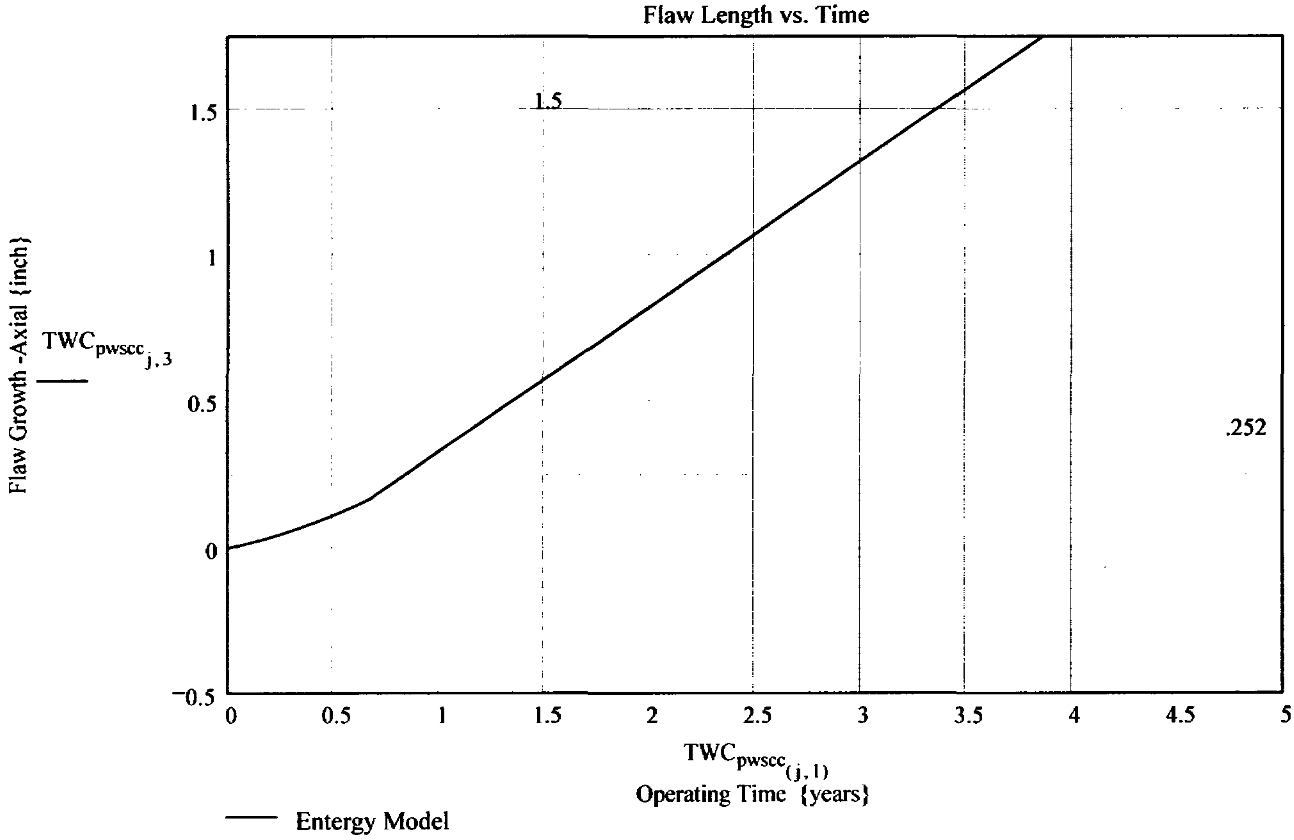
$FL_{Cntr} := BZ - l$ Flaw Center above Nozzle Bottom

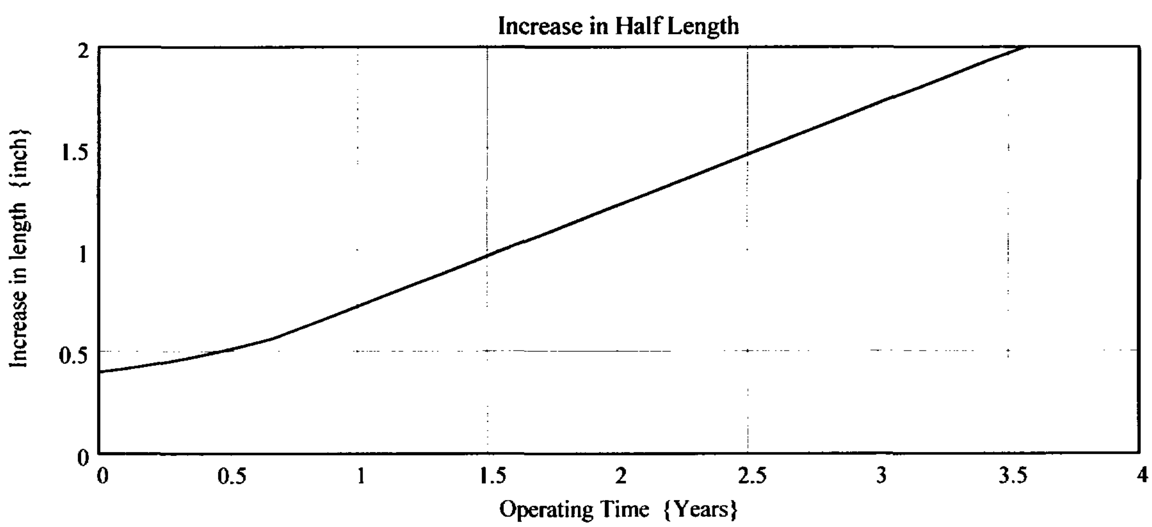
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - BZ}{20}$$

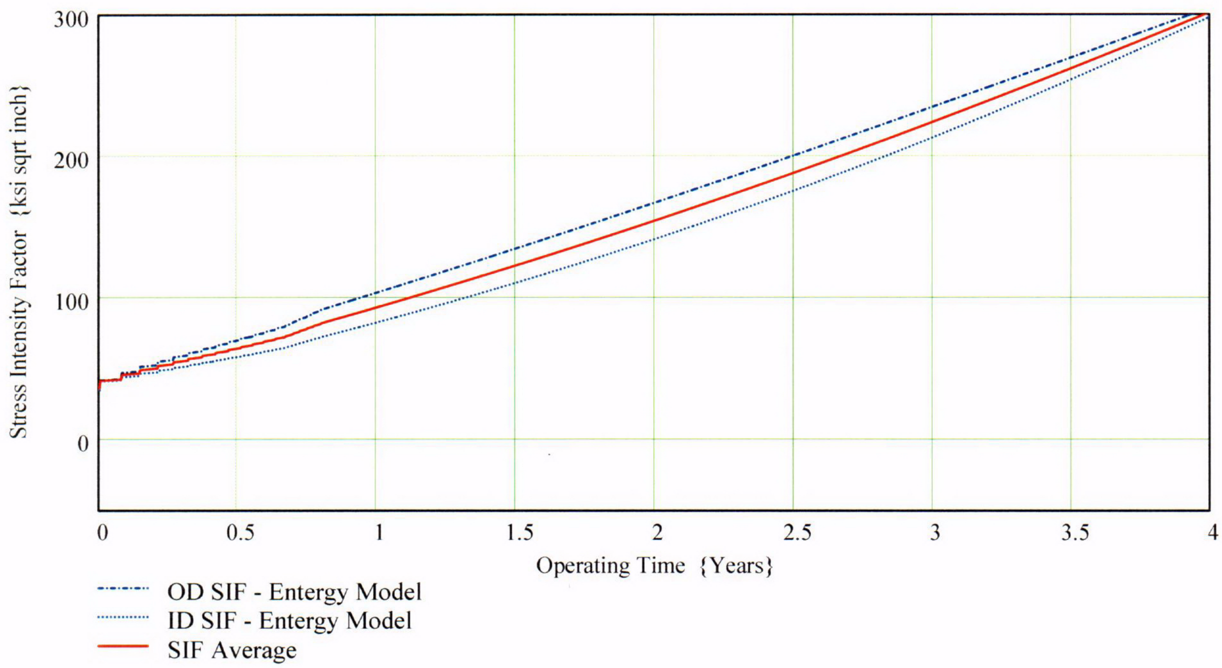
No User Input required beyond this Point

Sat Aug 09 11:44:49 AM 2003

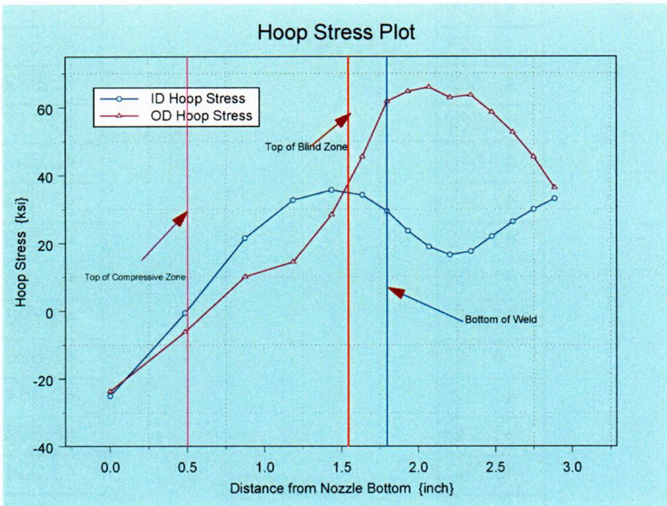
$Prop_{Length} = 0.252$

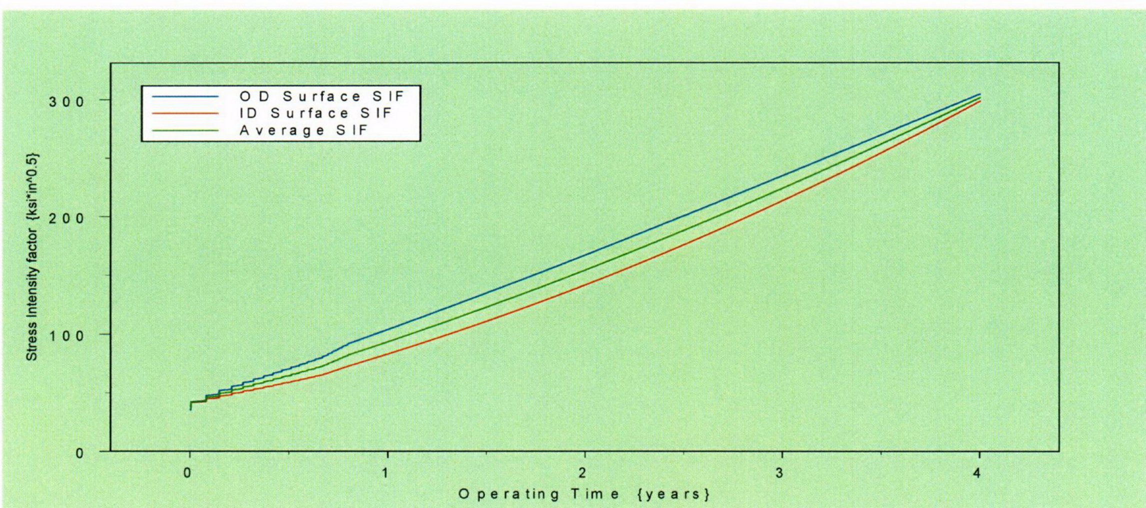


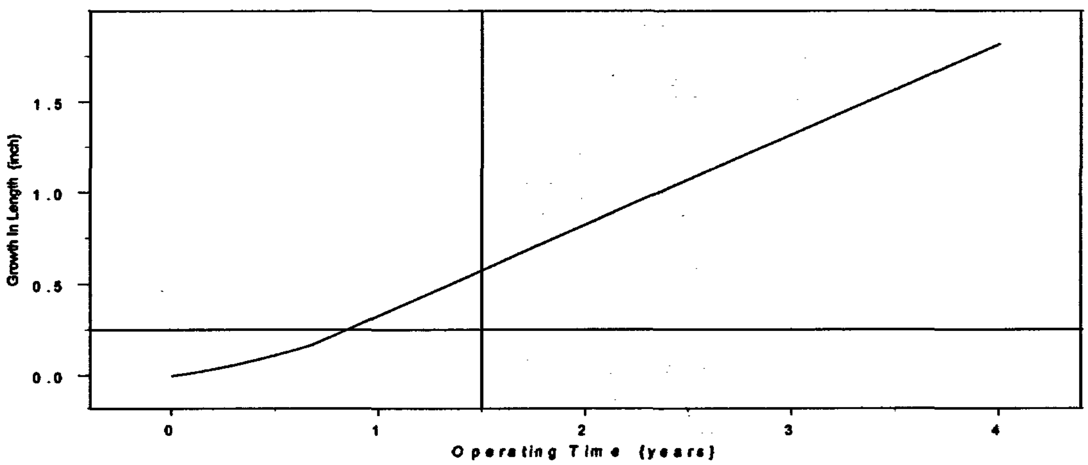



Stress Intensity Factor {ksi sqrt inch}
300
200
100
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {Years}
OD SIF - Entergy Model
ID SIF - Entergy Model
SIF Average

$TWC_{pwscc_{(j,6)}} =$	$TWC_{pwscc_{(j,7)}} =$	$TWC_{pwscc_{(j,8)}} =$
35.366	37.917	38.137
42.321	41.494	43.512
42.355	41.524	43.547
42.39	41.555	43.582
42.424	41.586	43.617
42.459	41.616	43.652
42.494	41.647	43.687
42.528	41.678	43.723
42.563	41.708	43.758
42.598	41.739	43.793
42.633	41.77	43.828
42.668	41.801	43.864
42.702	41.832	43.899
42.737	41.863	43.934
42.772	41.894	43.97
42.807	41.925	44.005


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


OD Surface SIF
ID Surface SIF
Average SIF
Stress Intensity factor {ksi*in^0.5}
Operating Time {years}
300
200
100
0
0
1
2
3
4


Growth In Length (inch)
1.5
1.0
0.5
0.0
0
1
2
3
4
Operating Time (years)

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

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

Refrences :

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

Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"8" Degree Nozzle, Downhill Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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

$UL_{Strs.Dist} := 1.786$ 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 (Twice detectable length)
$a_0 := 0.661 \cdot 0.07$	Initial Flaw Depth (Minimum Detecteble Depth was 5% TW)
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

Stress Input Data

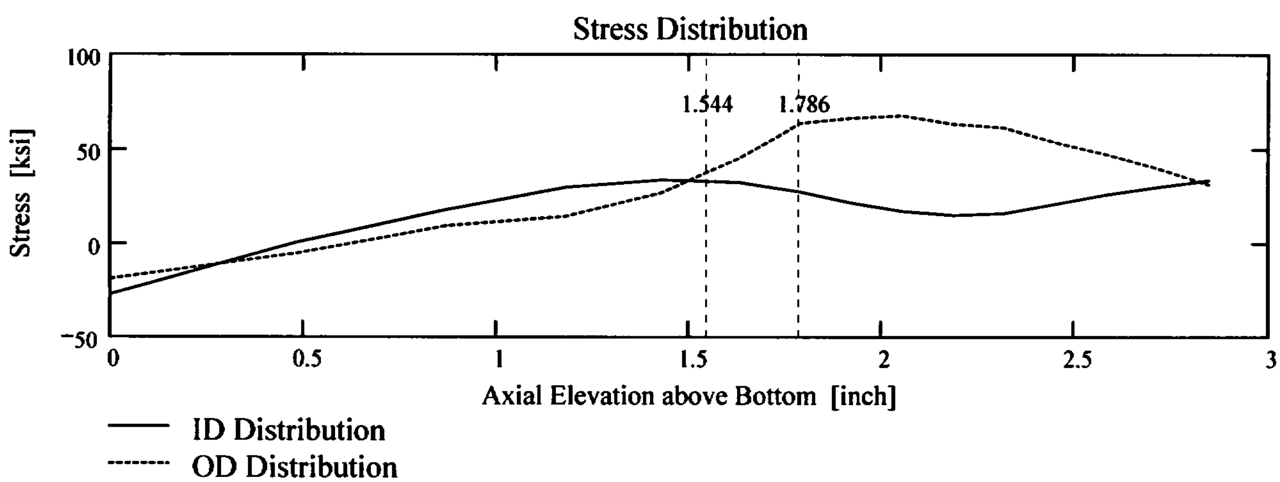
Input all available Nodal stress data in the table below. The column designations are as follows:

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

AllData :=

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

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



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

$$Data := \begin{pmatrix} 0 & -27.404 & -24.356 & -22.209 & -20.407 & -18.978 \\ 0.483 & 0.633 & -1.486 & -3.599 & -4.44 & -5.268 \\ 0.87 & 17.665 & 16.422 & 14.61 & 12.415 & 9.376 \\ 1.18 & 29.798 & 26.049 & 22.723 & 18.95 & 14.201 \\ 1.428 & 33.623 & 27.792 & 24.8 & 24.321 & 26.989 \\ 1.627 & 32.364 & 28.469 & 27.591 & 34.284 & 45.104 \\ 1.786 & 27.394 & 28.918 & 31.388 & 43.882 & 63.718 \\ 1.919 & 21.498 & 25.556 & 33.55 & 48.089 & 66.365 \\ 2.051 & 16.944 & 23.793 & 34.064 & 49.472 & 67.672 \\ 2.183 & 14.834 & 22.263 & 34.779 & 49.055 & 63.377 \end{pmatrix}$$

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

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

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

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

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

Flaw center Location above Nozzle Bottom

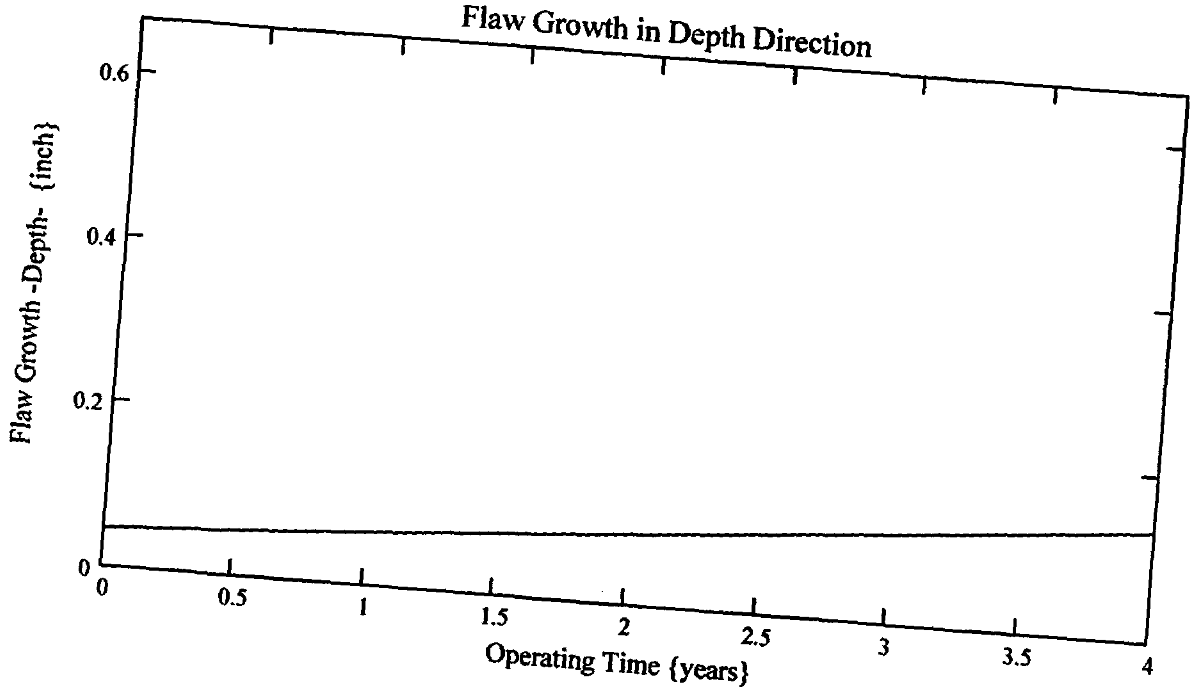
$$U_{Tip} := FL_{Cntr} + c_0$$

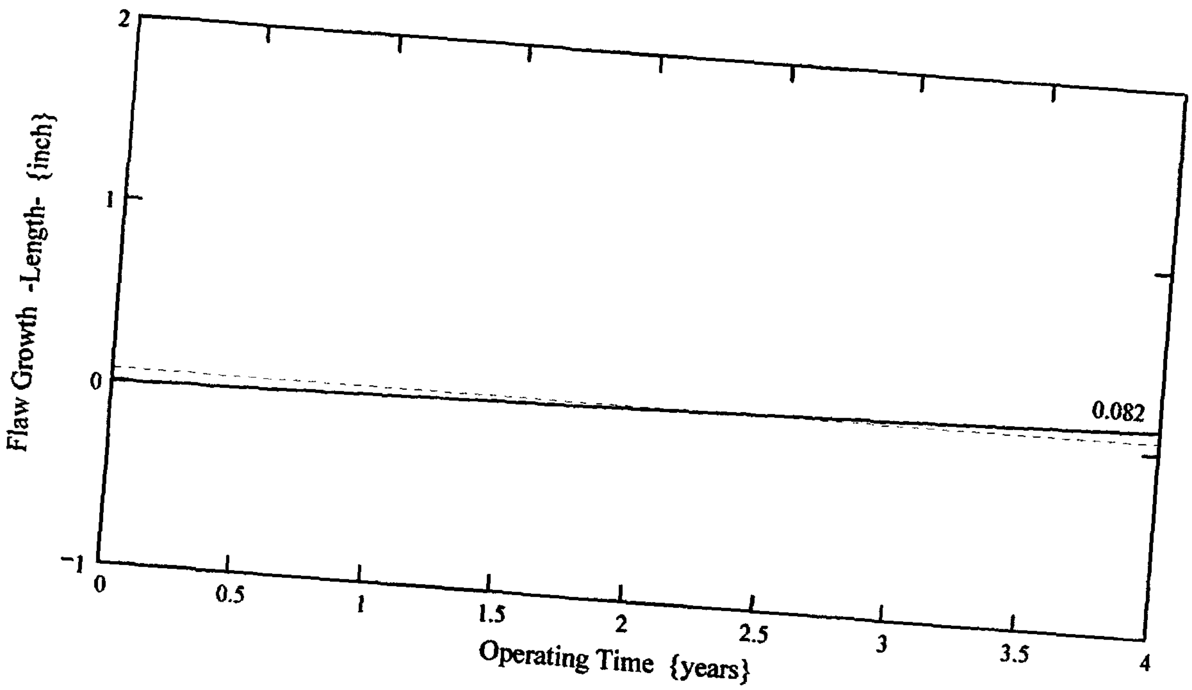
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

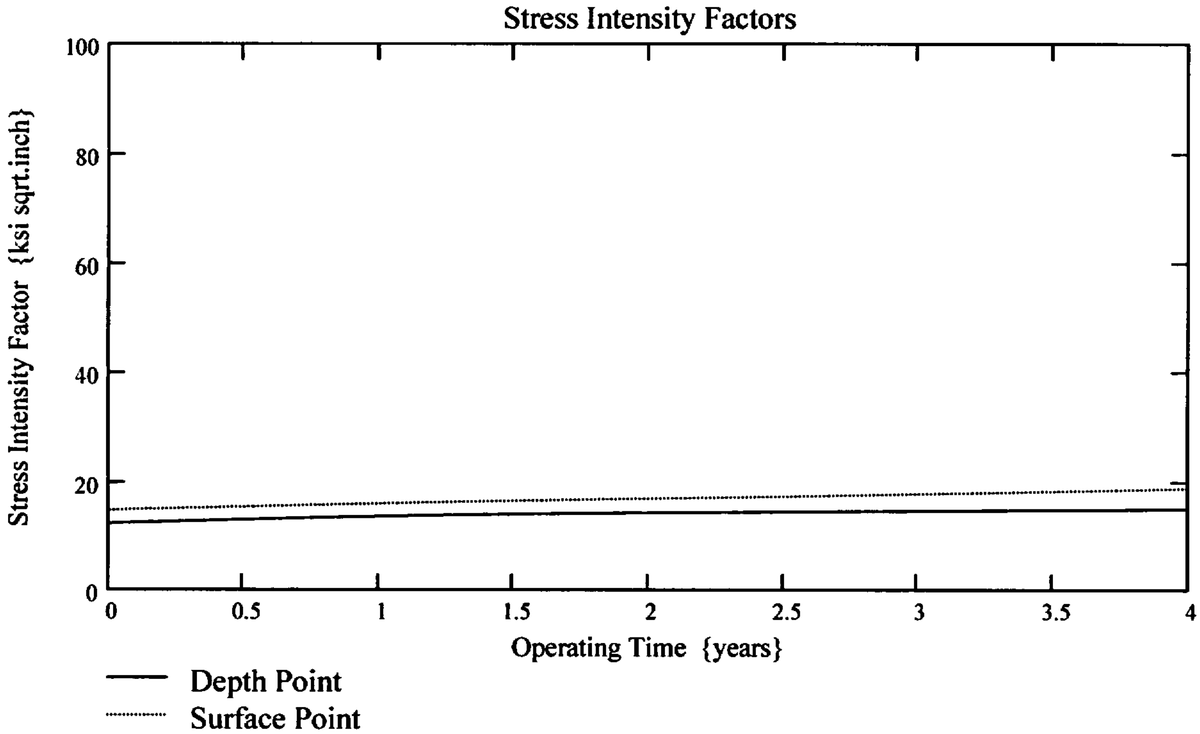
No User Input is required beyond this Point

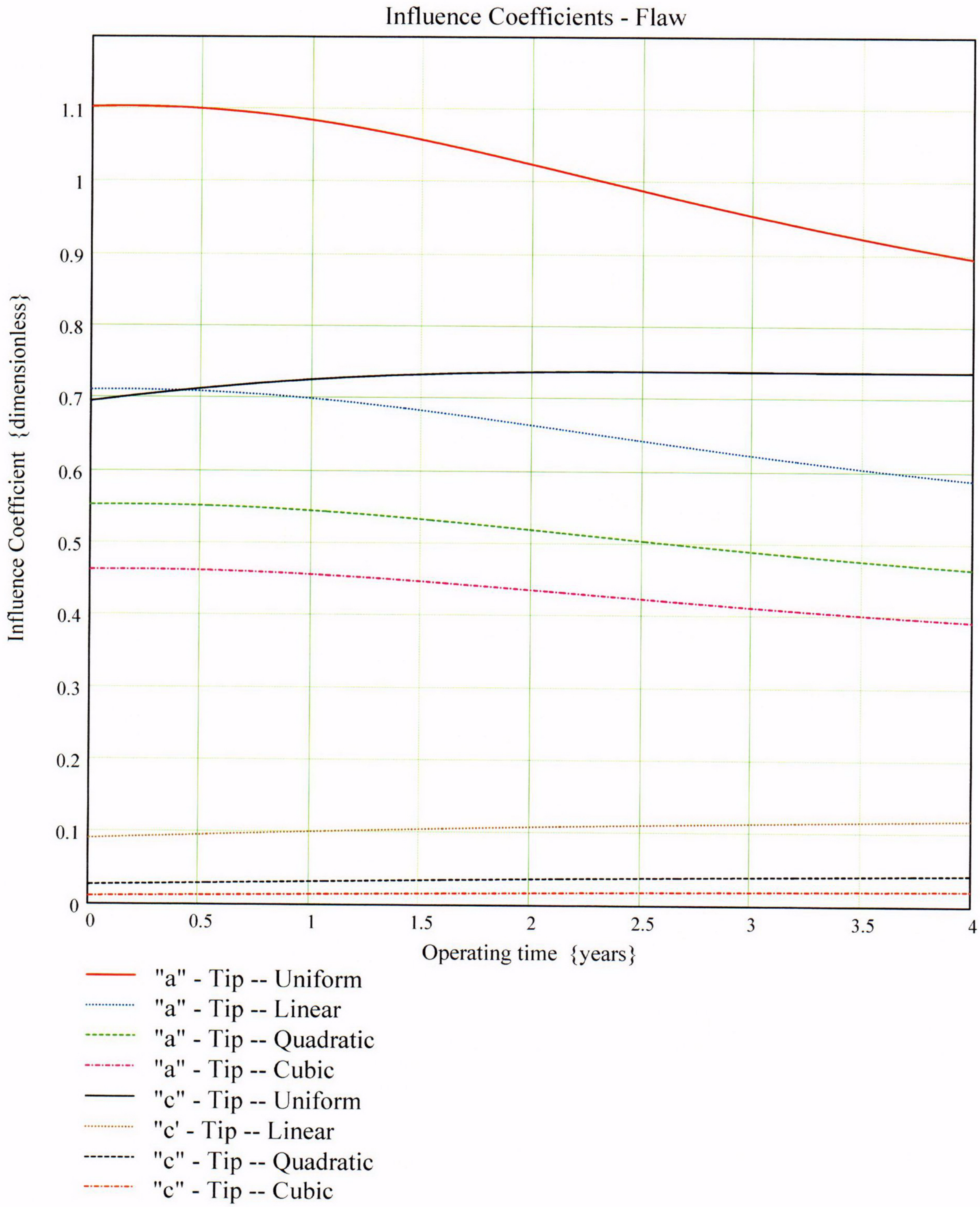
Sat Aug 09 10:59:39 AM 2003

$Prop_{Length} = 0.082$

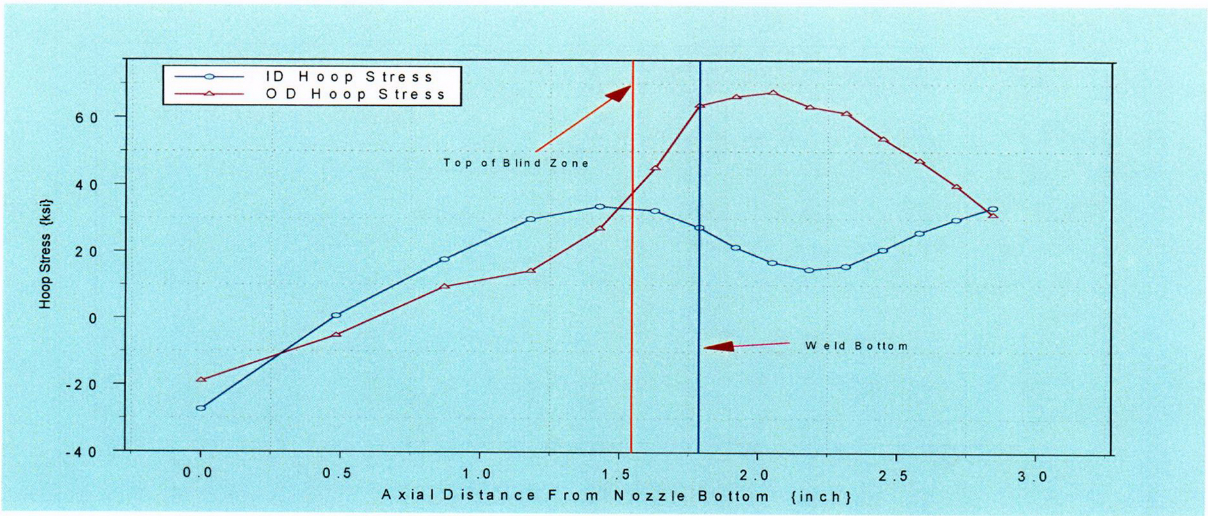


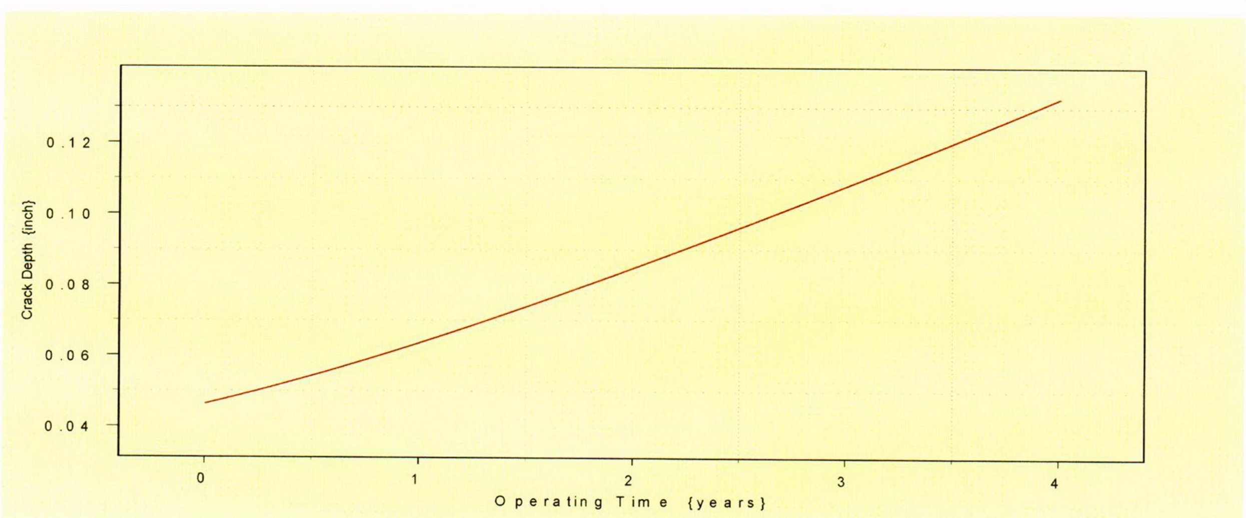


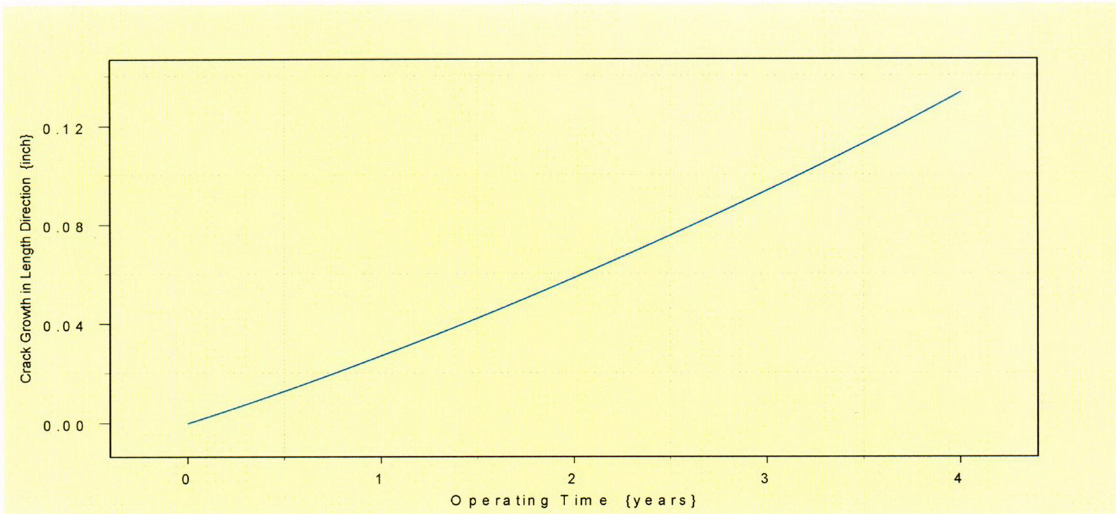

Stress Intensity Factors
100
80
60
40
20
0
Stress Intensity Factor {ksi sqrt.inch}
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point
Surface Point

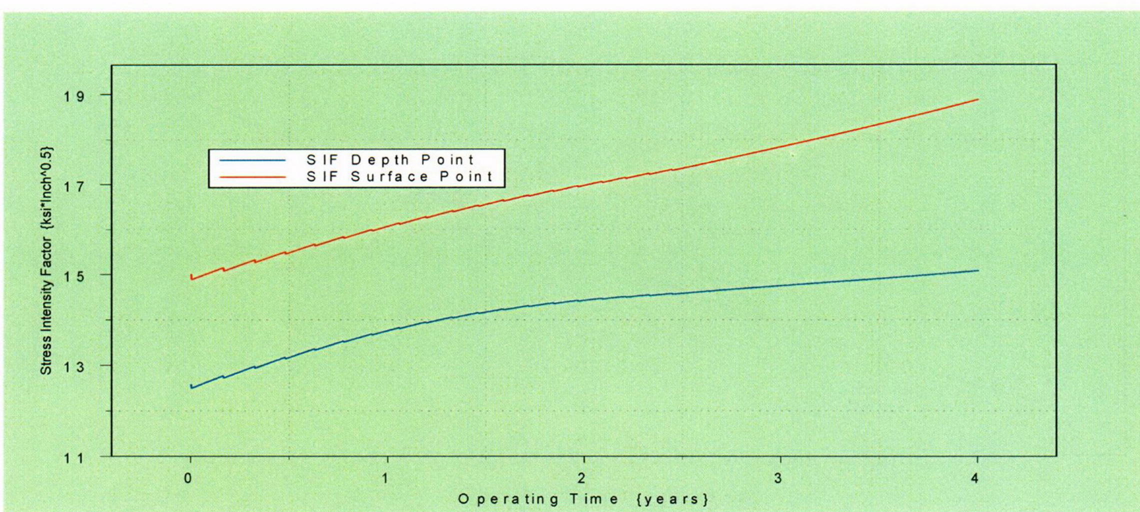

Influence Coefficients - Flaw
Influence Coefficient {dimensionless}
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating time {years}
"a" - Tip -- Uniform
"a" - Tip -- Linear
"a" - Tip -- Quadratic
"a" - Tip -- Cubic
"c" - Tip -- Uniform
"c' - Tip -- Linear
"c" - Tip -- Quadratic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

$CGR_{sambi_{(k,8)}} =$	$CGR_{sambi_{(k,6)}} =$	$CGR_{sambi_{(k,5)}} =$
1.103	14.996	12.571
1.103	14.886	12.495
1.103	14.89	12.499
1.103	14.895	12.504
1.103	14.899	12.509
1.103	14.903	12.513
1.103	14.907	12.518
1.103	14.912	12.522
1.103	14.916	12.527
1.103	14.92	12.531
1.103	14.925	12.536
1.103	14.929	12.541
1.103	14.933	12.545
1.103	14.938	12.55
1.103	14.942	12.554
1.103	14.946	12.559


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


Crack Depth {inch}
0.12
0.10
0.08
0.06
0.04
0
1
2
3
4
Operating Time {years}


Crack Growth in Length Direction {inch}
0.00
0.04
0.08
0.12
0
1
2
3
4
Operating Time {years}


Stress Intensity Factor {ksi*Inch^0.5}
11
13
15
17
19
SIF Depth Point
SIF Surface Point
0
1
2
3
4
Operating Time {years}