

## Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadeseam

Verified by: B. C. Gray

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

References :

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

### Arkansas Nuclear One Unit 2

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

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

### Through Wall Axial Flaw

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

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

BZ := 1.544

Location of Blind Zone above nozzle bottom (inch)

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

ULStrs.Dist := 6.628

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

Input Data :-

$L := 0.25$	Initial Flaw Length TW axial (Based on 10 Ksi average stress)
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\nu := 0.307$	Poissons ratio @ 600 F
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP}
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

$$t := R_o - R_i$$

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

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

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

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

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



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

### Stress Input Data

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

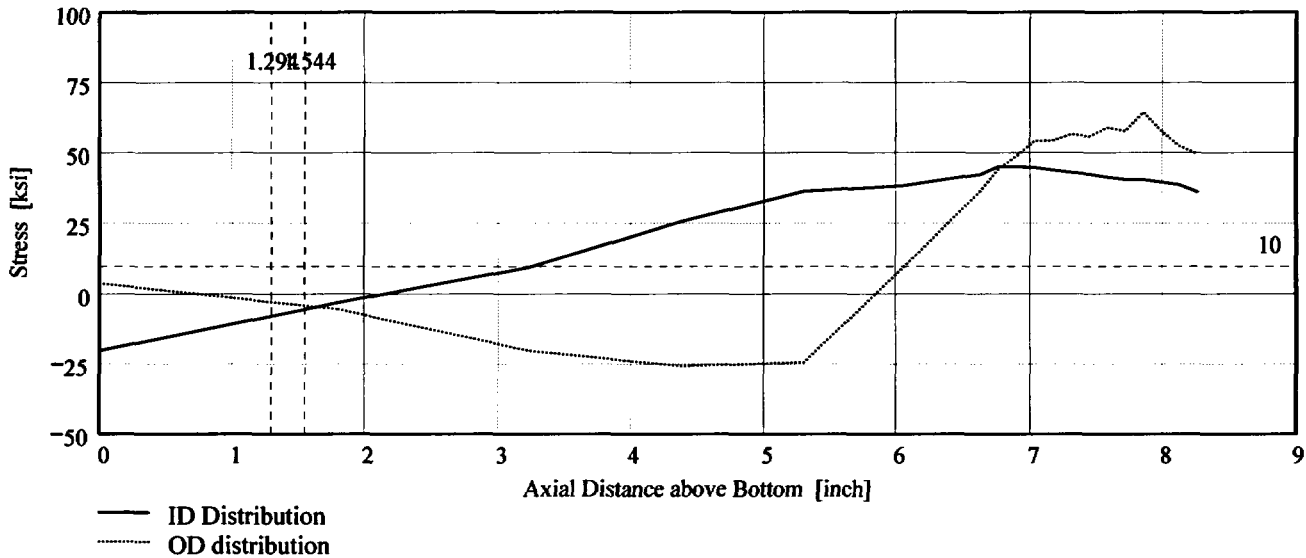
DataAll :=

	0	1	2	3	4	5
0	0	-20.18	-11.45	-5.94	-1.16	3.7
1	1.79	-3.02	-4.38	-5.44	-5.51	-5.34
2	3.23	9.4	12.13	-0.26	-12.62	-20.23
3	4.38	25.65	24.71	14.58	-15.3	-25.69
4	5.3	36.18	33.79	26.29	-5.92	-24.31
5	6.04	38.11	35.03	31.43	21.21	8.83
6	6.63	42.19	38.1	36.25	40.68	36.41
7	6.76	45.07	42.22	42.74	47.55	44.23
8	6.9	44.97	43.61	46.01	49.99	48.8
9	7.03	44.7	44.12	47.02	51.04	54.11
10	7.17	43.72	43.97	47.64	50.17	54.17
11	7.31	42.93	43.82	47.52	52.33	56.55

AllAxl := DataAll<sup>(0)</sup>

AllID := DataAll<sup>(1)</sup>

AllOD := DataAll<sup>(5)</sup>



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

Data :=

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

Axl := Data<sup>(0)</sup>

ID := Data<sup>(1)</sup>

OD := Data<sup>(5)</sup>

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

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

$FL_{Cntr} := BZ - 1$

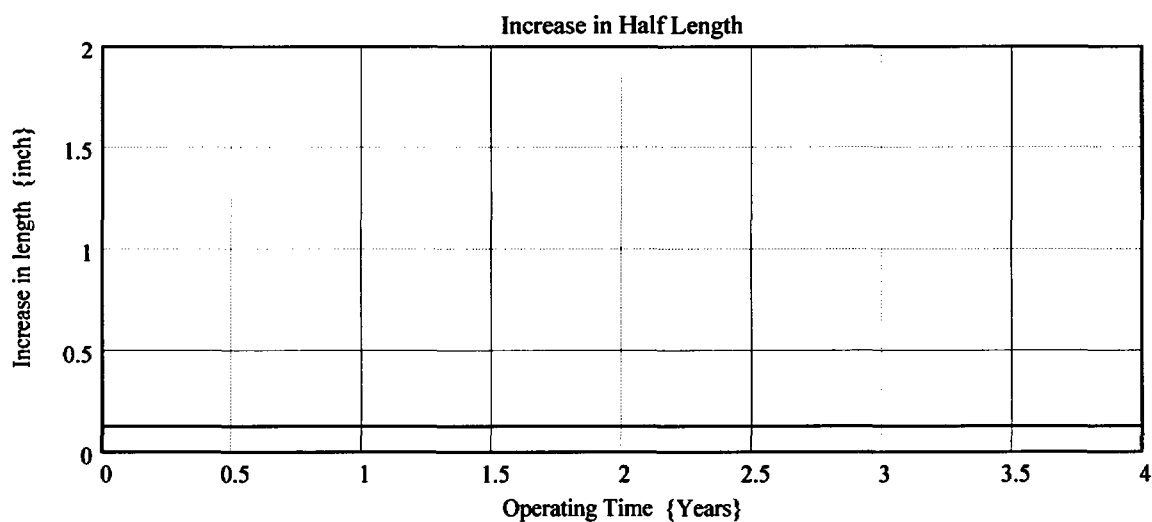
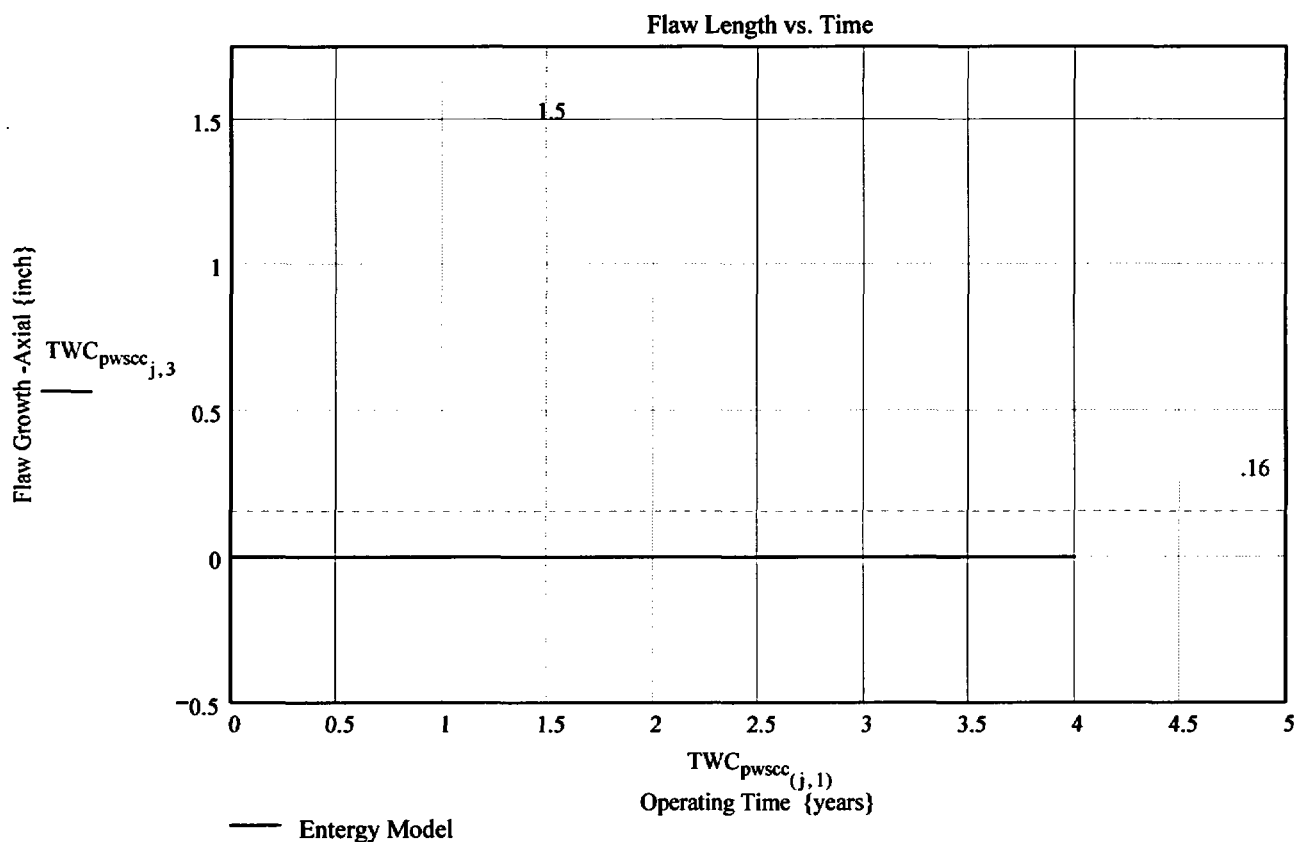
Flaw Center above Nozzle Bottom

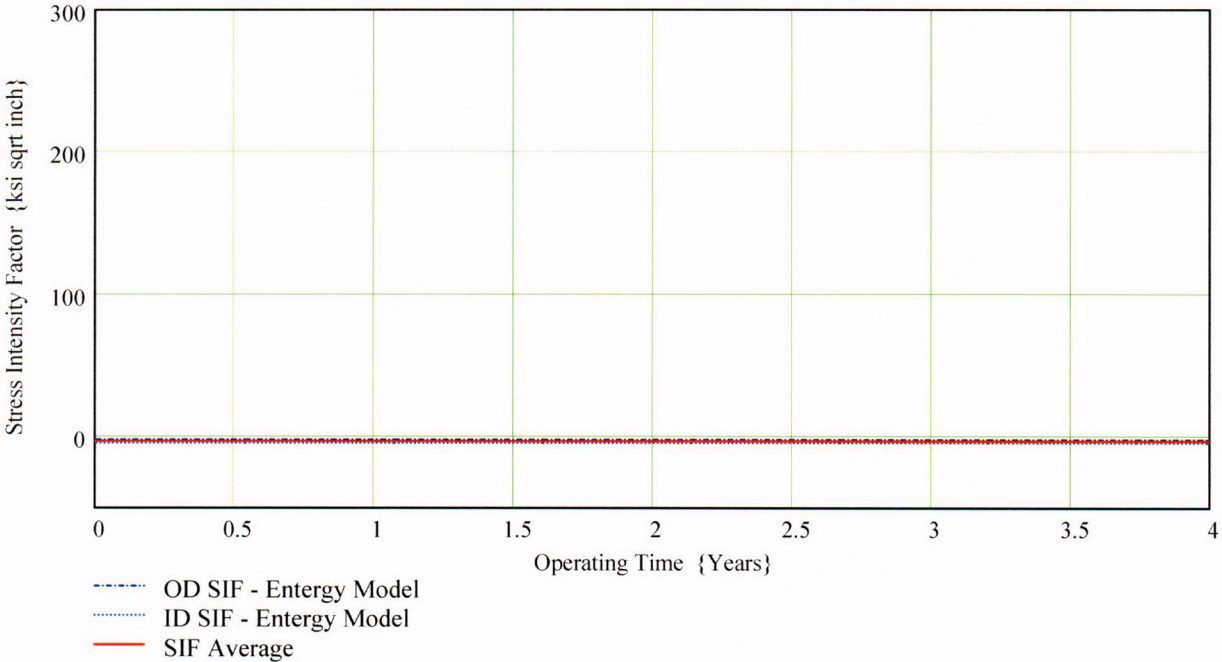
$$IncStrs.avg := \frac{ULStrs.Dist - BZ}{20}$$

**No User Input required beyond this Point**

Sat Aug 09 11:44:49 AM 2003

PropLength = 5.084





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

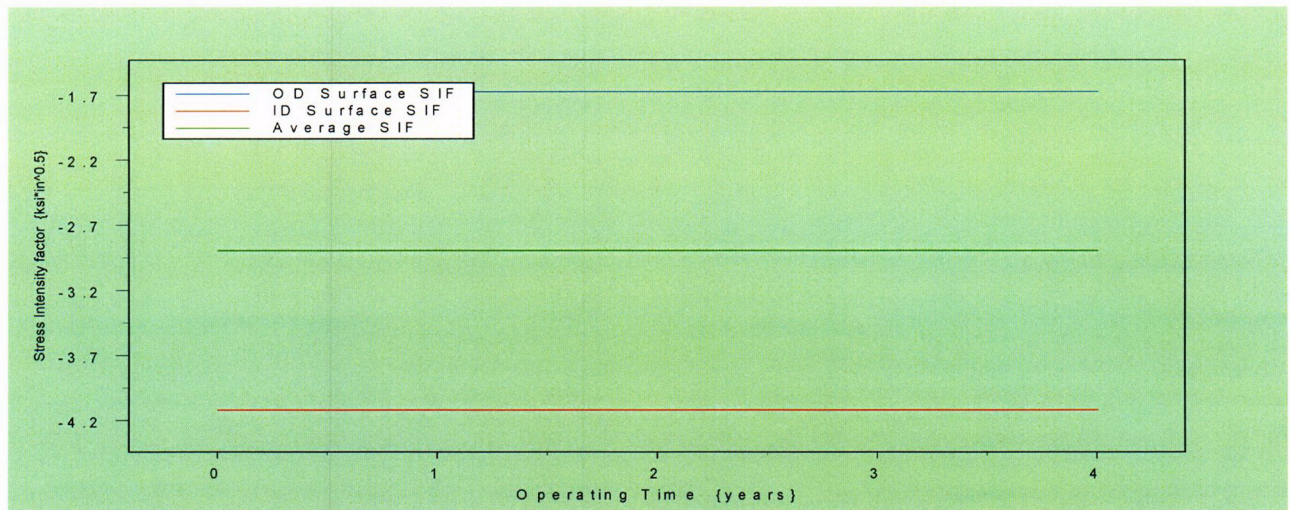
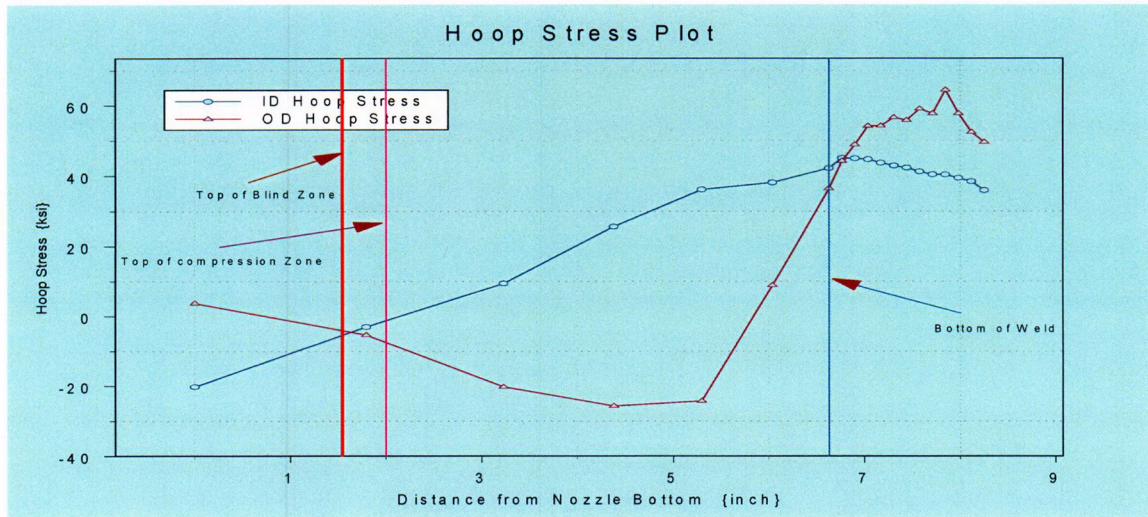
-1.672
-1.672
-1.672
-1.672
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-1.672
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-1.672
-1.672
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-1.672
-1.672

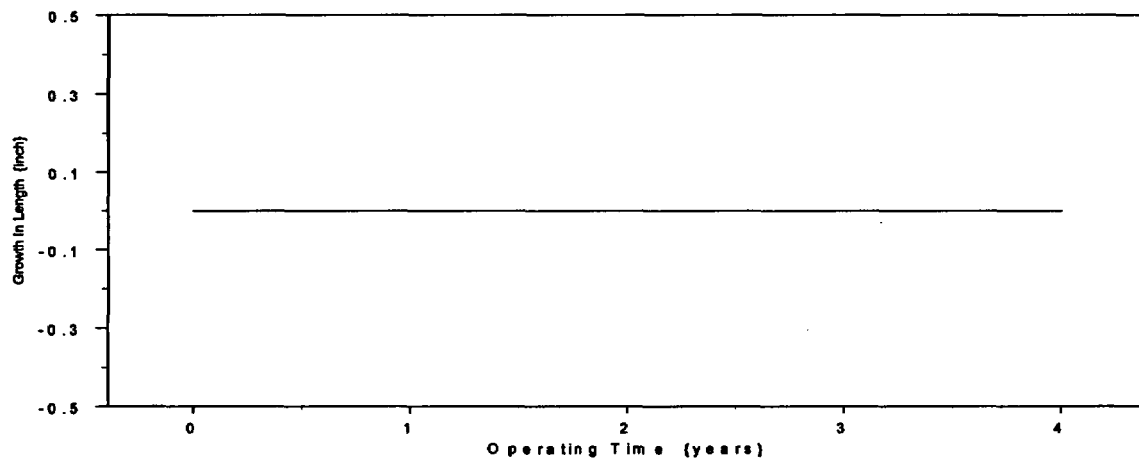
$TWC_{pwscc(j,7)} =$

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

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

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





Developed by:

Verified by:



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

**Developed by: J. S. Brihmadesar**

**Verified by: B. C. Gray**

**References :**

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

**Arkansas Nuclear One Unit 2**

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

**Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized**

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

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

**ID Surface Flaw**

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

**Ref<sub>point</sub> := 1.544**

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

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

**Val := 2**

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

**UL<sub>Strs.Dist</sub> := 4.034** Upper axial Extent for Stress Distribution to be used in the Analysis (Axial distance above nozzle bottom).

## Input Data :-

$L := 0.32$	Initial Flaw Length (Twice detectable length)
$a_0 := 0.661 \cdot 0.07$	Initial Flaw Depth (Minimum Detectable 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

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

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

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

$$C_0 := C_{01}$$

75<sup>th</sup> percentile MRP-55 Revision 1

## Stress Input Data

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

Column "0" = Axial distance from minimum to maximum recorded on data sheet (inches)

Column "1" = ID Stress data at each Elevation (ksi)

Column "2" = Quarter Thickness Stress data at each Elevation (ksi)

Column "3" = Mid Thickness Stress data at each Elevation (ksi)

Column "4" = Three quarter Thickness Stress data at each Elevation (ksi)

Column "5" = OD Stress data at each Elevation (ksi)

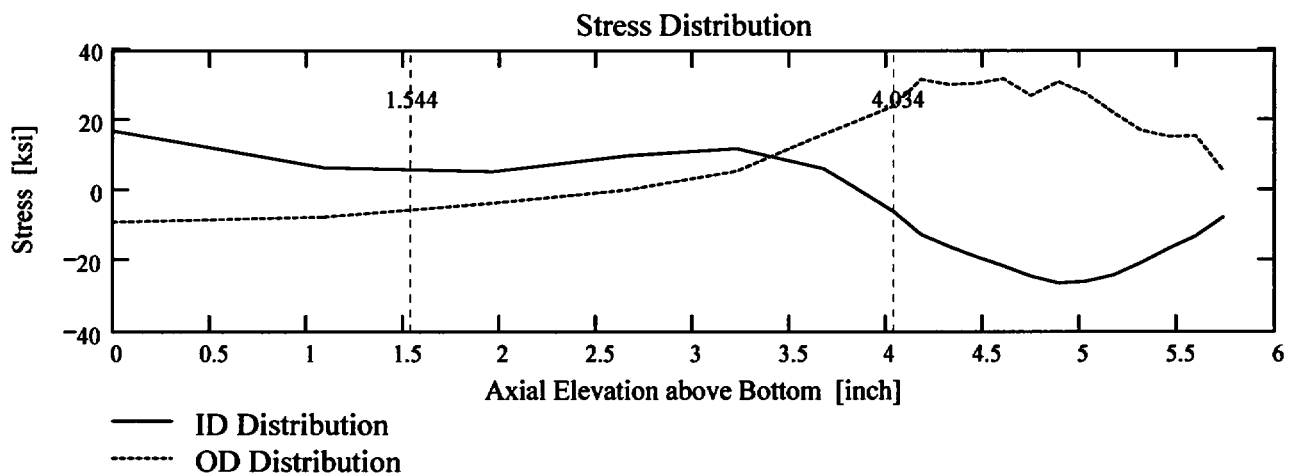
AllData :=

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

AXLen := AllData<sup>(0)</sup>

ID<sub>All</sub> := AllData<sup>(1)</sup>

OD<sub>All</sub> := AllData<sup>(5)</sup>



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

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

$$A_{x1} := Data^{(0)} \quad MD := Data^{(3)} \quad ID := Data^{(1)} \quad TQ := Data^{(4)} \quad QT := Data^{(2)} \quad OD := Data^{(5)}$$

$$R_{ID} := \text{regress}(A_{x1}, ID, 3)$$

$$R_{QT} := \text{regress}(A_{x1}, QT, 3)$$

$$R_{OD} := \text{regress}(A_{x1}, OD, 3)$$

$$R_{MD} := \text{regress}(A_{x1}, MD, 3)$$


$$R_{TQ} := \text{regress}(A_{x1}, TQ, 3)$$

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

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

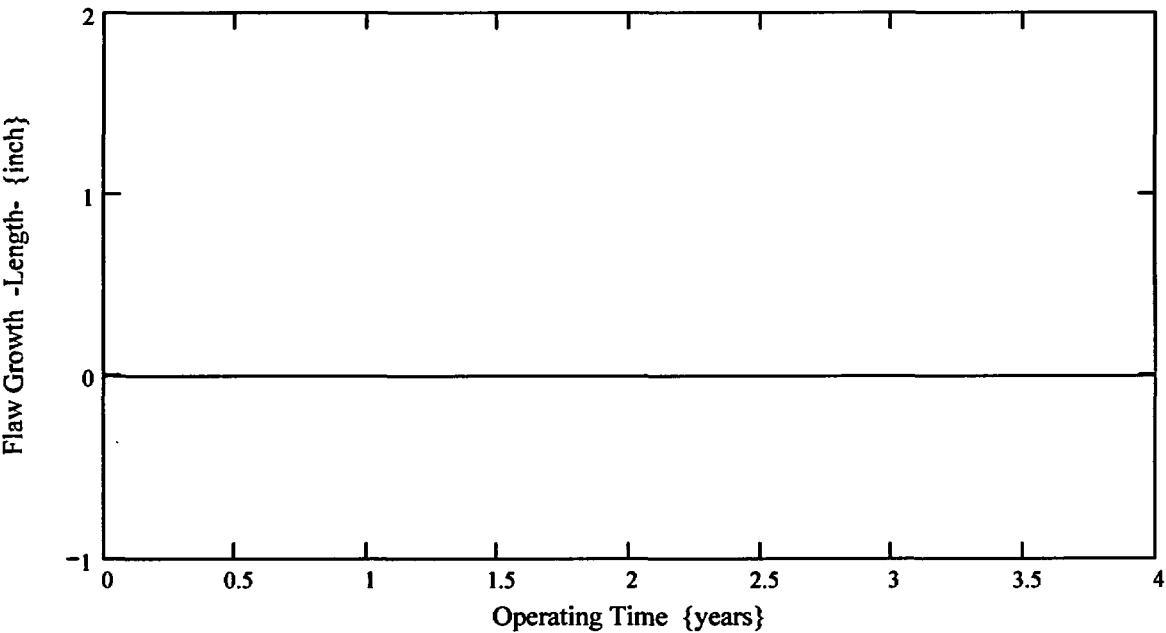
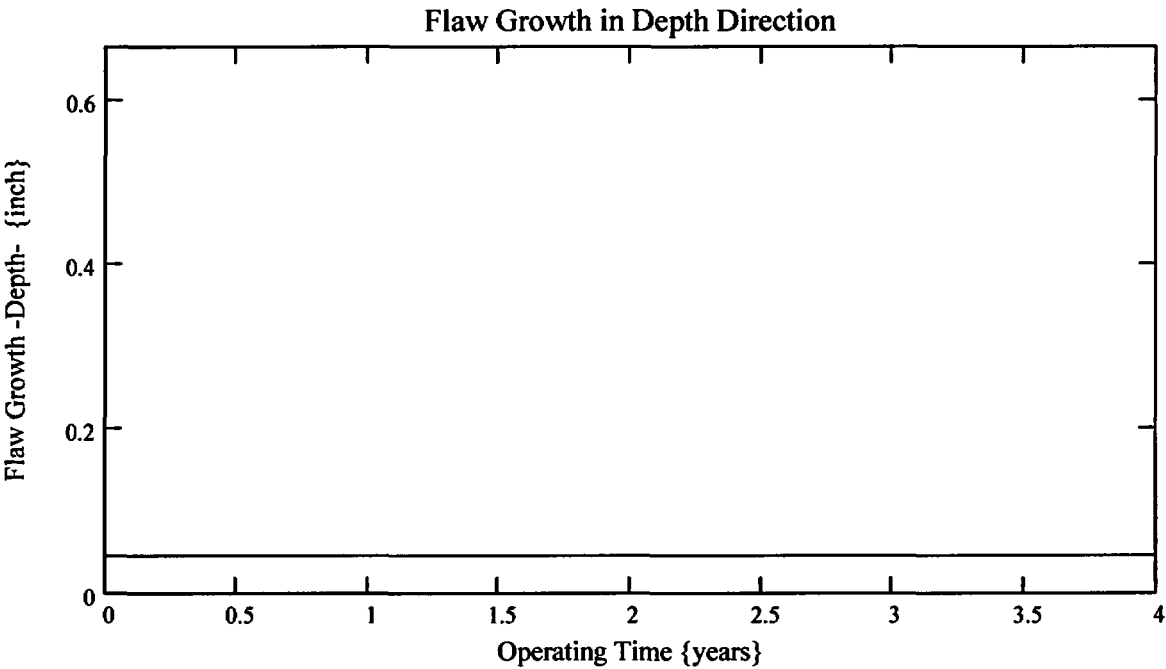
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

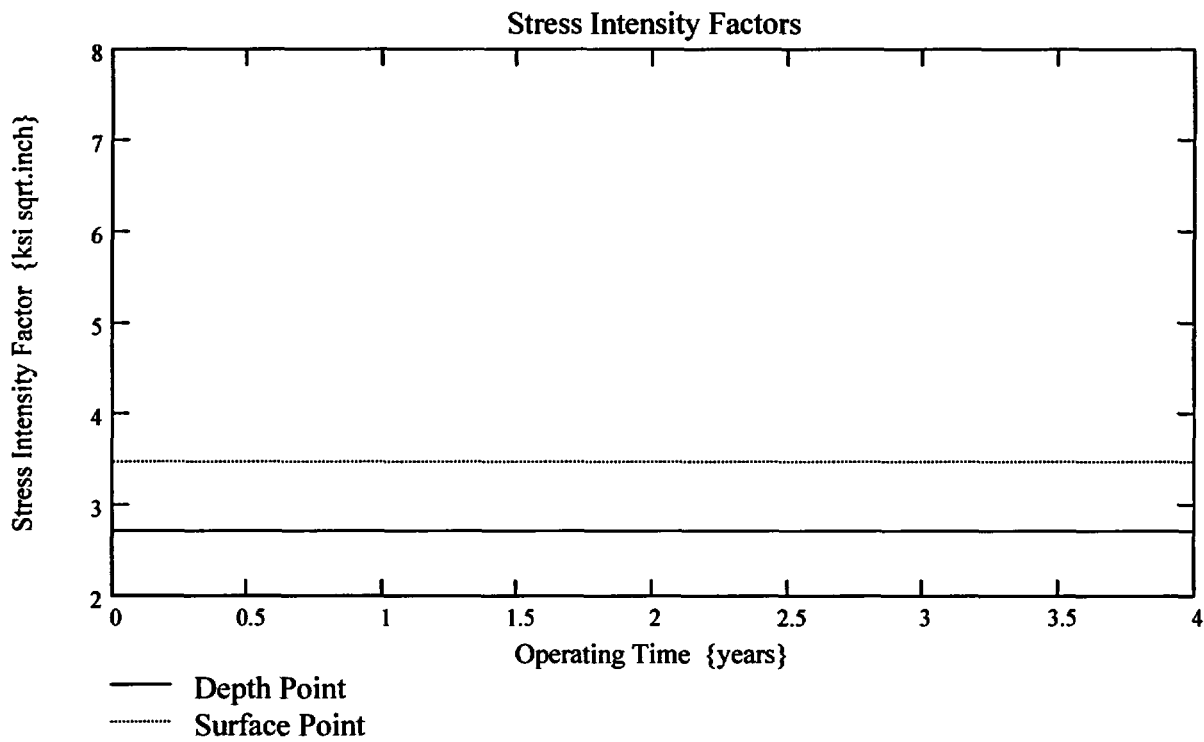
**No User Input is required beyond this Point**

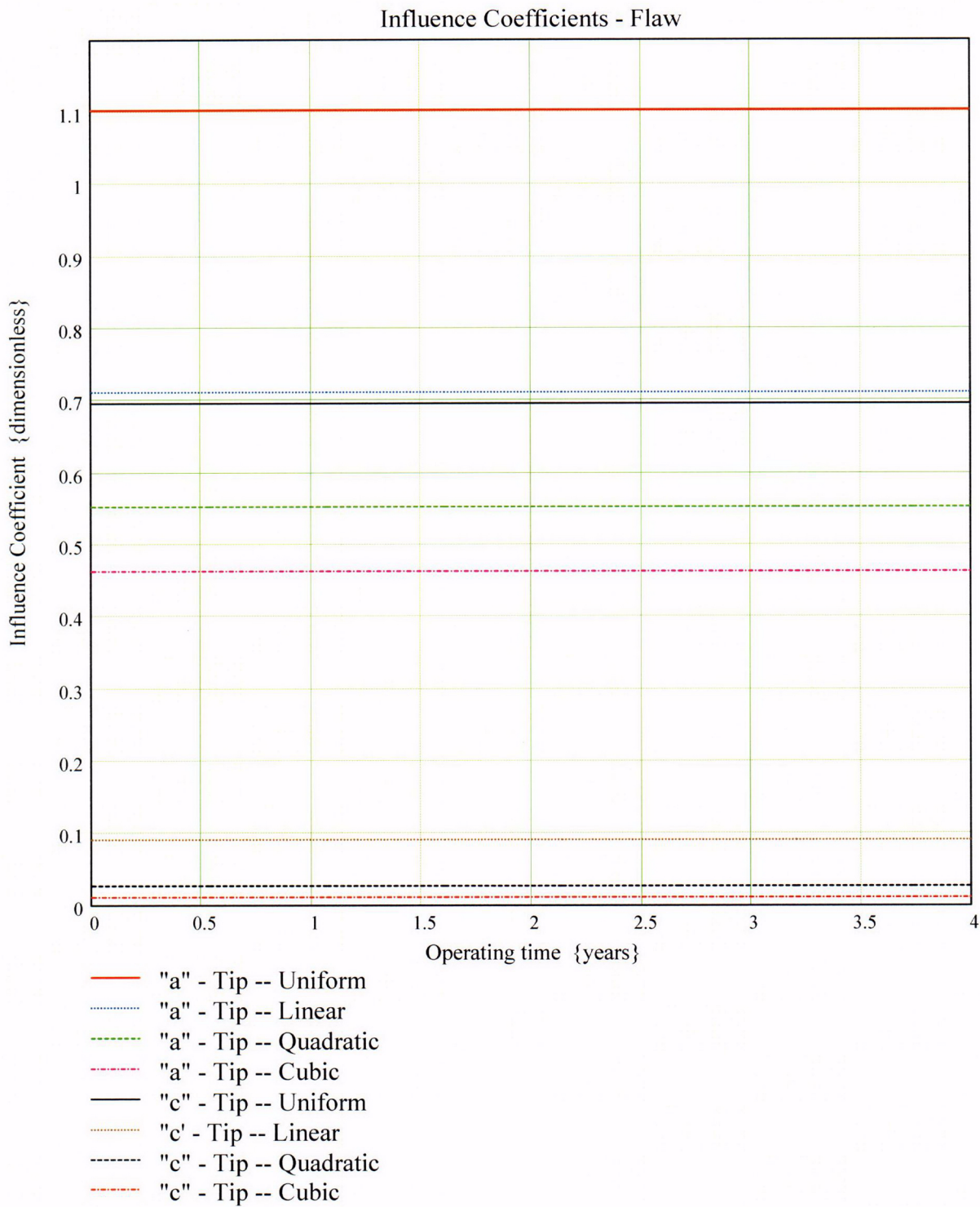
 Sat Aug 09 10:59:39 AM 2003

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PropLength = 2.33









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

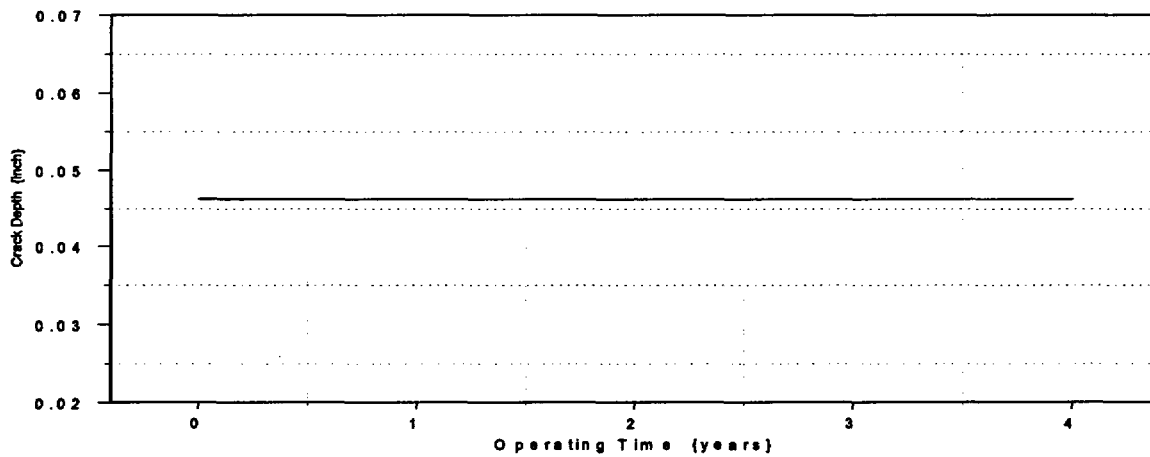
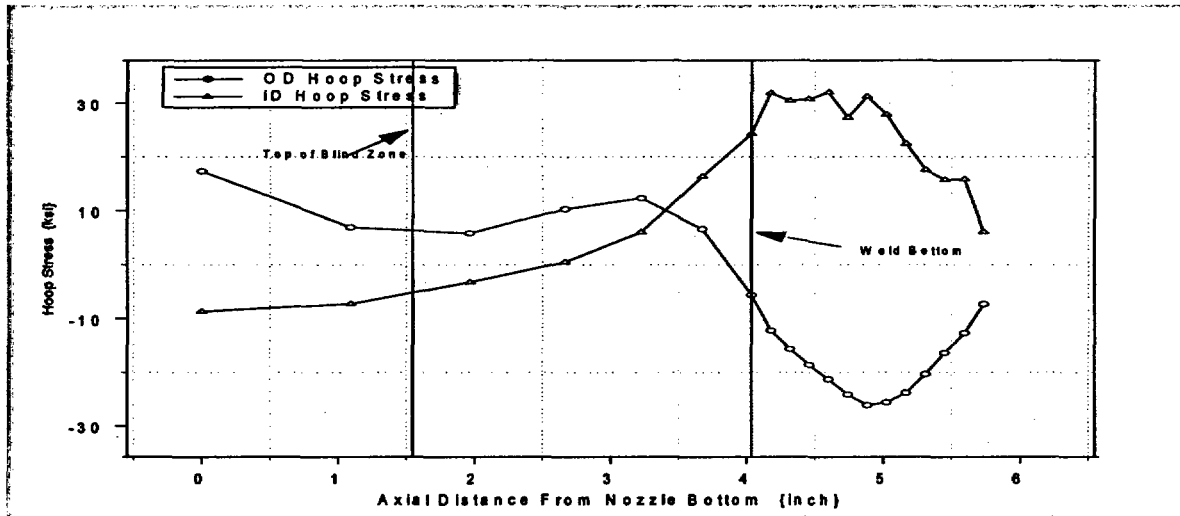
1.103
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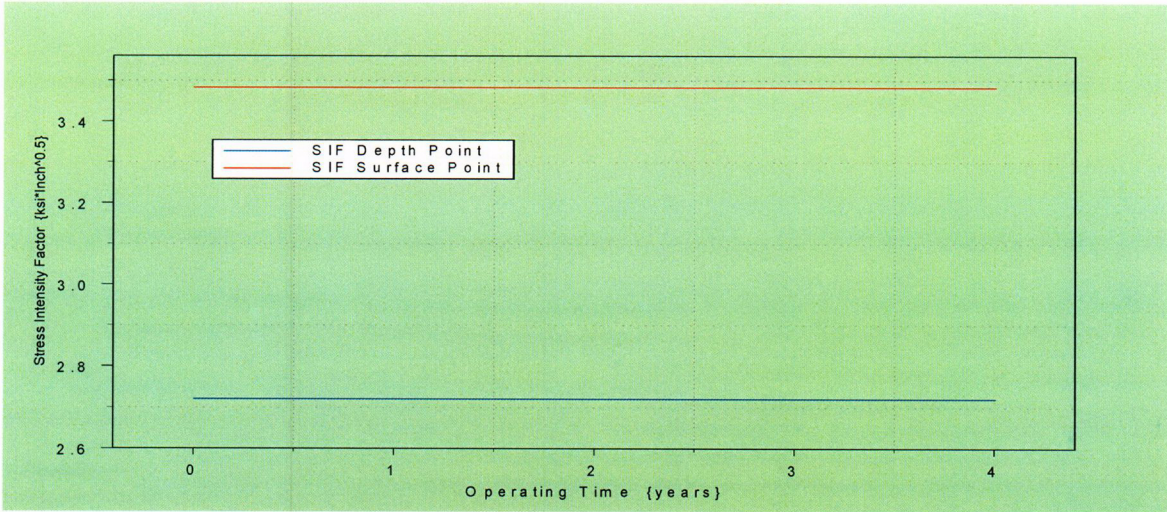
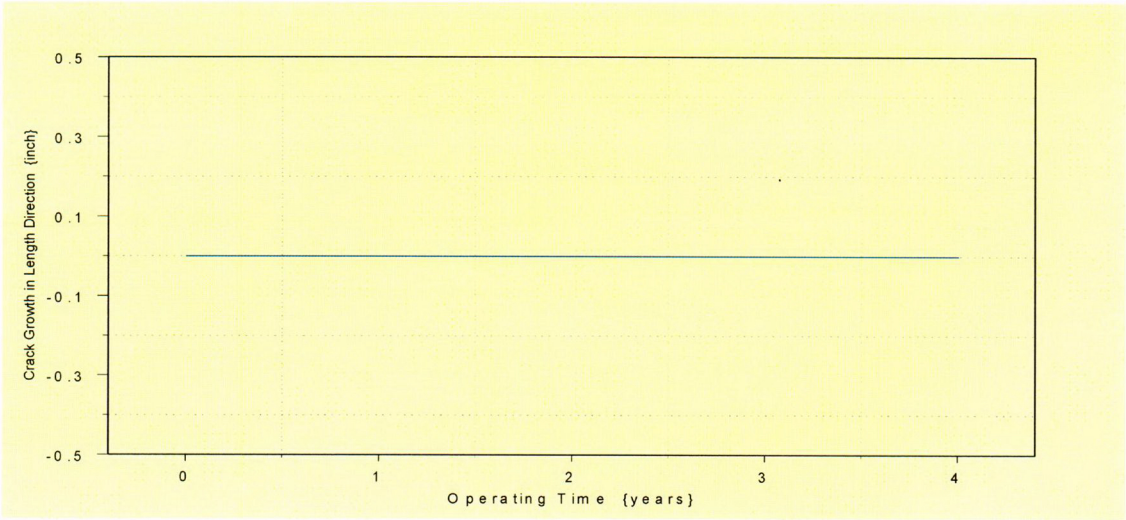
$CGR_{sambi(k,6)} =$

3.484
3.484
3.484
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3.484
3.484
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3.484

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

2.72
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2.72
2.72





## Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadesan

Verified by: B. C. Gray

### References :

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

## Arkansas Nuclear One Unit 2

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

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

Note : Used the Metric form of the equation from EPRI MRP 55-Rev. 1.

The correction is applied in the determination of the crack extension to obtain the value in inch/hr .

## OD Surface Flaw

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

Ref<sub>point</sub> := 1.544

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

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

Val := 2

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

UL<sub>Strs.Dist</sub> := 4.034

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

## Input Data :-

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

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

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

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

$$C_0 := C_{01}$$

75<sup>th</sup> percentile MRP-55 Revision 1

## Stress Input Data

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

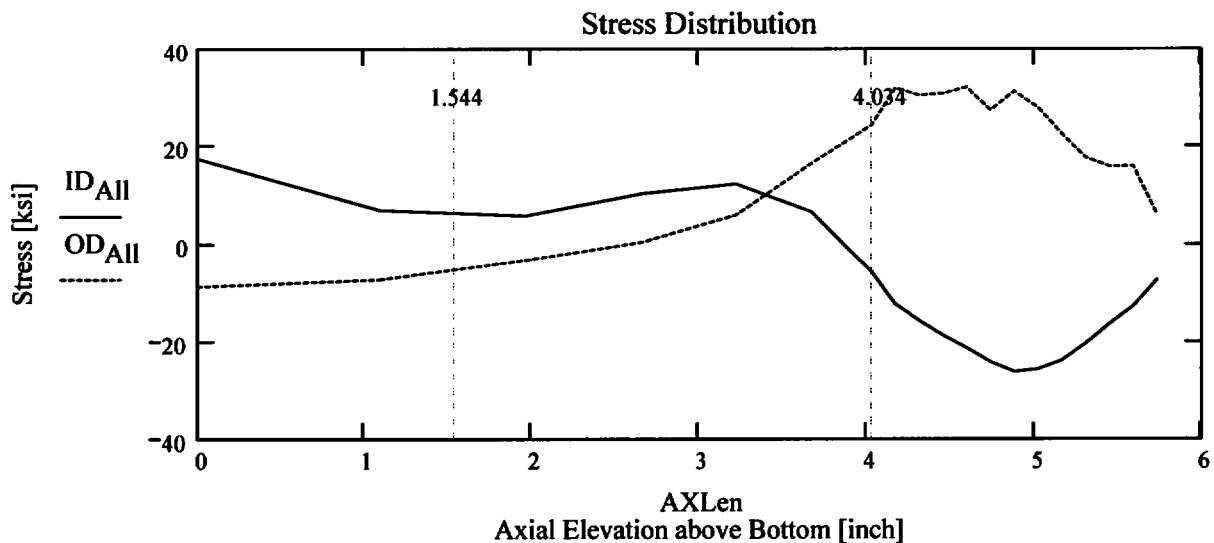
AllData :=

	0	1	2	3	4	5
0	0	17.35	8.19	2.28	-3.06	-8.64
1	1.09	6.89	1.47	-2.22	-5.44	-7.2
2	1.96	5.78	2.36	0.75	-0.95	-3.23
3	2.66	10.29	7.15	5.32	3.43	0.49
4	3.23	12.24	7.03	6.83	7.24	5.95
5	3.67	6.58	4.66	5.87	12.45	16.38
6	4.03	-5.62	-1.3	4.18	17.86	24.28
7	4.18	-12.25	-6.01	2.74	20.52	31.88
8	4.32	-15.64	-9.13	2.2	21.5	30.45
9	4.46	-18.61	-11.79	1.32	20.22	30.79
10	4.6	-21.26	-13.55	0.57	19.39	32.09

AXLen := AllData<sup>(0)</sup>

ID<sub>All</sub> := AllData<sup>(1)</sup>

OD<sub>All</sub> := AllData<sup>(5)</sup>



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

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

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

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

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

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

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

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


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

Flaw center Location Location above Nozzle Bottom

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

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

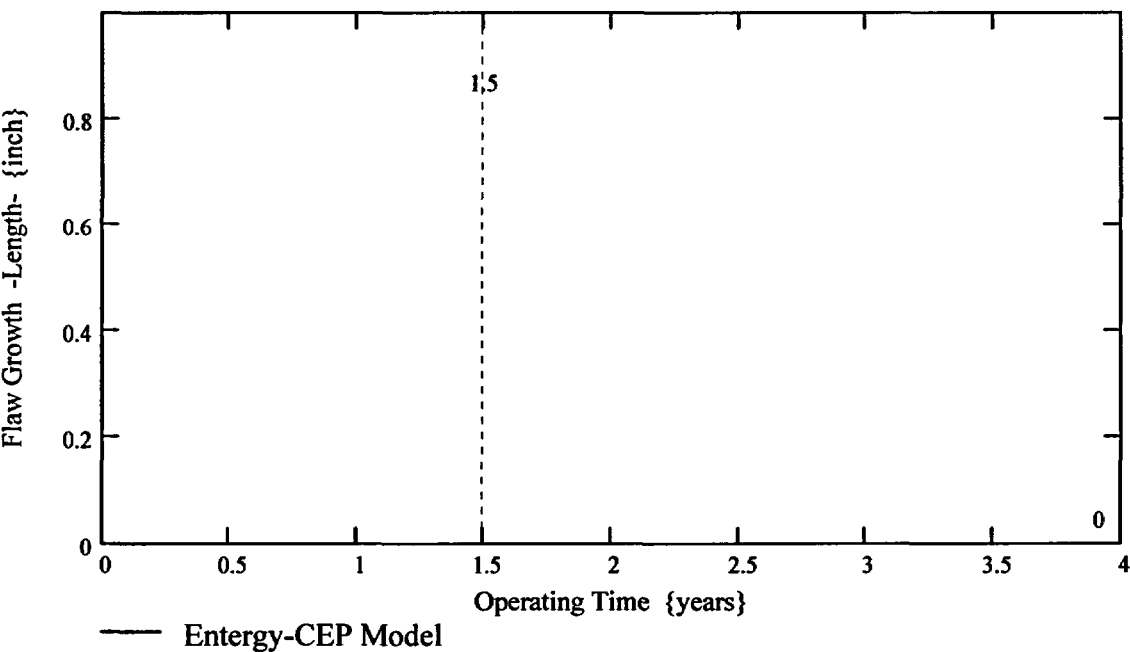
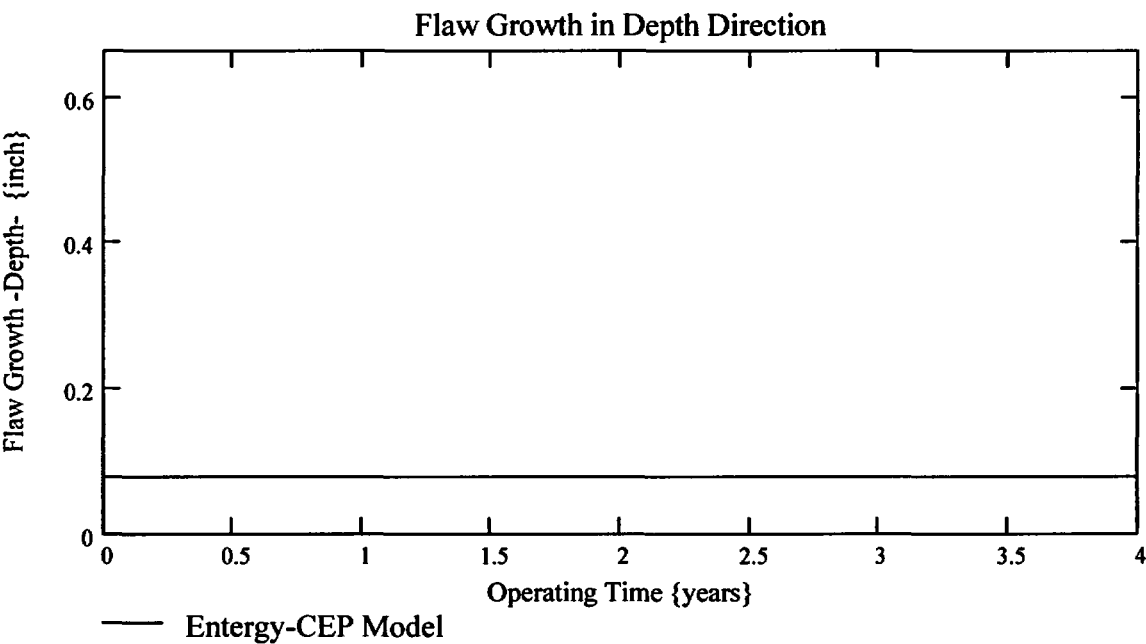
**No User Input is required beyond this Point**

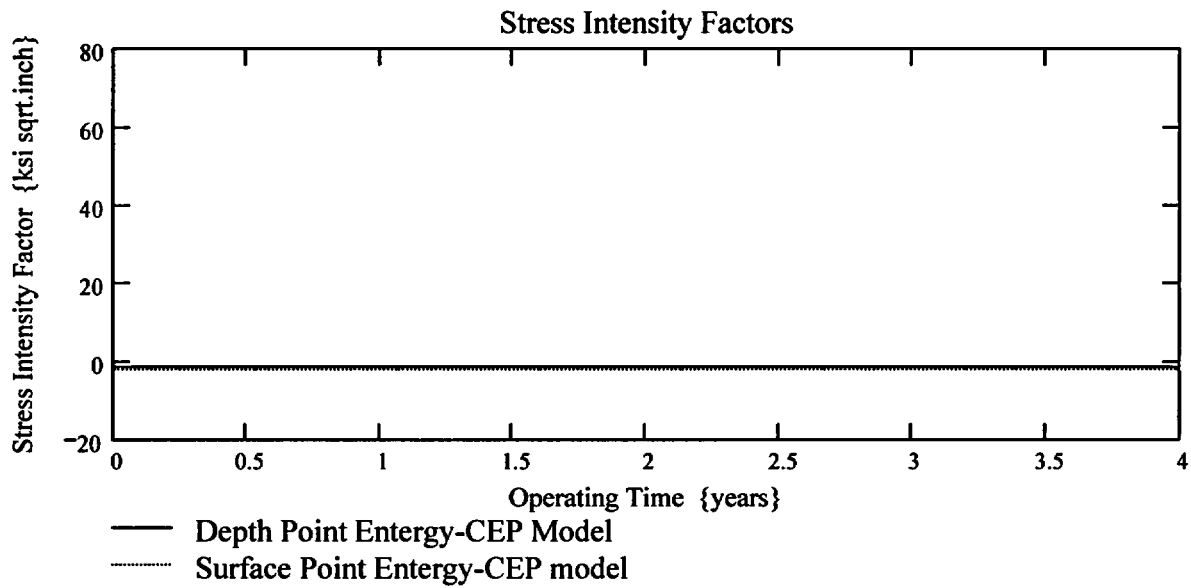
 Sat Aug 09 10:21:18 AM 2003

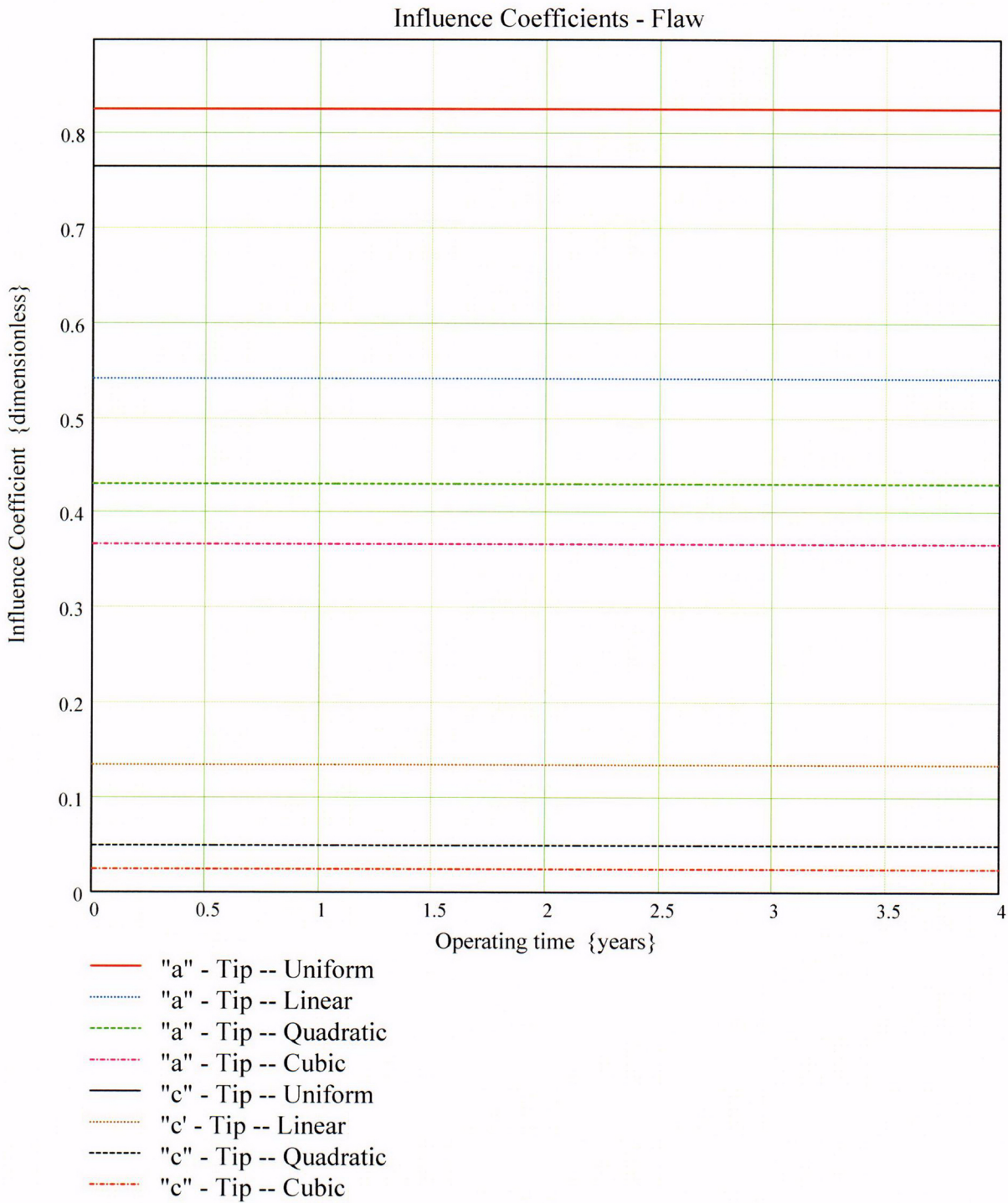
---



$\text{PropLength} = 2.33$







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

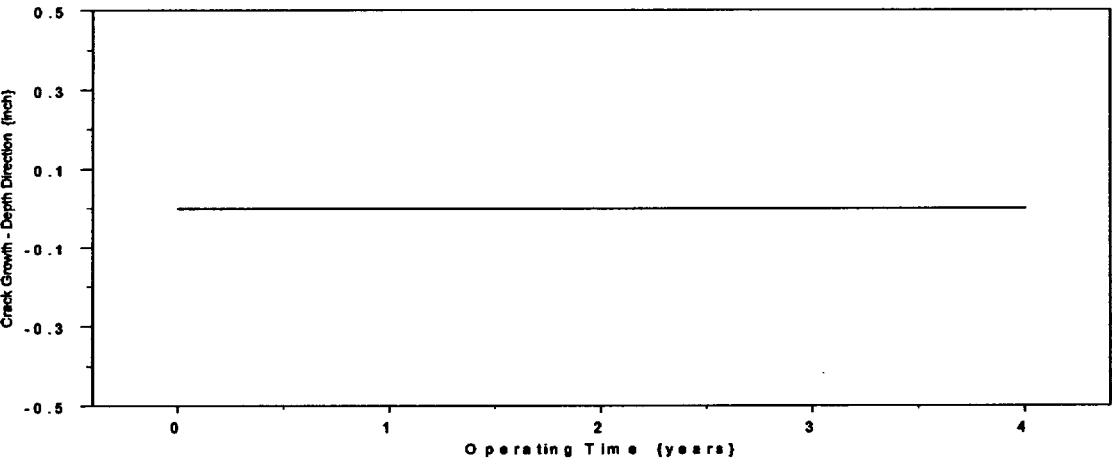
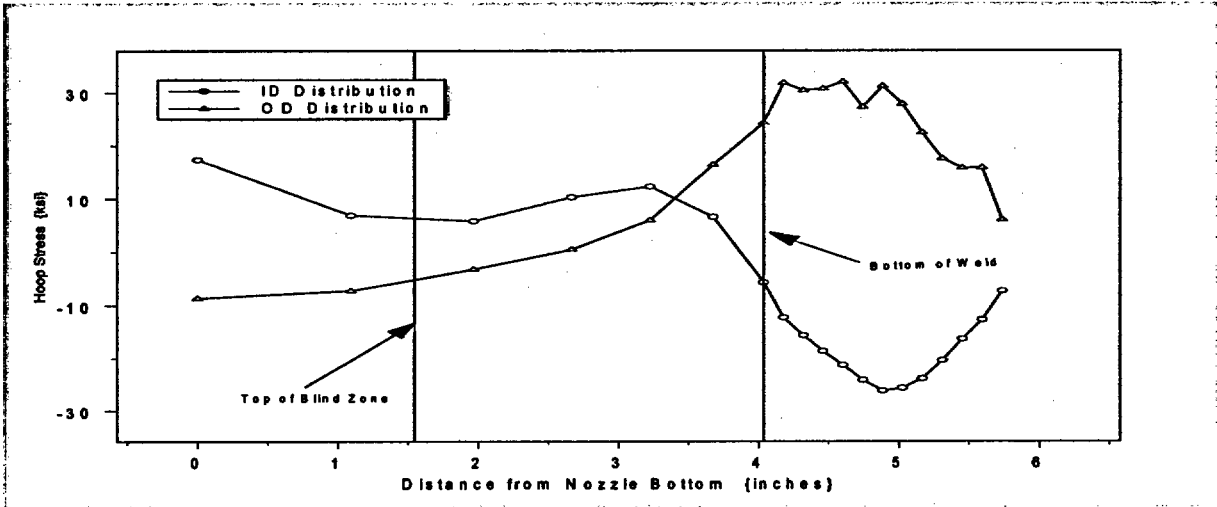
0.827
0.827
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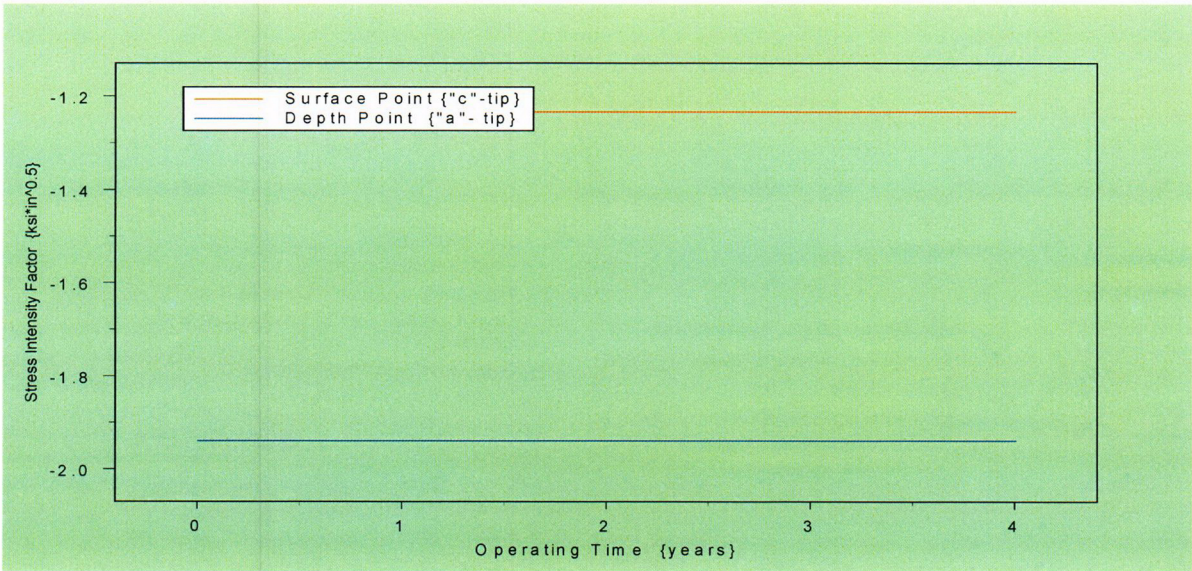
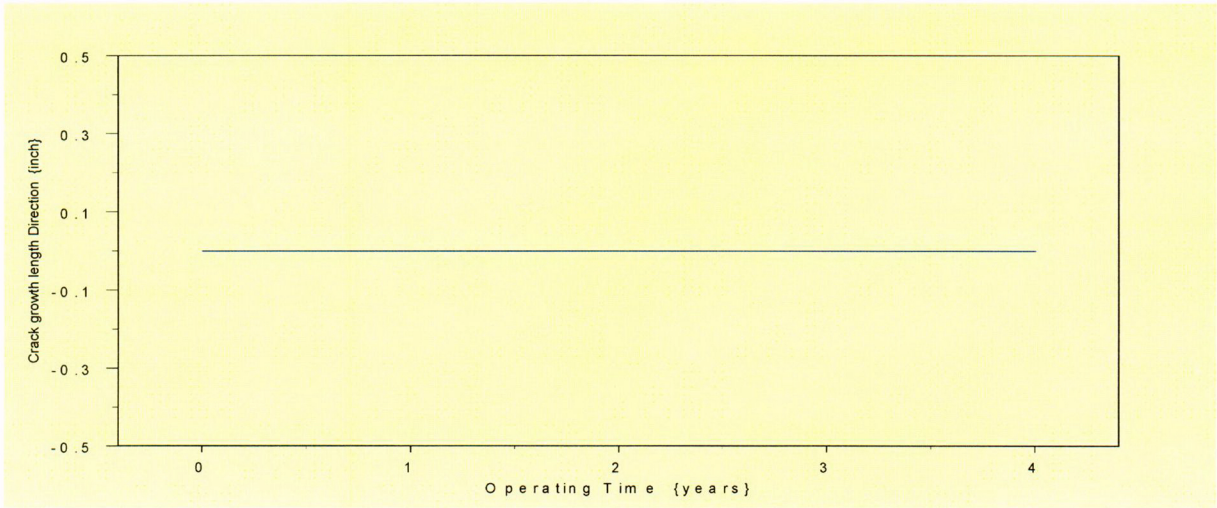
$CGR_{sambi(k,6)} =$

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

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

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





## Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadeseam

Verified by: B. C. Gray

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

### References :

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

### Arkansas Nuclear One Unit 2

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

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

### Through Wall Axial Flaw

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

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

BZ := 1.544

Location of Blind Zone above nozzle bottom (inch)

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

ULStrs.Dist := 4.034

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

Developed by:

Verified by:

Input Data :-

$L := 0.25$  Initial Flaw Length TW axial (Based on 10 Ksi average stress)

$od := 4.05$  Tube OD

$id := 2.728$  Tube ID

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

$Years := 4$  Number of Operating Years

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

$T := 604$  Estimate of Operating Temperature

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

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

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

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

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

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

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

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

$$t := R_o - R_i$$

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

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

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

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

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



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

### Stress Input Data

**Import the Required data from applicable Excel spread Sheet. The column designations are as follows:**

**Cloumn "0" = Axial distance from Minimum to Maximum recorded on the data sheet (inches)**

**Column "1" = ID Stress data at each Elevation (ksi)**

**Column "5" = OD Stress data at each Elevation (ksi)**

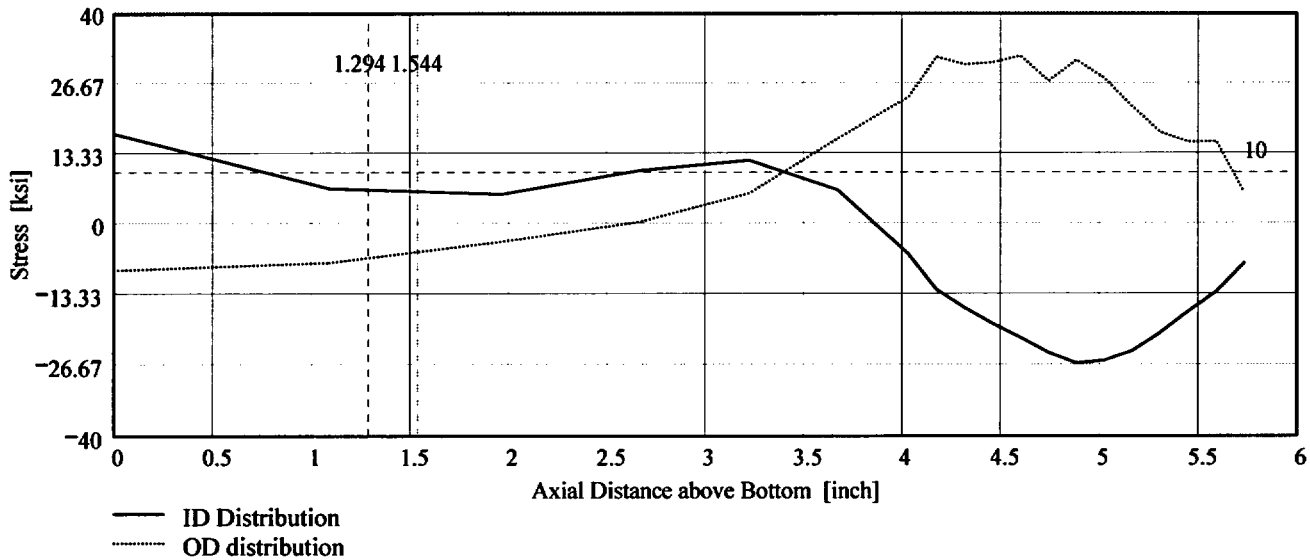
Data<sub>All</sub> :=

	0	1	2	3	4	5
0	0	17.35	8.19	2.28	-3.06	-8.64
1	1.09	6.89	1.47	-2.22	-5.44	-7.2
2	1.96	5.78	2.36	0.75	-0.95	-3.23
3	2.66	10.29	7.15	5.32	3.43	0.49
4	3.23	12.24	7.03	6.83	7.24	5.95
5	3.67	6.58	4.66	5.87	12.45	16.38
6	4.03	-5.62	-1.3	4.18	17.86	24.28
7	4.18	-12.25	-6.01	2.74	20.52	31.88
8	4.32	-15.64	-9.13	2.2	21.5	30.45
9	4.46	-18.61	-11.79	1.32	20.22	30.79
10	4.6	-21.26	-13.55	0.57	19.39	32.09

AllAx1 := Data<sub>All</sub><sup>(0)</sup>

AllID := Data<sub>All</sub><sup>(1)</sup>

AllOD := Data<sub>All</sub><sup>(5)</sup>



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).

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

$Ax1 := Data^{(0)}$

$ID := Data^{(1)}$

$OD := Data^{(5)}$

$R_{ID} := \text{regress}(Ax1, ID, 3)$


$R_{OD} := \text{regress}(Ax1, OD, 3)$

$FL_{Cntr} := BZ - 1$

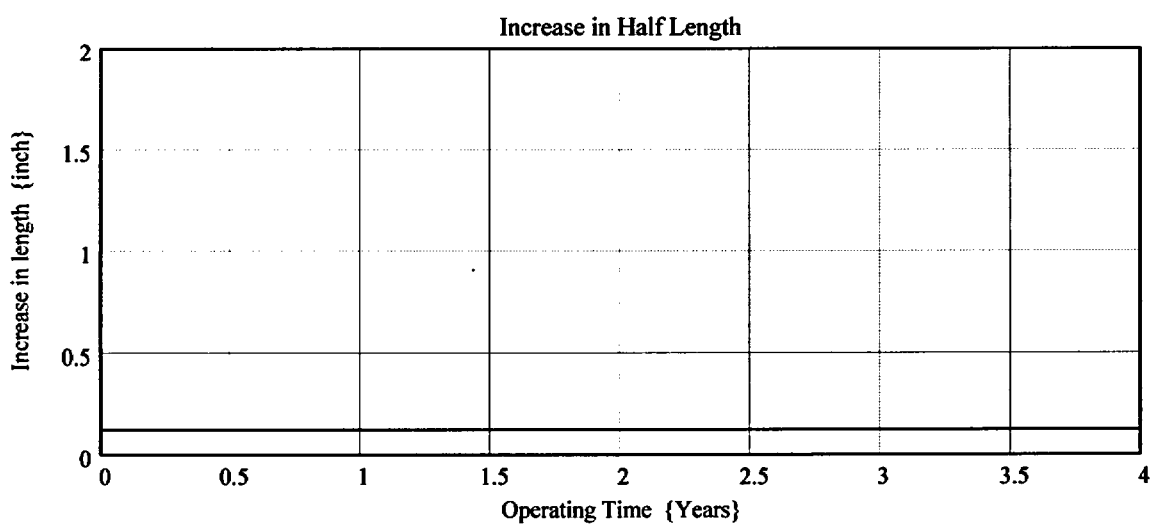
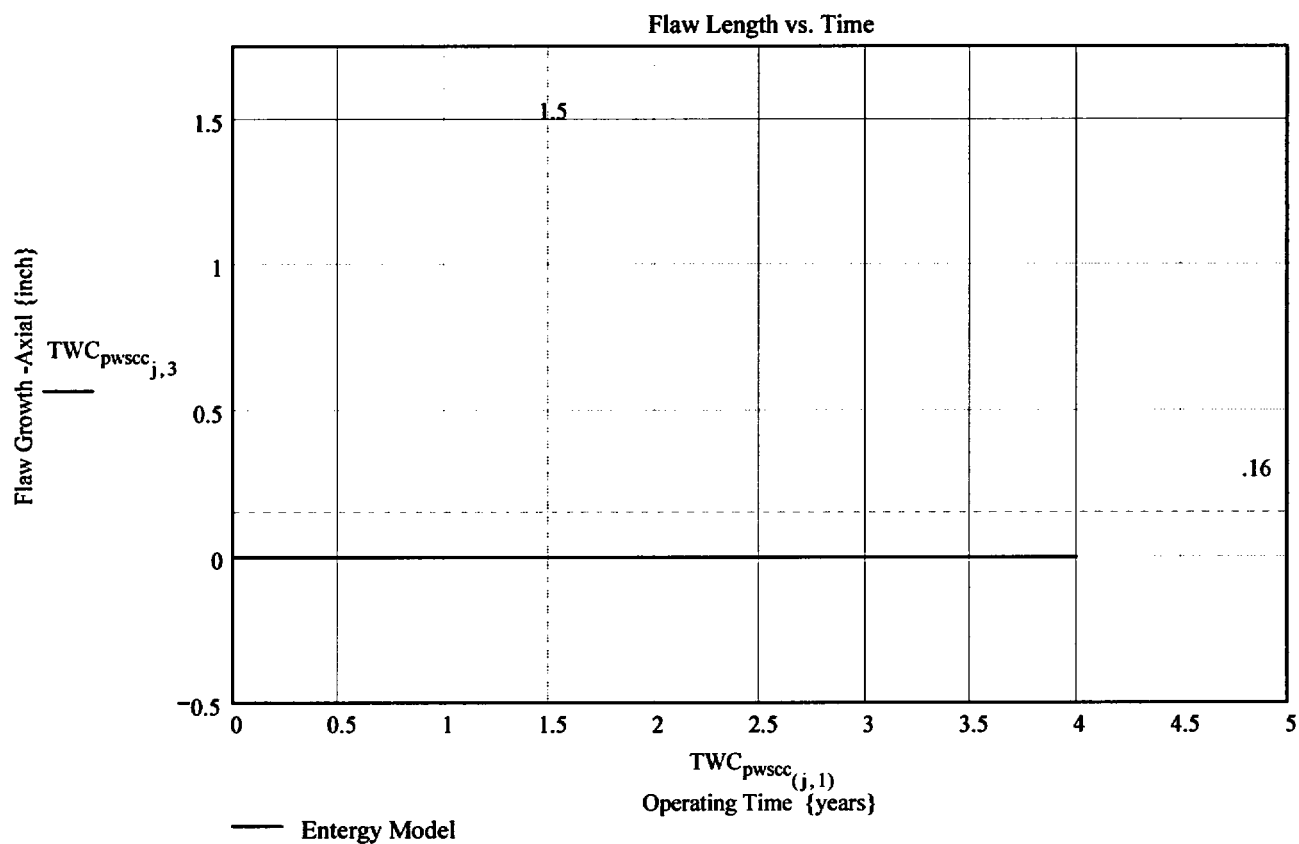
Flaw Center above Nozzle Bottom

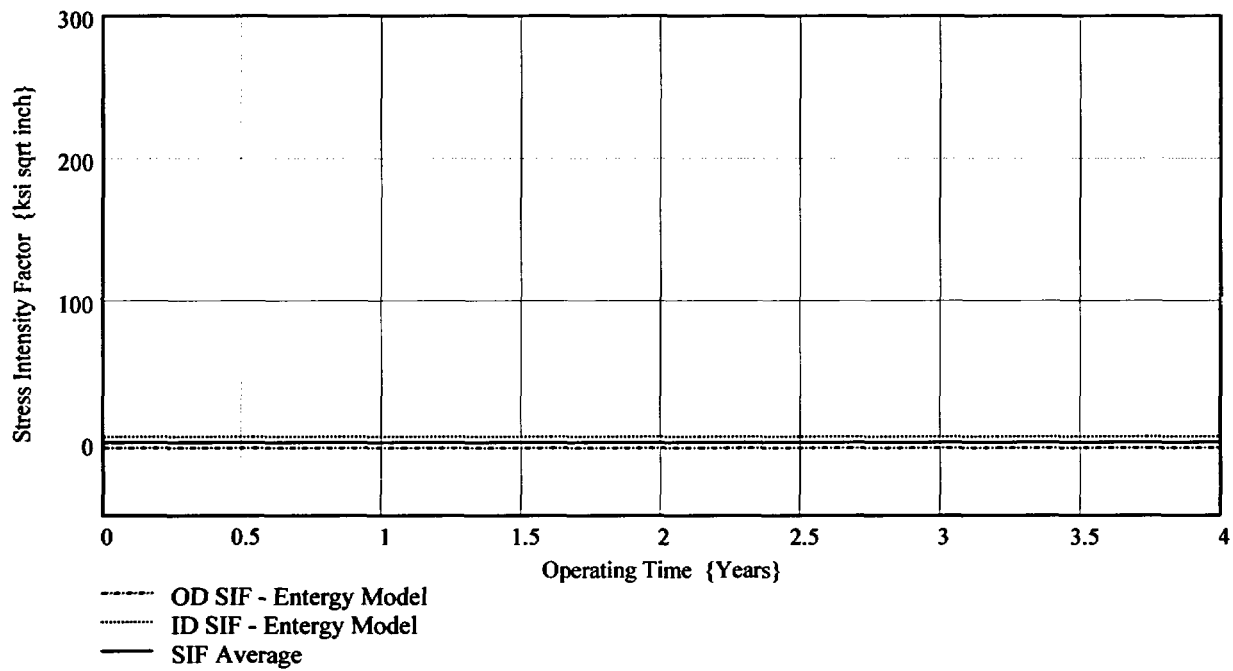
$$IncStrs.avg := \frac{ULStrs.Dist - BZ}{20}$$

**No User Input required beyond this Point**

 Sat Aug 09 11:44:49 AM 2003

PropLength = 2.49





Developed by:

Verified by:

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

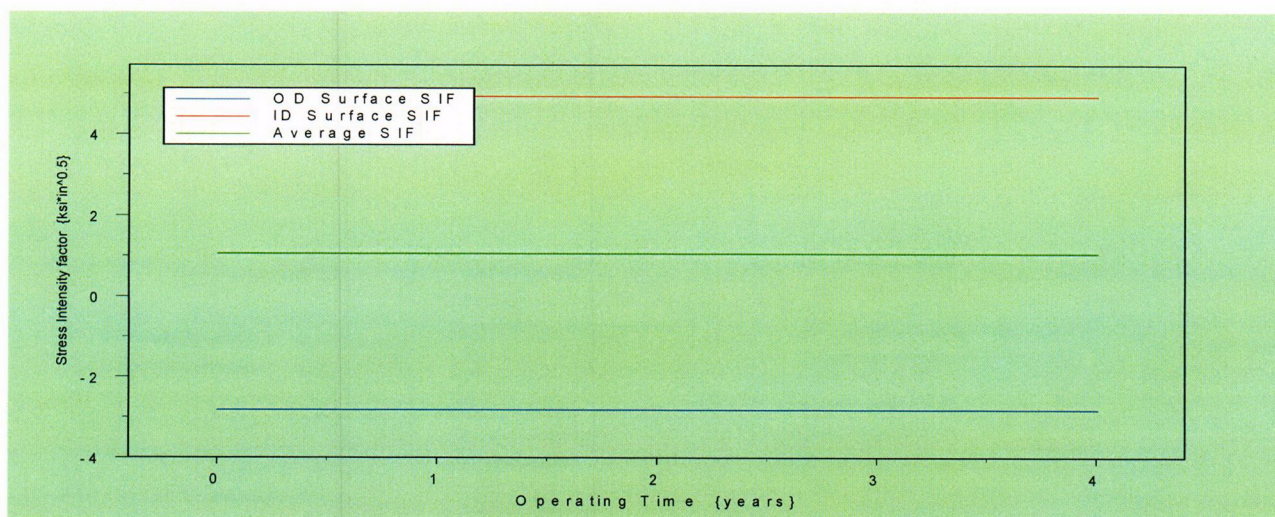
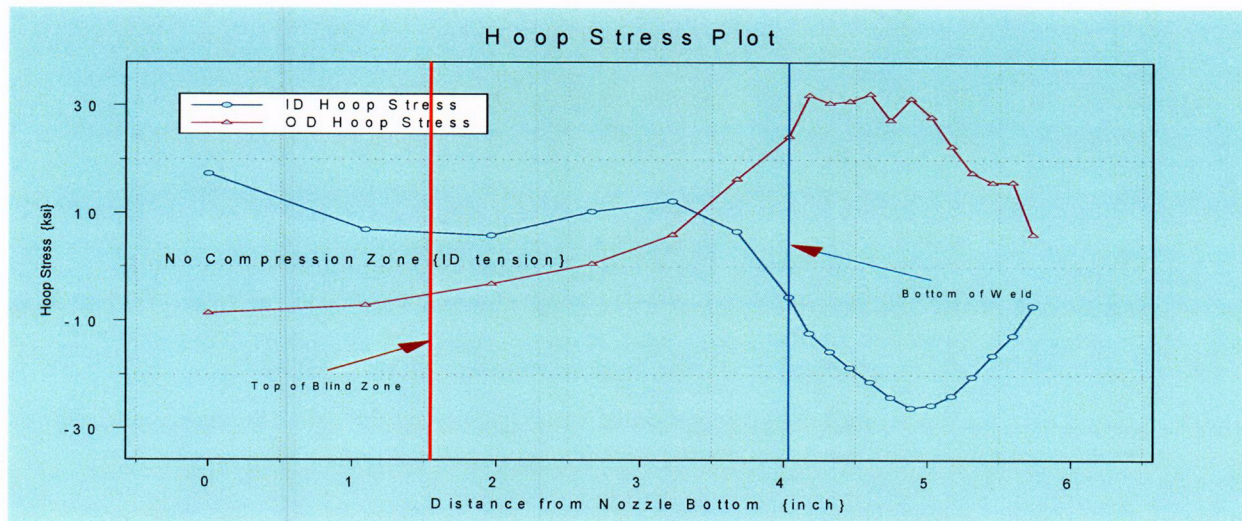
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817
-2.817

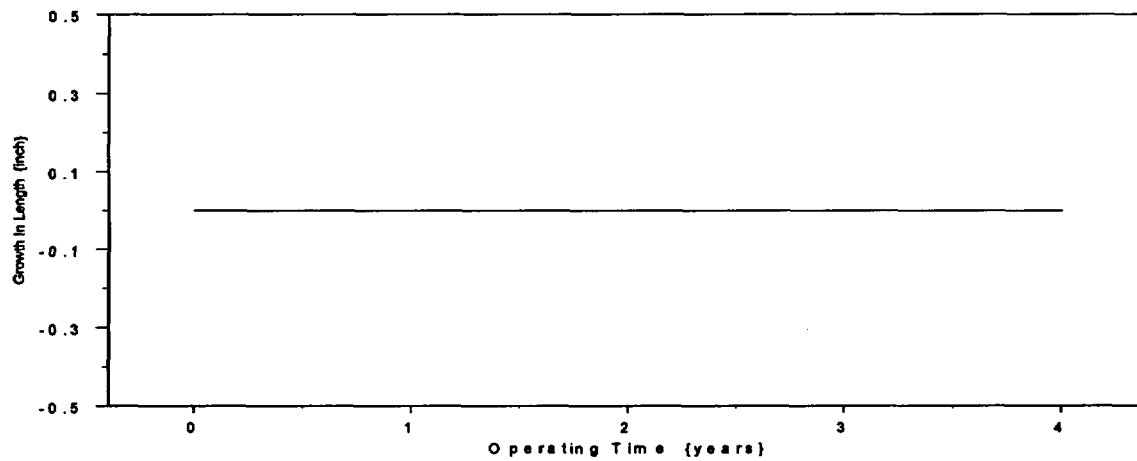
$TWC_{pwscc(j,7)} =$

4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929
4.929

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

1.141
1.141
1.141
1.141
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1.141
1.141
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1.141
1.141
1.141
1.141
1.141
1.141





Developed by:

Verified by:



## Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadesar

Verified by: B. C. Gray

### References :

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

## Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"49" Degree Nozzle, Downhill Azimuth, Augmented Analysis  
1.043" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

Note : Used the Metric form of the equation from EPRI MRP 55-Rev. 1.

The correction is applied in the determination of the crack extension to obtain the value in inch/hr .

## OD Surface Flaw

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

RefPoint := 1.043

This allows a 0.25 inch freespan below bottom of weld

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

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

Val := 2

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

ULStrs.Dist := 1.293

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

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

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

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

$$C_0 := C_{01}$$

75<sup>th</sup> percentile MRP-55 Revision 1

## Stress Input Data

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

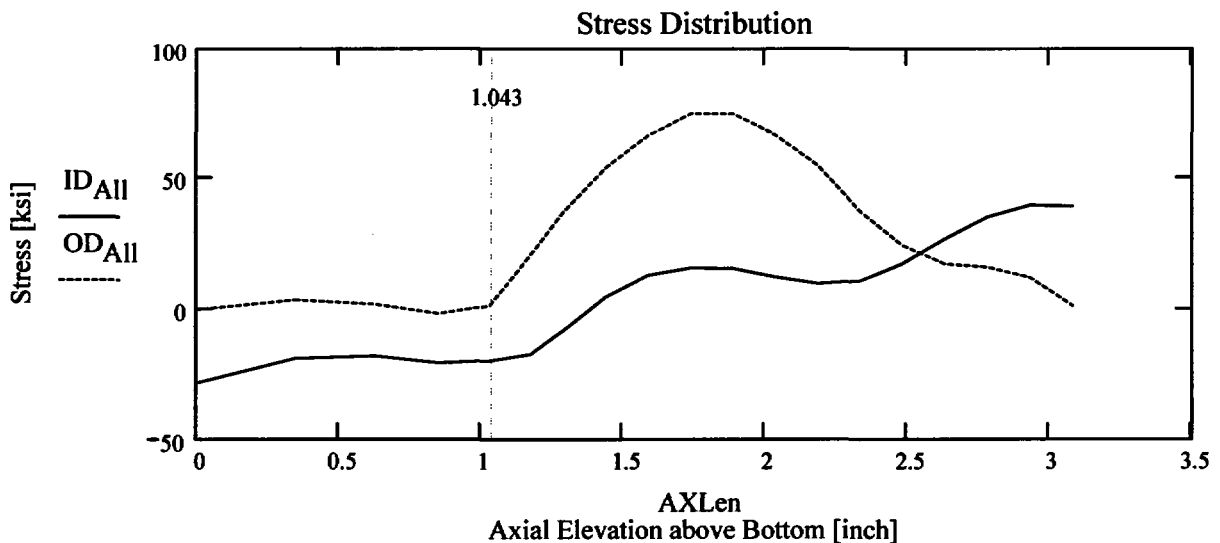
AllData :=

	0	1	2	3	4	5
0	0	-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

AXLen := AllData<sup>(0)</sup>

ID<sub>All</sub> := AllData<sup>(1)</sup>

OD<sub>All</sub> := AllData<sup>(5)</sup>



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).

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

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


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

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

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

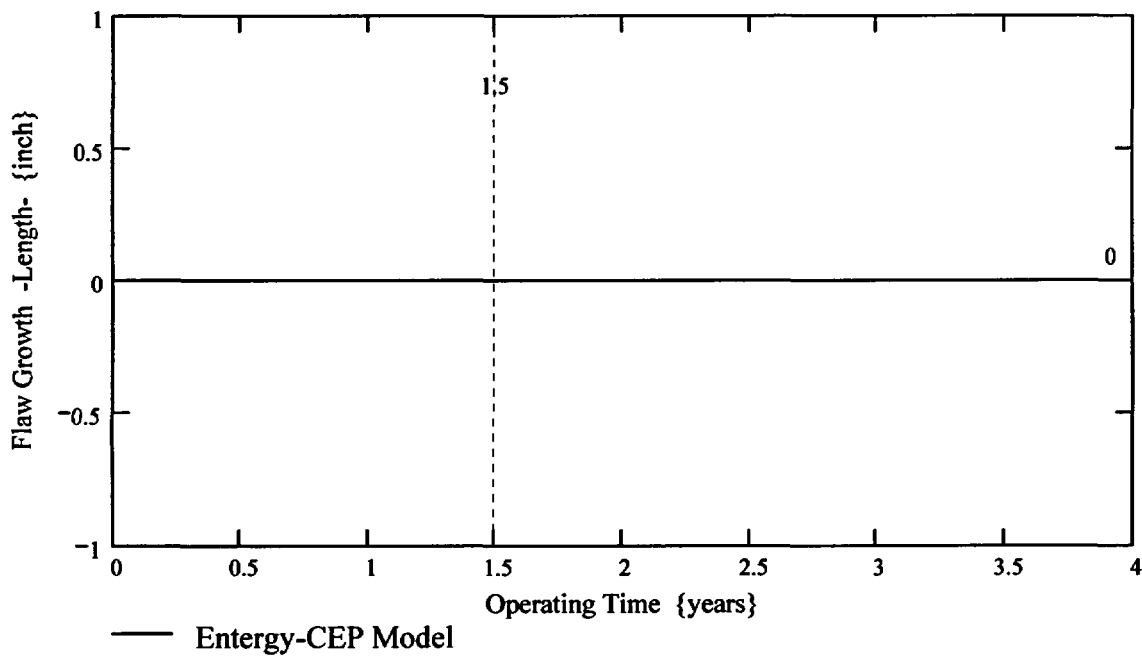
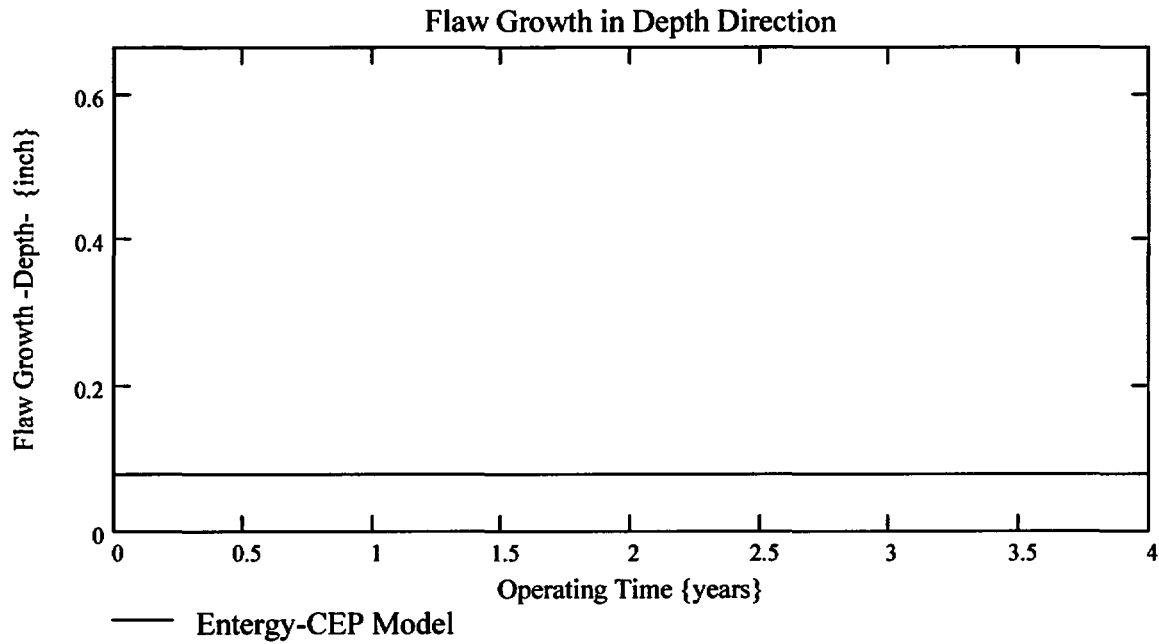
$$U_{Tip} := FL_{Cntr} + c_0 \quad IncStrs.avg := \frac{UL_{Strs.Dist} - U_{Tip}}{n}$$

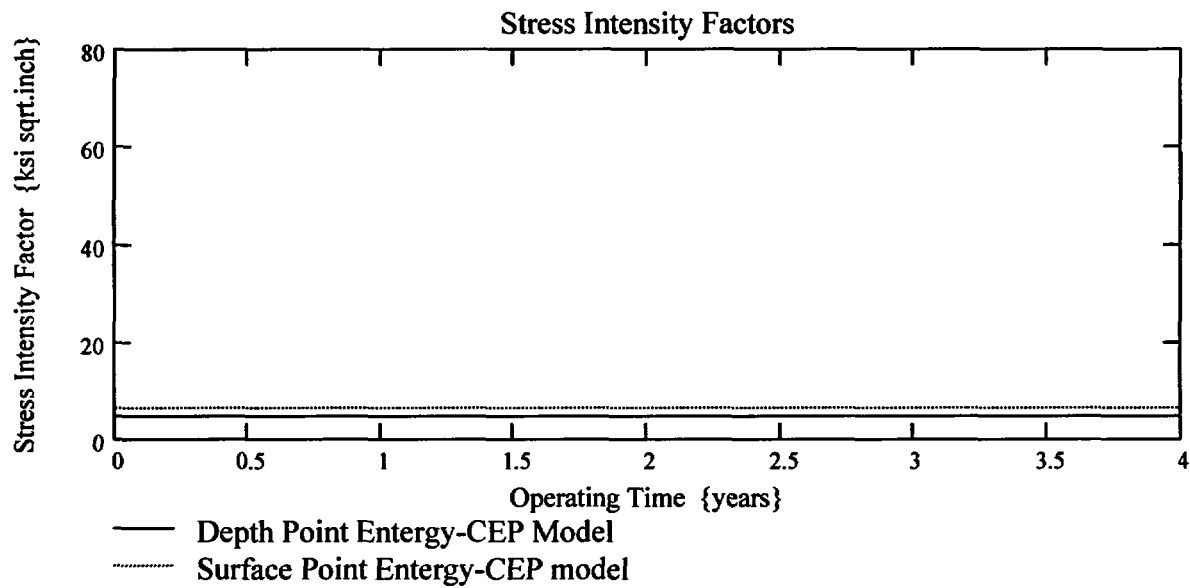
**No User Input is required beyond this Point**

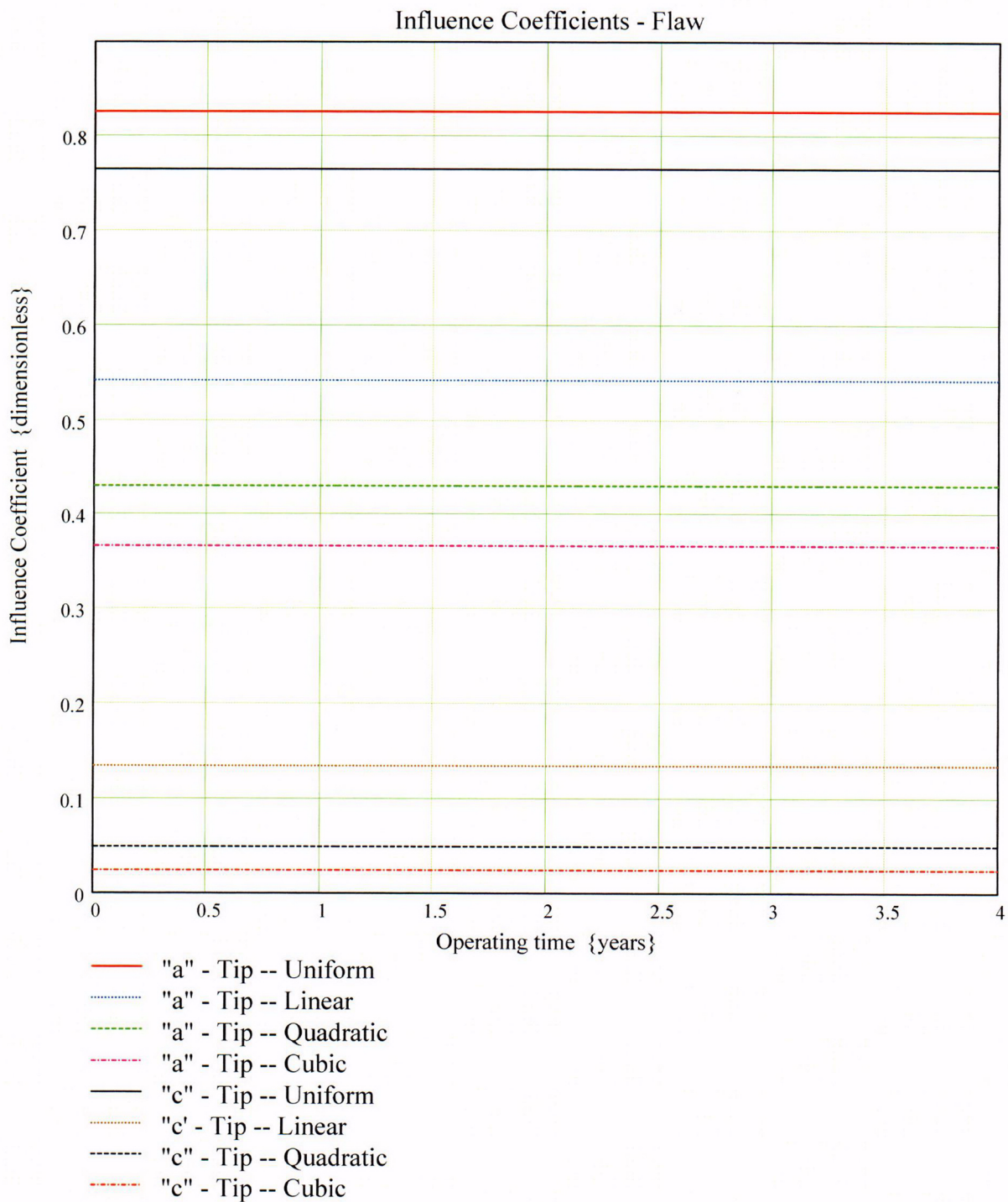
 Sat Aug 09 10:21:18 AM 2003

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$\text{PropLength} = 0.09$









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

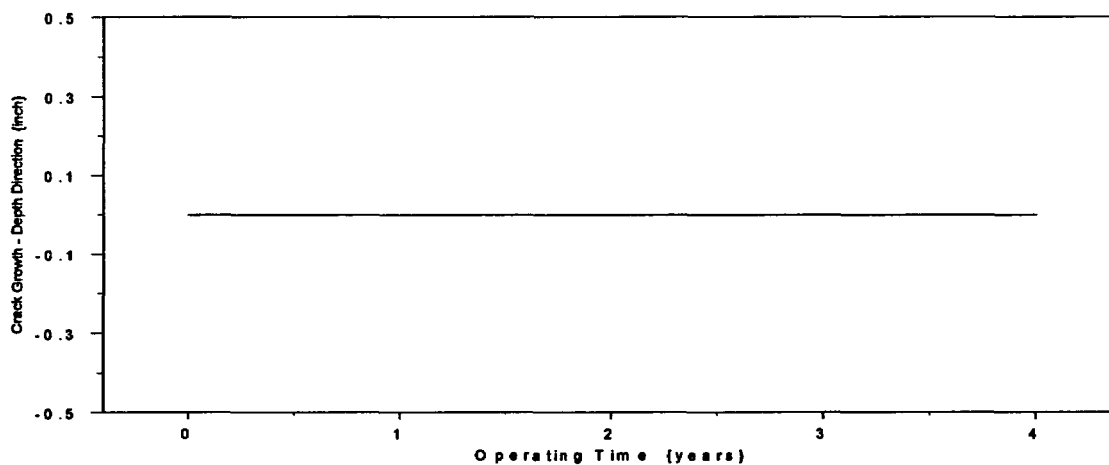
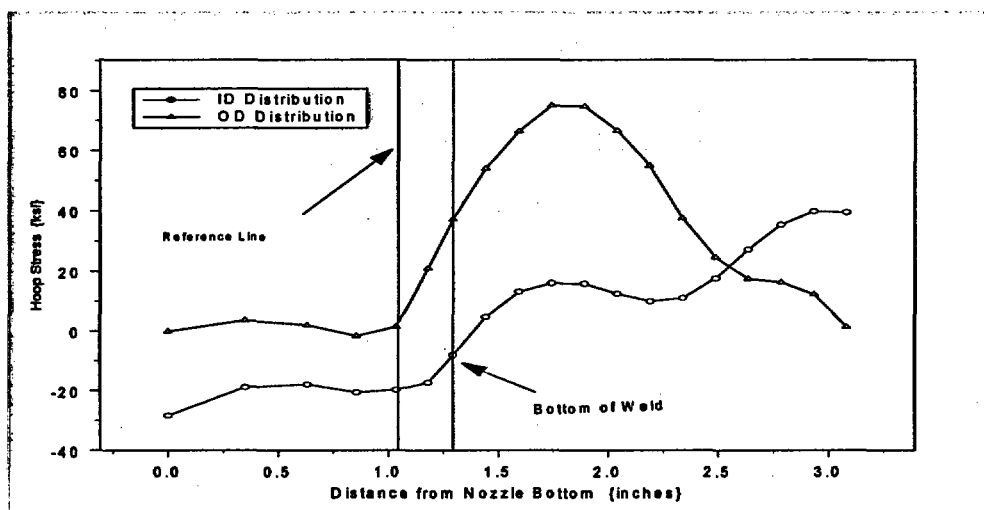
0.827
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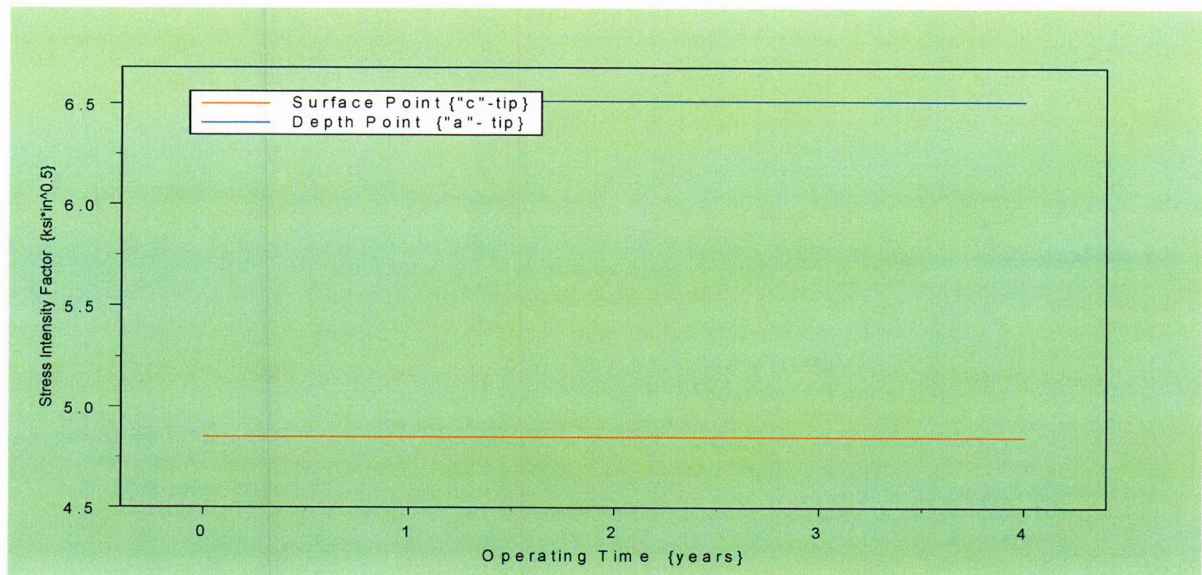
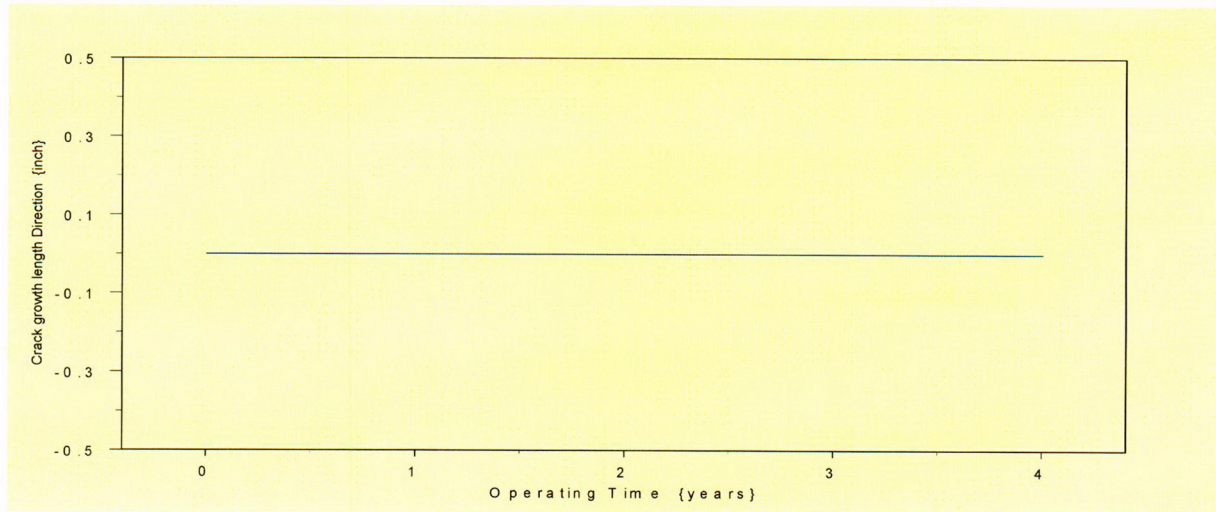
$$\text{CGR}_{\text{sambi}(k,6)} =$$

6.514
6.514
6.514
6.514
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6.514
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6.514
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6.514
6.514
6.514
6.514
6.514
6.514

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

4.851
4.851
4.851
4.851
4.851
4.851
4.851
4.851
4.851
4.851
4.851
4.851
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4.851





## Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadeseam

Verified by: B. C. Gray

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

### References :

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

### Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"49"Degree Nozzle, Downhill Azimuth, Augmented Analysis  
1.043 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 := 1.043

Location of Blind Zone above nozzle bottom (inch)

*This allows a 0.25 inch freespan below bottom of weld*

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

ULStrs.Dist := 1.293

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

Input Data :-

$L := 0.25$  Initial Flaw Length TW axial (Based on 10 Ksi average stress)

$od := 4.05$  Tube OD

$id := 2.728$  Tube ID

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

Years := 4 Number of Operating Years

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

$T := 604$  Estimate of Operating Temperature

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

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

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

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

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

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

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

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

### Stress Input Data

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

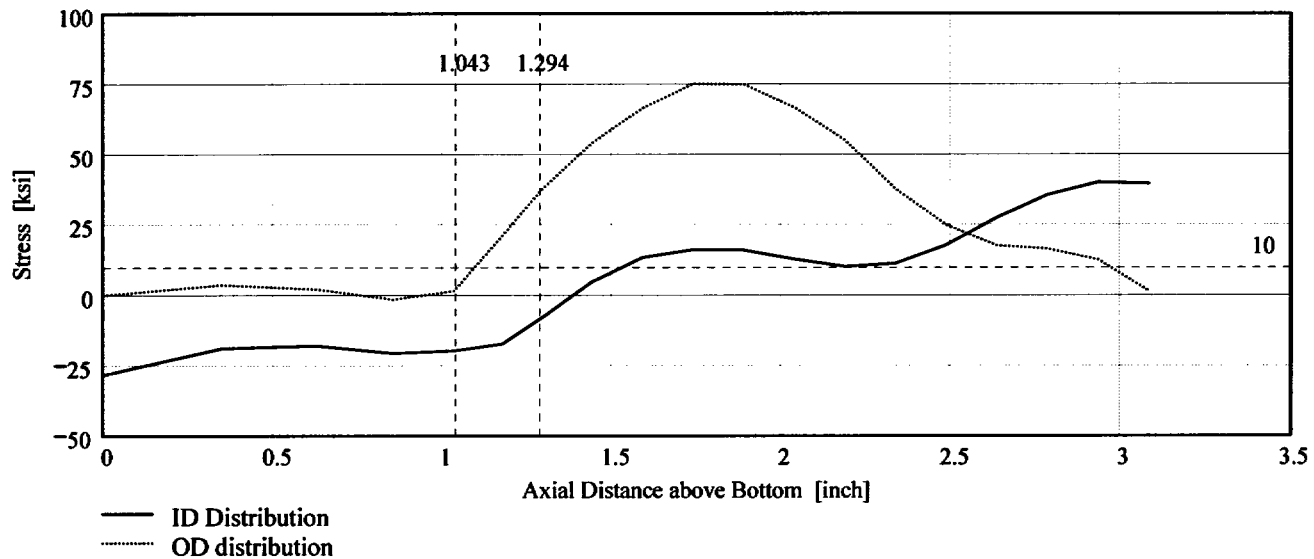
DataAll :=

	0	1	2	3	4	5
0	0	-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

AllAxI := DataAll<sup>(0)</sup>

AllID := DataAll<sup>(1)</sup>

AllOD := DataAll<sup>(5)</sup>



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).

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

$Ax1 := Data^{(0)}$

$ID := Data^{(1)}$

$OD := Data^{(5)}$

$R_{ID} := \text{regress}(Ax1, ID, 3)$

$R_{OD} := \text{regress}(Ax1, OD, 3)$

$FL_{Cntr} := BZ - 1$

Flaw Center above Nozzle Bottom

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

**No User Input required beyond this Point**

Sat Aug 09 11:44:49 AM 2003

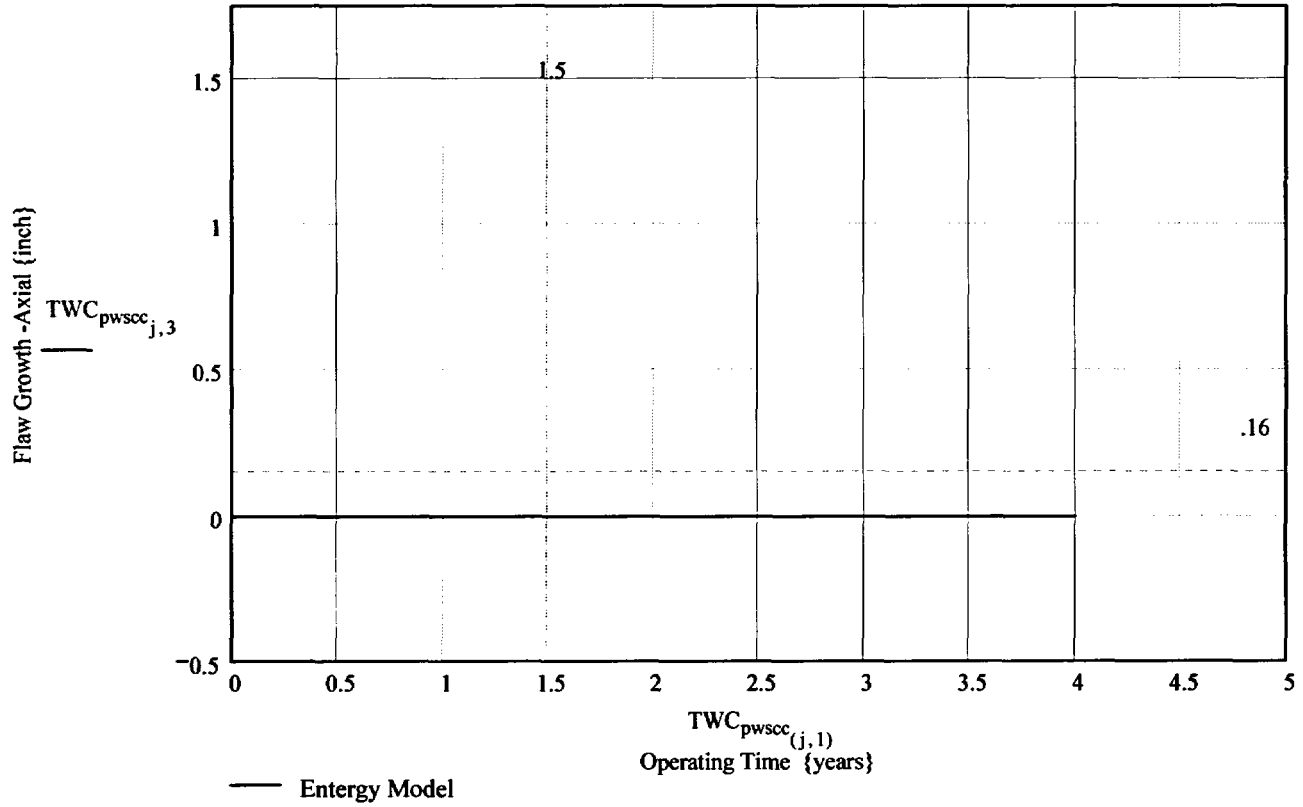
Developed by:

Verified by:

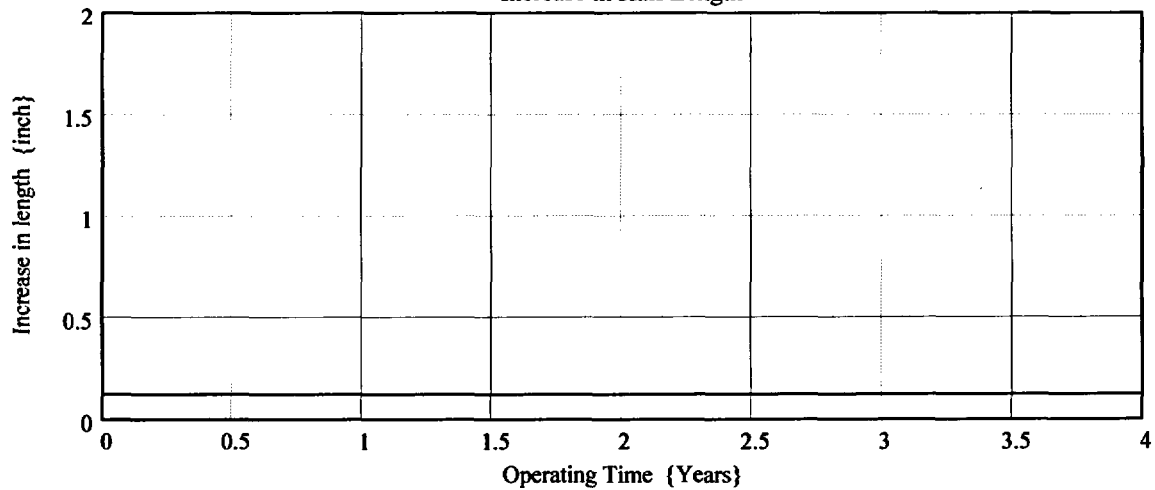


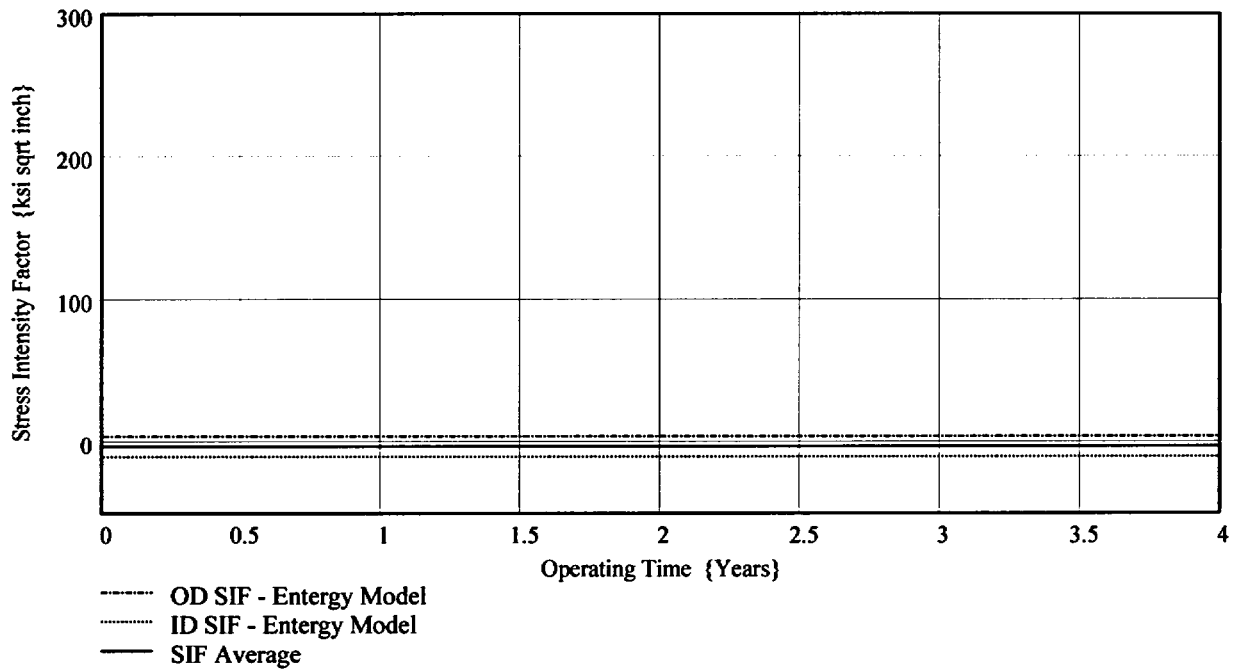
PropLength = 0.25

Flaw Length vs. Time



Increase in Half Length





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

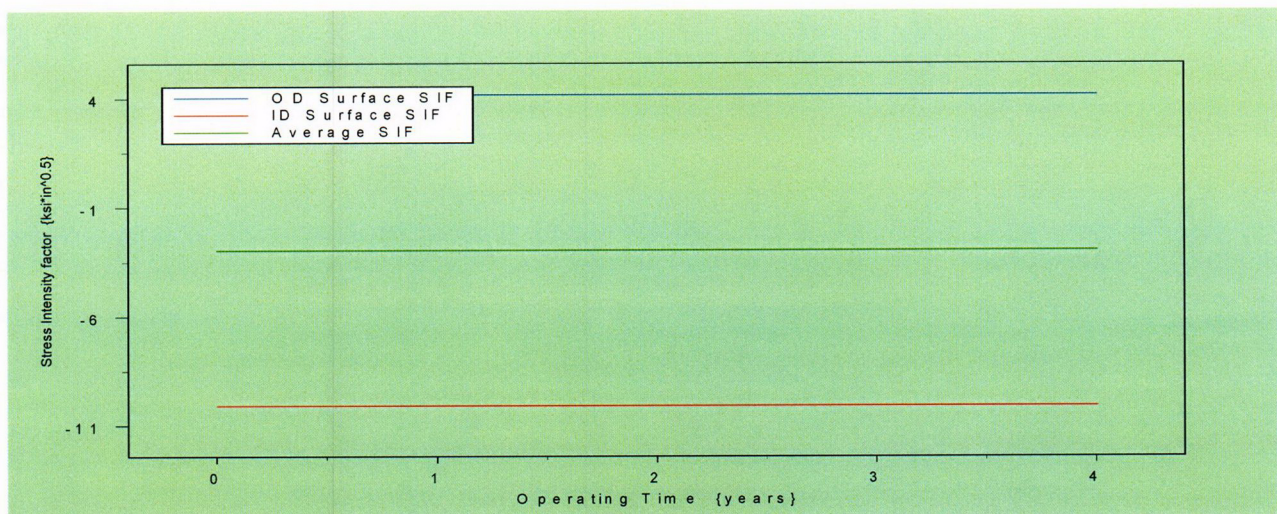
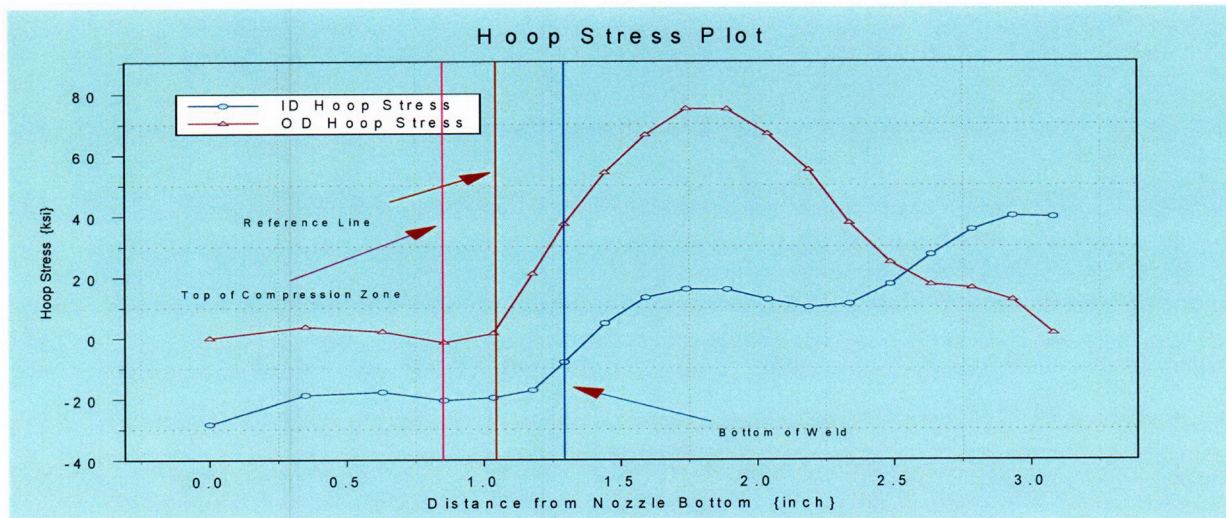
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175
4.175

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

-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1
-10.1

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

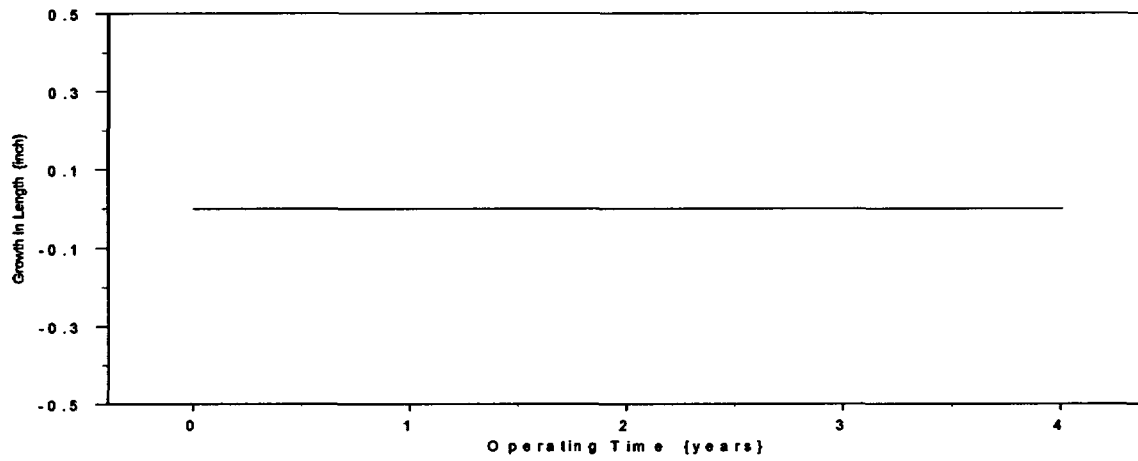
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132
-3.132



Developed by:

Verified by:

C10



Developed by:

Verified by:

## Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadesan

Verified by: B. C. Gray

### References :

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

## Arkansas Nuclear One Unit 2

**Component : Reactor Vessel CEDM -"28.8" Degree Nozzle, 22.5 degrees rotated from Downhill, 1.544" above Nozzle Bottom**

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

**Note :** *Used the Metric form of the equation from EPRI MRP 55-Rev. 1.*

*The correction is applied in the determination of the crack extension to obtain the value in inch/hr .*

## OD Surface Flaw

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

Ref<sub>Point</sub> := 1.544      Normal blind zone

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

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

Val := 2

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

UL<sub>Strs.Dist</sub> := 1.8317      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

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

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

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

$$C_0 := C_{01}$$

75<sup>th</sup> percentile MRP-55 Revision 1

## Stress Input Data

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

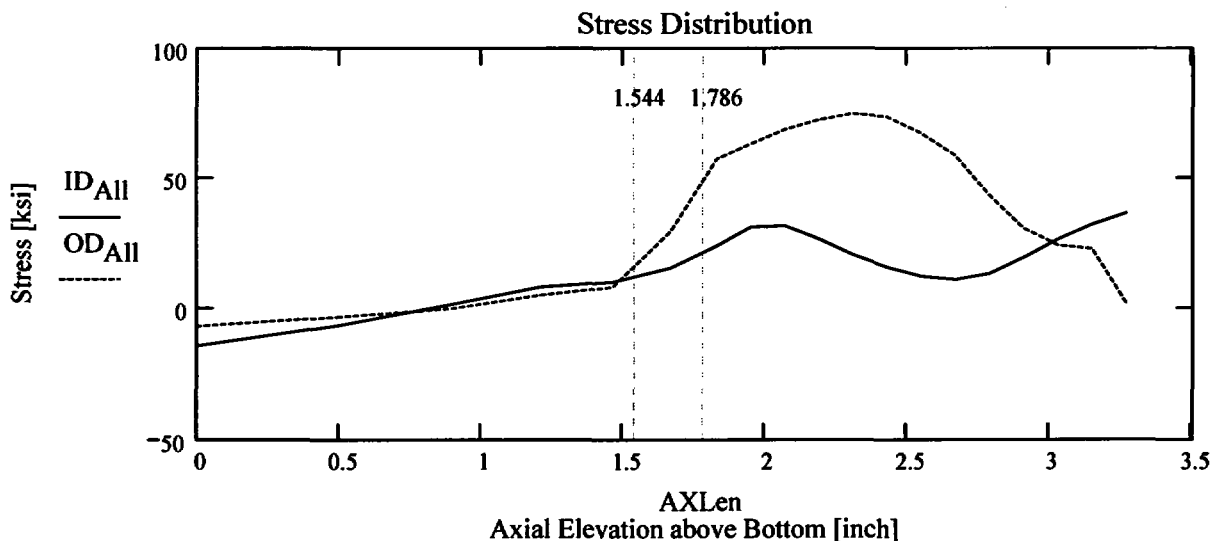
AllData :=

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

AXLen := AllData<sup>(0)</sup>

ID<sub>All</sub> := AllData<sup>(1)</sup>

OD<sub>All</sub> := AllData<sup>(5)</sup>





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).

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

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

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

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


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

Flaw center Location Location above Nozzle Bottom

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

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

**No User Input is required beyond this Point**

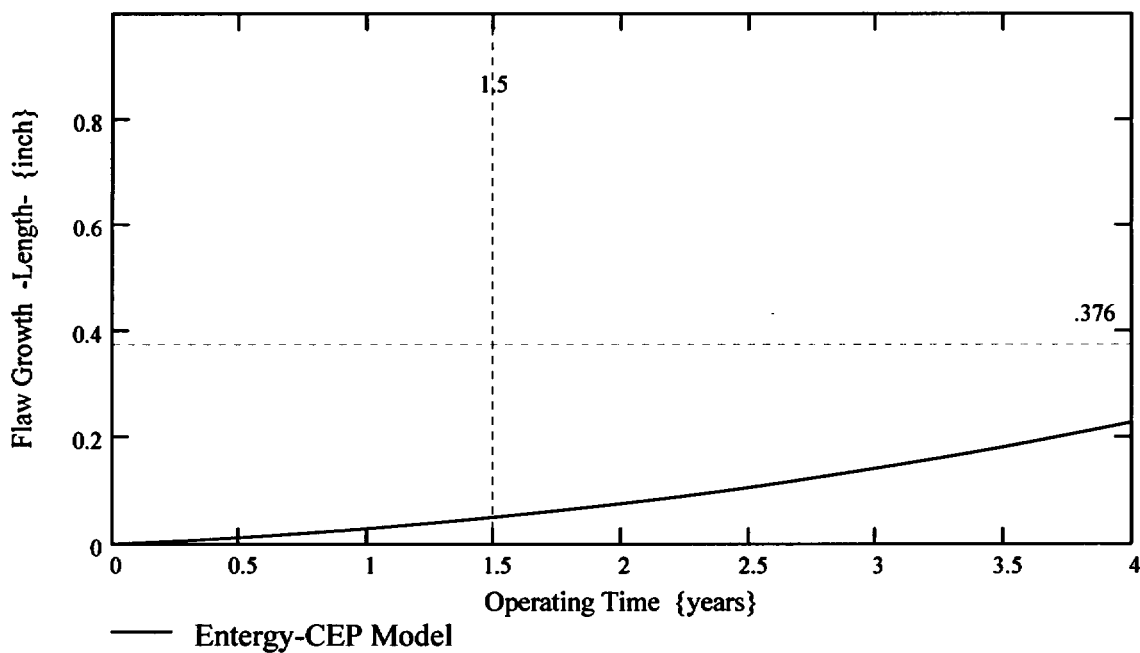
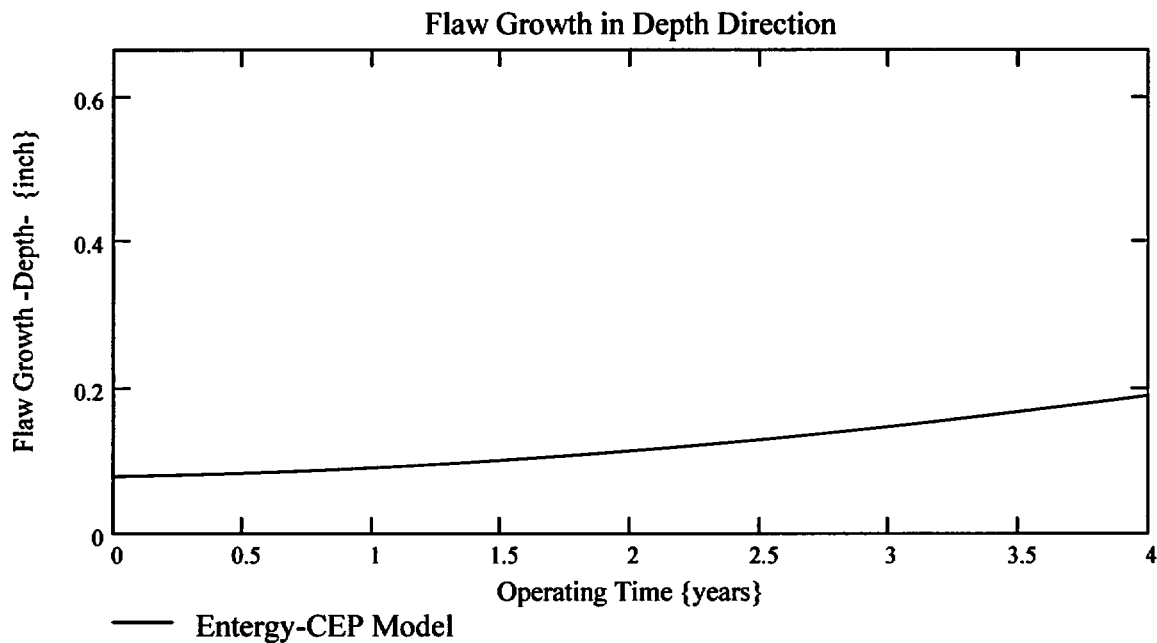
 Sat Aug 09 10:21:18 AM 2003

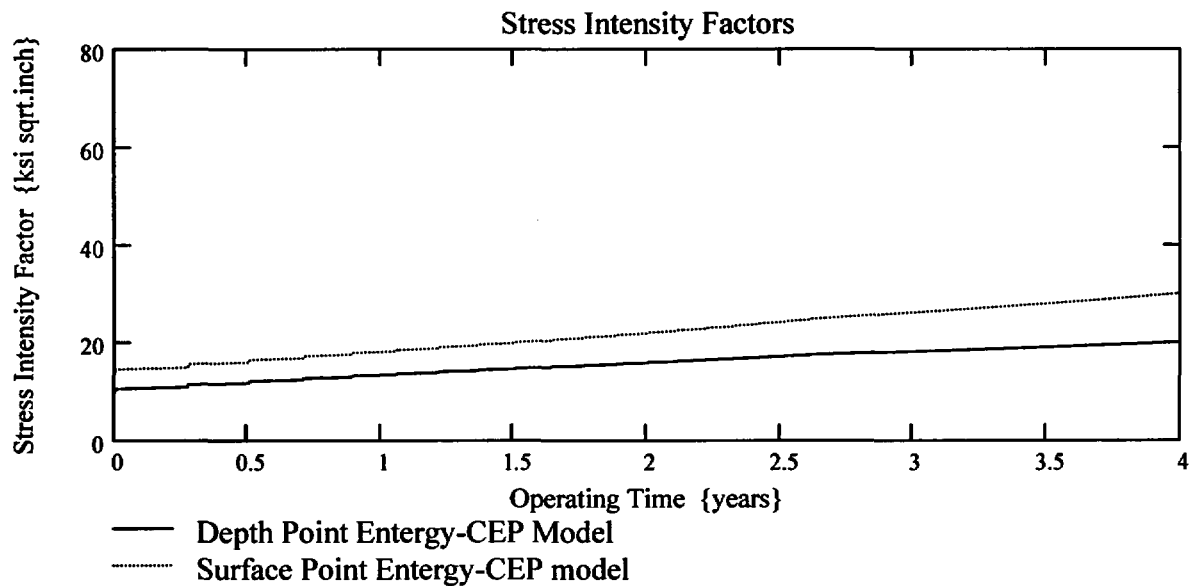
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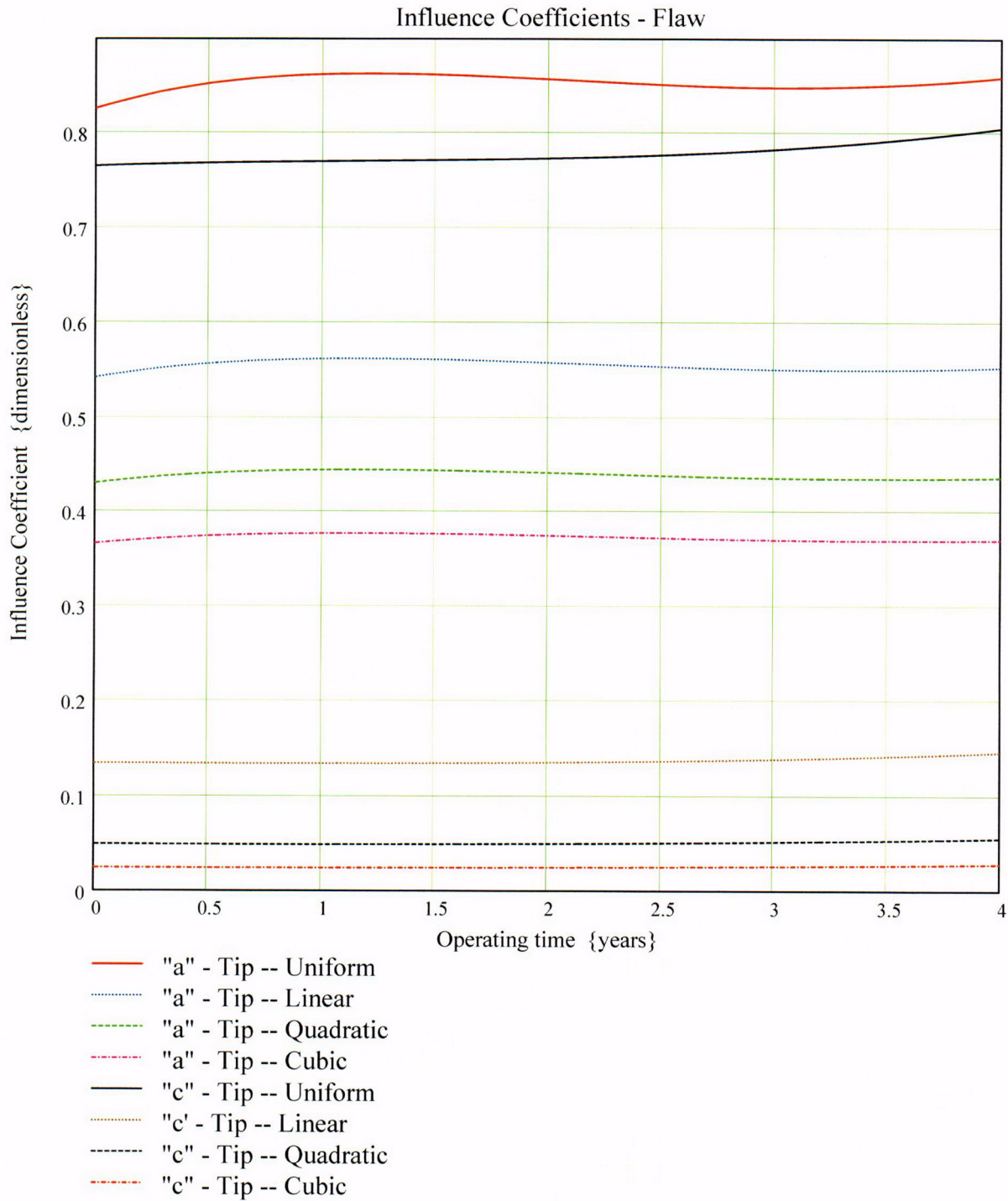
*Developed by:*  
*J. S. Brihmadesam*

*Verified by:*  
*B. C. Gray*

$\text{PropLength} = 0.128$







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

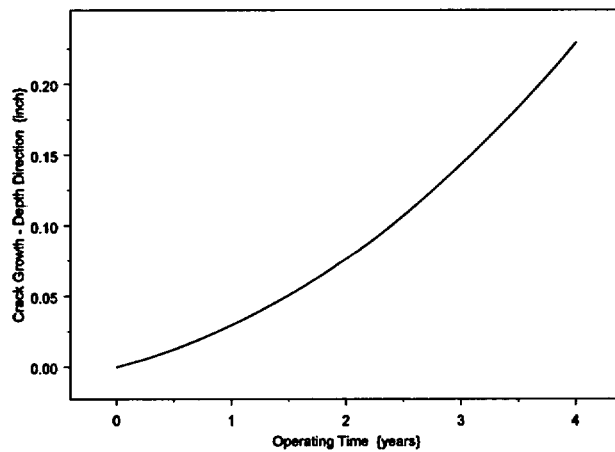
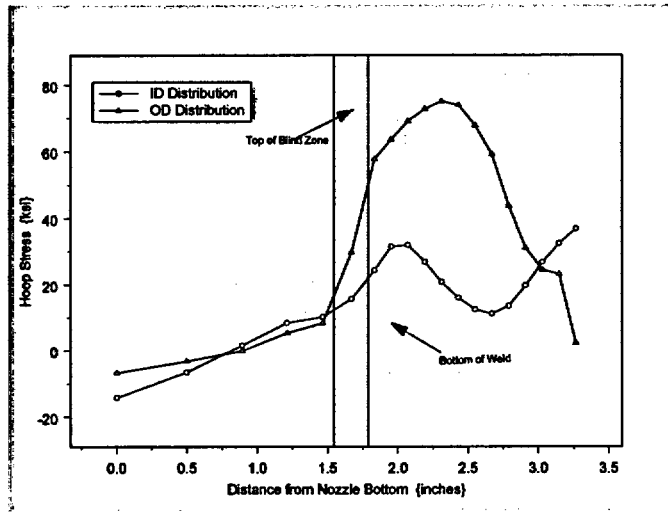
0.827
0.827
0.827
0.827
0.827
0.828
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0.829

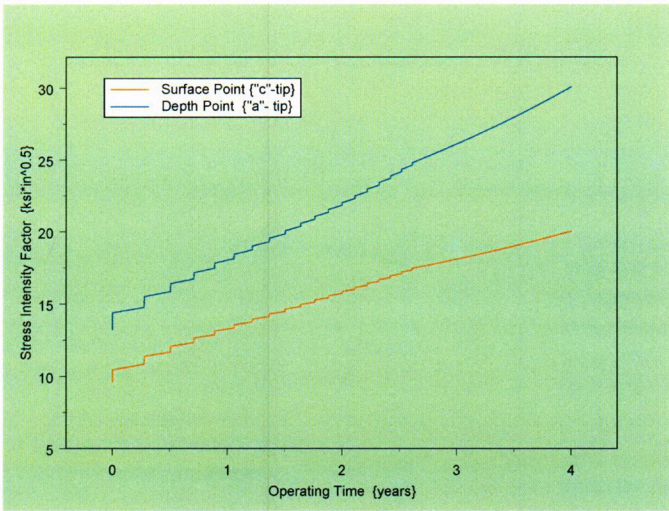
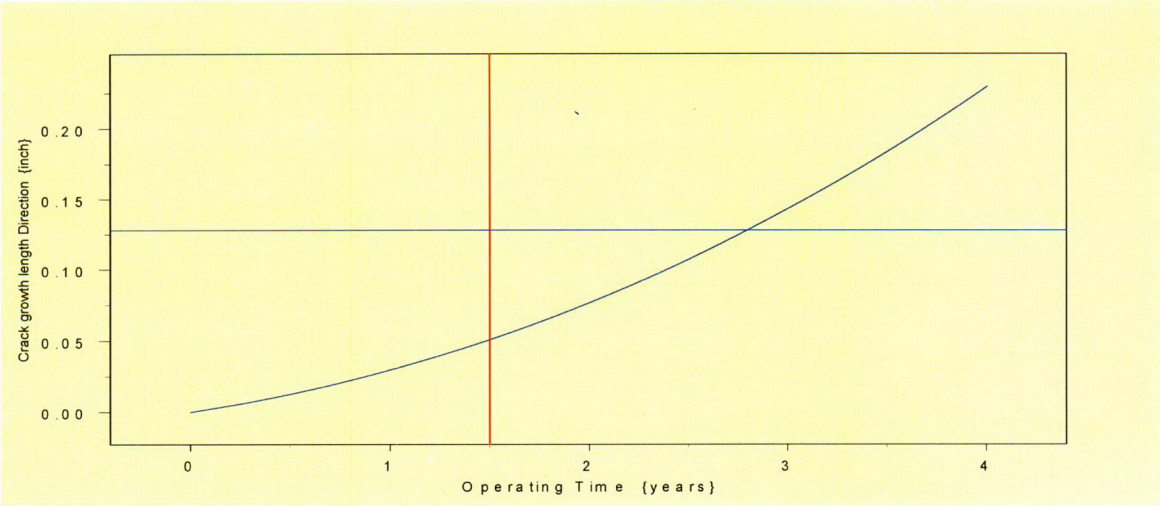
$$\text{CGR}_{\text{sambi}(k,6)} =$$

13.267
14.419
14.423
14.427
14.43
14.434
14.437
14.441
14.445
14.448
14.452
14.455
14.459
14.462
14.466
14.47

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

9.64
10.474
10.478
10.482
10.485
10.489
10.493
10.497
10.5
10.504
10.508
10.512
10.516
10.519
10.523
10.527







**Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw**

**Developed by Central Engineering Programs, Entergy Operations Inc**

**Developed by: J. S. Brihmadesar**

**Verified by: B. C. Gray**

**References :**

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

**Arkansas Nuclear One Unit 2**

**Component : Reactor Vessel CEDM -"49" Degree Nozzle, Downhill Azimuth, Augmented Analysis  
1.043" 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**

**This Attachment is Intentionally Blank**

 Sat Aug 09 10:21:18 AM 2003

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*Developed by:*  
**J. S. Brihmadesar**

*Verified by:*  
**B. C. Gray**

## Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadessam

Verified by: B. C. Gray

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

### References :

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

### Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"0"degree Nozzle, All Azimuth, Augmented Analysis  
1.25 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 := 1.25

Location of Blind Zone above nozzle bottom (inch)

Note: Lowered BZ. This allows a Freespan of 0.546 inch to bottom of weld

*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<sub>Strs</sub>.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

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

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

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

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

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

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

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

$$t := R_o - R_i$$

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

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

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

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

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

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

### Stress Input Data

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

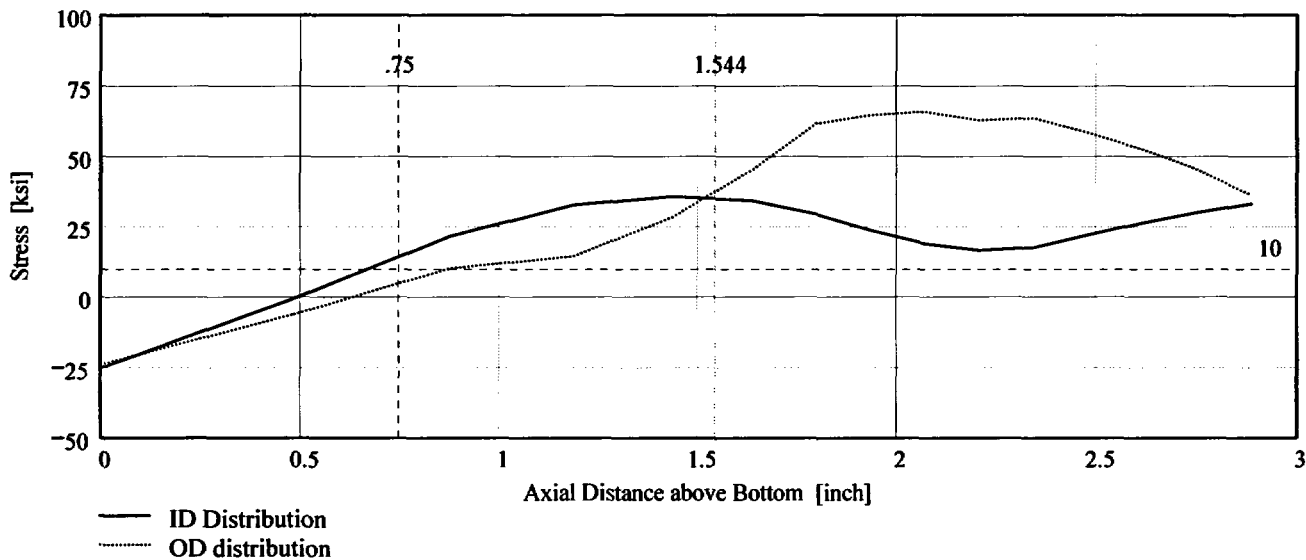
DataAll :=

	0	1	2	3	4	5
0	0	-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

AllAx1 := DataAll<sup>(0)</sup>

AllID := DataAll<sup>(1)</sup>

AllOD := DataAll<sup>(5)</sup>



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

$Ax1 := Data^{(0)}$

$ID := Data^{(1)}$

$OD := Data^{(5)}$

$R_{ID} := \text{regress}(Ax1, ID, 3)$

$R_{OD} := \text{regress}(Ax1, OD, 3)$

$FL_{Cntr} := BZ - 1$

Flaw Center above Nozzle Bottom

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

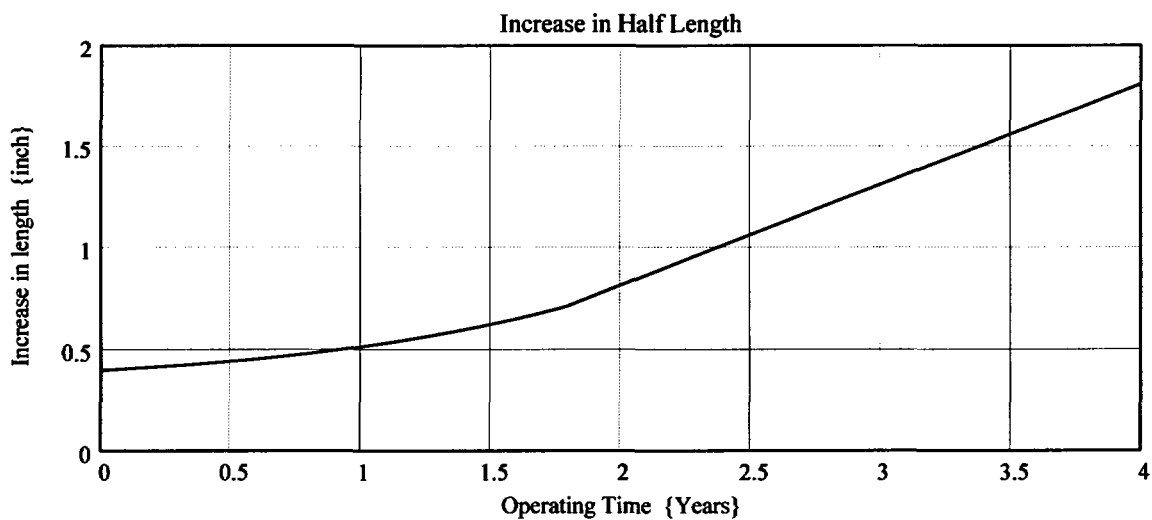
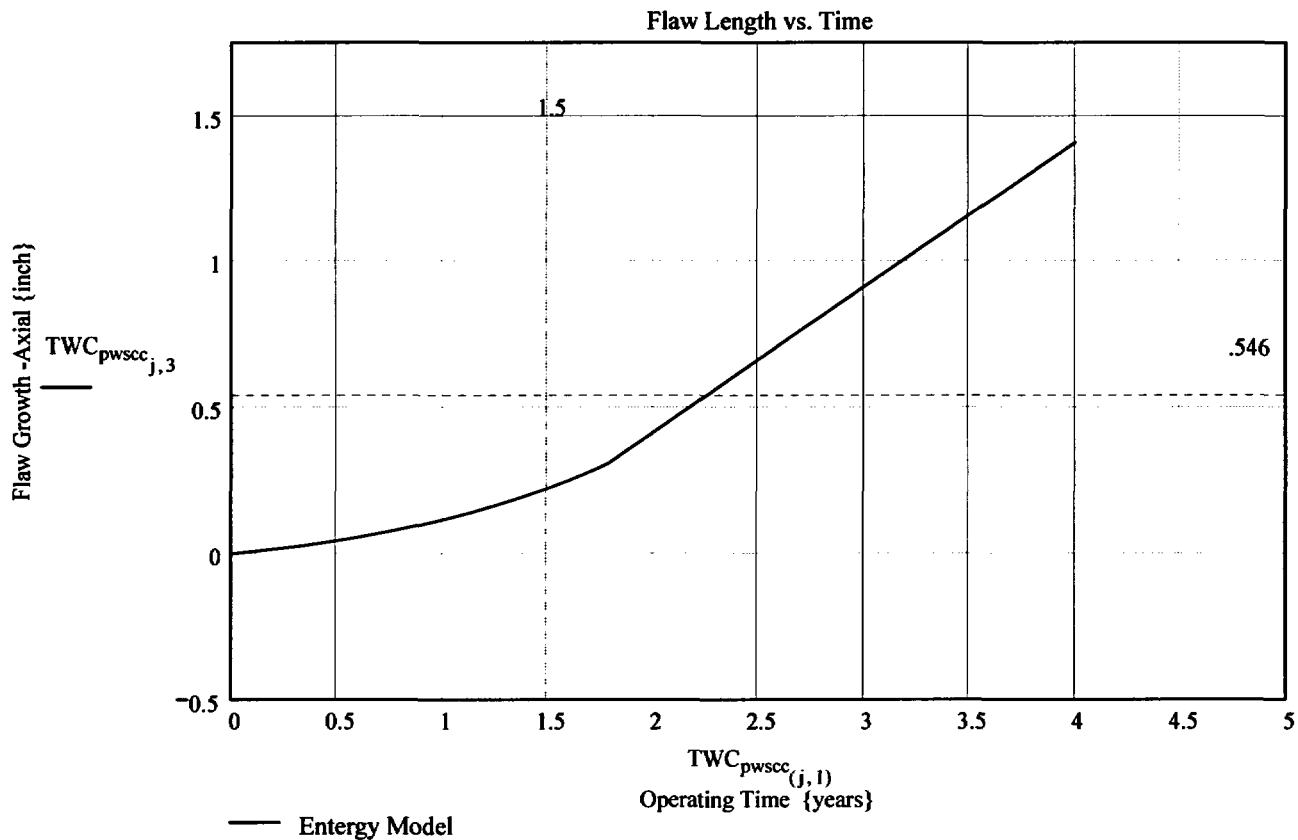
**No User Input required beyond this Point**

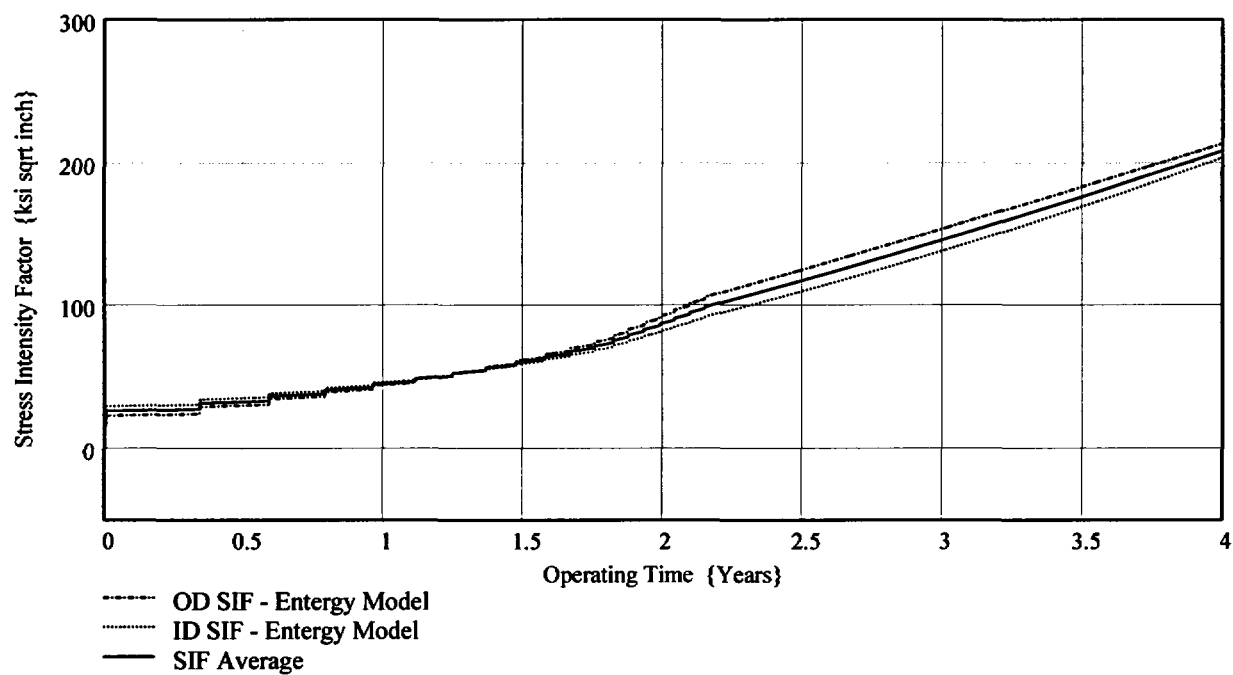
Sat Aug 09 11:44:49 AM 2003

Developed by:

Verified by:

PropLength = 0.546







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

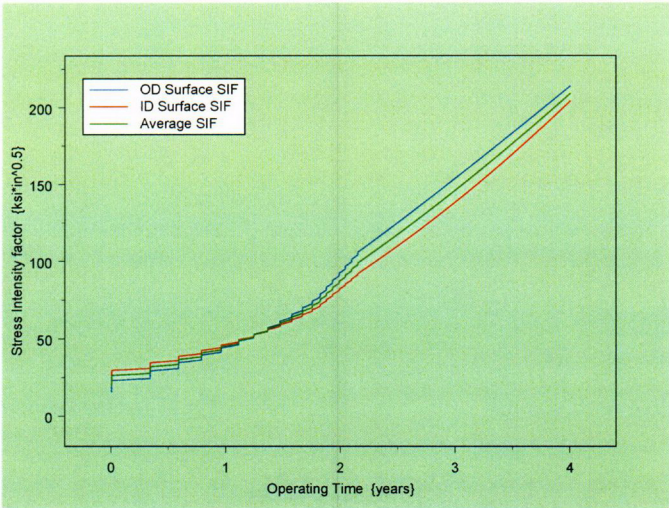
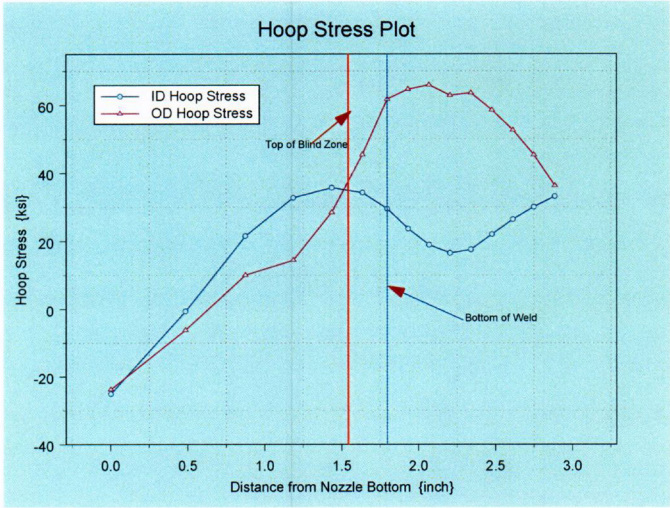
15.871
23.129
23.139
23.149
23.159
23.169
23.179
23.189
23.199
23.21
23.22
23.23
23.24
23.25
23.26
23.271

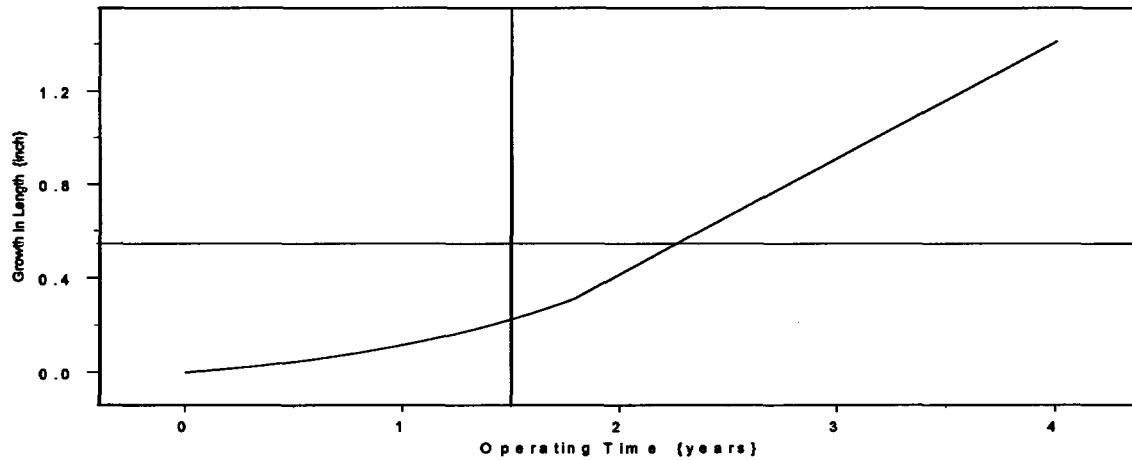
$TWC_{pwscc_{(j,7)}} =$

24.273
29.738
29.748
29.758
29.768
29.777
29.787
29.797
29.807
29.817
29.827
29.837
29.847
29.857
29.867
29.878

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

21.089
27.647
27.658
27.669
27.68
27.691
27.702
27.713
27.723
27.734
27.745
27.756
27.767
27.778
27.789
27.8





## Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadeseam

Verified by: B. C. Gray

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

### References :

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

### Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM - "8" Degree Nozzle, Downhill Azimuth, Augmented Analysis  
1.25 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 := 1.25

Location of Blind Zone above nozzle bottom (inch)

Note :- BZ lowered; This increases the freespan length to 0.536 inch

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

ULStrs.Dist := 1.786

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

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

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

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

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

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

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

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

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

$$t := R_o - R_i$$

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

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

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

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

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

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

### Stress Input Data

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

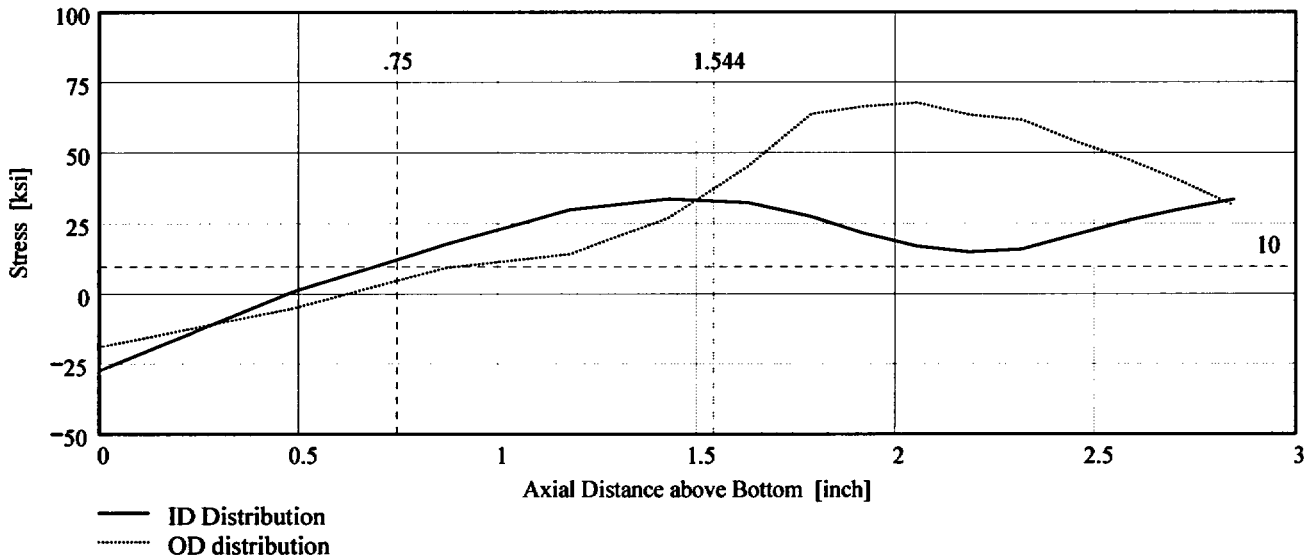
DataAll :=

	0	1	2	3	4	5
0	0	-27.4	-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

AllAx1 := DataAll<sup>(0)</sup>

AllID := DataAll<sup>(1)</sup>

AllOD := DataAll<sup>(5)</sup>



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

Data :=

0	-27.404	-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

$Ax1 := Data^{(0)}$

$ID := Data^{(1)}$

$OD := Data^{(5)}$

$R_{ID} := \text{regress}(Ax1, ID, 3)$

$R_{OD} := \text{regress}(Ax1, OD, 3)$

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

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

**No User Input required beyond this Point**

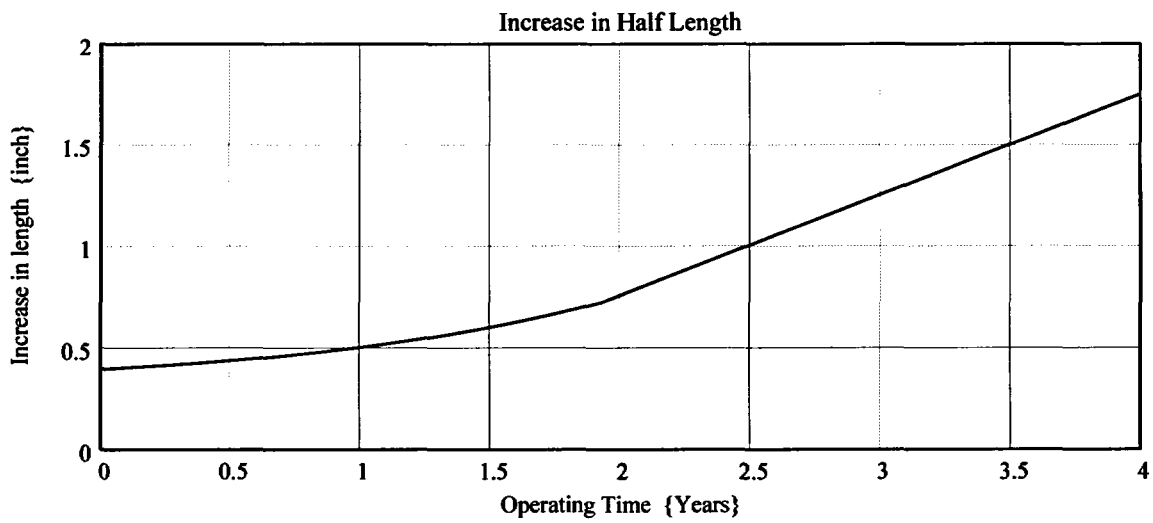
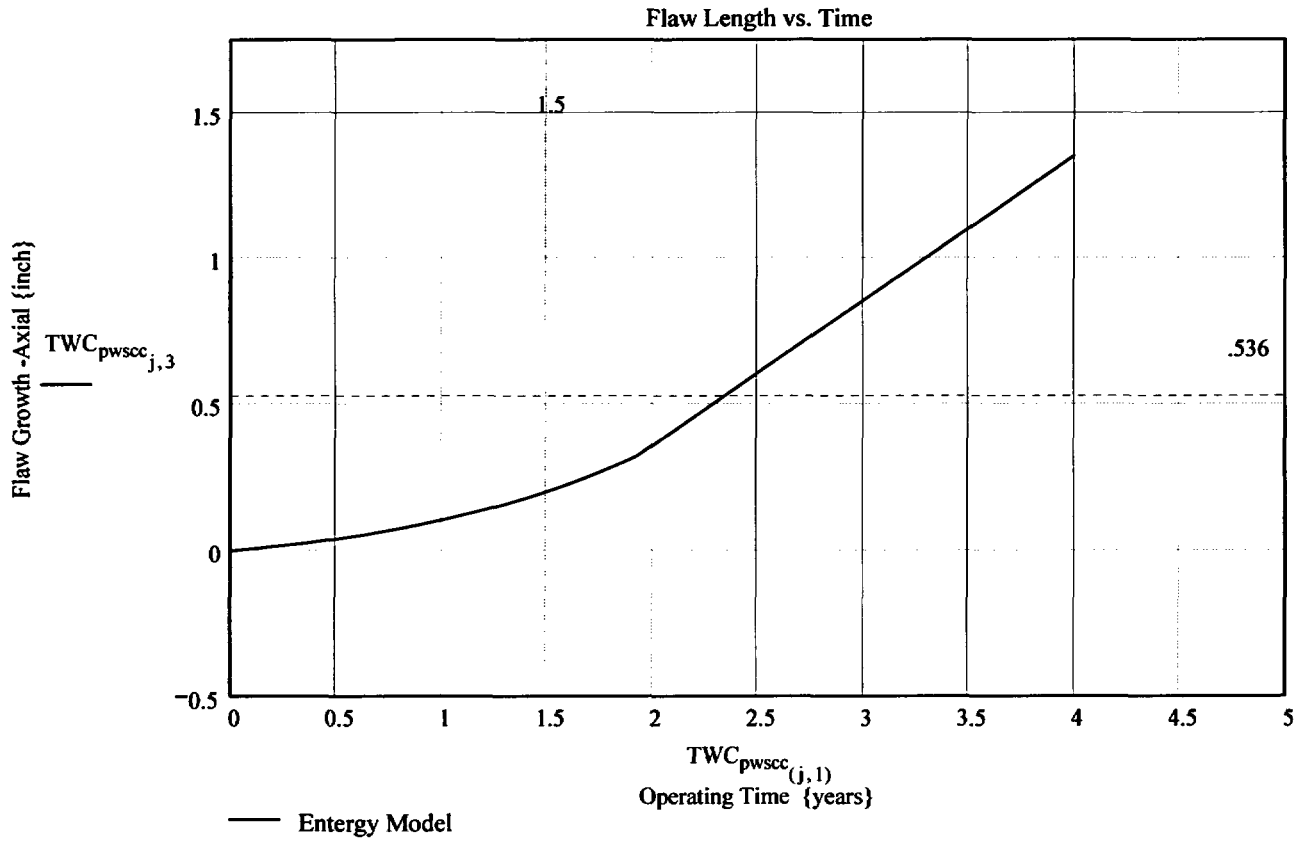
 Sat Aug 09 11:44:49 AM 2003

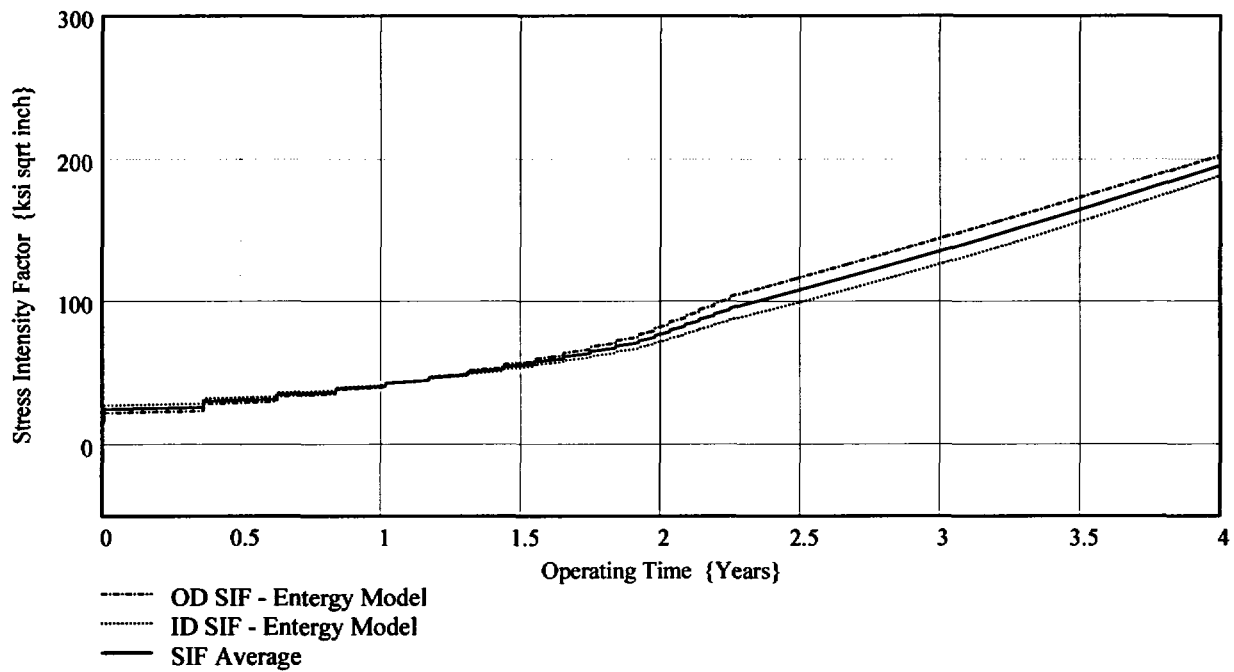
Developed by:

Verified by:



PropLength = 0.536





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

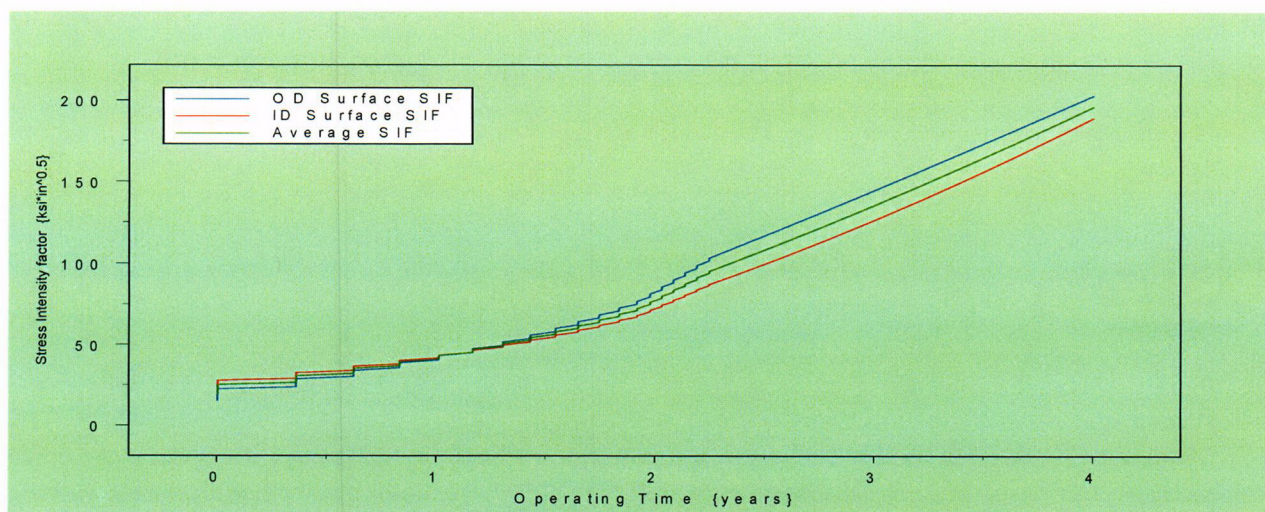
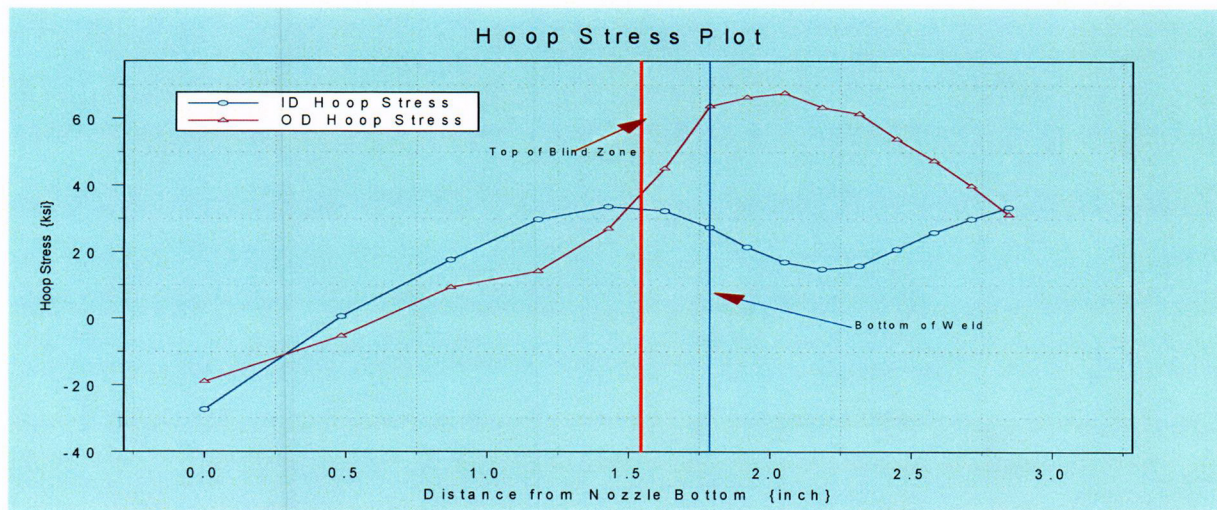
15.478
22.634
22.643
22.652
22.661
22.67
22.679
22.688
22.697
22.706
22.715
22.724
22.733
22.742
22.751
22.76

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

22.524
27.819
27.828
27.836
27.845
27.854
27.863
27.871
27.88
27.889
27.897
27.906
27.915
27.924
27.932
27.941

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

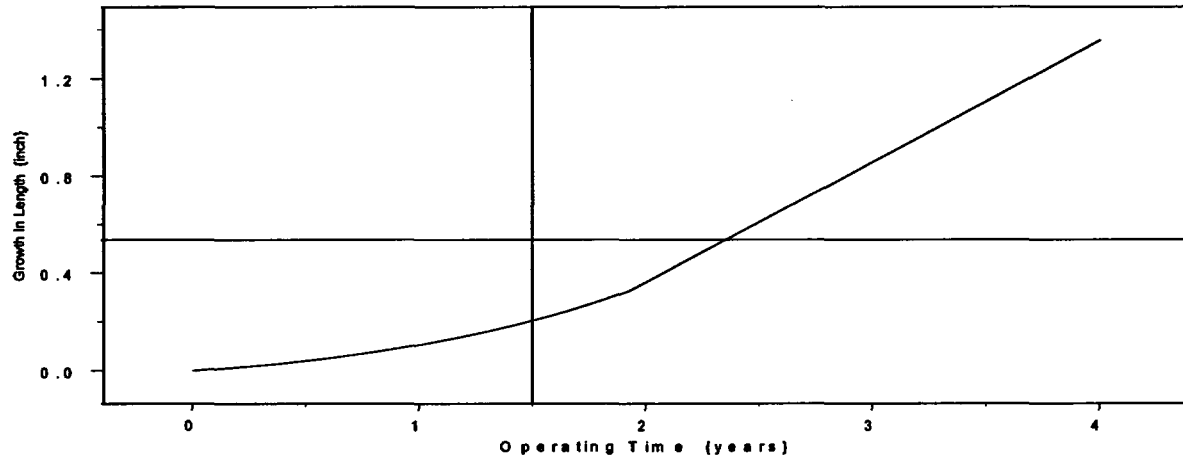
19.938
26.353
26.363
26.372
26.382
26.392
26.401
26.411
26.42
26.43
26.44
26.449
26.459
26.469
26.478
26.488



Developed by:

Verified by:

C114



Developed by:

Verified by:

## Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadessam

Verified by: B. C. Gray

### References :

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

## Arkansas Nuclear One Unit 2

**Component : Reactor Vessel CEDM -"49" Degree Nozzle, 22.5 degree from Downhill Azimuth, Augmented Analysis; 1.30" above Nozzle Bottom**

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

**Note : Used the Metric form of the equation from EPRI MRP 55-Rev. 1.**

The correction is applied in the determination of the crack extension to obtain the value in inch/hr .

## OD Surface Flaw

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

$Ref_{point} := 1.3$

This is the reduced Blind zone for augmented analysis; permits a 0.2504 inch free span & 0.09 inch Propagation Length

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

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

$Val := 2$

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

$UL_{Strs.Dist} := 1.5504$

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

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

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

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

$$C_0 := C_{01}$$

75<sup>th</sup> percentile MRP-55 Revision 1

## Stress Input Data

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

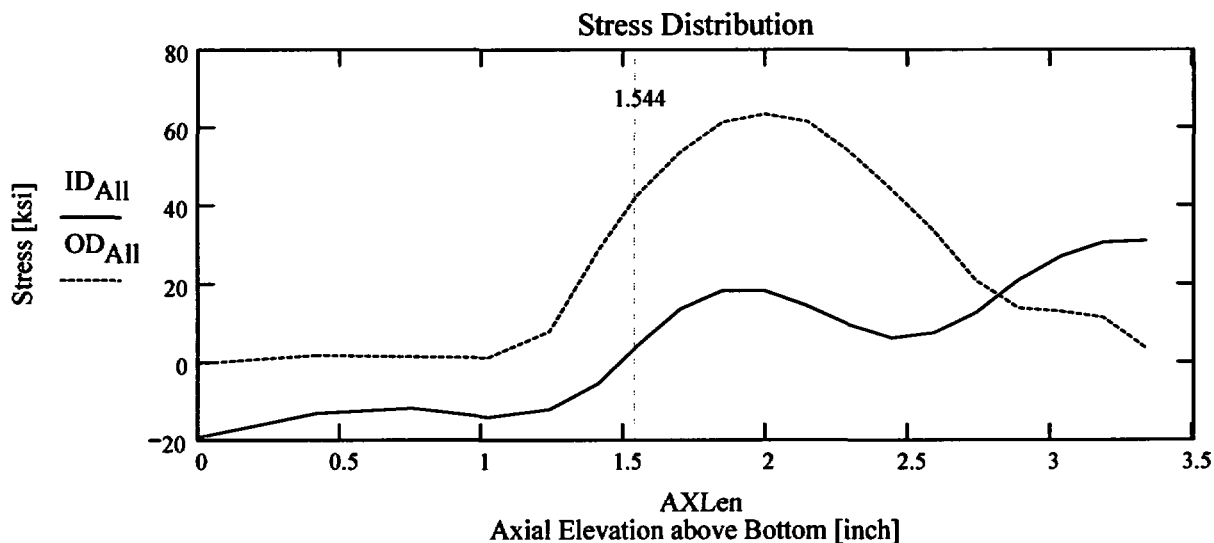
AllData :=

	0	1	2	3	4	5
0	0	-19.3	-12.52	-8.3	-4.31	-0.29
1	0.42	-13.15	-8.57	-4.68	-1.25	1.83
2	0.75	-11.83	-6.96	-2.68	0.03	1.46
3	1.02	-14.15	-8.31	-3.17	1.1	1.22
4	1.24	-12.13	-6.55	0	5.78	7.86
5	1.41	-5.38	-2.41	7.5	23.29	28.72
6	1.55	4.33	6.48	17.84	35.67	42.75
7	1.7	13.64	15.67	27.16	40.65	53.56
8	1.85	18.3	21.2	32.42	50.34	61.38
9	2	18.32	22.29	34.21	53.26	63.46
10	2.14	14.52	21.82	35.09	51.48	61.5
11	2.29	9.62	20.82	34.51	47.88	53.88
12	2.44	6.18	19.92	32.26	40.25	44.06

AXLen := AllData<sup>(0)</sup>

ID<sub>All</sub> := AllData<sup>(1)</sup>

OD<sub>All</sub> := AllData<sup>(5)</sup>





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).

$$Data := \begin{pmatrix} 0 & -19.301 & -12.523 & -8.304 & -4.314 & -0.289 \\ 0.419 & -13.153 & -8.572 & -4.68 & -1.255 & 1.834 \\ 0.755 & -11.834 & -6.958 & -2.685 & 0.028 & 1.463 \\ 1.024 & -14.146 & -8.315 & -3.168 & 1.103 & 1.221 \\ 1.239 & -12.132 & -6.552 & 3.002 \times 10^{-3} & 5.78 & 7.858 \\ 1.412 & -5.38 & -2.413 & 7.498 & 23.29 & 28.718 \\ 1.55 & 4.331 & 6.478 & 17.842 & 35.67 & 42.747 \\ 1.699 & 13.644 & 15.667 & 27.164 & 40.65 & 53.563 \\ 1.847 & 18.304 & 21.201 & 32.424 & 50.345 & 61.379 \\ 1.996 & 18.316 & 22.292 & 34.208 & 53.258 & 63.464 \end{pmatrix}$$

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

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

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

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

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

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


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

Flaw center Location Location above Nozzle Bottom

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

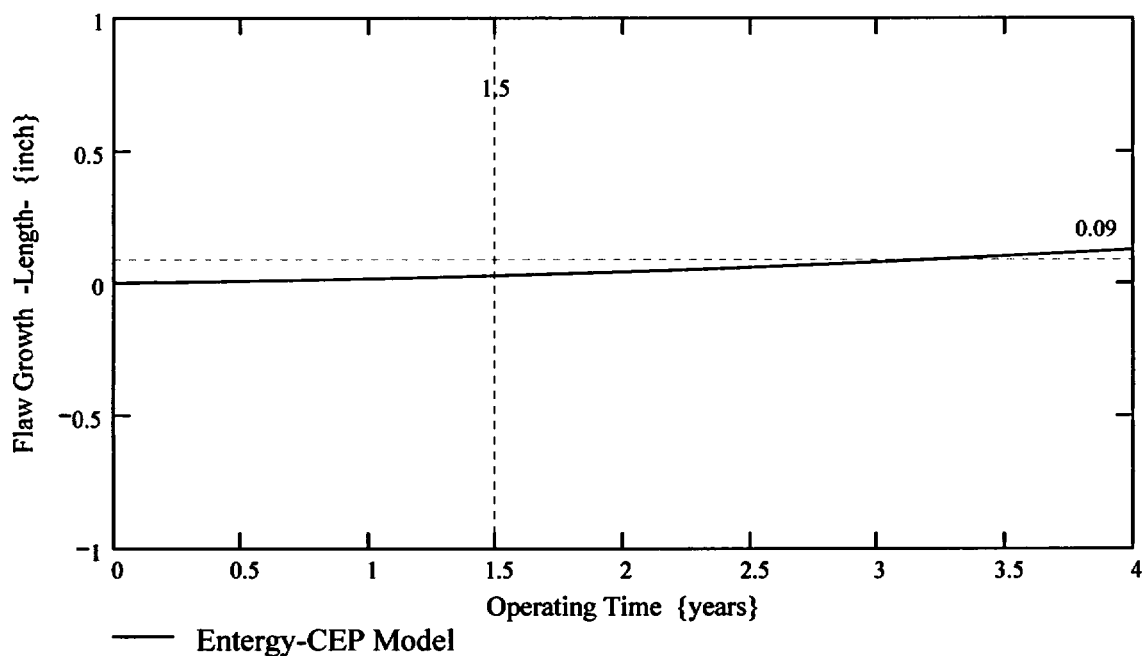
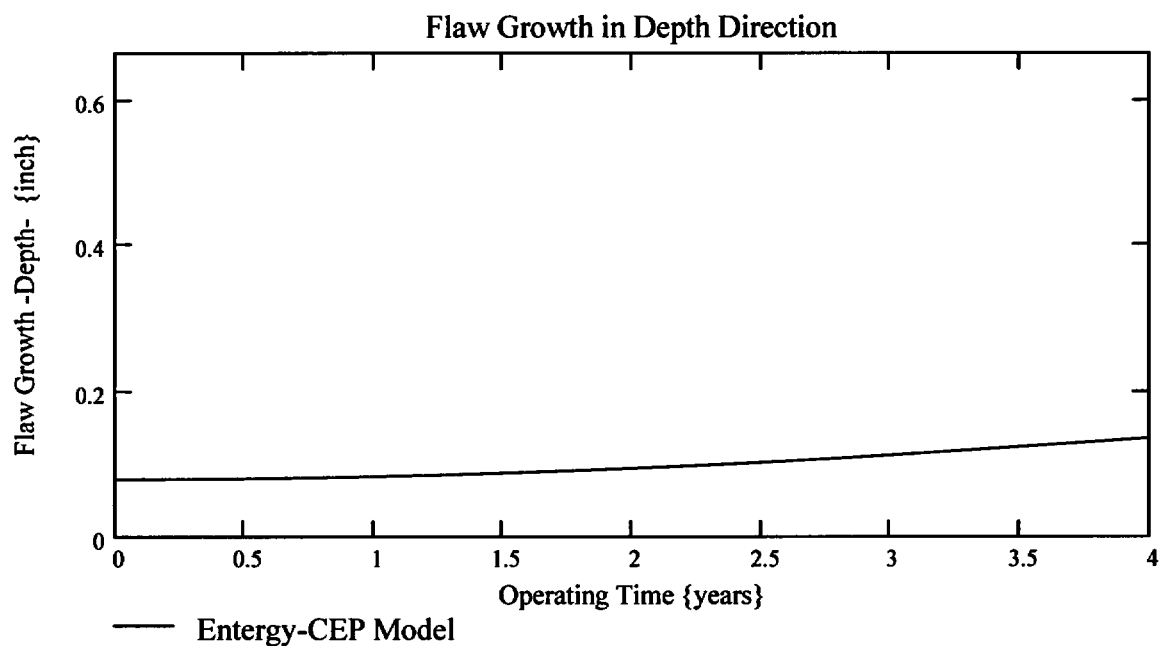
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{n}$$

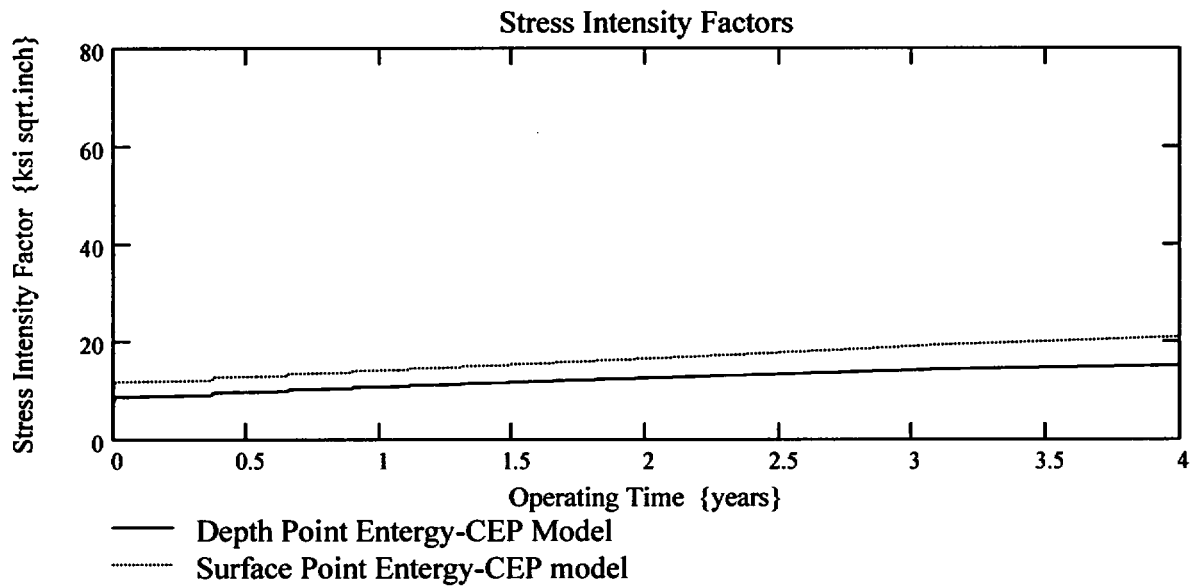
**No User Input is required beyond this Point**

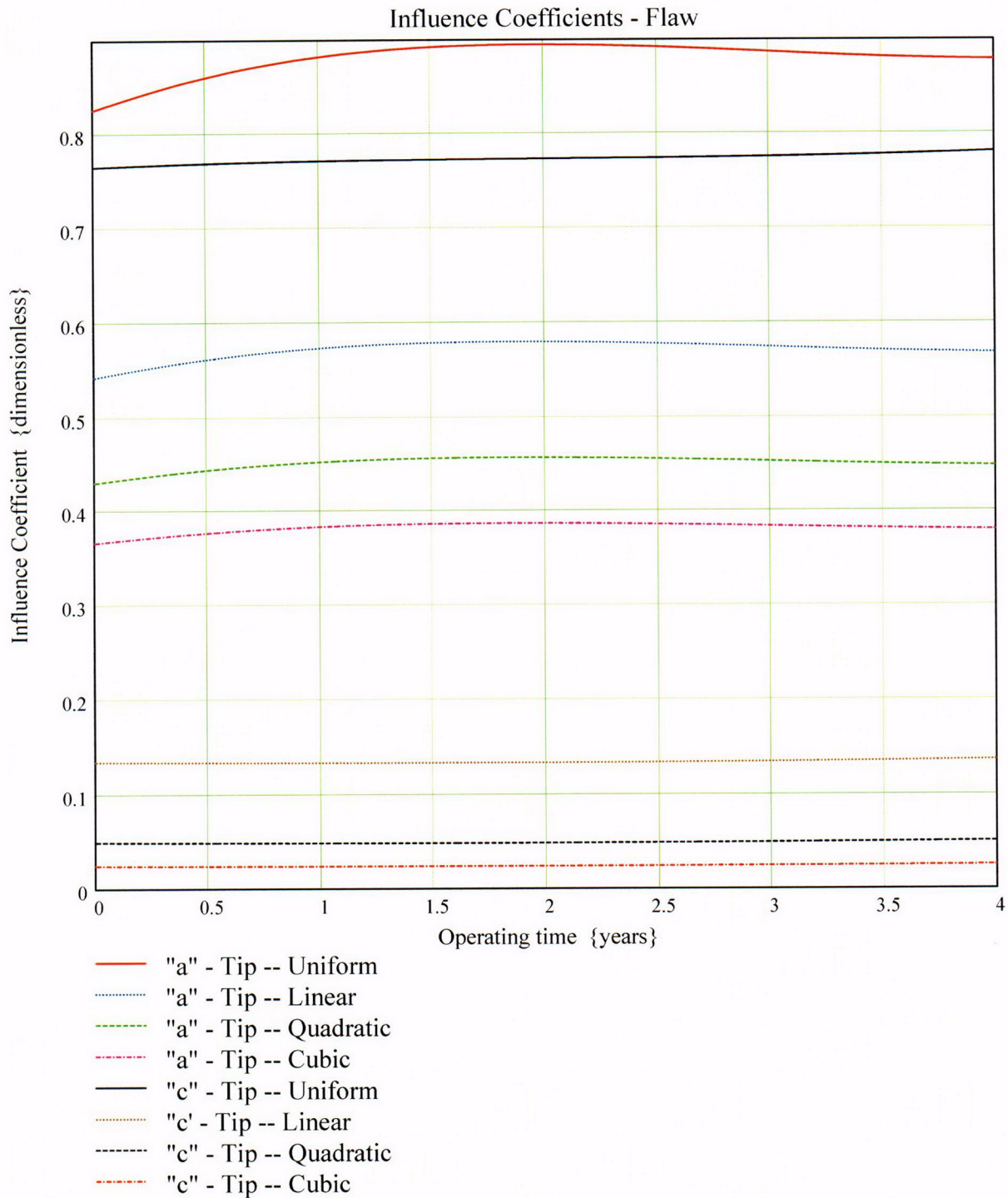
 Sat Aug 09 10:21:18 AM 2003

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PropLength = 0.09







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

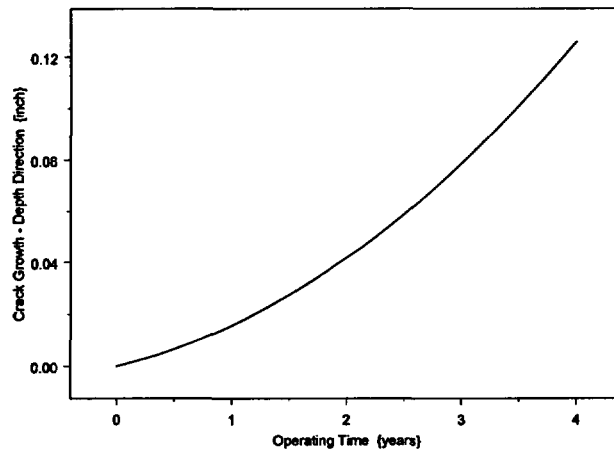
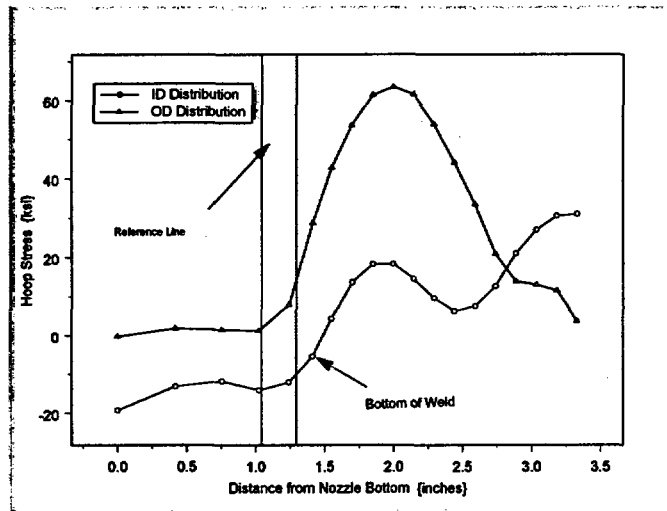
0.827
0.827
0.827
0.827
0.827
0.828
0.828
0.828
0.828
0.828
0.829
0.829
0.829
0.829
0.829
0.83

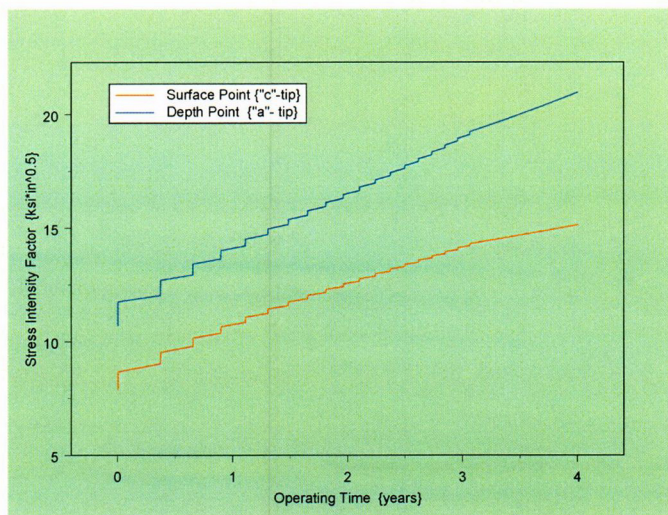
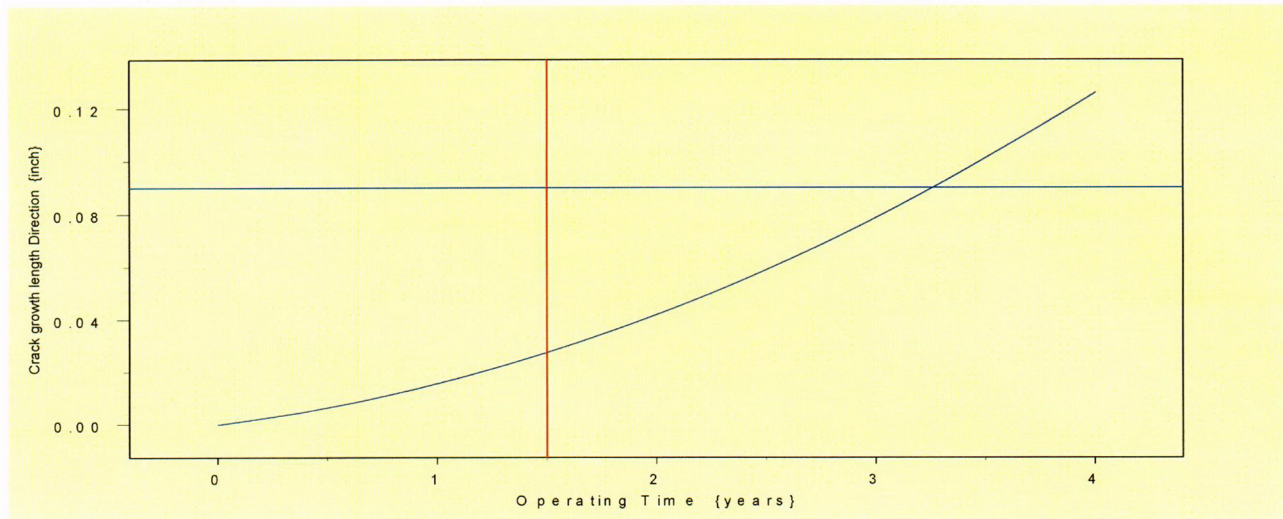
$CGR_{sambi(k,6)} =$

10.711
11.761
11.763
11.766
11.768
11.77
11.772
11.774
11.776
11.778
11.78
11.782
11.784
11.786
11.788
11.79

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

7.9
8.672
8.674
8.677
8.68
8.683
8.685
8.688
8.691
8.693
8.696
8.699
8.702
8.704
8.707
8.71







## Primary Water Stress Corrosion Crack Growth Analysis - OD Surface Flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadesan

Verified by: B. C. Gray

### References :

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

## Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"49" Degree Nozzle, 45 degree from Downhill Azimuth, Augmented Analysis; 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

Note : Used the Metric form of the equation from EPRI MRP 55-Rev. 1.

The correction is applied in the determination of the crack extension to obtain the value in inch/hr .

## OD Surface Flaw

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

Ref<sub>point</sub> := 1.544

This is the as-built Blind Zone

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

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

Val := 2

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

UL<sub>Strs.Dist</sub> := 2.1632

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

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

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

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

$$C_0 := C_{01}$$

75<sup>th</sup> percentile MRP-55 Revision 1

## Stress Input Data

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

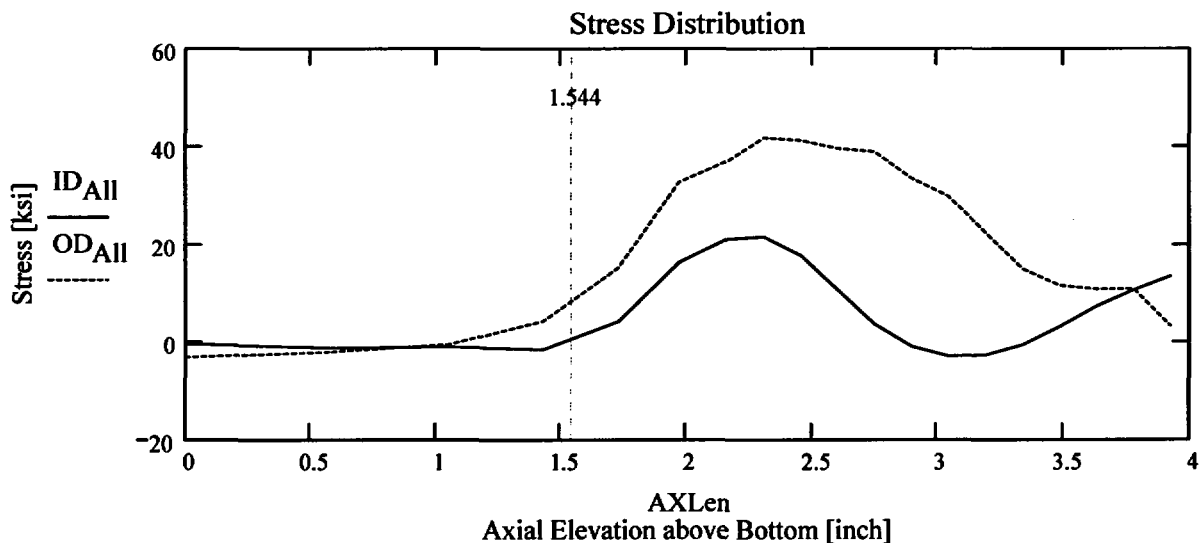
AllData :=

	0	1	2	3	4	5
0	0	-0.41	-1.36	-1.84	-2.37	-3.16
1	0.58	-1.26	-1.49	-1.71	-1.95	-2.07
2	1.05	-1.02	-0.22	0.35	0.52	-0.5
3	1.43	-1.56	0.62	2.58	4.9	4.26
4	1.73	4.17	4.31	8.86	13.38	15.25
5	1.97	16.26	12.54	16.93	28.26	32.67
6	2.16	21.13	17.13	20.09	34.28	36.98
7	2.31	21.59	19.09	21.93	34.05	41.72
8	2.46	17.7	17.82	22.18	34.47	41.21
9	2.6	10.69	14.25	21.11	33.32	39.55
10	2.75	3.59	10.95	19.96	31.01	38.94
11	2.9	-0.98	8.74	18.34	28.35	33.45
12	3.04	-2.94	7.02	18.06	26	29.85

AXLen := AllData<sup>(0)</sup>

ID<sub>All</sub> := AllData<sup>(1)</sup>

OD<sub>All</sub> := AllData<sup>(5)</sup>



Observing the stress distribution select the region in the table above labeled Data<sub>All</sub> 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).

$$\text{Data} := \begin{pmatrix} 0 & -0.414 & -1.359 & -1.842 & -2.369 & -3.157 \\ 0.585 & -1.256 & -1.488 & -1.714 & -1.95 & -2.073 \\ 1.053 & -1.023 & -0.223 & 0.347 & 0.516 & -0.495 \\ 1.429 & -1.559 & 0.622 & 2.583 & 4.895 & 4.258 \\ 1.729 & 4.165 & 4.315 & 8.86 & 13.38 & 15.252 \\ 1.97 & 16.258 & 12.541 & 16.926 & 28.26 & 32.667 \\ 2.163 & 21.131 & 17.131 & 20.087 & 34.279 & 36.98 \\ 2.31 & 21.593 & 19.093 & 21.933 & 34.049 & 41.718 \\ 2.457 & 17.702 & 17.82 & 22.18 & 34.468 & 41.213 \end{pmatrix}$$

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

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

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

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


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

Flaw center Location Location above Nozzle Bottom

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

$$\text{IncStrs.avg} := \frac{U_{\text{LStrs.Dist}} - U_{\text{Tip}}}{n}$$

**No User Input is required beyond this Point**

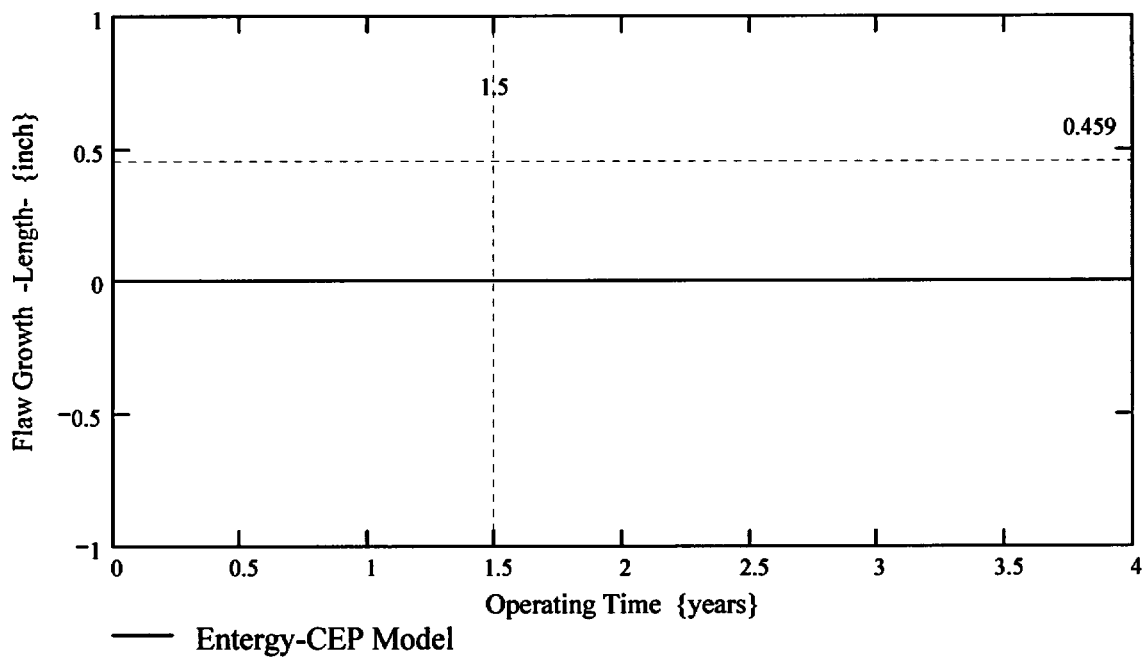
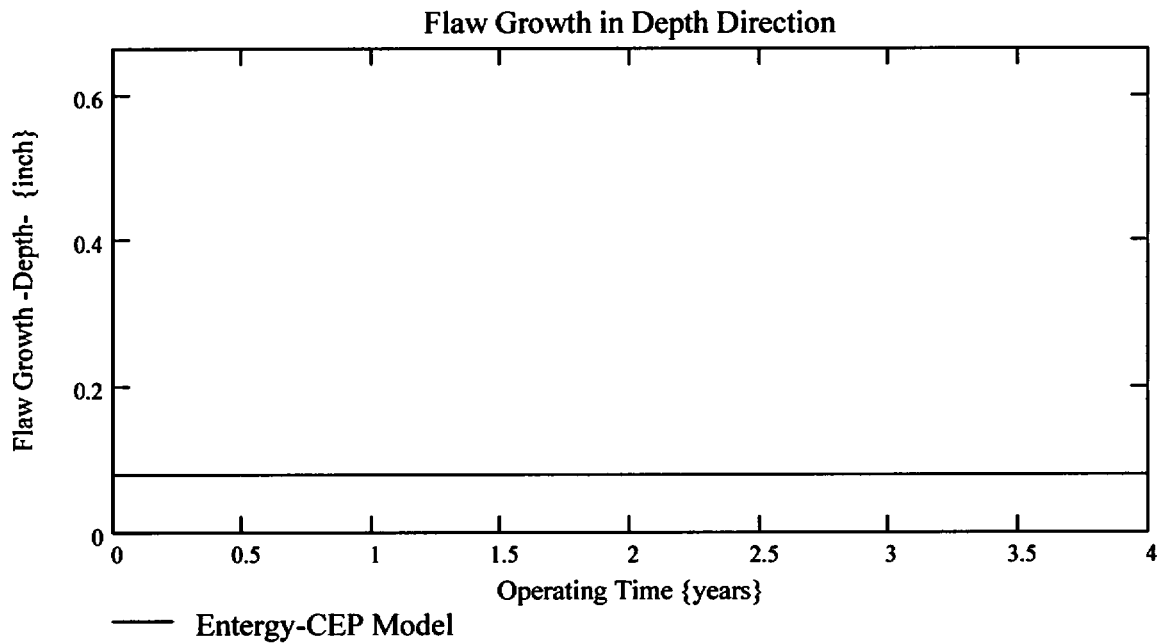
 Sat Aug 09 10:21:18 AM 2003

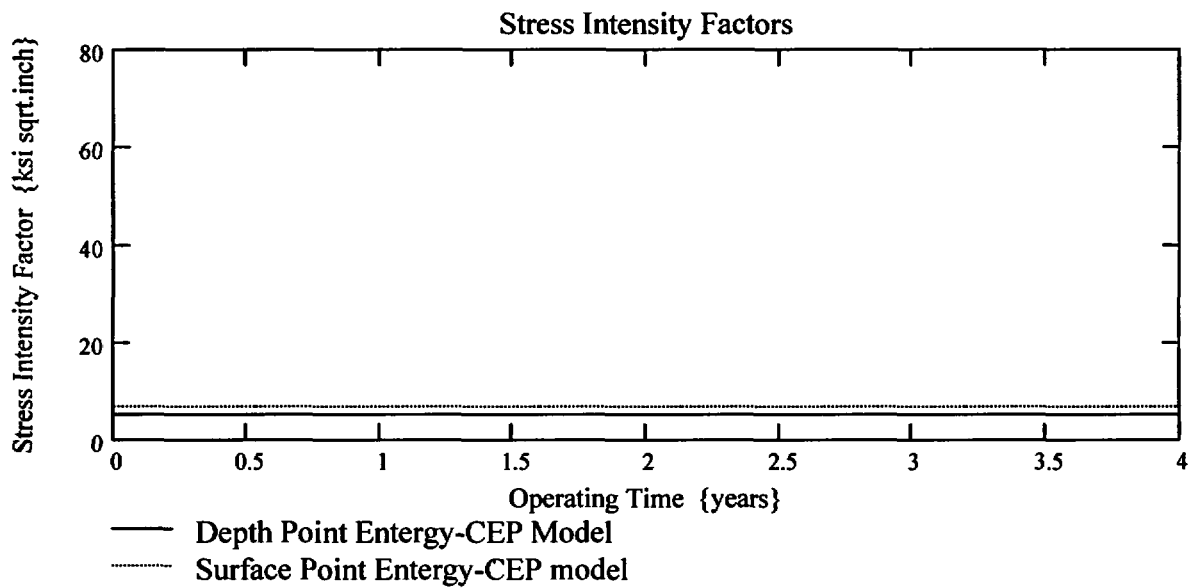
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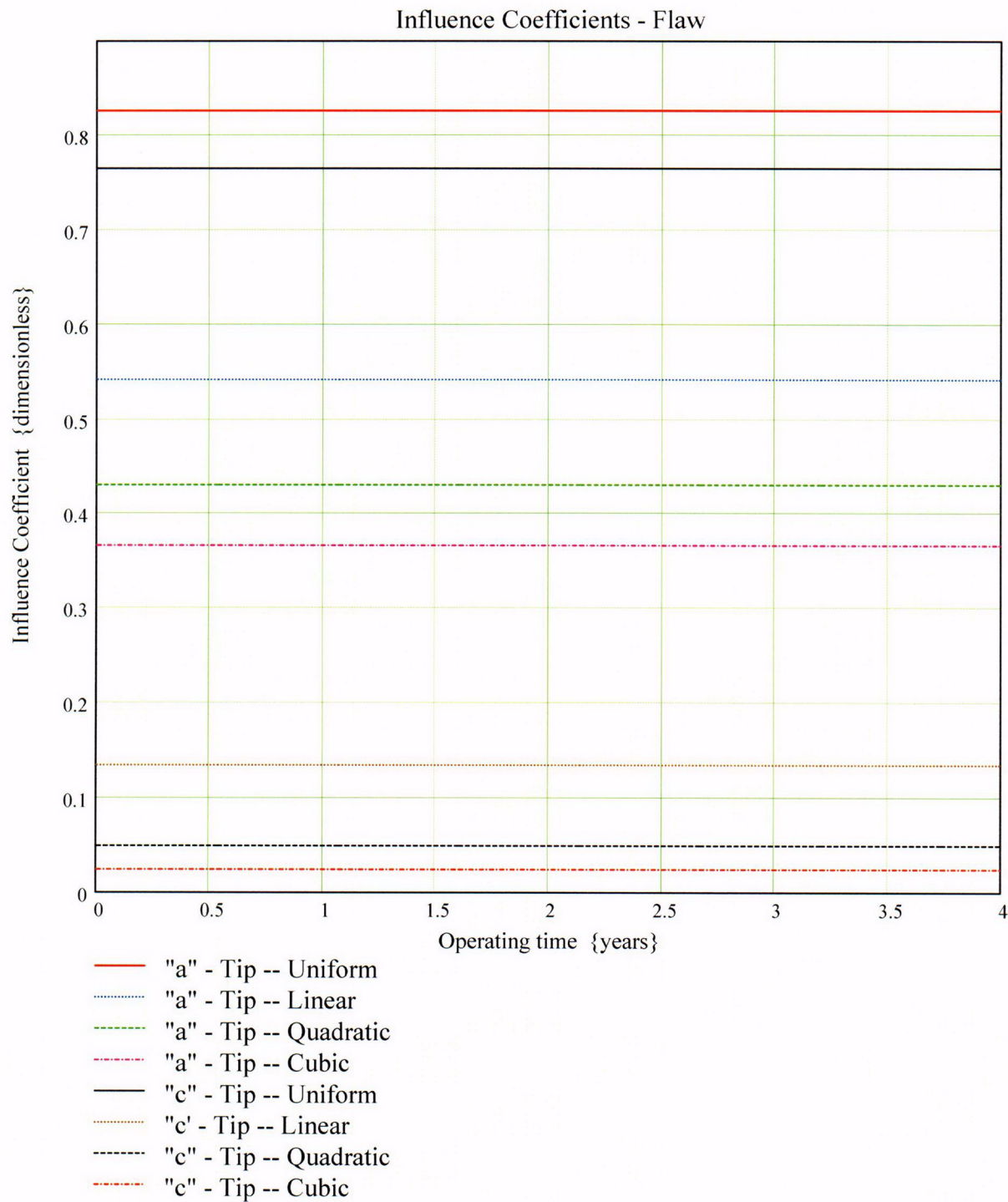
*Developed by:*  
**J. S. Brihmadesan**

*Verified by:*  
**B. C. Gray**

$\text{PropLength} = 0.459$









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

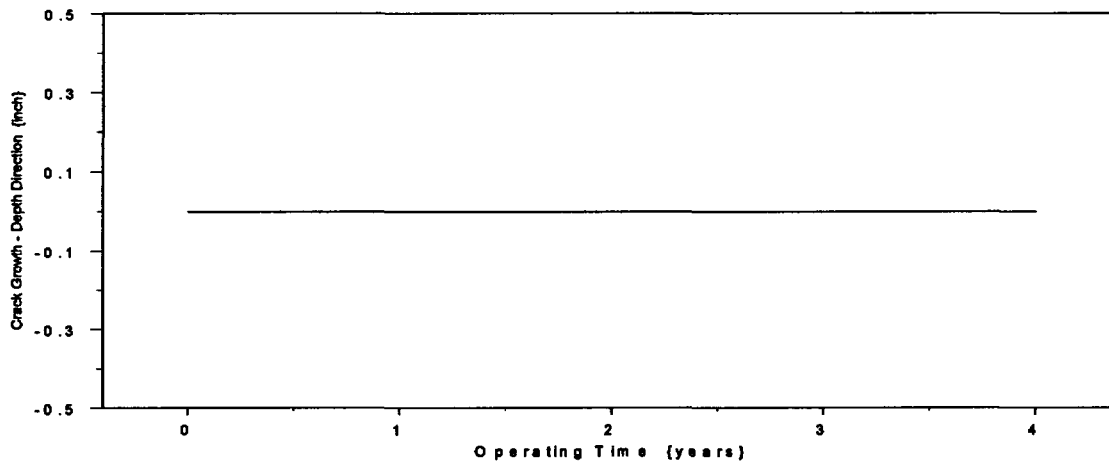
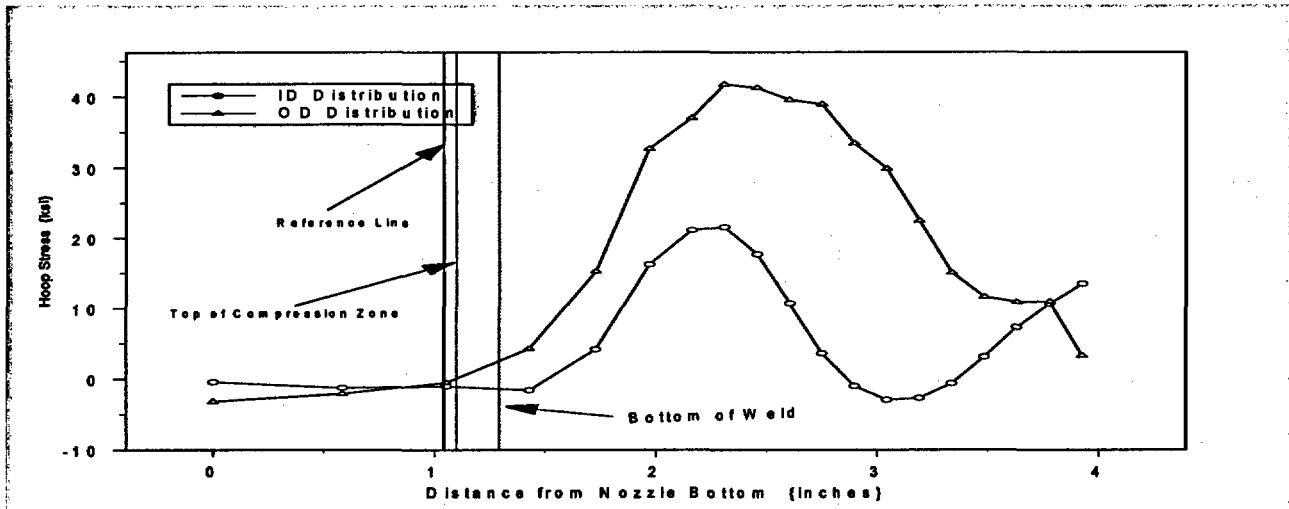
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
0.827
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0.827

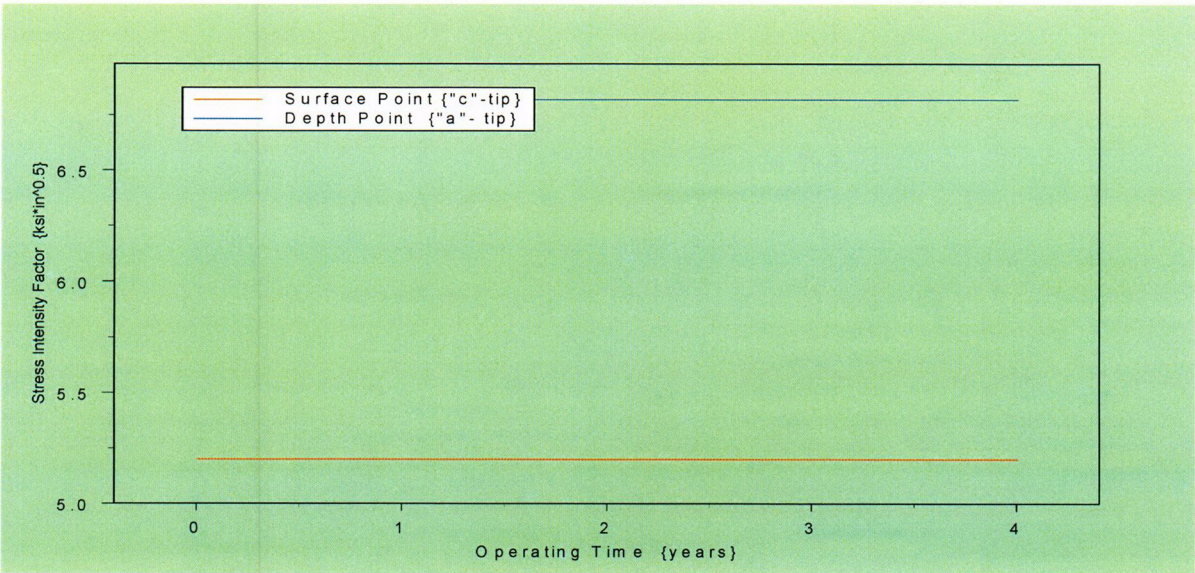
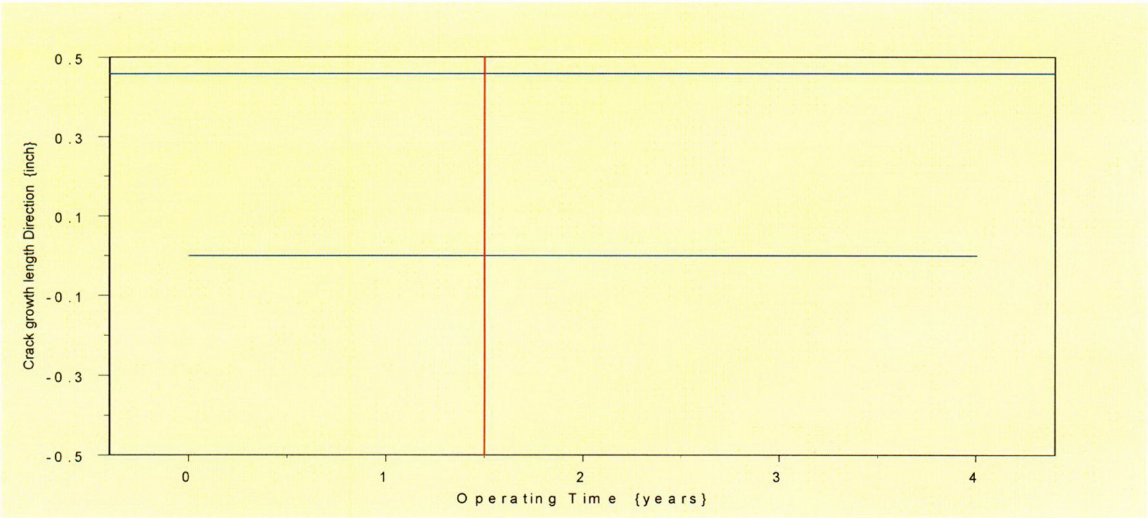
$CGR_{sambi(k,6)} =$

6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82
6.82

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

5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201
5.201





## Stress Corrosion Crack Growth Analysis Throughwall flaw

Developed by Central Engineering Programs, Entergy Operations Inc

Developed by: J. S. Brihmadesan

Verified by: B. C. Gray

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

### References :

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

### Arkansas Nuclear One Unit 2

Component : Reactor Vessel CEDM -"49" Degree Nozzle, 22.5 degree from Downhill Azimuth, Augmented Analysis  
1.3 inch above Nozzle Bottom

Calculation Reference: MRP 75 th Percentile and Flaw Pressurized

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

### Through Wall Axial Flaw

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

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

BZ := 1.3

*This is the reduced blind zone location for augmented analysis; allows a  
propagation length of 0.25 inch and a freespan length of 0.025*

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

ULStrs.Dist := 1.5504

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

Input Data :-

$L := 0.25$  Initial Flaw Length TW axial (Based on 10 Ksi average stress)

$od := 4.05$  Tube OD

$id := 2.728$  Tube ID

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

$Years := 4$  Number of Operating Years

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

$T := 604$  Estimate of Operating Temperature

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

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

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

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

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

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

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

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

$$t := R_o - R_i$$

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

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

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

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

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

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

### Stress Input Data

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

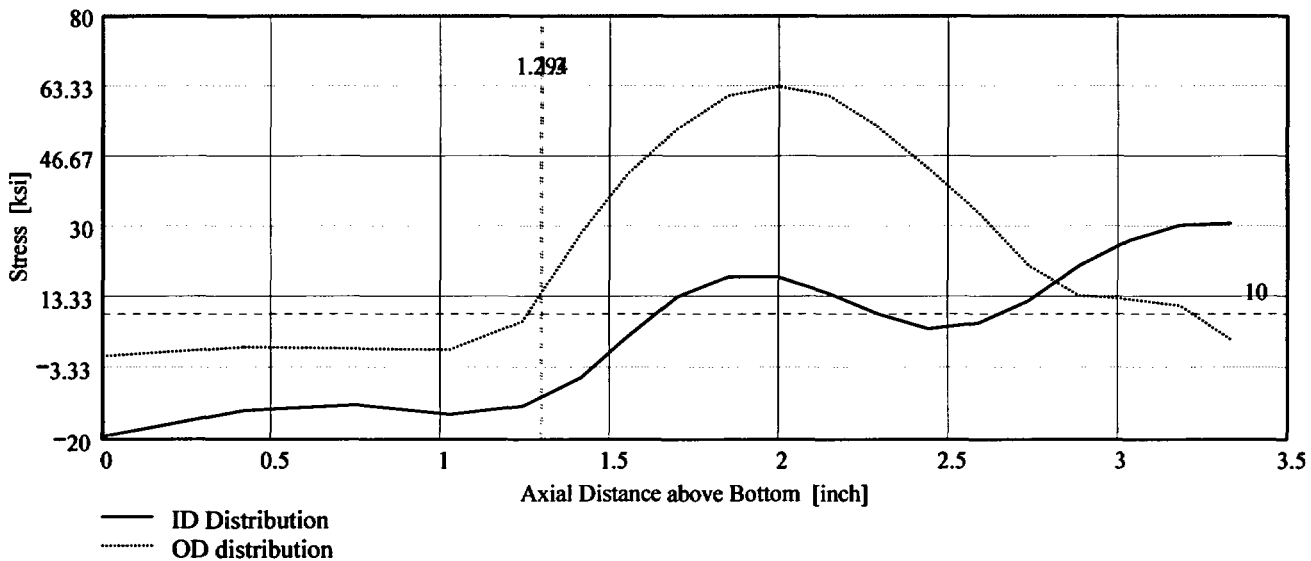
DataAll :=

	0	1	2	3	4	5
0	0	-19.3	-12.52	-8.3	-4.31	-0.29
1	0.42	-13.15	-8.57	-4.68	-1.25	1.83
2	0.75	-11.83	-6.96	-2.68	0.03	1.46
3	1.02	-14.15	-8.31	-3.17	1.1	1.22
4	1.24	-12.13	-6.55	0	5.78	7.86
5	1.41	-5.38	-2.41	7.5	23.29	28.72
6	1.55	4.33	6.48	17.84	35.67	42.75
7	1.7	13.64	15.67	27.16	40.65	53.56
8	1.85	18.3	21.2	32.42	50.34	61.38
9	2	18.32	22.29	34.21	53.26	63.46
10	2.14	14.52	21.82	35.09	51.48	61.5
11	2.29	9.62	20.82	34.51	47.88	53.88

AllAx1 := DataAll<sup>(0)</sup>

AllID := DataAll<sup>(1)</sup>

AllOD := DataAll<sup>(5)</sup>



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	-19.301	-12.523	-8.304	-4.314	-0.289
0.419	-13.153	-8.572	-4.68	-1.255	1.834
0.755	-11.834	-6.958	-2.685	0.028	1.463
1.024	-14.146	-8.315	-3.168	1.103	1.221
1.239	-12.132	-6.552	$3.002 \times 10^{-3}$	5.78	7.858
1.412	-5.38	-2.413	7.498	23.29	28.718
1.55	4.331	6.478	17.842	35.67	42.747
1.699	13.644	15.667	27.164	40.65	53.563
1.847	18.304	21.201	32.424	50.345	61.379
1.996	18.316	22.292	34.208	53.258	63.464

$Ax1 := Data^{(0)}$

$ID := Data^{(1)}$

$OD := Data^{(5)}$

$R_{ID} := \text{regress}(Ax1, ID, 3)$

$R_{OD} := \text{regress}(Ax1, OD, 3)$

$FL_{Cntr} := BZ - 1$

Flaw Center above Nozzle Bottom

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

**No User Input required beyond this Point**

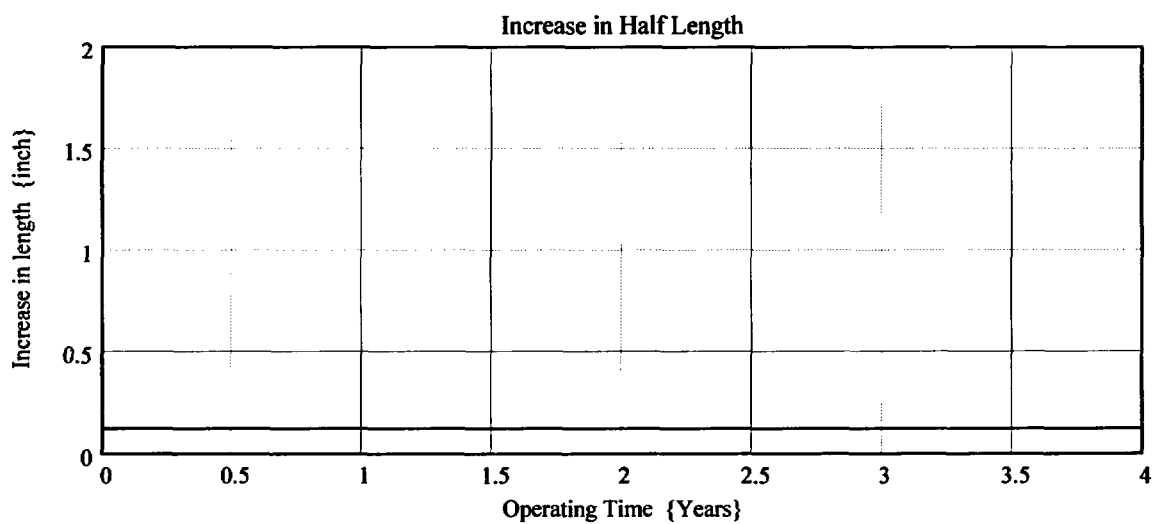
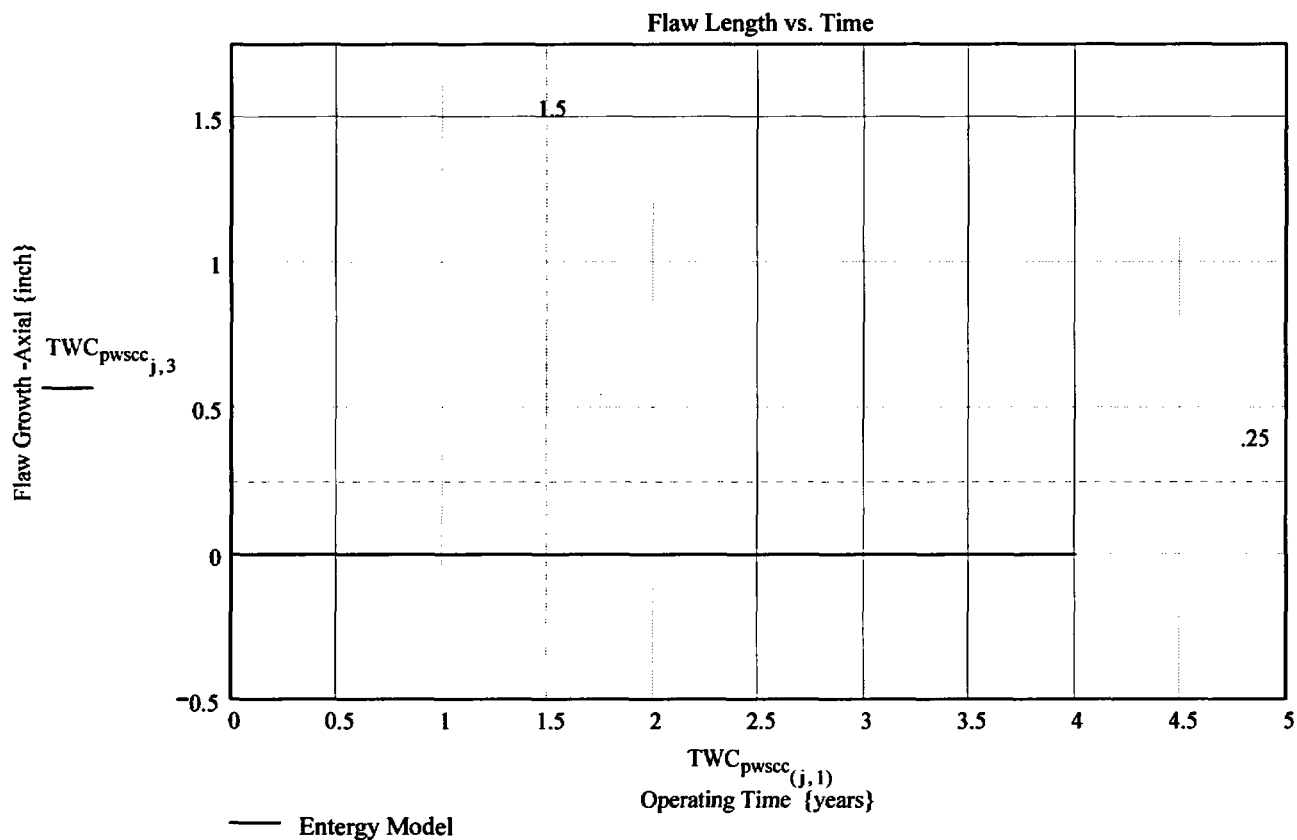
 Sat Aug 09 11:44:49 AM 2003

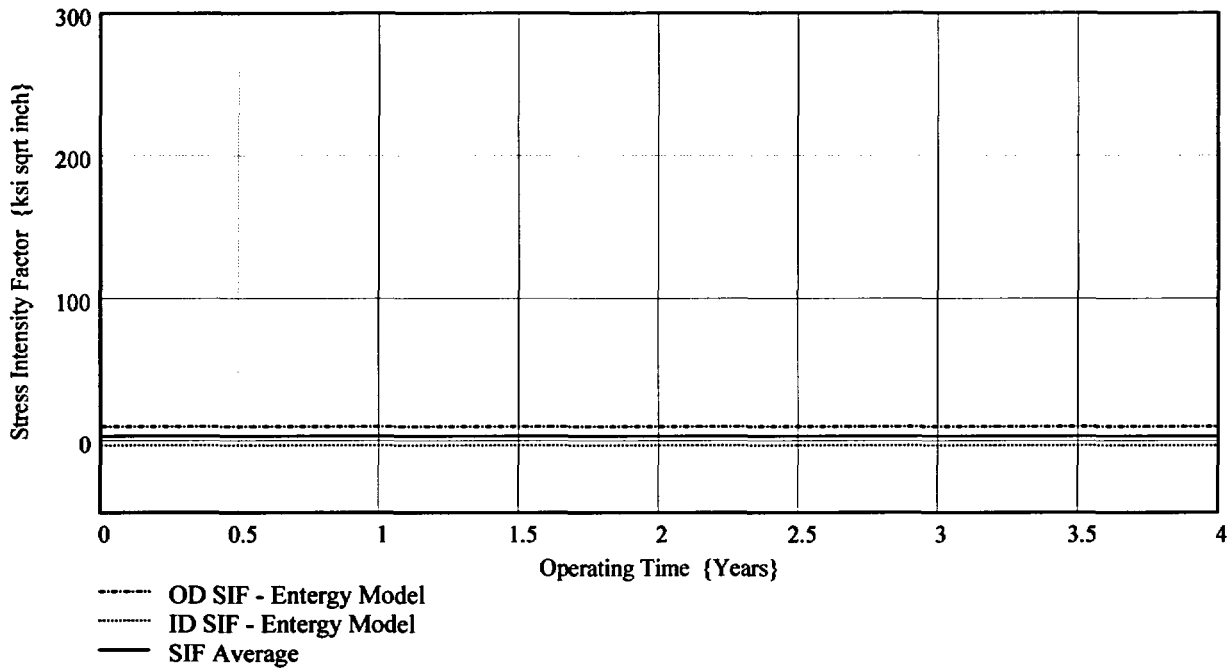
Developed by:

Verified by:



PropLength = 0.25





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

10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656
10.656

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

-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835
-2.835

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

3.829
3.829
3.829
3.829
3.829
3.829
3.829
3.829
3.829
3.829
3.829
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