Appendix A

This Appendix contains design information, UT analysis data and an evaluation to determine the best-estimate as-built configuration.

This Appendix has five (5) Attachments.

Design Input Sheet for Fracture Mechanics Evaluation of CEDM nozzles below the Attachment J-weld {ANO Unit 2 and WSES Unit 3}

Item	Source	Input Used	Concurrence[1]
Thread length	E-234-760-2 ANO-2 E-74170-112-01 WSES-3	1.25 inches	Site Design Engineering: ANO:______ WSES3: Nina Ray
Chamfer Dimension	Same Drawing as above	0.094	Site Design Engineering. ANO:______ WSES3: Nina Ray
NDE Dead Zone	Ronnie Swain's Notes of 4/23/03 attached to e-mail of 4/23/03	0.300	Site Quality Programs/NDE ANO:______ WSES3:______
Residual Stress Distribution	DEI calculations : C-7736-00-5 ANO-2 C-7736-00-4 WSES-3	Nodal stresses below J-weld	DEI Calculations were performed for Westinghouse under contract to Westinghouse for ANO-2 and WSES3 RVHP evaluations. Westinghouse {OEM} provided design input. Westinghouse and DEI have Appendix "B" qualified QA program and these calculations were performed under the applicable program. This provides reasonable assurance that the results are applicable.
PWSCC Crack Growth rate	EPRI-MRP 55 revision 1.	Seventy-fifth Percentile Curve	EPRI report based on information provided by all utilities and the analyses for the report was performed under EPRI QA program. The report was reviewed by Utility peer group {MRP} for correctness, completeness and applicability. The information is reasonable for use for ANO-2 and WSES-3 application.
Nozzle Dimensions {ID and OD)	E-234-760-2 ANO-2 E-74170-112-01 WSES-3	OD = 4.05"; ID = 2.719" OD = 4.05"; ID = ~~2.719"~~, 2.728 NR	Site Design Engineering: ANO:______ WSE3: Nina Ray

1: *Concurrence is only required for items that have a signature block. The Residual Stress results and PWSCC crack growth rate report have been provided under approved QA programs and there is reasonable assurance of the result's accuracy. Hence for these two items specific concurrence is not required.*

NDE Dead Zone Design Input

June 6, 2003

Design Input to Engineering Report M-EP-2003-002:

At the request of Entergy, Westinghouse reviewed UT data for 10 penetrations taken from the 2R15 ANO-2 reactor head inspection. This inspection was performed with a 7010 ultrasonic end-effector, using 0.250" diameter, 24mm PCS Time-of-Flight-Diffraction ultrasonic transducers. The penetrations were chosen by their location on the head, in order to provide a representative sample of the entire head. The analysis was performed in order to determine the ultrasonic dead band located immediately above the threaded region of the CEDM nozzles. This review determined the dead band to be 0.200".

Ronald V. Swain
UT Level III
Waterford 3 SES

To support the crack growth rate evaluation for the portion of the CEDM nozzle that extends below the J-groove weld on the ANO-2 and W-3 heads, the length of this portion of the nozzle is required. Because this length varies with the nozzle location, an Excel spreadsheet was developed to calculate the various parameters of the nozzle J-groove weld configuration.

To describe the geometry, the following nomenclature is used: The location of the nozzle relative to the curvature of the head is identified by the angle in degrees between the vertical centerline of the head, and a line created by the radius of curvature of the bottom surface of the cladding where it intersects with the centerline of the nozzle. The nozzle locations included in the crack growth rate evaluation are identified as the following:

ANO-2			Waterford-3	
Nozzle location	Penetration No.		Nozzle location	Penetration No.
0°	1		0°	1
8.8°	2, 3, 4, 5		7.8°	2, 3
28.8°	30, 31, 32, 33, 34, 35, 36, 37		29.1°	36, 37, 38, 39, 40, 41, 42, 43
49.6°	70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81		49.7°	88, 89, 90, 91

The point location around the OD of the nozzle is identified by the azimuth angle with the zero degree azimuth location being the point furthest from the vertical centerline of the head, which is also the lowest point that the J-groove weld attaches to the nozzle (the "low-hillside"). The length of the portion of the nozzle that extends down below the J-groove weld is calculated at the zero degree azimuth for each of the nozzle locations evaluated.

The length, "L", of the portion of the nozzle that extends down below the J-groove weld is defined as the vertical distance from the point where the surface of the cladding would intersect with the outside surface of the nozzle at the zero degree azimuth location down to the bottom of the nozzle (see attached sketch).

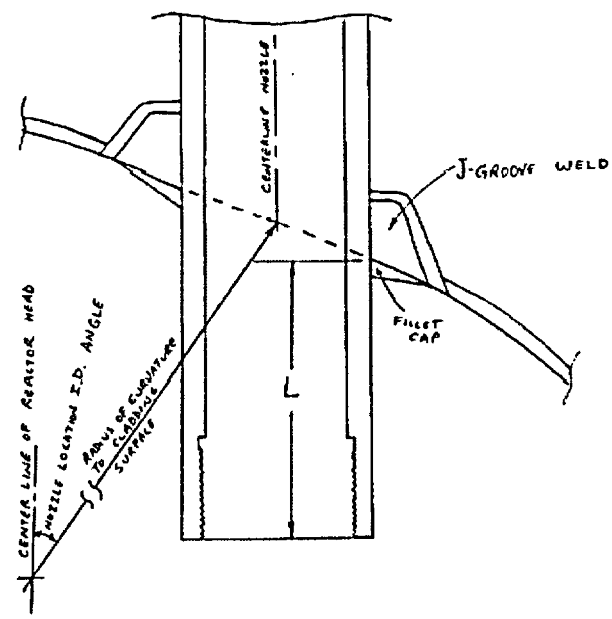
Using ANO drawings M-2001-C2-23, M-2001-C2-26, M-2001-C2-32, M-2001-C2-55, and M-2001-C2-107, and Waterford drawings 1564-506, 1564-1036, and 1564-4086, the length "L" was calculated as shown in the following table:

ANO-2			Waterford-3	
Nozzle location	L (inches)		Nozzle location	L (inches)
0°	2.50		0°	2.88
8.8°	2.49		7.8°	2.88
28.8°	2.48		29.1°	2.86
49.6°	2.48		49.7°	2.92

Verified by:

ANO-2	
Jamie GoBell (signature)	6/4/03
Jamie GoBell	Date

Waterford-3	
Nara Ray (signature)	6/4/03
Nara Ray	Date


J-GROOVE WELD
FILLET CAP
L
CENTERLINE NOZZLE
CENTER LINE OF REACTOR HEAD
NOZZLE LOCATION I.D. ANGLE
RADIUS OF CURVATURE TO CLADDING SURFACE

Evaluation of a Sister Plant (Plant A)
Ultrasonic Testing Data

Purpose:

Using the Plant A UT data estimate the weld dimensions for comparison with Design Drawing to develop a as-built configuration for the welds.

Process:

The UT data from the Zero degree transducer measure the elevation, using the encoder information, for the end of the blind zone, the beginning of the weld (fillet weld toe), and the top of the weld. From this preliminary information determine the available freespan and the total weld length. This is to be performed for both the Downhill (0° azimuth) and the Uphill (180° azimuth).

Results:

The results are provided in a table in the following pages. The columns highlighted in "yellow" contain the desired information. This information is used to perform the comparison with design drawing.

	Downhill Side of CEDM						Uphill Side of CEDM					
Nozzle	Azimuth	Data Axial Position (inch)			Estimated Location (inch)		Azimuth	Data Axial Position (inch)			Estimated Location (inch)	
Number	Degrees	Dead zone	Bottom of fillet	Top of J-weld	Bottom of fillet	Top of J-weld	Degrees	Dead zone	Bottom of fillet	Top of J-weld	Bottom of fillet	Top of J-weld
1	1.000	1.320	2.440	3.680	1.120	2.360	129.000	1.440	2.560	3.800	1.120	2.360
2	2.000	1.160	2.360	3.640	1.200	2.480	178.000	1.200	3.040	4.360	1.840	3.160
3	0.000	0.720	1.680	3.160	0.960	2.440	180.000	0.760	2.440	3.920	1.680	3.160
4	0.000	0.600	1.640	3.000	1.040	2.400	180.000	0.600	2.600	3.920	2.000	3.320
5	N/A				0.000	0.000					0.000	0.000
6	358.000	-0.040	0.960	2.600	1.000	2.640	178.000	0.040	2.200	3.520	2.160	3.480
7	356.000	1.040	2.120	3.600	1.080	2.560	180.000	1.080	3.120	4.560	2.040	3.480
8	10.000	0.400	1.600	2.920	1.200	2.520	182.000	0.360	2.920	4.200	2.560	3.840
9	0.000	0.040	1.120	2.720	1.080	2.680	192.000	-0.040	2.440	3.760	2.480	3.800
10	356.000	0.160	1.200	2.680	1.040	2.520	180.000	0.200	2.680	3.960	2.480	3.760
11	352.000	0.960	2.040	3.520	1.080	2.560	172.000	0.960	3.440	4.840	2.480	3.880
12	6.000	1.120	2.120	3.600	1.000	2.480	182.000	1.160	3.720	5.080	2.560	3.920
13	358.000	1.160	2.320	3.880	1.160	2.720	174.000	1.160	3.840	5.120	2.680	3.960
14	98.000	1.040	2.000	3.640	0.960	2.600	294.000	1.000	3.560	5.000	2.560	4.000
15	356.000	0.080	1.200	2.640	1.120	2.560	176.000	0.040	2.760	4.120	2.720	4.080
16	2.000	0.040	1.160	2.640	1.120	2.600	182.000	0.000	2.640	4.080	2.640	4.080
17	0.000	0.960	1.960	3.320	1.000	2.360	176.000	0.920	3.560	4.720	2.640	3.800
18	0.000	0.160	1.320	2.680	1.160	2.520	180.000	0.240	2.840	4.000	2.600	3.760
19	2.000	1.120	2.280	3.640	1.160	2.520	182.000	1.040	3.760	4.960	2.720	3.920
20	4.000	0.880	1.920	3.520	1.040	2.640	180.000	0.960	3.880	5.440	2.920	4.480
21	0.000	1.160	1.880	3.600	0.720	2.440	188.000	1.200	4.080	5.600	2.880	4.400
22	354.000	0.120	1.080	2.640	0.960	2.520	170.000	0.040	3.080	4.600	3.040	4.560
23	6.000	0.040	0.920	2.600	0.880	2.560	182.000	0.080	3.040	4.520	2.960	4.440
24	0.000	0.040	0.920	2.400	0.880	2.360	172.000	0.000	3.120	4.480	3.120	4.480
25	6.000	0.040	0.920	2.560	0.880	2.520	178.000	0.040	3.200	4.640	3.160	4.600
26	350.000	0.360	1.320	2.760	0.960	2.400	178.000	0.320	3.400	4.760	3.080	4.440
27	358.000	0.160	0.880	2.760	0.720	2.600	182.000	0.160	3.200	4.720	3.040	4.560
28	356.000	0.320	1.160	2.800	0.840	2.480	180.000	0.280	3.440	5.040	3.160	4.760
29	358.000	0.120	1.120	2.600	1.000	2.480	178.000	0.080	3.320	4.760	3.240	4.680
30	358.000	0.040	0.800	2.640	0.760	2.600	182.000	0.000	3.200	4.800	3.200	4.800
31	6.000	0.080	1.000	2.760	0.920	2.680	186.000	0.040	3.360	4.840	3.320	4.800
32	358.000	-0.040	0.920	2.440	0.960	2.480	178.000	-0.080	3.040	4.520	3.120	4.600
33	0.000	0.040	0.840	2.360	0.800	2.320	180.000	0.000	2.960	4.560	2.960	4.560
34	2.000	-0.080	0.680	2.520	0.760	2.600	174.000	-0.080	2.960	4.560	3.040	4.640
35	354.000	0.080	0.800	2.560	0.720	2.480	182.000	0.080	3.040	4.800	2.960	4.720
36	354.000	0.360	1.000	2.880	0.640	2.520	186.000	0.360	3.840	5.480	3.480	5.120
37	0.000	0.200	0.840	2.720	0.640	2.520	180.000	0.160	3.680	5.320	3.520	5.160
38	356.000	0.440	1.280	2.960	0.840	2.520	180.000	0.480	3.840	5.520	3.360	5.040
39	354.000	0.120	0.800	2.560	0.680	2.440	174.000	0.080	3.520	5.200	3.440	5.120
40	358.000	0.560	1.240	2.880	0.680	2.320	182.000	0.480	4.240	5.480	3.760	5.000
41	0.000	0.040	0.880	2.360	0.840	2.320	180.000	0.080	3.600	4.960	3.520	4.880
42	358.000	0.200	0.960	2.600	0.760	2.400	178.000	0.200	3.680	5.200	3.480	5.000
43	358.000	0.240	0.920	2.760	0.680	2.520	180.000	0.280	3.680	5.240	3.400	4.960
44	0.000	0.000	0.720	2.760	0.720	2.760	184.000	0.000	3.760	5.640	3.760	5.640
45	358.000	0.040	0.680	2.680	0.640	2.640	178.000	0.040	3.880	5.600	3.840	5.560
46	6.000	0.120	0.720	2.600	0.600	2.480	178.000	0.120	3.920	5.520	3.800	5.400
47	0.000	0.120	0.680	2.680	0.560	2.560	180.000	0.160	3.960	5.600	3.800	5.440
48	358.000	0.400	1.080	3.160	0.680	2.760	170.000	0.480	4.320	6.120	3.840	5.640
49	0.000	-0.080	0.480	2.520	0.560	2.600	176.000	-0.080	3.720	5.560	3.800	5.640
50	0.000	0.120	0.840	2.840	0.720	2.720	180.000	0.080	3.960	5.800	3.880	5.720
51	0.000	1.280	1.800	4.040	0.520	2.760	180.000	1.240	5.200	7.000	3.960	5.760
52	8.000	0.120	0.600	2.680	0.480	2.560	180.000	0.160	4.000	5.640	3.840	5.480
53	358.000	0.040	0.840	2.480	0.800	2.440	182.000	-0.040	3.960	5.440	4.000	5.480
54	0.000	0.160	0.600	2.800	0.440	2.640	180.000	0.200	4.000	5.800	3.800	5.600
55	354.000	0.120	0.840	2.720	0.720	2.600	170.000	0.080	3.880	5.680	3.800	5.600
56	4.000	1.120	1.960	3.840	0.840	2.720	180.000	1.080	4.800	6.840	3.720	5.760
57	2.000	0.160	0.760	2.680	0.600	2.520	182.000	0.160	4.360	5.960	4.200	5.800
58	358.000	0.160	1.000	2.680	0.840	2.520	178.000	0.080	4.040	5.800	3.960	5.720
59	N/A				0.000	0.000					0.000	0.000
60	N/A				0.000	0.000					0.000	0.000
61	354.000	-0.080	0.360	2.720	0.440	2.800	178.000	-0.080	4.240	6.160	4.320	6.240
62	358.000	0.320	0.920	2.760	0.600	2.440	182.000	0.320	4.640	6.320	4.320	6.000
63	2.000	0.160	0.640	2.880	0.480	2.720	182.000	0.080	4.280	6.320	4.200	6.240
64	2.000	-0.120	0.480	2.360	0.600	2.480	182.000	-0.120	3.880	5.800	4.000	5.920
65	2.000	0.080	0.600	2.440	0.520	2.360	178.000	0.080	4.200	5.960	4.120	5.880
66	352.000	0.080	0.680	2.600	0.600	2.520	180.000	0.080	4.120	6.160	4.040	6.080
67	358.000	0.320	1.040	2.800	0.720	2.480	178.000	0.320	4.440	6.320	4.120	6.000
68	0.000	0.040	0.680	2.920	0.640	2.880	180.000	0.120	5.000	7.120	4.880	7.000
69	352.000	0.280	0.520	3.080	0.240	2.800	176.000	0.360	5.000	7.160	4.640	6.800
70	4.000	0.160	0.560	2.800	0.400	2.640	184.000	0.240	5.000	6.960	4.760	6.720
71	354.000	0.120	0.440	2.960	0.320	2.840	176.000	0.160	4.840	6.840	4.680	6.680
72	2.000	0.040	0.520	2.800	0.480	2.760	178.000	0.120	4.840	6.960	4.720	6.840
73	N/A				0.000	0.000					0.000	0.000
74	344.000	0.120	0.640	2.640	0.520	2.520	168.000	0.200	5.120	6.840	4.920	6.640
75	0.000	0.120	0.720	2.600	0.600	2.480	184.000	0.200	4.880	6.760	4.680	6.560
76	0.000	0.040	0.640	2.720	0.600	2.680	180.000	0.080	4.640	6.600	4.560	6.520
77	4.000	0.000	0.360	2.480	0.360	2.480	180.000	0.000	4.720	6.760	4.720	6.760
78	352.000	0.200	1.080	3.080	0.880	2.880	176.000	0.280	5.520	7.200	5.240	6.920
79	2.000	1.040	1.720	3.880	0.680	2.840	182.000	1.120	6.080	8.040	4.960	6.920
80	4.000	0.000	0.400	2.600	0.400	2.600	184.000	0.080	5.200	7.040	5.120	6.960
81	0.000	-0.080	0.200	2.400	0.280	2.480	180.000	0.040	5.040	6.920	5.000	6.880
82	6.000	0.000	0.440	2.640	0.440	2.640	178.000	0.000	5.200	7.040	5.200	7.040
83	0.000	0.160	0.600	3.040	0.440	2.880	180.000	0.200	5.040	7.360	4.840	7.160
84	0.000	0.240	0.560	2.960	0.320	2.720	176.000	0.320	5.200	7.400	4.880	7.080
85	358.000	0.240	0.600	2.840	0.360	2.600	178.000	0.360	5.080	7.080	4.720	6.720
86	358.000	-0.040	0.400	2.800	0.440	2.840	178.000	0.040	5.200	7.160	5.160	7.120
87	0.000	0.080	0.440	2.720	0.360	2.640	176.000	0.160	5.120	7.200	4.960	7.040
88	0.000	0.000	0.400	3.080	0.400	3.080	180.000	0.120	5.840	8.440	5.720	8.320
89	0.000	0.240	0.440	2.840	0.200	2.600	180.000	0.280	6.040	8.400	5.760	8.120
90	358.000	-0.080	0.080	2.760	0.160	2.840	182.000	0.040	5.880	8.080	5.840	8.040
91	N/A				0.000	0.000					0.000	0.000

Attachment 5

Comparative Evaluation of Design Drawing and UT data to develop As-Built Configuration

Purpose:

Compare the design drawing information with the as-measured UT data from a Sister Plant (plant A) CEDM inspection to determine the differences between the as-designed and as-measured configuration. Based on this evaluation develop the as-built configuration to minimize the differences.

Process:

Use the as-designed information from design drawings and set the blind zone elevation, from the nozzle bottom at 1.544 inches. Based on the location of the blind zone determine the length of the freespan and the weld height for the as-designed case.

This is to be done for the two azimuthal locations, namely the downhill (0° azimuth) and the uphill (180° azimuth). Use similar information from the UT analysis data, Attachment 3, to determine the differences. The comparisons are made for several nozzle groups to ensure an accurate evaluation.

Results:

The results are presented in the following pages. The first table provides the determination of differences. These results show a consistent difference between the as-designed condition and the as-measured condition. The differences on the uphill side indicate that the J-weld may be longer than the assumed as-designed condition. On the downhill side the differences suggest that both the J-weld to be longer and a larger fillet radius. The large fillet radius effect is observed for the higher head angle nozzle group (> 29.1°).

The second set of table was developed by increasing the J-weld length for all nozzle groups by 0.3 inch and increasing the fillet radius for the downhill side fillet on the higher angle nozzle groups (groups with head angles > 29.1°). The comparison between this configuration and the as-measured data is consistently minimized as shown in the second table.

It should be noted that five nozzle groups were used in the comparison to ensure that an accurate as-built configuration could be developed.

Table 1: Comparison between the As-Designed and As-Measured (UT data) Configuration

0.0° Nozzle		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 1	All HS	1.12	0 08	2.36	0.18	1.24	0.09

As-Designed Dimensions		
All HS	Bottom	1.0362
All HS	Top	2.1825
All HS	Length	1.1463

Weld Bottom Stats Low and High HS	Weld Top Stats Low and High HS
0.08	0.18

7.8° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 2	Low HS	1.20	0.19	2.48	0.30	1.28	0.11
	High HS	1.84	0.18	3.16	0.37	1.32	0.19
Nozzle 3	Low HS	0.96	-0.05	2.44	0.26	1.48	0.31
	High HS	1.68	0.02	3.16	0.37	1.48	0.35

Low HS	Bottom	1.0102
	Top	2.1790
High HS	Bottom	1.6596
	Top	2.7895
Low HS	Length	1.1688
High HS	Length	1.1299

	Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
	0.19	0.18	0.30	0.37
	-0.05	0.02	0.26	0.37
avg	**0.07**	**0.10**	**0.28**	**0.37**
stdev	**0.17**	**0.11**	**0.03**	**0.00**
stdev/avg	2.4	1.1	0.1	0.0

29.1° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 36	Low HS	0.64	-0.39	2.52	0.33	1.88	0.72
	High HS	3.48	-0.02	5.12	0.39	1.64	0.40
Nozzle 37	Low HS	0.64	-0.39	2.52	0.33	1.88	0.72
	High HS	3.52	0.02	5.16	0.43	1.64	0.40
Nozzle 38	Low HS	0.84	-0.19	2.52	0.33	1.68	0.52
	High HS	3.36	-0.14	5.04	0.31	1.68	0.44
Nozzle 39	Low HS	0.68	-0.35	2.44	0.25	1.76	0.60
	High HS	3.44	-0.06	5.12	0.39	1.68	0.44
Nozzle 40	Low HS	0.68	-0.35	2.32	0.13	1.64	0.48
	High HS	3.76	0.26	5.00	0.27	1.24	0.00
Nozzle 41	Low HS	0.84	-0.19	2.32	0.13	1.48	0.32
	High HS	3.52	0.02	4.88	0.15	1.36	0.12
Nozzle 42	Low HS	0.76	-0.27	2.40	0.21	1.64	0.48
	High HS	3 48	-0 02	5.00	0.27	1.52	0.28
Nozzle 43	Low HS	0.68	-0.35	2.52	0.33	1.84	0.68
	High HS	3.40	-0.10	4.96	0 23	1.56	0.32

Low HS	Bottom	1.0339
	Top	2.1943
High HS	Bottom	3.4969
	Top	4.7345
Low HS	Length	1.1604
High HS	Length	1.2376

	Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
	-0.39	-0.02	0.33	0.39
	-0.39	0.02	0.33	0.43
	-0.19	-0.14	0.33	0.31
	-0.35	-0.06	0.25	0.39
	-0.35	0.26	0.13	0.27
	-0.19	0.02	0.13	0.15
	-0.27	-0.02	0.21	0.27
	-0.35	-0.10	0 33	0.23
avg	**-0.31**	**0.00**	**0.25**	**0.30**
stdev	**0.08**	**0.12**	**0.09**	**0.09**
stdev/avg	-0.3	-63.6	0.4	0.3

42.4° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 68	Low HS	0.64	-0.39	2.88	0.53	2.24	0.93
	High HS	4.88	-0.19	7.00	0.45	2.12	0 64
Nozzle 69	Low HS	0.24	-0.79	2.80	0.45	2.56	1.25
	High HS	4.64	-0 43	6.80	0.25	2.16	0.68
Nozzle 70	Low HS	0.40	-0.63	2.64	0.29	2.24	0.93
	High HS	4.76	-0.31	6.72	0.17	1.96	0.48
Nozzle 71	Low HS	0.32	-0.71	2.84	0.49	2.52	1.21
	High HS	4.68	-0.39	6.68	0.13	2.00	0 52
Nozzle 72	Low HS	0.48	-0.55	2.76	0.41	2.28	0.97
	High HS	4.72	-0.35	6 84	0.29	2.12	0 64
Nozzle 73	Low HS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	High HS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Nozzle 74	Low HS	0.52	-0.51	2.52	0.17	2.00	0.69
	High HS	4.92	-0.15	6 64	0.09	1.72	0.24
Nozzle 75	Low HS	0.60	-0.43	2.48	0.13	1.88	0.57
	High HS	4.68	-0.39	6.56	0.01	1.88	0.40
Nozzle 76	Low HS	0.60	-0.43	2.68	0.33	2.08	0.77
	High HS	4.56	-0.51	6.52	-0.03	1.96	0.48
Nozzle 77	Low HS	0.36	-0.67	2.48	0.13	2.12	0.81
	High HS	4.72	-0.35	6.76	0.21	2.04	0.56
Nozzle 78	Low HS	0.88	-0.15	2.88	0.53	2.00	0.69
	High HS	5.24	0.17	6.92	0.37	1.68	0.20
Nozzle 79	Low HS	0.68	-0.35	2.84	0.49	2.16	0.85
	High HS	4 96	-0.11	6.92	0 37	1.96	0.48

Low HS	Bottom	1.0328
	Top	2.3466
High HS	Bottom	5.0734
	Top	6 5487
Low HS	Length	1.3138
High HS	Length	1.4753

	Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
	-0.39	-0.19	0.53	0.45
	-0.79	-0.43	0.45	0.25
	-0.63	-0.31	0.29	0.17
	-0.71	-0.39	0.49	0.13
	-0.55	-0.35	0.41	0.29
	-0.51	-0.15	0.17	0.09
	-0.43	-0.39	0.13	0.01
	-0.43	-0.51	0.33	-0.03
	-0.67	-0.35	0.13	0.21
	-0.15	0.17	0.53	0.37
	-0.35	-0.11	0.49	0.37
avg	**-0.51**	**-0.28**	**0.36**	**0.21**
stdev	**0.19**	**0.19**	**0.16**	**0.15**
stdev/avg	-0.4	-0.7	0.4	0.7

49.7° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 88	Low HS	0.40	-0.56	3.08	0.66	2.68	1.22
	High HS	5.72	-0.53	8.32	0.49	2 60	1.02

Low HS	Bottom	0.9602
	Top	2.4185
High HS	Bottom	6.2468
	Top	7.8308

Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
-0.56	-0.53	0.66	0.49
-0.76	-0.49	0.18	0.29

Table 2: Comparison between proposed As-Built and As-Measured (UT data) Configuration

0.0° Nozzle		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 1	All HS	1.12	0.09	2.36	-0.12	1.24	-0.21

Modified ("As-Built") Dimensions

All HS	Bottom	1.0324
All HS	Top	2.4825
All HS	Length	1.4501

Weld Bottom Stats Low and High HS	Weld Top Stats Low and High HS
0.09	-0.12

7.8° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 2	Low HS	1.20	0.19	2.48	0.00	1.28	-0.19
	High HS	1.84	0.18	3.16	0.07	1.32	-0.11
Nozzle 3	Low HS	0.96	-0.05	2.44	-0.04	1.48	0.01
	High HS	1.68	0.02	3.16	0.07	1.48	0.05

Low HS	Bottom	1.0060
	Top	2.4790
High HS	Bottom	1.6573
	Top	3.0895
Low HS	Length	1.4730
High HS	Length	1.4322

	Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
	0.19	0.18	0.00	0.07
	-0.05	0.02	-0.04	0.07
avg	**0.07**	**0.10**	**-0.02**	**0.07**
stdev	**0.17**	**0.11**	**0.03**	**0.00**
stdev/avg	2.3	1.1	-1.5	0.0

29.1° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 36	Low HS	0.64	0.00	2.52	0.03	1.88	0.03
	High HS	3.48	-0.02	5.12	0.09	1.64	0.10
Nozzle 37	Low HS	0.64	0.00	2.52	0.03	1.88	0.03
	High HS	3.52	0.02	5.16	0.13	1.64	0.10
Nozzle 38	Low HS	0.84	0.20	2.52	0.03	1.68	-0.17
	High HS	3.36	-0.14	5.04	0.01	1.68	0.14
Nozzle 39	Low HS	0.68	0.04	2.44	-0.05	1.76	-0.09
	High HS	3.44	-0.06	5.12	0.09	1.68	0.14
Nozzle 40	Low HS	0.68	0.04	2.32	-0.17	1.64	-0.21
	High HS	3.76	0.26	5.00	-0.03	1.24	-0.30
Nozzle 41	Low HS	0.84	0.20	2.32	-0.17	1.48	-0.37
	High HS	3.52	0.02	4.88	-0.15	1.36	-0.18
Nozzle 42	Low HS	0.76	0.12	2.40	-0.09	1.64	-0.21
	High HS	3.48	-0.02	5.00	-0.03	1.52	-0.02
Nozzle 43	Low HS	0.68	0.04	2.52	0.03	1.84	-0.01
	High HS	3.40	-0.10	4.96	-0.07	1.56	0.02

Low HS	Bottom	0.6412
	Top	2.4943
High HS	Bottom	3.4969
	Top	5.0345
Low HS	Length	1.8531
High HS	Length	1.5376

	Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
	0.00	-0.02	0.03	0.09
	0.00	0.02	0.03	0.13
	0.20	-0.14	0.03	0.01
	0.04	-0.06	-0.05	0.09
	0.04	0.26	-0.17	-0.03
	0.20	0.02	-0.17	-0.15
	0.12	-0.02	-0.09	-0.03
	0.04	-0.10	0.03	-0.07
avg	**0.08**	**0.00**	**-0.05**	**0.00**
stdev	**0.08**	**0.12**	**0.09**	**0.09**
stdev/avg	1.1	-63.6	-1.8	188.5

42.4° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 68	Low HS	0.64	0.03	2.88	0.23	2.24	0.20
	High HS	4.88	-0.19	7.00	0.15	2.12	0.34
Nozzle 69	Low HS	0.24	-0.37	2.80	0.15	2.56	0.52
	High HS	4.64	-0.43	6.80	-0.05	2.16	0.38
Nozzle 70	Low HS	0.40	-0.21	2.64	-0.01	2.24	0.20
	High HS	4.76	-0.31	6.72	-0.13	1.96	0.18
Nozzle 71	Low HS	0.32	-0.29	2.84	0.19	2.52	0.48
	High HS	4.68	-0.39	6.68	-0.17	2.00	0.22
Nozzle 72	Low HS	0.48	-0.13	2.76	0.11	2.28	0.24
	High HS	4.72	-0.35	6.84	-0.01	2.12	0.34
Nozzle 73	Low HS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	High HS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Nozzle 74	Low HS	0.52	-0.09	2.52	-0.13	2.00	-0.04
	High HS	4.92	-0.15	6.64	-0.21	1.72	-0.06
Nozzle 75	Low HS	0.60	-0.01	2.48	-0.17	1.88	-0.16
	High HS	4.68	-0.39	6.56	-0.29	1.88	0.10
Nozzle 76	Low HS	0.60	-0.01	2.68	0.03	2.08	0.04
	High HS	4.56	-0.51	6.52	-0.33	1.96	0.18
Nozzle 77	Low HS	0.36	-0.25	2.48	-0.17	2.12	0.08
	High HS	4.72	-0.35	6.76	-0.09	2.04	0.26
Nozzle 78	Low HS	0.88	0.27	2.88	0.23	2.00	-0.04
	High HS	5.24	0.17	6.92	0.07	1.68	-0.10
Nozzle 79	Low HS	0.68	0.07	2.84	0.19	2.16	0.12
	High HS	4.96	-0.11	6.92	0.07	1.96	0.18

Low HS	Bottom	0.6083
	Top	2.6466
High HS	Bottom	5.0734
	Top	6.8487
Low HS	Length	2.0383
High HS	Length	1.7753

	Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
	0.03	-0.19	0.23	0.15
	-0.37	-0.43	0.15	-0.05
	-0.21	-0.31	-0.01	-0.13
	-0.29	-0.39	0.19	-0.17
	-0.13	-0.35	0.11	-0.01
	-0.09	-0.15	-0.13	-0.21
	-0.01	-0.39	-0.17	-0.29
	-0.01	-0.51	0.03	-0.33
	-0.25	-0.35	-0.17	-0.09
	0.27	0.17	0.23	0.07
	0.07	-0.11	0.19	0.07
avg	**-0.09**	**-0.28**	**0.06**	**-0.09**
stdev	**0.19**	**0.19**	**0.16**	**0.15**
stdev/avg	-2.1	-0.7	2.5	-1.7

49.7° Nozzles		Bottom Measured	Bottom Δ	Top Measured	Top Δ	Length Measured	Length Δ
Nozzle 88	Low HS	0.40	-0.02	3.08	0.36	2.68	0.38
	High HS	5.72	-0.46	8.32	0.19	2.60	0.65

Low HS	Bottom	0.4228
	Top	2.7185
High HS	Bottom	6.1780
	Top	8.1308

Weld Bottom Stats Low HS	Weld Bottom Stats High HS	Weld Top Stats Low HS	Weld Top Stats High HS
-0.02	-0.46	0.36	0.19
-0.22	-0.42	-0.12	-0.01

Appendix B

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

This Appendix has three (3) Attachments.

ID Surface Flaws

Entergy Operations Inc.
Central Engineering Programs

Apendix xx; Attachment yy
Page 1 of 30

Engineering Report
M-EP-aaa-bbb-cc

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

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

Refrences :

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

Waterford Steam Electric Station Unit 3

Component : Reactor Vessel CEDM -"8.8" Degree Nozzle, "0" Degree Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

ID Surface Flaw

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

C17

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 1$$

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

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

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

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

Input Data :-

$L := .35$	Initial Flaw Length
$a_0 := 0.035$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth (MRP)
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

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

General calculations to develop the constants needed for the analyses.

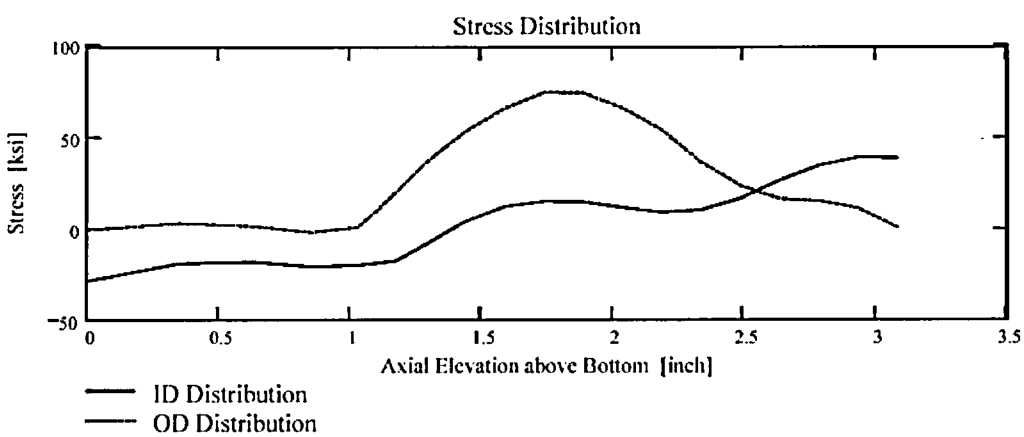
Stress Input Data

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

AllData :=

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

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



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

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

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

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

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

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

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

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

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

Flaw center Location above Nozzle Bottom

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

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

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

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

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

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

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

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

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

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

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

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

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

$j := 1..N$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$IDRG_1 := regress(Y, SIG_1, 3)$ $IDRG_2 := regress(Y, SIG_2, 3)$

$IDRG_3 := regress(Y, SIG_3, 3)$ $IDRG_4 := regress(Y, SIG_4, 3)$

$IDRG_5 := regress(Y, SIG_5, 3)$ $IDRG_6 := regress(Y, SIG_6, 3)$

$IDRG_7 := regress(Y, SIG_7, 3)$ $IDRG_8 := regress(Y, SIG_8, 3)$

$IDRG_9 := regress(Y, SIG_9, 3)$ $IDRG_{10} := regress(Y, SIG_{10}, 3)$

$IDRG_{11} := regress(Y, SIG_{11}, 3)$ $IDRG_{12} := regress(Y, SIG_{12}, 3)$

$IDRG_{13} := regress(Y, SIG_{13}, 3)$ $IDRG_{14} := regress(Y, SIG_{14}, 3)$

$IDRG_{15} := regress(Y, SIG_{15}, 3)$ $IDRG_{16} := regress(Y, SIG_{16}, 3)$

$IDRG_{17} := regress(Y, SIG_{17}, 3)$ $IDRG_{18} := regress(Y, SIG_{18}, 3)$

$IDRG_{19} := regress(Y, SIG_{19}, 3)$ $IDRG_{20} := regress(Y, SIG_{20}, 3)$

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

SICF Coefficient Determination

Jsb :=

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

Partial data table for the SICF determination.

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

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

ambi :=

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

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

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

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

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

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

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

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

"a-Tip" Uniform Term

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

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

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

Programming steps shown for determining the SICF.

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

Recursive Loop for Calculation of PWSCC Crack Growth

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

Start of the recursive loop showing the loop initialization.

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

$$\sigma_0 \leftarrow \begin{array}{|l} IDRG_{1_3} \text{ if } c_j \le c_0 \\ IDRG_{2_3} \text{ if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\ IDRG_{3_3} \text{ if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg} \\ IDRG_{4_3} \text{ if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg} \\ IDRG_{5_3} \text{ if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg} \\ IDRG_{6_3} \text{ if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg} \\ IDRG_{7_3} \text{ if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg} \\ IDRG_{8_3} \text{ if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg} \\ IDRG_{9_3} \text{ if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg} \\ IDRG_{10_3} \text{ if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg} \end{array}$$

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

$$\xi_0 \leftarrow \sigma_0$$

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

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

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

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

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

$$x_0 \leftarrow 0.0$$

$$x_1 \leftarrow 0.25$$

$$x_2 \leftarrow 0.5$$

$$x_3 \leftarrow 0.75$$

$$x_4 \leftarrow 1.0$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

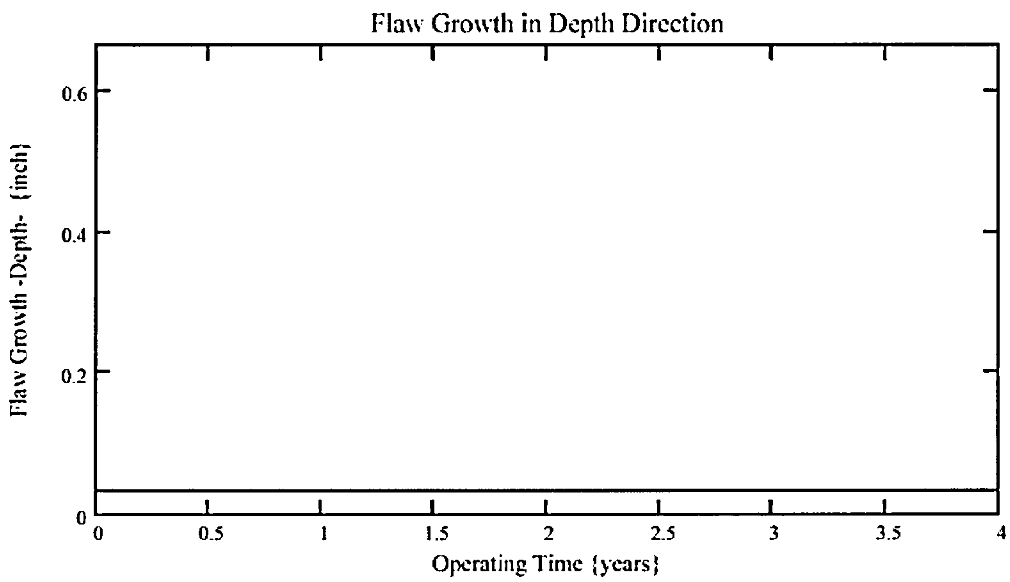
Typical output statements within the recursive loop showing the storing of variables that are required for loop operation and those of interest in displaying the time dependent trend.

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

output

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

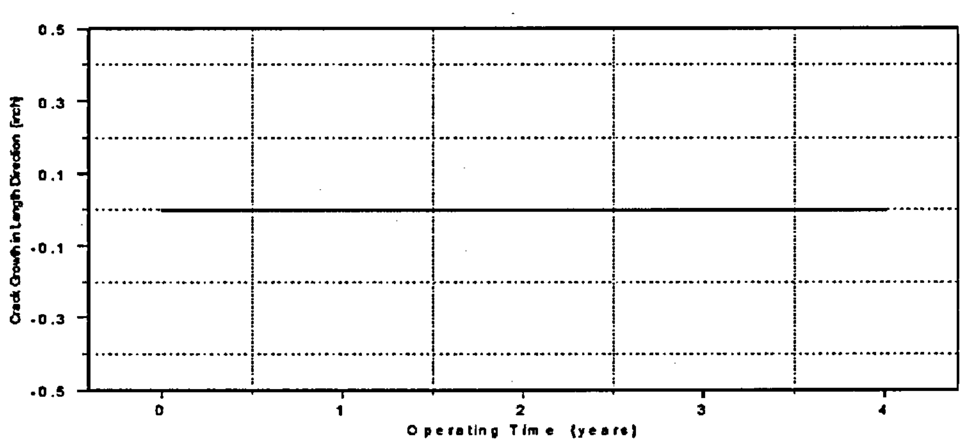
$Prop_{Length} = 0.506$



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

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

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



Typical Axum graphics for use in the report.

End of the Mathcad worksheet Description

Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw

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

Refrences :

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

Waterford Steam Electric Station Unit 3

Component : Reactor Vessel CEDM -"8.8" Degree Nozzle, "0" Degree Azimuth, 1.544" above Nozzle Bottom

Calculation Basis: MRP 75 th Percentile and Flaw Face Pressurized

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

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

OD Surface Flaw

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

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

$$Ref_{Point} := 1.544$$

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

$$Val := 1$$

Input Data :-

$L := 0.3966$	Initial Flaw Length
$a_0 := 0.0661$	Initial Flaw Depth
$od := 4.05$	Tube OD
$id := 2.728$	Tube ID
$P_{Int} := 2.235$	Design Operating Pressure (internal)
$Years := 4$	Number of Operating Years
$I_{lim} := 1500$	Iteration limit for Crack Growth loop
$T := 604$	Estimate of Operating Temperature
$\alpha_{0c} := 2.67 \cdot 10^{-12}$	Constant in MRP PWSCC Model for I-600 Wrought @ 617 deg. F
$Q_g := 31.0$	Thermal activation Energy for Crack Growth {MRP}
$T_{ref} := 617$	Reference Temperature for normalizing Data deg. F

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

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

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

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

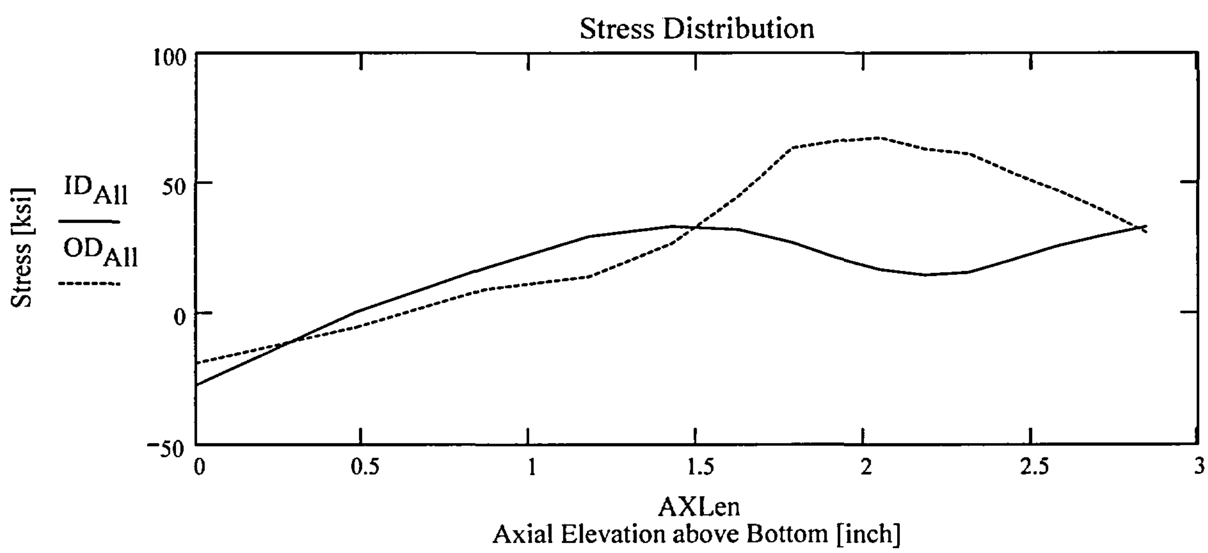
Stress Input Data

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

AllData :=

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

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



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

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

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

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

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

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

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

No User Input is required beyond this Point

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

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

$Loc_0 := FL_{Cntr} - L$

$i := 1..N+3$

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

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

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

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

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

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

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

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

$j := 1..N$

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

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

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

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

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

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

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

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

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

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

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

$SIG_3 := stack(S_{od_3}, S_{tq_3}, S_{md_3}, S_{qt_3}, S_{id_3})$

$SIG_4 := stack(S_{od_4}, S_{tq_4}, S_{md_4}, S_{qt_4}, S_{id_4})$

$SIG_5 := stack(S_{od_5}, S_{tq_5}, S_{md_5}, S_{qt_5}, S_{id_5})$

$SIG_6 := stack(S_{od_6}, S_{tq_6}, S_{md_6}, S_{qt_6}, S_{id_6})$

$SIG_7 := stack(S_{od_7}, S_{tq_7}, S_{md_7}, S_{qt_7}, S_{id_7})$

$SIG_8 := stack(S_{od_8}, S_{tq_8}, S_{md_8}, S_{qt_8}, S_{id_8})$

$SIG_9 := stack(S_{od_9}, S_{tq_9}, S_{md_9}, S_{qt_9}, S_{id_9})$

$SIG_{10} := stack(S_{od_{10}}, S_{tq_{10}}, S_{md_{10}}, S_{qt_{10}}, S_{id_{10}})$

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

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

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

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

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

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

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

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

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

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

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

$ODRG_1 := regress(Y, SIG_1, 3)$

$ODRG_2 := regress(Y, SIG_2, 3)$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$Prop_{Length} = 0.242$

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

Data Tables for External falws from Reference 1

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

Jsb :=

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

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

Sambi :=

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

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

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

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

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

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

"a-Tip" Uniform Term

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

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

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

Linear Term

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

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

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

Quadratic Term

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

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

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

Cubic Term

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

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

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

"C" Tip Coefficients

Uniform Term

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

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

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

Linear Term

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

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

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

Quadratic Term

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

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

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

Cubic Term

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

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

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

Calculations : Recursive calculations to estimate flaw growth

Calculations : Recursive calculations to estimate flaw growth.

Recursive Loop for Calculation of PWSCC Crack Growth Entergy Model

$CGR_{sambi} :=$

$j \leftarrow 0$

$a_0 \leftarrow a_0$

$c_0 \leftarrow c_0$

$NCB_0 \leftarrow C_{blk}$

while $j \leq I_{lim}$

$\sigma_0 \leftarrow$

$ODRG1_3$ if $c_j \leq c_0$

$ODRG2_3$ if $c_0 < c_j \leq c_0 + Inc_{Strs.avg}$

$ODRG3_3$ if $c_0 + Inc_{Strs.avg} < c_j \leq c_0 + 2 \cdot Inc_{Strs.avg}$

$ODRG4_3$ if $c_0 + 2 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 3 \cdot Inc_{Strs.avg}$

$ODRG5_3$ if $c_0 + 3 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 4 \cdot Inc_{Strs.avg}$

$ODRG6_3$ if $c_0 + 4 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 5 \cdot Inc_{Strs.avg}$

$ODRG7_3$ if $c_0 + 5 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 6 \cdot Inc_{Strs.avg}$

$ODRG8_3$ if $c_0 + 6 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 7 \cdot Inc_{Strs.avg}$

$ODRG9_3$ if $c_0 + 7 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 8 \cdot Inc_{Strs.avg}$

$ODRG10_3$ if $c_0 + 8 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 9 \cdot Inc_{Strs.avg}$

$ODRG11_3$ if $c_0 + 9 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 10 \cdot Inc_{Strs.avg}$

$ODRG12_3$ if $c_0 + 10 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 11 \cdot Inc_{Strs.avg}$

$ODRG13_3$ if $c_0 + 11 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 12 \cdot Inc_{Strs.avg}$

$ODRG14_3$ if $c_0 + 12 \cdot Inc_{Strs.avg} < c_j \leq c_0 + 13 \cdot Inc_{Strs.avg}$

ODRG if $c_0 + 13 \cdot Inc$ $< c_j \leq c_0 + 14 \cdot Inc$

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

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

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

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

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

$$ODRG_{20_3} \text{ otherwise}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$ODRG_{20_4}$ otherwise

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$ODRG_{18_5}$ if $c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$

$$ODRG_{18_5} \text{ if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$

$$ODRG_{19_5} \text{ if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$$

$$ODRG_{20_5} \text{ otherwise}$$

$$\sigma_3 \leftarrow ODRG_{1_6} \text{ if } c_j \le c_0$$

$$ODRG_{2_6} \text{ if } c_0 < c_j \le c_0 + Inc_{Strs.avg}$$

$$ODRG_{3_6} \text{ if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$$

$$ODRG_{4_6} \text{ if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$$

$$ODRG_{5_6} \text{ if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$$

$$ODRG_{6_6} \text{ if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$$

$$ODRG_{7_6} \text{ if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$$

$$ODRG_{8_6} \text{ if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$$

$$ODRG_{9_6} \text{ if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$$

$$ODRG_{10_6} \text{ if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$$

$$ODRG_{11_6} \text{ if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$$

$$ODRG_{12_6} \text{ if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$$

$$ODRG_{13_6} \text{ if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$$

$$ODRG_{14_6} \text{ if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$$

$$ODRG_{15_6} \text{ if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$$

$$ODRG_{16_6} \text{ if } c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$$

$$ODRG_{17_6} \text{ if } c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$$

$$ODRG_{18_6} \text{ if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$

$$ODRG_{19_6} \text{ if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$$

$ODRG20_6$ otherwise

$\xi_0 \leftarrow \sigma_0$

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

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

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

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

$x_0 \leftarrow 0.0$

$x_1 \leftarrow 0.25$

$x_2 \leftarrow 0.5$

$x_3 \leftarrow 0.75$

$x_4 \leftarrow 1.0$

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

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

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

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

$\sigma_{10} \leftarrow RG_4$

$\sigma_{20} \leftarrow RG_5$

$\sigma_{30} \leftarrow RG_6$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$D_{ag_j} \leftarrow \left| D_{a_j}\cdot CF_{inhr}\cdot C_{blk} \quad \text{if } K_{\alpha_j} < 80.0\right.$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$j \leftarrow j + 1$

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

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

cg_{j-1}

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

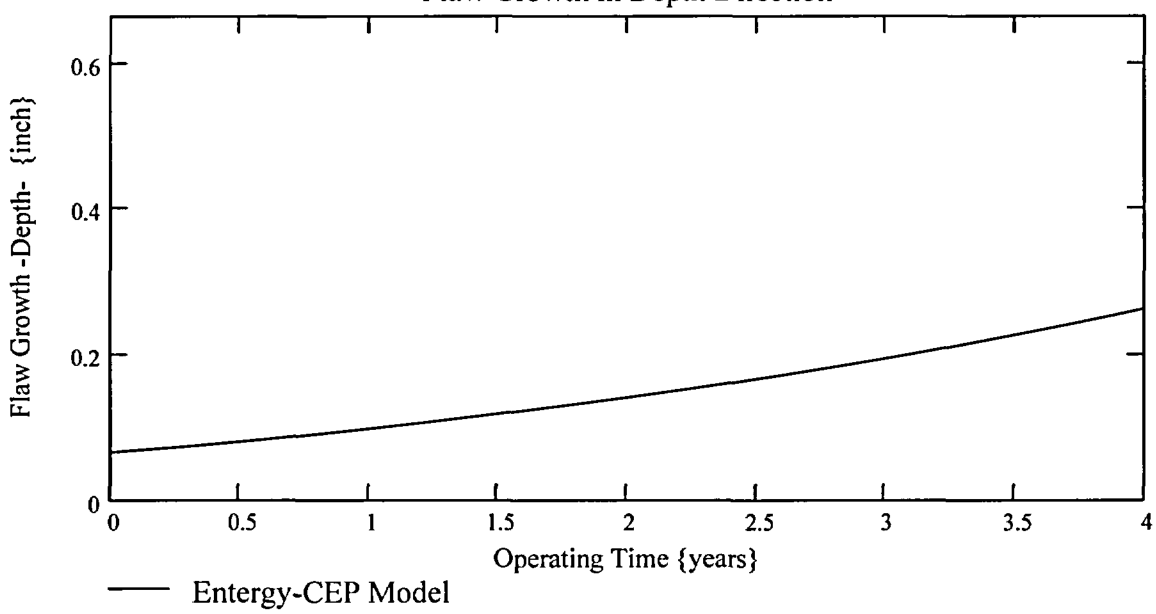
$NCB_j \leftarrow NCB_{j-1} + C_{blk}$

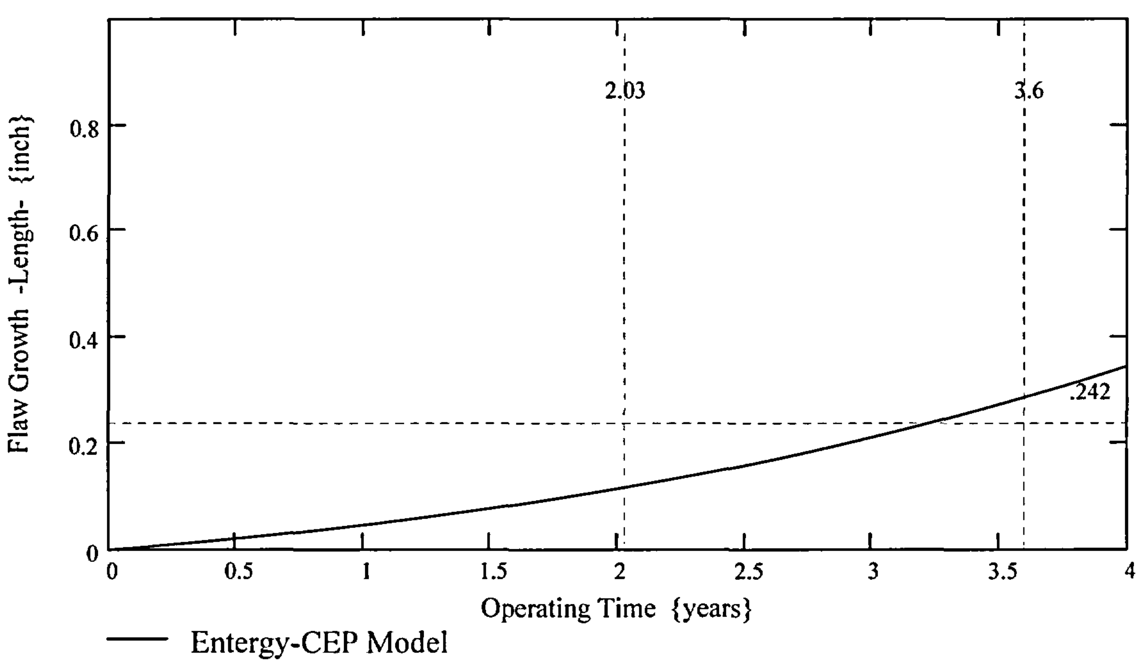
output

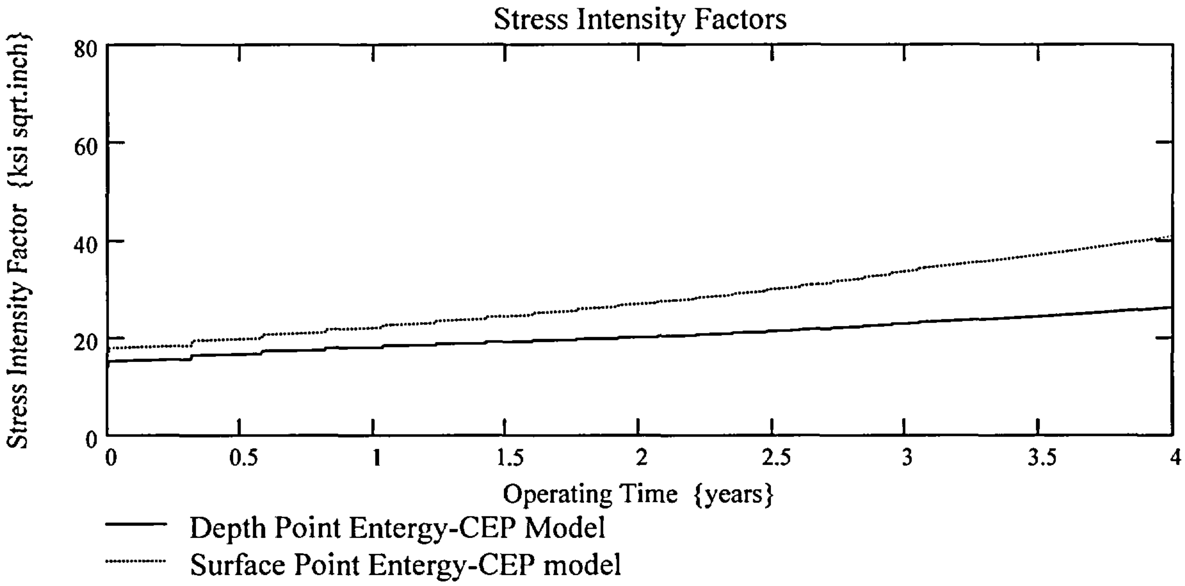
$k := 0..I_{lim}$

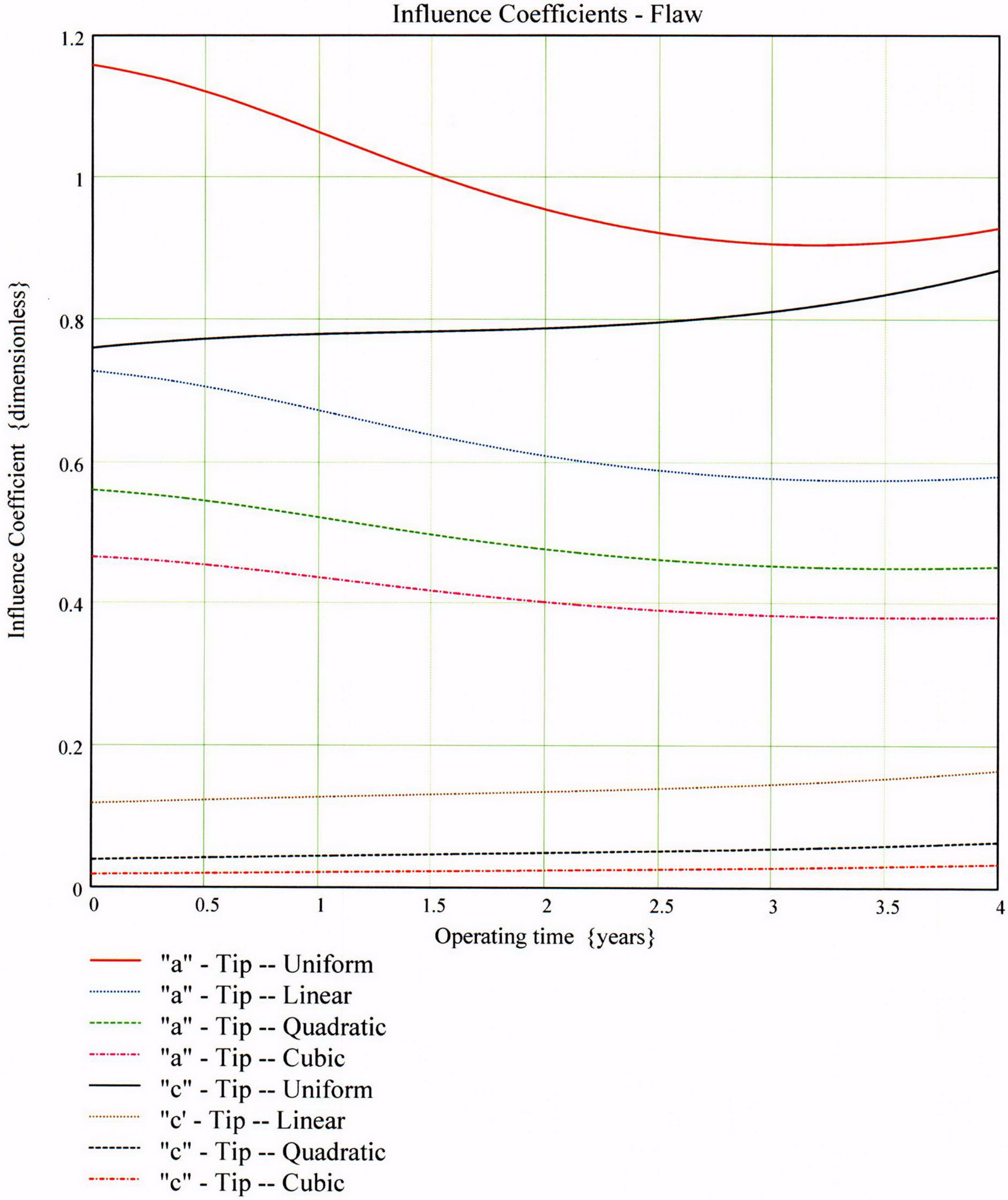
$Prop_{Length} = 0.242$

Flaw Growth in Depth Direction






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


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

C19

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

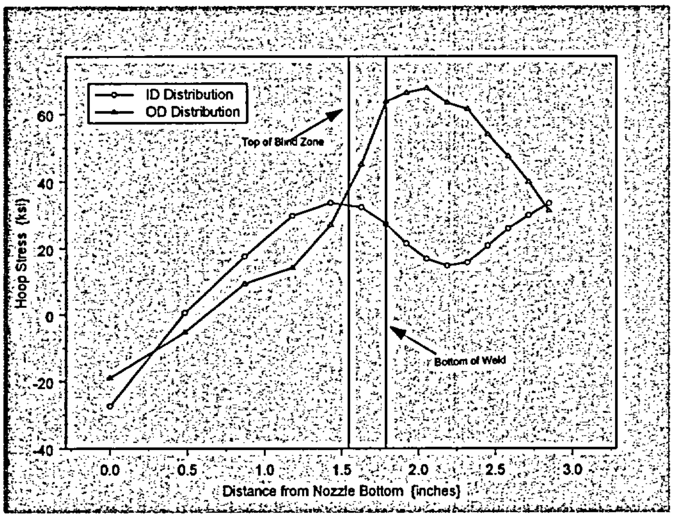
1.158
1.158
1.158
1.158
1.158
1.158
1.158
1.157
1.157
1.157
1.157
1.157
1.157
1.156
1.156
1.156

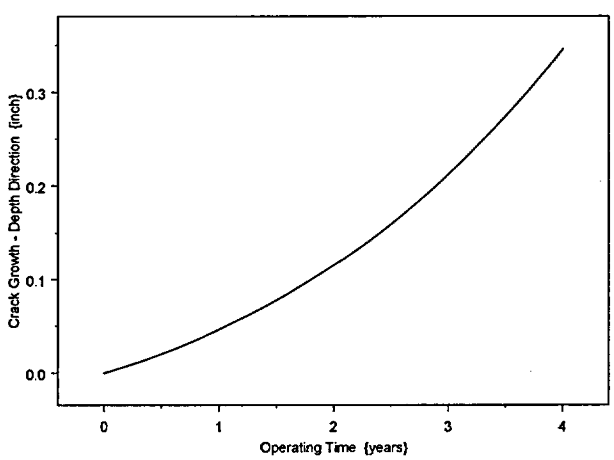
$CGR_{sambi_{(k,6)}} =$

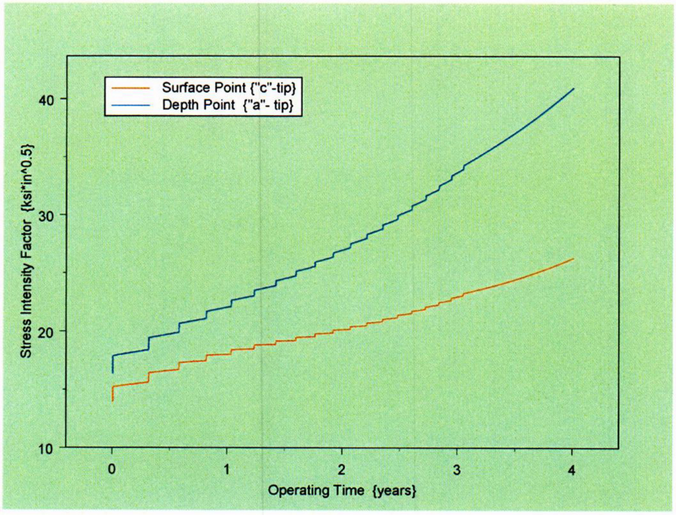
16.383
17.9
17.905
17.91
17.915
17.919
17.924
17.929
17.934
17.939
17.943
17.948
17.953
17.958
17.962
17.967

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

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


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


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


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

C20