## 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] |
|---|---|---|---|
| Length from bottom of nozzle to top of thread relief counterbore (includes 1 inch thread length plus ¼ inch thread relief counterbore) | Drawing M-2001-C2-23 revision 4 (CE drawing E-234-760-2) ANO-2<br>E-74170-112-01 WSES-3 | 1.25 inches | Site Design Engineering:<br>ANO: Jamie GoBell 5/8/03<br>WSES3: |
| Maximum Chamfer Dimension along the axis of the nozzle, including 1/32" tolerance | Same Drawing as above | 0.094 inches | Site Design Engineering.<br>ANO: Jamie GoBell 5/8/03<br>WSES3: |
| 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<br>ANO:<br>WSES3: |
| Residual Stress Distribution | DEI calculations :<br>C-7736-00-5 ANO-2<br>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} | Drawing M-2001-C2-23 revision 4 (CE drawing E-234-760-2) ANO-2<br>E-74170-112-01 WSES-3 | OD = 4.05"; ID = 2.719"<br>OD = 4.05"; ID = 2.719" | Site Design Engineering:<br>ANO: Jamie GoBell 5/8/03<br>WSE3: |

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).

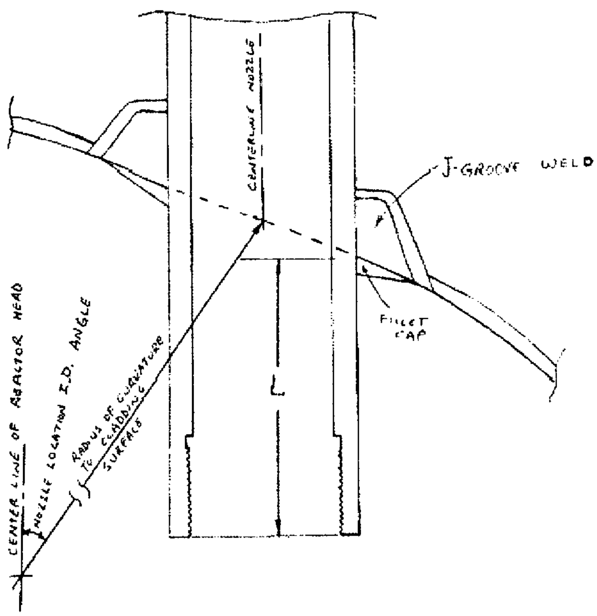
Using ANO drawings M-2001-C2-23, M-2001-C2-26, M-2001-C2-32, M-2001-C2-55, and M-2001-C2-107, and Waterford drawings 1564-506, 1564-1036, and 1564-4086, the length "L" was calculated as shown in the following table:

| 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
CENTER LINE OF REACTOR HEAD
NOZZLE LOCATION I.D. ANGLE
RADIUS OF CURVATURE TO CLADDING SURFACE

# ANO-2 UT Data Measurements

**UT data obtained during last Refueling Outage**
**(April 2002)**
**Data from review of Zero degree UT Scan**

**CEDM Dimensions taken from the 0 degree UT data on the ANO-2 RPV Head**

| OZZLE # eld | | Dead Zone to Bottom of Fillet | Dead Zone to Top of J- |
|---|---|---|---|
| 1 | | 0.32" | 1.24" |
| | On nozzle #1, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable. | | |
| 2 | Low HS | 0.24" | 1.20" |
| | High HS | 0.84" | 1.84" |
| 3 | Low HS | 0.16" | 1.24" |
| | High HS | 0.92" | 1.88" |
| 4 | Low HS | 0.18" | 1.24" |
| | High HS | 0.80" | 1.92" |
| 5 | Low HS | 0.32" | 1.24" |
| | High HS | 1.00" | 1.96" |
| 6 | Low HS | 0.44" | 1.40" |
| | High HS | 1.32" | 2.36" |
| 7 | Low HS | 0.32" | 1.52" |
| | High HS | 1.24" | 2.36" |
| 8 | Low HS | 0.20" | 1.44" |
| | High HS | 1.12" | 2.28" |
| 9 | Low HS | 0.48" | 1.52" |
| | High HS | 1.44" | 2.48" |
| 10 | Low HS | 0.12" | 1.60" |
| | High HS | 1.68" | 2.68" |
| | On nozzle #10, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable. | | |
| 11 | Low HS | 0.16" | 1.52" |
| | High HS | 1.64" | 2.76" |
| 12 | Low HS | 0.16" | 1.36" |

| | | | |
|---|---|---|---|
| | High HS | 1.52" | 2.80" |

On nozzle #12, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable.

| | | | |
|---|---|---|---|
| 13 | Low HS | 0.16" | 1.56" |
| | High HS | 1.68" | 2.80" |

On nozzle #13, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable.

| | | | |
|---|---|---|---|
| 14 | Low HS | 0.0" | 1.08" |
| | High HS | 1.40" | 2.48" |

On nozzle #14, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable.

| | | | |
|---|---|---|---|
| 15 | Low HS | 0.16" | 1.60" |
| | High HS | 1.92" | 3.08" |
| 16 | Low HS | 0.12" | 1.44" |
| | High HS | 1.84" | 3.04" |
| 17 | Low HS | 0.08" | 1.44" |
| | High HS | 1.80" | 3.04" |
| 18 | Low HS | 0.24" | 1.48" |
| | High HS | 1.76" | 3.08" |
| 19 | Low HS | 0.16" | 1.52" |
| | High HS | 1.76" | 3.16" |
| 20 | Low HS | 0.48" | 1.52" |
| | High HS | 1.88" | 3.08" |
| 21 | Low HS | 0.24" | 1.44" |
| | High HS | 1.92" | 2.92" |

On nozzle #21, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable.

| | | | |
|---|---|---|---|
| 22 | Low HS | 0.12" | 1.48" |
| | High HS | 2.32" | 3.56" |
| 23 | Low HS | 0.0" | 1.32" |
| | High HS | 2.36" | 3.56" |
| 24 | Low HS | 0.12" | 1.32" |
| | High HS | 2.28" | 3.32" |

| | | | |
|---|---|---|---|
| 25 | Low HS | 0.28" | 1.56" |
| | High HS | 2.44" | 3.60" |
| 26 | Low HS | 0.08" | 1.36" |
| | High HS | 2.44" | 3.56" |
| 27 | Low HS | 0.0" | 1.72" |
| | High HS | 2.52" | 3.64" |
| 28 | Low HS | 0.24" | 1.48" |
| | High HS | 2.36" | 3.76" |
| 29 | Low HS | 0.16" | 1.60" |
| | High HS | 2.56" | 3.84" |
| 30 | Low HS | 0.16" | 1.36" |
| | High HS | 2.48" | 3.76" |
| 31 | Low HS | 0.20" | 1.32" |
| | High HS | 2.56" | 3.56" |
| 32 | Low HS | 0.16" | 1.24" |
| | High HS | 2.60" | 3.64" |
| 33 | Low HS | 0.0" | 1.40" |
| | High HS | 2.24" | 3.72" |
| 34 | Low HS | 0.20" | 1.08" |
| | High HS | 2.12" | 3.68" |
| 35 | Low HS | 0.16" | 1.40" |
| | High HS | 2.76" | 3.88" |
| 36 | Low HS | 0.04" | 1.60" |
| | High HS | 2.48" | 3.80" |
| 37 | Low HS | 0.24" | 1.52" |
| | High HS | 2.68" | 4.00" |
| | No A-Scan data present for nozzle #37 | | |
| 38 | Low HS | 0.0" | 1.20" |
| | High HS | 3.16" | 4.32" |
| 39 | Low HS | 0.0" | 1.08" |
| | High HS | 2.68" | 4.16" |

| | | | |
|---|---|---|---|
| 40 | Low HS | 0.0" | 1.04" |
| | High HS | 2.60" | 4.04" |
| 41 | Low HS | 0.0" | 1.00" |
| | High HS | 2.84" | 4.24" |
| 42 | Low HS | 0.0" | 1.08" |
| | High HS | 2.72" | 4.04" |
| 43 | Low HS | 0.0" | 1.36" |
| | High HS | ?? (probe lift-off) | 4.28" |
| 44 | Low HS | 0.08" | 1.32" |
| | High HS | 3.20" | 4.40" |
| 45 | Low HS | 0.0" | 1.12" |
| | High HS | 3.00" | 4.24" |
| 46 | Low HS | 0.0" | 1.08" |
| | High HS | 2.92" | 4.40" |
| 47 | Low HS | 0.0" | 1.04" |
| | High HS | 3.16" | 4.28" |
| 48 | CD BLANK/ NO DATA AVAILABLE | | |
| 49 | CD BLANK/ NO DATA AVAILABLE | | |
| 50 | CD BLANK/ NO DATA AVAILABLE | | |
| 51 | Low HS | 0.0" | 1.04" |
| | High HS | 2.96" | 4.56" |
| 52 | Low HS | 0.0" | 1.16" |
| | High HS | 3.40" | 4.60" |
| 53 | FAULTY CD/ NO DATA AVAILABLE | | |
| 54 | Low HS | 0.0" | 1.04" |
| | High HS | 3.16" | 4.64" |
| 55 | Low HS | 0.0" | 1.12" |
| | High HS | 3.28" | 4.72" |
| 56 | Low HS | 0.0" | 1.40" |
| | High HS | 3.36" | 4.76" |
| 57 | Low HS | 0.0" | 1.16" |

| | | | |
|---|---|---|---|
| | High HS | 3.28" | 4.64" |
| 58 | Low HS | 0.16" | 1.12" |
| | High HS | 3.60" | 4.88" |
| 59 | Low HS | 0.08" | 1.12" |
| | High HS | 3.44" | 4.68" |
| 60 | Low HS | 0.08" | 0.96" |
| | High HS | 3.40" | 4.64" |
| 61 | Low HS | 0.0" | 1.28" |
| | High HS | 3.64" | 4.92" |
| 62 | Low HS | 0.0" | 1.00" |
| | High HS | 3.84" | 5.12" |
| | On nozzle #62, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable | | |
| 63 | Low HS | 0.04" | 1.16" |
| | High HS | 3.76" | 5.08" |
| 64 | Low HS | 0.04" | 0.96" |
| | High HS | ?? (probe lift-off) | 5.08" |
| 65 | Low HS | 0.0" | 1.00" |
| | High HS | 3.76" | 4.96" |
| 66 | Low HS | 0.0" | 1.00" |
| | High HS | 3.72" | 4.88" |
| 67 | Low HS | 0.08" | 1.56" |
| | High HS | 3.92" | 5.44" |
| 68 | Low HS | 0.0" | 1.52" |
| | High HS | 3.84" | 5.32" |
| 69 | Low HS | 0.0" | 1.36" |
| | High HS | 3.88" | 5.20" |
| 70 | Low HS | 0.0" | 1.44" |
| | High HS | 5.04" | 6.52" |
| 71 | Low HS | 0.0" | 1.32" |
| | High HS | 5.04" | 6.52" |

| | | | |
|---|---|---|---|
| 72 | Low HS | 0.0" | 1.32" |
| | High HS | 5.08" | 6.52" |
| 73 | Low HS | 0.0" | 1.20" |
| | High HS | 5.00" | 6.44" |
| 74 | Low HS | 0" | ~~1.88"~~ 1.20" |
| | High HS | 5.12" | 6.28" |
| 75 | Low HS | 0" | 1.20" |
| | High HS | 5.00" | 6.40" |
| 76 | Low HS | 0.0" | 1.60" |
| | High HS | 4.64" | 6.52" |
| 77 | Low HS | 0.0" | 1.52" |
| | High HS | 5.20" | 6.44" |
| | On nozzle #77, the dead zone is not visible on this data, so the accuracy of these dimensions are questionable | | |
| 78 | Low HS | 0.0" | 1.48" |
| | High HS | 5.16" | 6.68" |
| 79 | Low HS | 0.0" | 1.64" |
| | High HS | 4.96" | 6.52" |
| 80 | Low HS | 0.0" | 1.44" |
| | High HS | 4.96" | 6.52" |
| 81 | Low HS | 0" | 1.56" |
| | High HS | 5.08" | 6.48" |

# Analysis of UT information and Information from Design Drawings

1) Comparison of Freespan length to develop as-built nozzle configuration for Finite Element Model.
2) Development of nozzle dimension and fillet weld profile.

Analysis sequence:

1) Using design drawing information and blind zone elevation of 1.544 inch, determine design based freespan length.
2) Compare the as-designed freespan length with UT measured freespan length at both the downhill and uphill locations.
3) Record the differences.
4) Based on an evaluation of the differences, develop nozzle dimension and expected fillet weld profile.
5) Develop nozzle configuration for FEA model.

# Design Analysis Information

## 0° Nozzle

| | | | | | | |
|---|---|---|---|---|---|---|
| As Designed Length | All HS | 1.21 | Bottom | 0.56 | Top | 1.77 |

## 8.8° Nozzle

| | | |
|---|---|---|
| As Designed Bottom | Low HS | 0.54 |
| | High HS | 1.17 |
| As Designed Top | Low HS | 1.73 |
| | High HS | 2.41 |
| As Designed Length | Low HS | 1.19 |
| | High HS | 1.24 |

## 28.8° Nozzle

| | | |
|---|---|---|
| As Designed Bottom | Low HS | 0.44 |
| | High HS | 2.69 |
| As Designed Top | Low HS | 1.64 |
| | High HS | 4.09 |
| As Designed Length | Low HS | 1.19 |
| | High HS | 1.40 |

## 49.6° Nozzle

| | | |
|---|---|---|
| As Designed Bottom | Low HS | 0.21 |
| | High HS | 5.05 |
| As Designed Top | Low HS | 1.51 |
| | High HS | 6.75 |
| As Designed Length | Low HS | 1.30 |
| | High HS | 1.71 |

## Comparison of UT and design Data

| **0.0° Nozzle** | | Bottom | | Top | | Length | |
|---|---|---|---|---|---|---|---|
| | | Measured | Diff | Measured | Diff | Measured | Diff |
| Nozzle 1 | All HS | 0.32 | -0.24 | 1.24 | -0.53 | 0.92 | -0.29 |

| **8.8° Nozzle** | | Bottom | | Top | | Length | |
|---|---|---|---|---|---|---|---|
| | | Measured | Diff | Measured | Diff | Measured | Diff |
| Nozzle 2 | Low HS | 0.24 | -0.30 | 1.20 | -0.53 | 0.96 | -0.23 |
| | High HS | 0.84 | -0.33 | 1.84 | -0.57 | 1.00 | -0.24 |
| Nozzle 3 | Low HS | 0.16 | -0.38 | 1.24 | -0.49 | 1.08 | -0.11 |
| | High HS | 0.92 | -0.25 | 1.88 | -0.53 | 0.96 | -0.28 |
| Nozzle 4 | Low HS | 0.18 | -0.36 | 1.24 | -0.49 | 1.06 | -0.13 |
| | High HS | 0.80 | -0.37 | 1.92 | -0.49 | 1.12 | -0.12 |
| Nozzle 5 | Low HS | 0.32 | -0.22 | 1.24 | -0.49 | 0.92 | -0.27 |
| | High HS | 1.00 | -0.17 | 1.96 | -0.45 | 0.96 | -0.28 |

1) Note the differences between the bottom and top locations (Diff Column); They are consistent but the differences are 0.33 inch at bottom (both downhill & uphill) and 0.53 inch at the top (both downhill & uphill). This indicates that the nozzle may be shorter.
2) The average between the differences is about 0.4 inch, hence a nozzle that is shorter by 0.4 inches would minimize the differences between the as-designed and UT measurements.
3) The measurement for weld length (diff. in Length column) is small and random; indicating that the weld profile is close to the as-designed condition.
4) A nozzle configuration with a shorter (2.08 inches vs. 2.48 inches) by 0.4 inch with an as-designed weld profile provides the best estimate for the as-built configuration of these two nozzle groups.

**Evaluation of the 28.8° Nozzle Group:**

| **28.8° Nozzle** | | Bottom Measured | Bottom Diff | Top Measured | Top Diff | Length Measured | Length Diff |
|---|---|---|---|---|---|---|---|
| Nozzle 30 | Low HS | 0.16 | -0.28 | 1.36 | -0.28 | 1.20 | 0.01 |
| | High HS | 2.48 | -0.21 | 3.76 | -0.33 | 1.28 | -0.12 |
| Nozzle 31 | Low HS | 0.20 | -0.24 | 1.32 | -0.32 | 1.12 | -0.07 |
| | High HS | 2.56 | -0.13 | 3.56 | -0.53 | 1.00 | -0.40 |
| Nozzle 32 | Low HS | 0.16 | -0.28 | 1.24 | -0.40 | 1.08 | -0.11 |
| | High HS | 2.60 | -0.09 | 3.64 | -0.45 | 1.04 | -0.36 |
| Nozzle 33 | Low HS | 0.00 | -0.44 | 1.40 | -0.24 | 1.40 | **0.21** |
| | High HS | 2.24 | -0.45 | 3.72 | -0.37 | 1.48 | 0.08 |
| Nozzle 34 | Low HS | 0.20 | -0.24 | 1.08 | -0.56 | 0.88 | -0.31 |
| | High HS | 2.12 | -0.57 | 3.68 | -0.41 | 1.56 | **0.16** |
| Nozzle 35 | Low HS | 0.16 | -0.28 | 1.40 | -0.24 | 1.24 | 0.05 |
| | High HS | 2.76 | 0.07 | 3.88 | -0.21 | 1.12 | -0.28 |
| Nozzle 36 | Low HS | 0.04 | -0.40 | 1.60 | -0.04 | 1.56 | **0.37** |
| | High HS | 2.48 | -0.21 | 3.80 | -0.29 | 1.32 | -0.08 |
| Nozzle 37 | Low HS | 0.24 | -0.20 | 1.52 | -0.12 | 1.28 | 0.09 |
| | High HS | 2.68 | -0.01 | 4.00 | -0.09 | 1.32 | -0.08 |

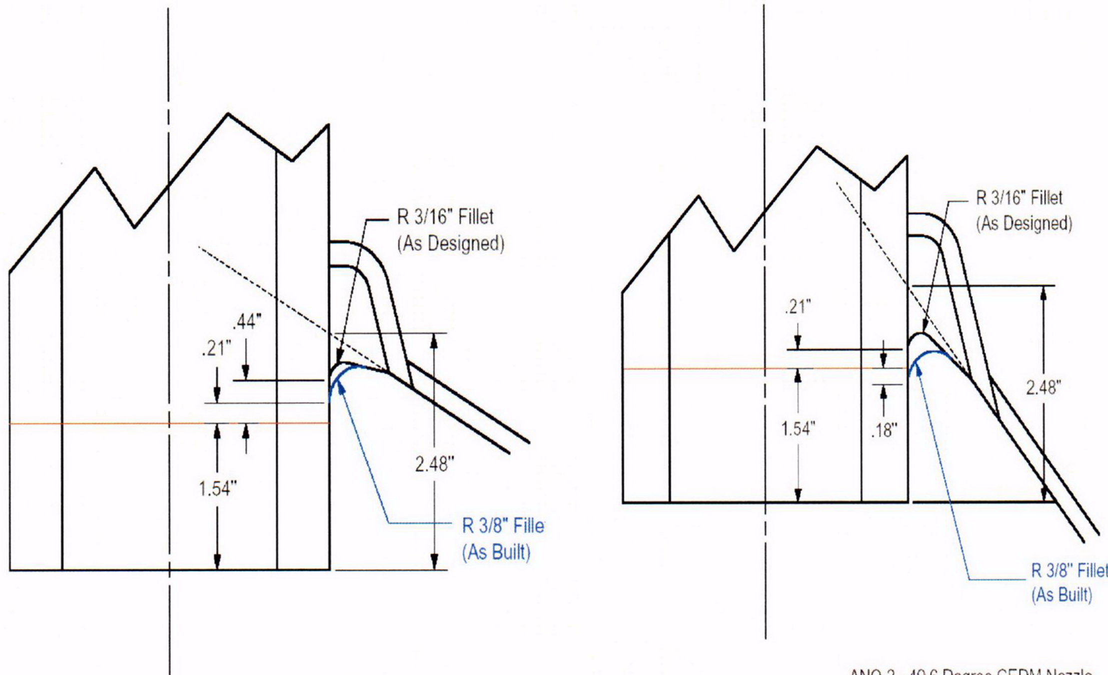
1) Differences between the bottom and top locations are varied.
2) At the downhill (low HS) location the differences between the bottom and top are significant.
3) At the uphill (High HS) location the differences are not very significant.
4) This indicates that the weld profile at the down hill location are different from that at the uphill location.
5) Experience from another CE fabricated RV head indicated that the Fillet weld at the downhill location had a larger radius than specified (⅜ as found vs. 3/16 as-specified).
6) The weld size at the uphill location is close to the as-designed condition.
7) The nozzle lengths appear to be close to the as-designed value of 2.48 inches.
8) A nozzle configuration having a as-designed length, as-designed weld profile at the uphill location, and a larger fillet radius at the downhill location will minimize the observed differences between the as-designed and UT (as-measured) data.

**49.6° Nozzle Group**

| **49.6° Nozzle** | | Bottom Measured | Bottom Diff | Top Measured | Top Diff | Length Measured | Length Diff |
|---|---|---|---|---|---|---|---|
| Nozzle 70 | Low HS | 0.00 | -0.21 | 1.44 | -0.07 | 1.44 | **0.14** |
| | High HS | 5.04 | -0.01 | 6.52 | -0.23 | 1.48 | -0.23 |
| Nozzle 71 | Low HS | 0.00 | -0.21 | 1.32 | -0.19 | 1.32 | 0.02 |
| | High HS | 5.04 | -0.01 | 6.52 | -0.23 | 1.48 | -0.23 |
| Nozzle 72 | Low HS | 0.00 | -0.21 | 1.32 | -0.19 | 1.32 | 0.02 |
| | High HS | 5.08 | 0.03 | 6.52 | -0.23 | 1.44 | -0.27 |
| Nozzle 73 | Low HS | 0.00 | -0.21 | 1.20 | -0.31 | 1.20 | -0.10 |
| | High HS | 5.00 | -0.05 | 6.44 | -0.31 | 1.44 | -0.27 |
| Nozzle 74 | Low HS | 0.00 | -0.21 | 1.20 | -0.31 | 1.20 | -0.10 |
| | High HS | 5.12 | 0.07 | 6.28 | -0.47 | 1.16 | -0.55 |
| Nozzle 75 | Low HS | 0.00 | -0.21 | 1.20 | -0.31 | 1.20 | -0.10 |
| | High HS | 5.00 | -0.05 | 6.40 | -0.35 | 1.40 | -0.31 |
| Nozzle 76 | Low HS | 0.00 | -0.21 | 1.60 | 0.09 | 1.60 | **0.30** |
| | High HS | 4.64 | -0.41 | 6.52 | -0.23 | 1.88 | **0.17** |
| Nozzle 77 | Low HS | | | | | | |
| | High HS | | | | | | |
| Nozzle 78 | Low HS | 0.00 | -0.21 | 1.48 | -0.03 | 1.48 | **0.18** |
| | High HS | 5.16 | 0.11 | 6.68 | -0.07 | 1.52 | -0.19 |
| Nozzle 79 | Low HS | 0.00 | -0.21 | 1.64 | 0.13 | 1.64 | **0.34** |
| | High HS | 4.96 | -0.09 | 6.52 | -0.23 | 1.56 | -0.15 |
| Nozzle 80 | Low HS | 0.00 | -0.21 | 1.44 | -0.07 | 1.44 | **0.14** |
| | High HS | 4.96 | -0.09 | 6.52 | -0.23 | 1.56 | -0.15 |
| Nozzle 81 | Low HS | 0.00 | -0.21 | 1.56 | 0.05 | 1.56 | **0.26** |
| | High HS | 5.08 | 0.03 | 6.48 | -0.27 | 1.40 | -0.31 |

1) Observations are similar to that fro the 28.8° nozzle group. Therefore a similar nozzle configuration would exist.
2) The estimated as-built nozzle configuration for this group is similar to that for the 28.8° nozzle group.
3) Using this approach it is demonstrated that the weld bottom at the downhill location would fall 0.18 inch below the dead zone for this group of nozzles.
4) Sketches in the following pages show the estimated as-built configurations for the 28.8° nozzle group and the 49.6° nozzle group.

**Sketches for Estimated As-Built configuration for the 28.8° and 49.6° nozzle Groups**




ANO 2 - 28.8 Degree CEDM Nozzle

ANO 2 - 49.6 Degree CEDM Nozzle

Sketches showing estimated as-built configurations. The blue lines show the estimated as-built profiles for the weld (fillet cap) at the downhill locatrion.

C14

# Appendix B

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

**This Appendix has three (3) Attachments.**

# ID Surface Flaws



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

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

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

Refrences :

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

**Arkansas Nuclear One Unit 2**

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

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

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

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

**ID Surface Flaw**

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

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 1$$

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

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

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

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

**Input Data :-**

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

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

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

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

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

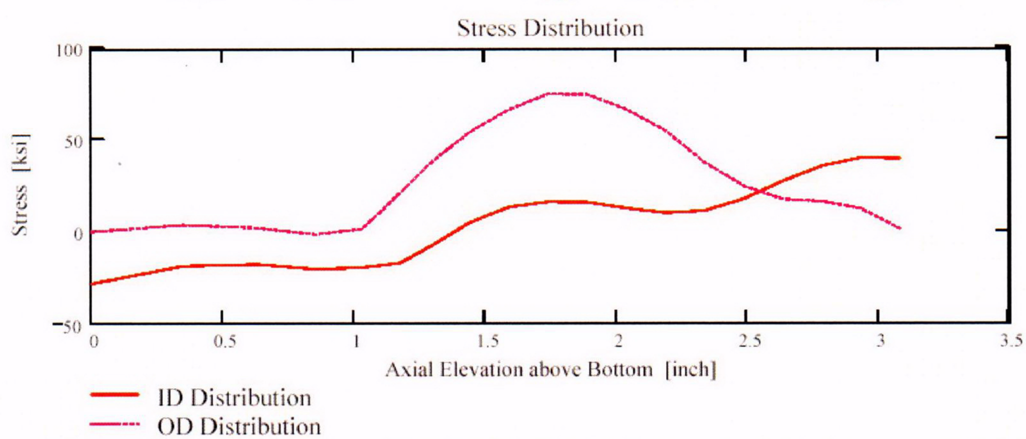
**Stress Input Data**

*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 |

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




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

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

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

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

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

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

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

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

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

Flaw center Location above Nozzle Bottom

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

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

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*

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

$$i := 1..N + 3$$

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

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

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

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

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

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

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

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

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

$j := 1..N$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

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

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

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

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

**"a-Tip" Uniform Term**

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

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

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

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

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 – $\sigma_1$, quadratic- $\sigma_2$ , and cubic - $\sigma_3$). 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 $\sigma_{00}$ 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.

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

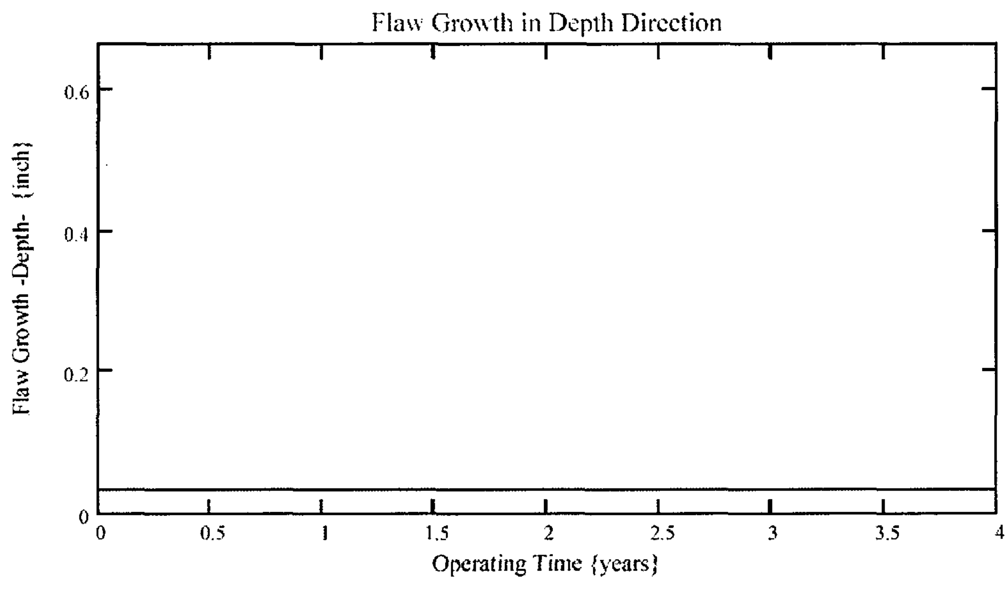
Typical output statements within the recursive loop showing the storing of variables that are required for loop operation and those of interest in displaying the time dependent trend.

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

output

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

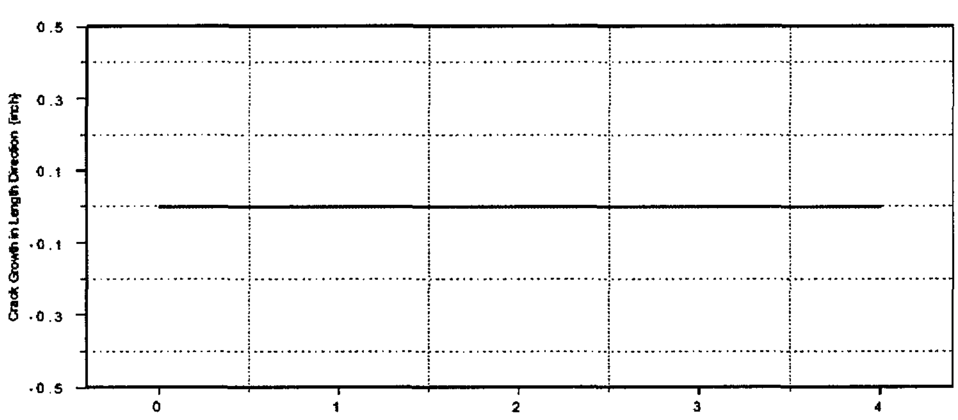
$Prop_{Length} = 0.506$




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

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

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




Typical Axum graphics for use in the report.

## End of the Mathcad worksheet Description

**Primary Water Stress Corrosion Crack Growth Analysis - OD SurfaceFlaw**

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

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

## Arkansas Nuclear One Unit 2

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

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

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

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

**OD Surface Flaw**

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

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

$$Ref_{Point} := 1.544$$

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

$$Val := 1$$

## Input Data :-

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

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

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

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

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

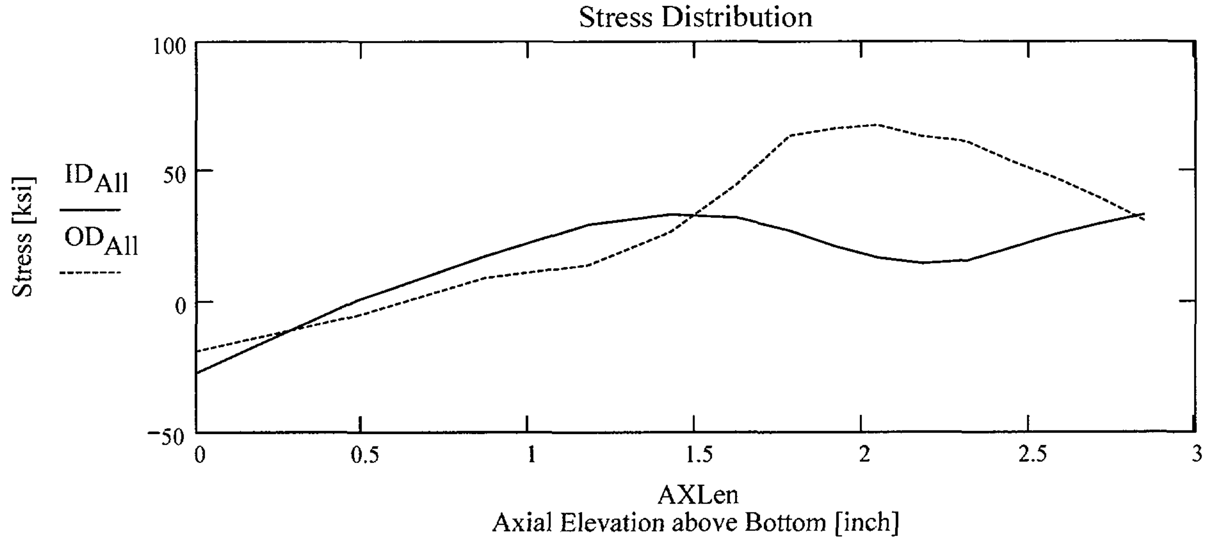
**Stress Input Data**

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

AllData :=

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

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




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

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

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

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

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

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

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

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

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

Flaw center Location Location above Nozzle Bottom

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

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

## No User Input is required beyond this Point

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

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

$Loc_0 := FL_{Cntr} - L$

$i := 1..N+3$

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

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

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

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

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

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

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

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

$j := 1..N$

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

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

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

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

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

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

## 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)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$Prop_{Length} = 0.242$

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

# Data Tables for External falws from Reference 1

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

Jsb :=

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

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

Sambi :=

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

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

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

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

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

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

**"a-Tip" Uniform Term**

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

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

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

**Linear Term**

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

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

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

**Quadratic Term**

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

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

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

**Cubic Term**

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

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

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

**"C" Tip Coefficients**

**Uniform Term**

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

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

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

**Linear Term**

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

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

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

**Quadratic Term**

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

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

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

**Cubic Term**

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

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

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

**Calculations : Recursive calculations to estimate flaw growth**

**Calculations : Recursive calculations to estimate flaw growth.**

**Recursive Loop for Calculation of PWSCC Crack Growth Entergy Model**

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

$$\sigma_0 \leftarrow \left| \begin{array}{ll} ODRG_{1_3} & \text{if } c_j \le c_0 \\ ODRG_{2_3} & \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg} \\ ODRG_{3_3} & \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg} \\ ODRG_{4_3} & \text{if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg} \\ ODRG_{5_3} & \text{if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg} \\ ODRG_{6_3} & \text{if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg} \\ ODRG_{7_3} & \text{if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg} \\ ODRG_{8_3} & \text{if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg} \\ ODRG_{9_3} & \text{if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg} \\ ODRG_{10_3} & \text{if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg} \\ ODRG_{11_3} & \text{if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg} \\ ODRG_{12_3} & \text{if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg} \\ ODRG_{13_3} & \text{if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg} \\ ODRG_{14_3} & \text{if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg} \\ ODRG & \text{if } c_0 + 13 \cdot Inc_{...} < c_j \le c_0 + 14 \cdot Inc_{...} \end{array} \right.$$

$$\text{ODRG}_{15_3} \text{ if } c_0 + 13\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 14\cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{16_3} \text{ if } c_0 + 14\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 15\cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{17_3} \text{ if } c_0 + 15\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 16\cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{18_3} \text{ if } c_0 + 16\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 17\cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{19_3} \text{ if } c_0 + 17\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 18\cdot \text{Inc}_{\text{Strs.avg}}$$

$$\text{ODRG}_{20_3} \text{ otherwise}$$

$$\sigma_1 \leftarrow \begin{cases} \text{ODRG}_{1_4} & \text{if } c_j \le c_0 \\ \text{ODRG}_{2_4} & \text{if } c_0 < c_j \le c_0 + \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{3_4} & \text{if } c_0 + \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 2\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{4_4} & \text{if } c_0 + 2\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 3\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{5_4} & \text{if } c_0 + 3\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 4\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{6_4} & \text{if } c_0 + 4\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 5\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{7_4} & \text{if } c_0 + 5\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 6\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{8_4} & \text{if } c_0 + 6\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 7\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{9_4} & \text{if } c_0 + 7\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 8\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{10_4} & \text{if } c_0 + 8\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 9\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{11_4} & \text{if } c_0 + 9\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 10\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{12_4} & \text{if } c_0 + 10\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 11\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{13_4} & \text{if } c_0 + 11\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 12\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{14_4} & \text{if } c_0 + 12\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 13\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{15_4} & \text{if } c_0 + 13\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 14\cdot \text{Inc}_{\text{Strs.avg}} \\ \text{ODRG}_{16_4} & \text{if } c_0 + 14\cdot \text{Inc}_{\text{Strs.avg}} < c_j \le c_0 + 15\cdot \text{Inc}_{\text{Strs.avg}} \end{cases}$$

$$ODRG17_4 \quad \text{if } c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$$

$$ODRG18_4 \quad \text{if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$

$$ODRG19_4 \quad \text{if } c_0 + 17 \cdot Inc_{Strs.avg} < c_j \le c_0 + 18 \cdot Inc_{Strs.avg}$$

$$ODRG20_4 \quad \text{otherwise}$$

$$\sigma_2 \leftarrow \; ODRG1_5 \quad \text{if } c_j \le c_0$$

$$ODRG2_5 \quad \text{if } c_0 < c_j \le c_0 + Inc_{Strs.avg}$$

$$ODRG3_5 \quad \text{if } c_0 + Inc_{Strs.avg} < c_j \le c_0 + 2 \cdot Inc_{Strs.avg}$$

$$ODRG4_5 \quad \text{if } c_0 + 2 \cdot Inc_{Strs.avg} < c_j \le c_0 + 3 \cdot Inc_{Strs.avg}$$

$$ODRG5_5 \quad \text{if } c_0 + 3 \cdot Inc_{Strs.avg} < c_j \le c_0 + 4 \cdot Inc_{Strs.avg}$$

$$ODRG6_5 \quad \text{if } c_0 + 4 \cdot Inc_{Strs.avg} < c_j \le c_0 + 5 \cdot Inc_{Strs.avg}$$

$$ODRG7_5 \quad \text{if } c_0 + 5 \cdot Inc_{Strs.avg} < c_j \le c_0 + 6 \cdot Inc_{Strs.avg}$$

$$ODRG8_5 \quad \text{if } c_0 + 6 \cdot Inc_{Strs.avg} < c_j \le c_0 + 7 \cdot Inc_{Strs.avg}$$

$$ODRG9_5 \quad \text{if } c_0 + 7 \cdot Inc_{Strs.avg} < c_j \le c_0 + 8 \cdot Inc_{Strs.avg}$$

$$ODRG10_5 \quad \text{if } c_0 + 8 \cdot Inc_{Strs.avg} < c_j \le c_0 + 9 \cdot Inc_{Strs.avg}$$

$$ODRG11_5 \quad \text{if } c_0 + 9 \cdot Inc_{Strs.avg} < c_j \le c_0 + 10 \cdot Inc_{Strs.avg}$$

$$ODRG12_5 \quad \text{if } c_0 + 10 \cdot Inc_{Strs.avg} < c_j \le c_0 + 11 \cdot Inc_{Strs.avg}$$

$$ODRG13_5 \quad \text{if } c_0 + 11 \cdot Inc_{Strs.avg} < c_j \le c_0 + 12 \cdot Inc_{Strs.avg}$$

$$ODRG14_5 \quad \text{if } c_0 + 12 \cdot Inc_{Strs.avg} < c_j \le c_0 + 13 \cdot Inc_{Strs.avg}$$

$$ODRG15_5 \quad \text{if } c_0 + 13 \cdot Inc_{Strs.avg} < c_j \le c_0 + 14 \cdot Inc_{Strs.avg}$$

$$ODRG16_5 \quad \text{if } c_0 + 14 \cdot Inc_{Strs.avg} < c_j \le c_0 + 15 \cdot Inc_{Strs.avg}$$

$$ODRG17_5 \quad \text{if } c_0 + 15 \cdot Inc_{Strs.avg} < c_j \le c_0 + 16 \cdot Inc_{Strs.avg}$$

$$ODRG18_5 \quad \text{if } c_0 + 16 \cdot Inc_{Strs.avg} < c_j \le c_0 + 17 \cdot Inc_{Strs.avg}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$ODRG20_6$ otherwise

$\xi_0 \leftarrow \sigma_0$

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

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

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

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

$x_0 \leftarrow 0.0$

$x_1 \leftarrow 0.25$

$x_2 \leftarrow 0.5$

$x_3 \leftarrow 0.75$

$x_4 \leftarrow 1.0$

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

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

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

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

$\sigma_{10} \leftarrow RG_4$

$\sigma_{20} \leftarrow RG_5$

$\sigma_{30} \leftarrow RG_6$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$j \leftarrow j + 1$

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

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

$$\ldots cg_{j-1}$$

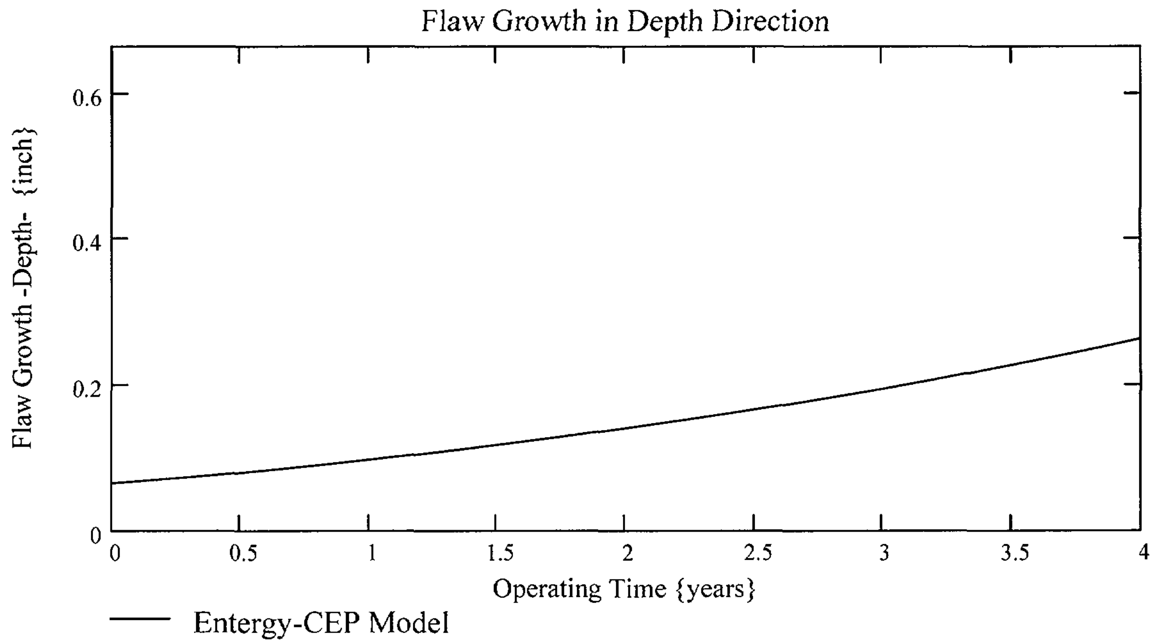
$$a_j \leftarrow \begin{cases} t & \text{if } a_j \geq t \\ a_j & \text{otherwise} \end{cases}$$

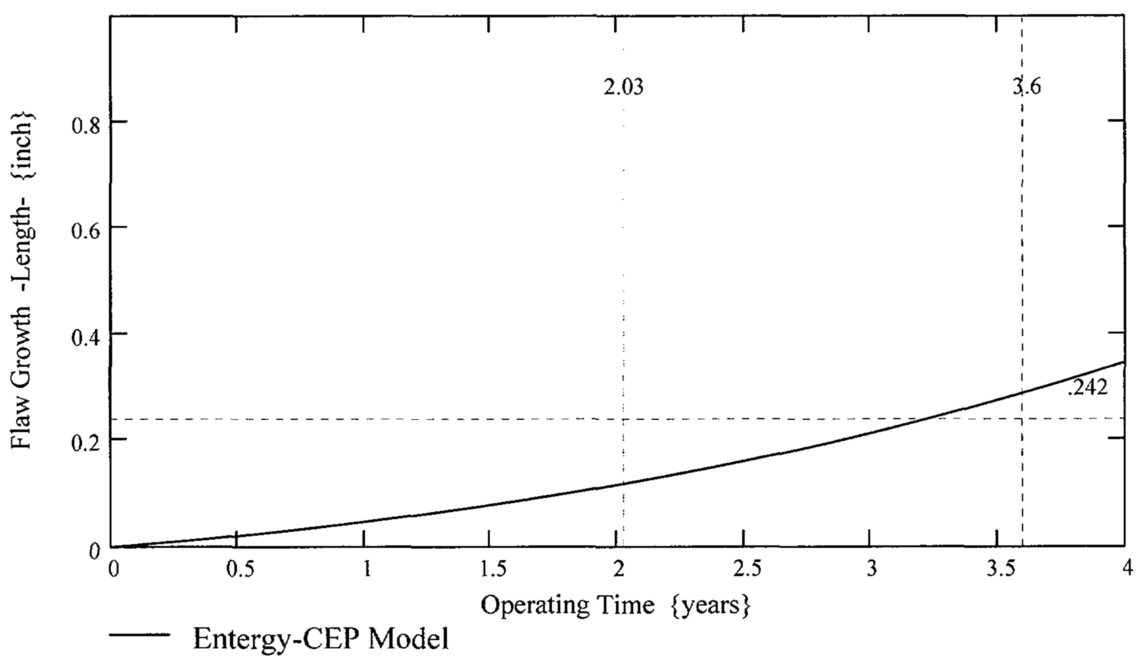
$$NCB_j \leftarrow NCB_{j-1} + C_{blk}$$

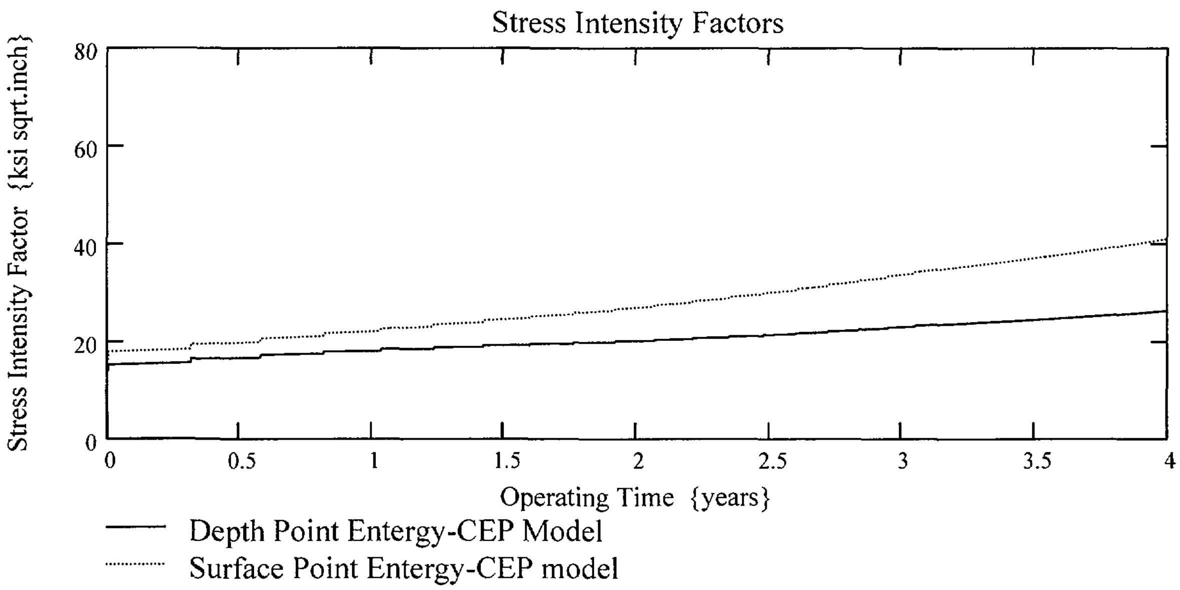
output

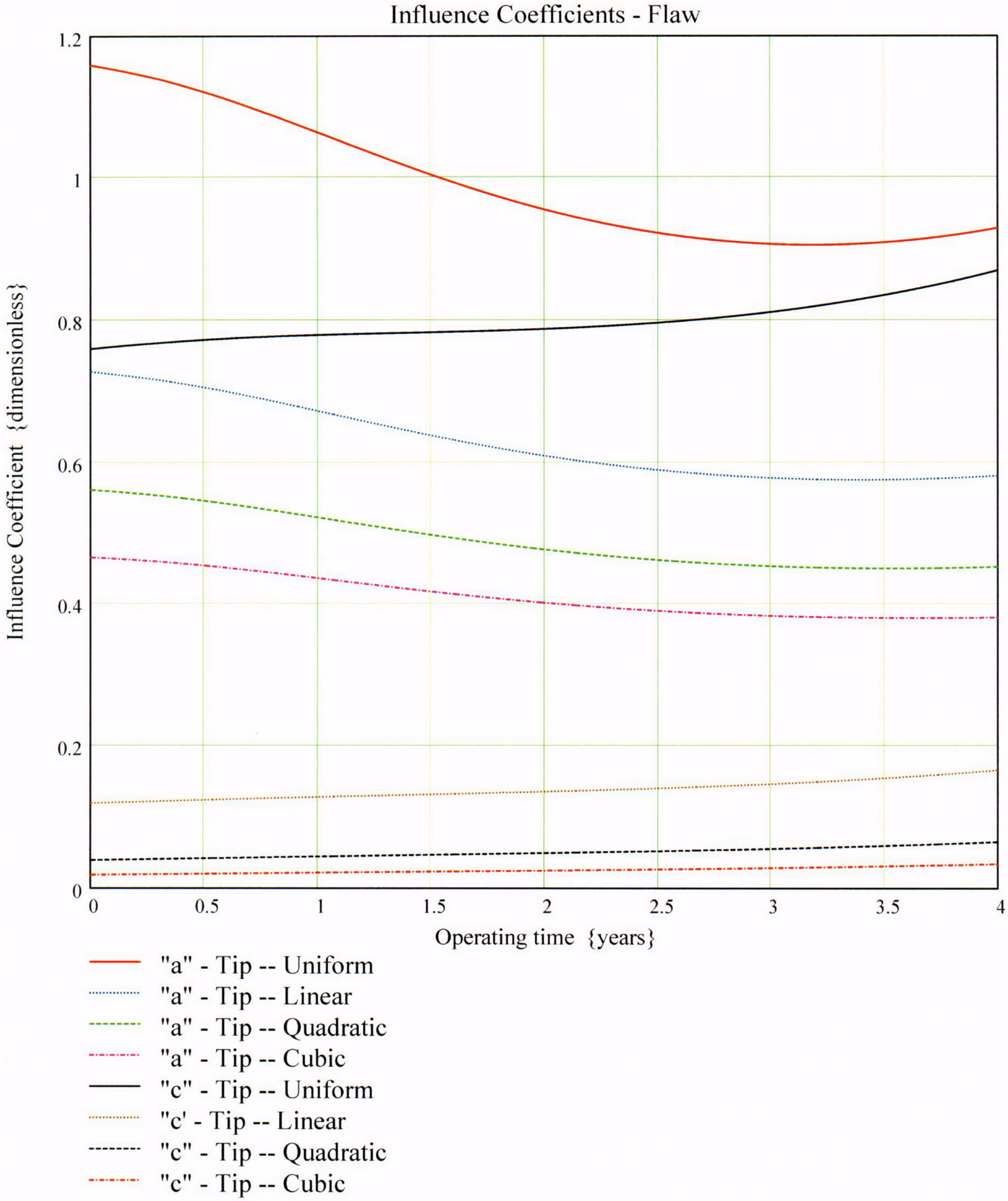
$$k := 0 .. I_{lim}$$

$Prop_{Length} = 0.242$

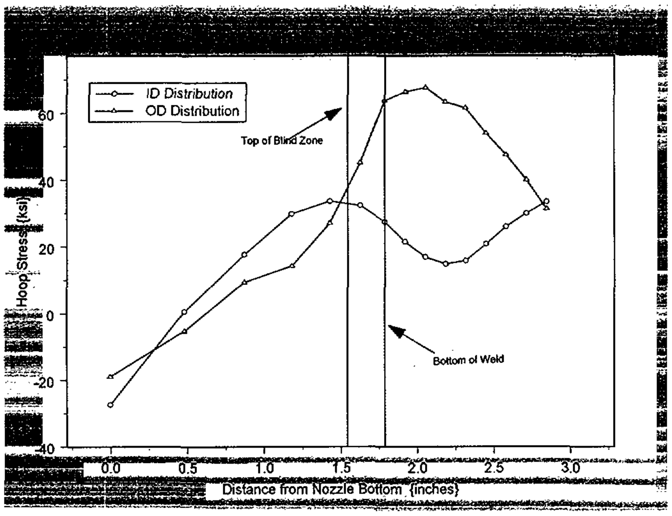


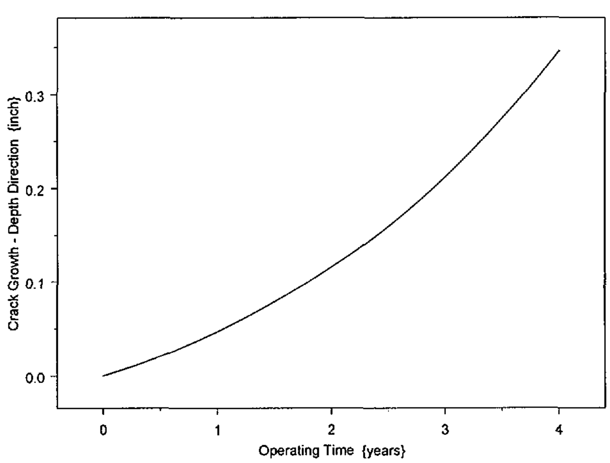



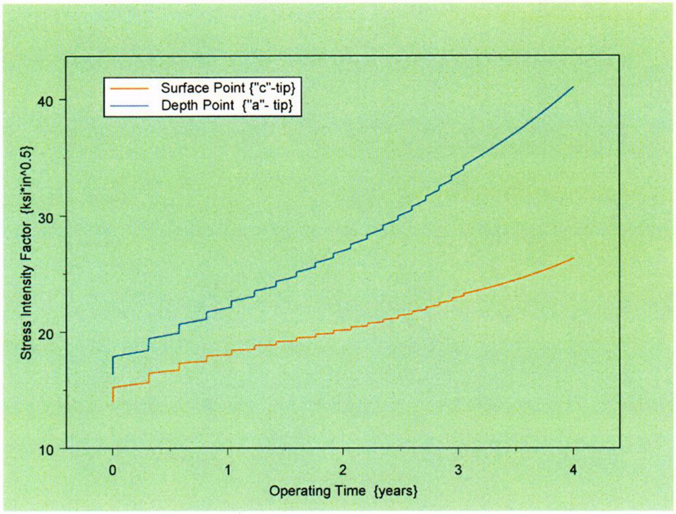

Stress Intensity Factors
Stress Intensity Factor {ksi sqrt.inch}
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Operating Time {years}
Depth Point Entergy-CEP Model
Surface Point Entergy-CEP model


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

| $CGR_{sambi_{(k,8)}} =$ | $CGR_{sambi_{(k,6)}} =$ | $CGR_{sambi_{(k,5)}} =$ |
|---|---|---|
| 1.158 | 16.383 | 14 |
| 1.158 | 17.9 | 15.225 |
| 1.158 | 17.905 | 15.229 |
| 1.158 | 17.91 | 15.233 |
| 1.158 | 17.915 | 15.237 |
| 1.158 | 17.919 | 15.241 |
| 1.158 | 17.924 | 15.245 |
| 1.157 | 17.929 | 15.249 |
| 1.157 | 17.934 | 15.253 |
| 1.157 | 17.939 | 15.257 |
| 1.157 | 17.943 | 15.261 |
| 1.157 | 17.948 | 15.265 |
| 1.157 | 17.953 | 15.269 |
| 1.156 | 17.958 | 15.273 |
| 1.156 | 17.962 | 15.277 |
| 1.156 | 17.967 | 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)
0.0
0.1
0.2
0.3
0
1
2
3
4
Operating Time {years}


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

# Through-Wall Axial Crack Model

## Stress Corrosion Crack Growth Analysis Throughwall flaw

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

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

Refrences :

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

### Arkansas Nuclear One Unit 2

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

**Calculation Reference: MRP 75 th Percentile and Flaw Pressurized**

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

**Through Wall Axial Flaw**

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

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

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

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

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

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

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

**Input Data :-**

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

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

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

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

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

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

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

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

**Stress Input Data**

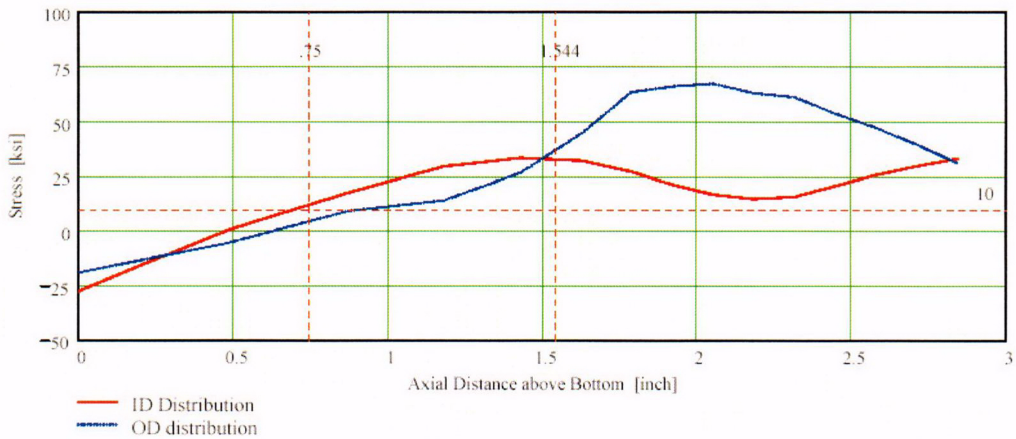
***Import the Required data from applicable Excel spread Sheet. The column designations are as follo***
***Cloumn "0" = Axial distance from Minimum to Maximum recorded on the data sheet (inches)***
***Column "1" = ID Stress data at each Elevation (ksi)***
***Column "5" = OD Stress data at each Elevation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

$Data_{All} :=$

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

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

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




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

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

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

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

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

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

C18

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

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

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

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

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

$Loc_0 := FL_{Cntr} - L$

$i := 1..N + 3$

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

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

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

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

$j := 1..N$

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

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

The moving average stress, the membrane ($\sigma_m$) containing the internal pressure ($P_{Int}$) and the bending component ($\sigma_b$) are computed.

Membrane Stress

$\sigma_m =$

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

Bending Stress

$\sigma_b =$

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

OD Stress

$S_{od} =$

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

ID Stress

$S_{id} =$

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

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

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

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

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

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

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

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

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

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

$$A_{em_i} \leftarrow 1.0090 + 0.3621 \cdot \lambda_i + 0.0565 \cdot (\lambda_i)^2 - 0.0082 \cdot (\lambda_i)^3 + 0.0004 \cdot (\lambda_i)^4 - 8.326 \cdot 10^{-6} \cdot (\lambda_i)^5$$

$$A_{bm_i} \leftarrow -0.0063 + 0.0919 \cdot \lambda_i - 0.0168 \cdot (\lambda_i)^2 - 0.0052 \cdot (\lambda_i)^3 + 0.0008 \cdot (\lambda_i)^4 - 2.9701 \cdot 10^{-5} \cdot (\lambda_i)^5$$

$$A_{eb_i} \leftarrow 0.0029 + 0.0707 \cdot \lambda_i - 0.0197 \cdot (\lambda_i)^2 + 0.0034 \cdot (\lambda_i)^3 - 0.0003 \cdot (\lambda_i)^4 + 8.8052 \cdot 10^{-6} \cdot (\lambda_i)^5$$

$$A_{bb_i} \leftarrow 0.9961 - 0.3806 \cdot \lambda_i + 0.1239 \cdot (\lambda_i)^2 - 0.0211 \cdot (\lambda_i)^3 + 0.0017 \cdot (\lambda_i)^4 - 4.9939 \cdot 10^{-5} \cdot (\lambda_i)^5$$

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

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

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

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

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

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

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

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

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

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

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

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

$$
\begin{aligned}
&K_{App_i} \leftarrow \frac{K_{AppOD_i} + K_{AppID_i}}{2} \\
&K_{\alpha_i} \leftarrow K_{App_i} \cdot 1.099 \\
&K_{\alpha_i} \leftarrow \begin{cases} 9.0 & \text{if } K_{\alpha_i} \le 9.0 \\ K_{\alpha_i} & \text{otherwise} \end{cases}
\end{aligned}
$$

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

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

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

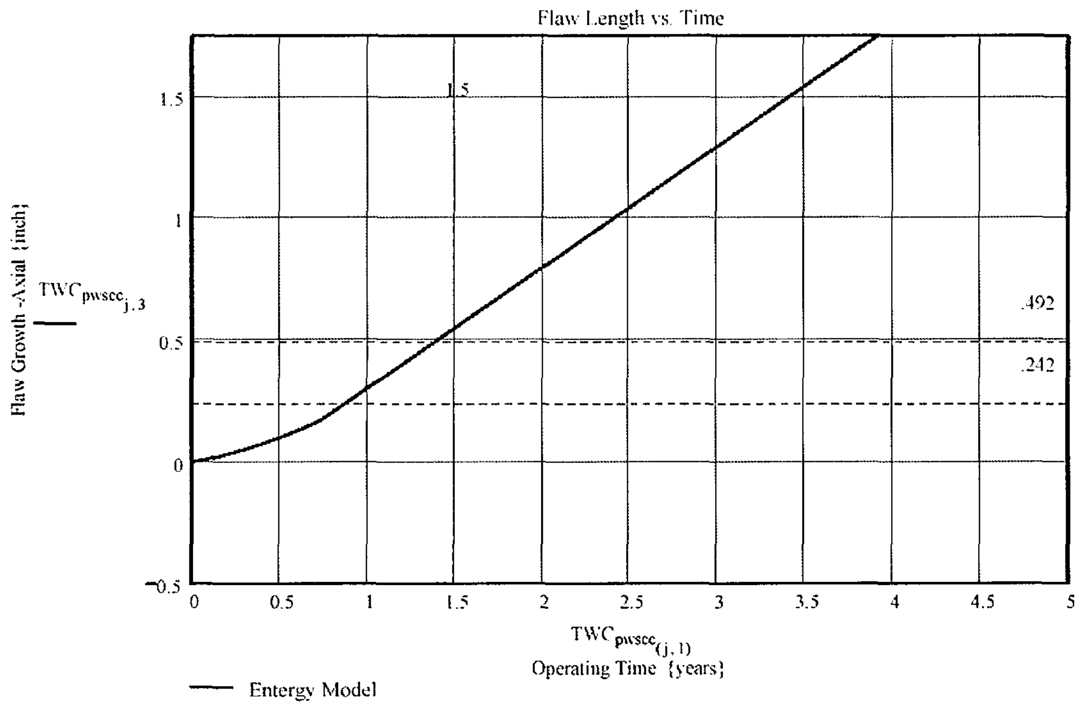
$$
\begin{aligned}
&output_{(i,0)} \leftarrow i \\
&output_{(i,1)} \leftarrow \frac{NCB_i}{365 \cdot 24} \\
&output \leftarrow \lambda_i
\end{aligned}
$$

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

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

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

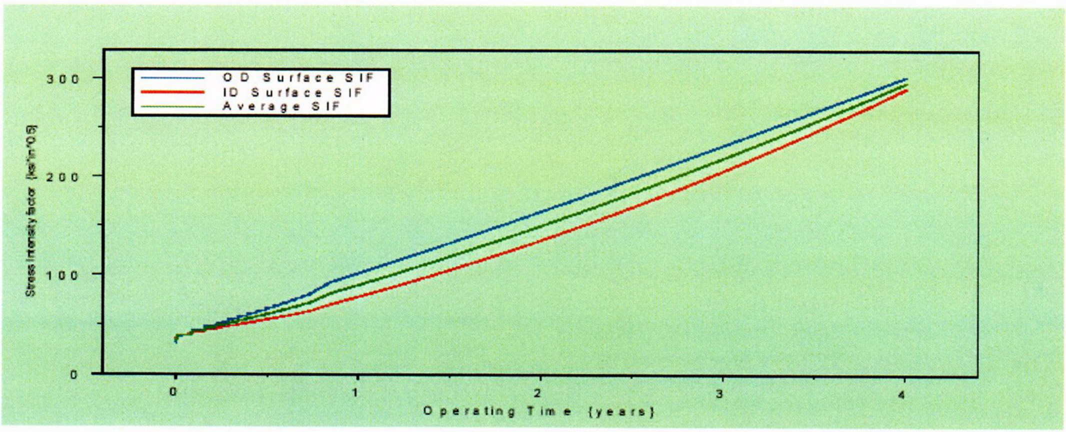
$Prop_{Length} = 0.242$




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

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

Typical tabular output to ensure proper functioning of the model.




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

# Appendix C

## Mathcad worksheet for CEDM Deterministic Fracture Mechanics Analyses

**This Appendix has 48 Attachments. Attachment 32 is Intentionally Blank**

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

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

Refrences :

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

## Arkansas Nuclear One Unit 2

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

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

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

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

## ID Surface Flaw

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

$$Ref_{Point} := 1.544$$

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

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

$$Val := 2$$

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

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

## Input Data :-

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

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

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

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

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

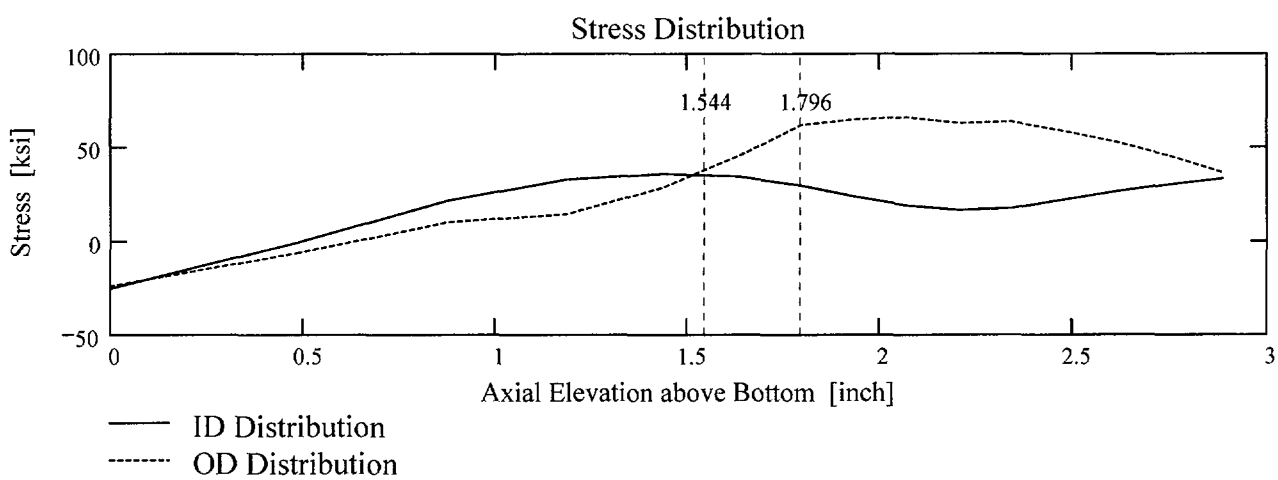
## Stress Input Data

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

AllData :=

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

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



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

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

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

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

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

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

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

Flaw center Location above Nozzle Bottom

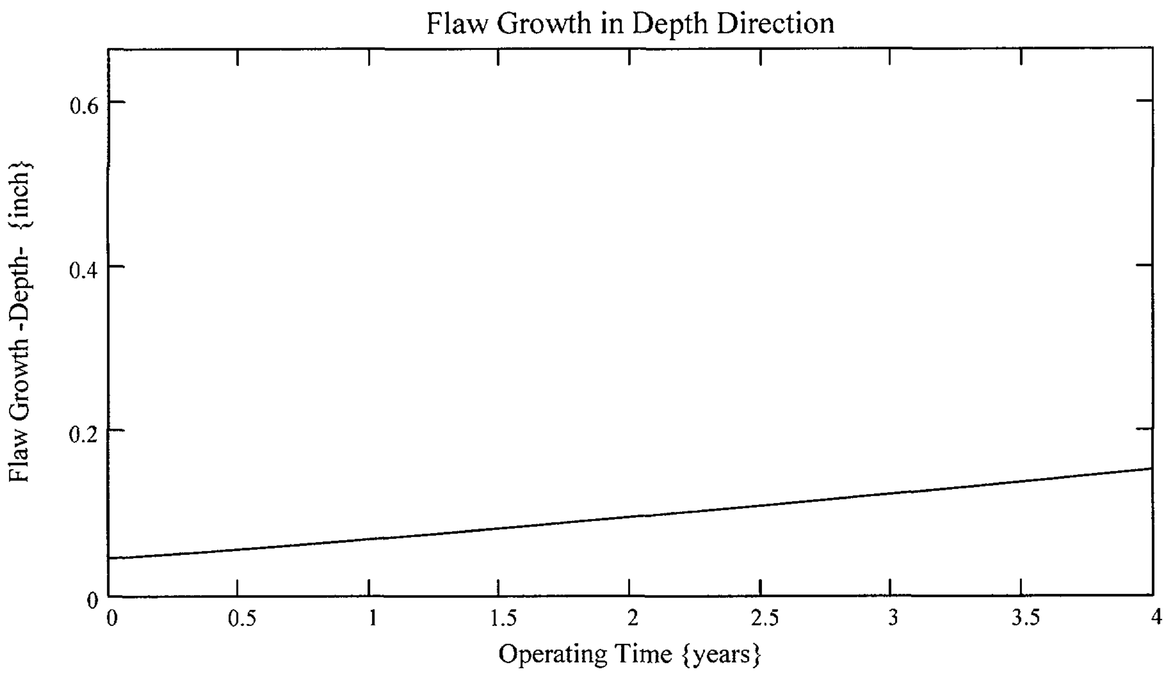
$$U_{Tip} := FL_{Cntr} + c_0$$

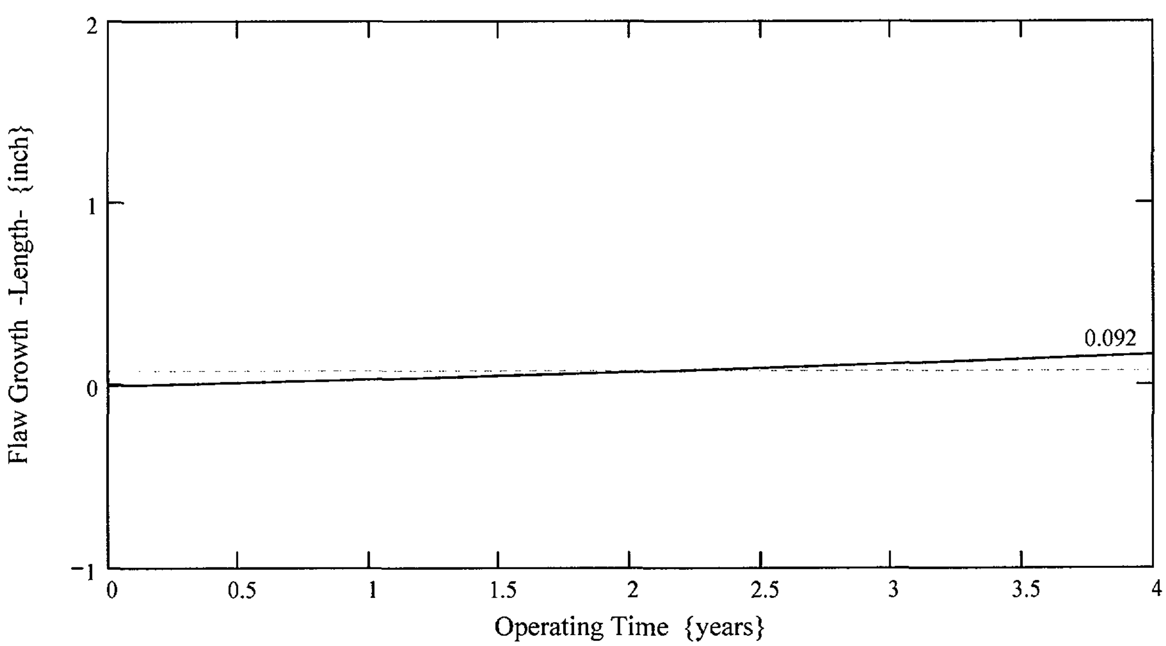
$$Inc_{Strs.avg} := \frac{UL_{Strs.Dist} - U_{Tip}}{20}$$

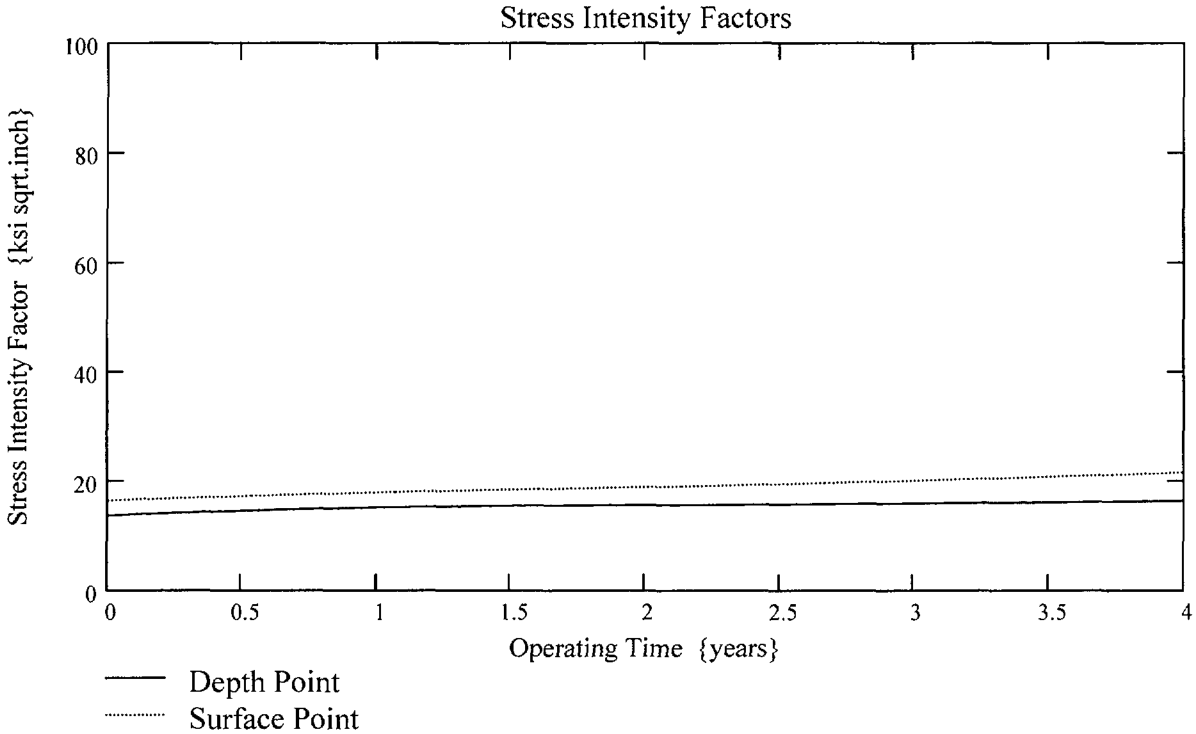
**No User Input is required beyond this Point**

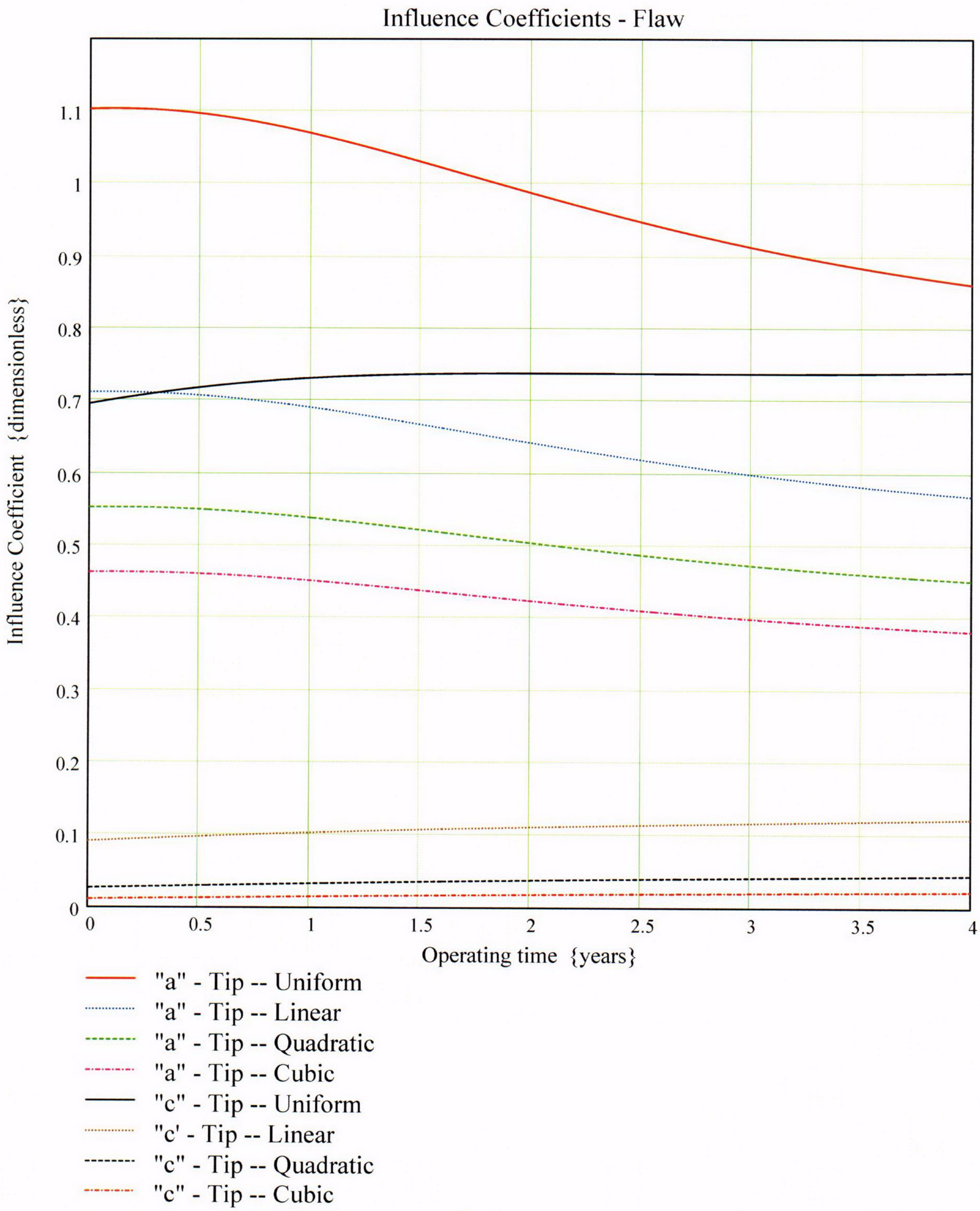
Sat Aug 09 10:59:39 AM 2003

$Prop_{Length} = 0.092$




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


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

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

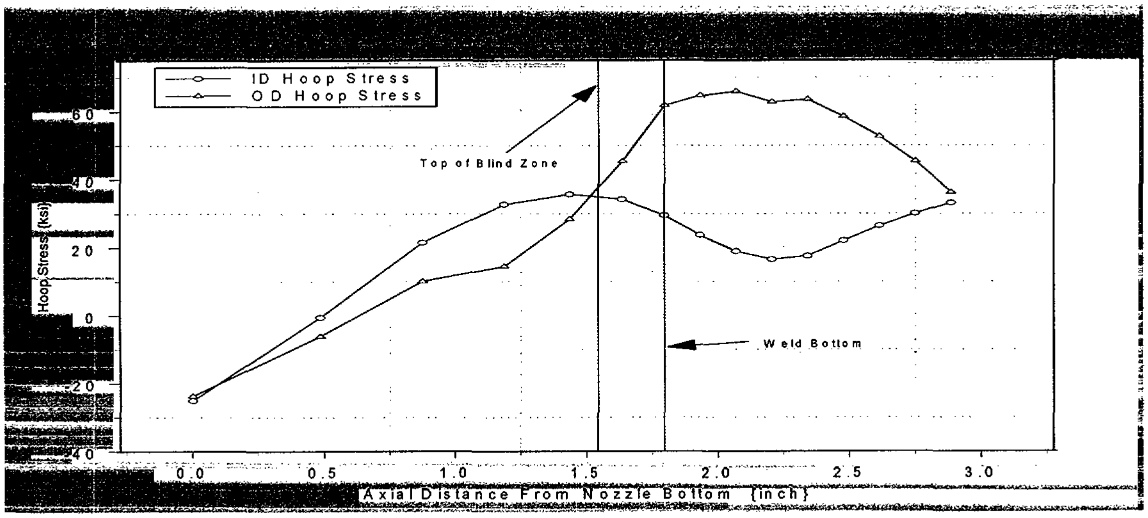
| |
|---|
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |
| 1.103 |

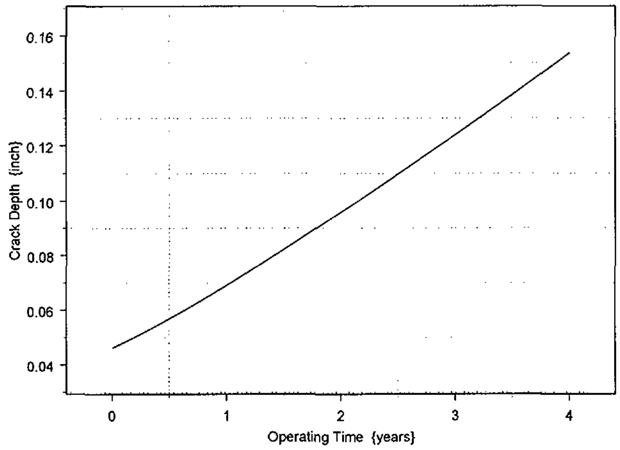
$CGR_{sambi_{(k,6)}} =$

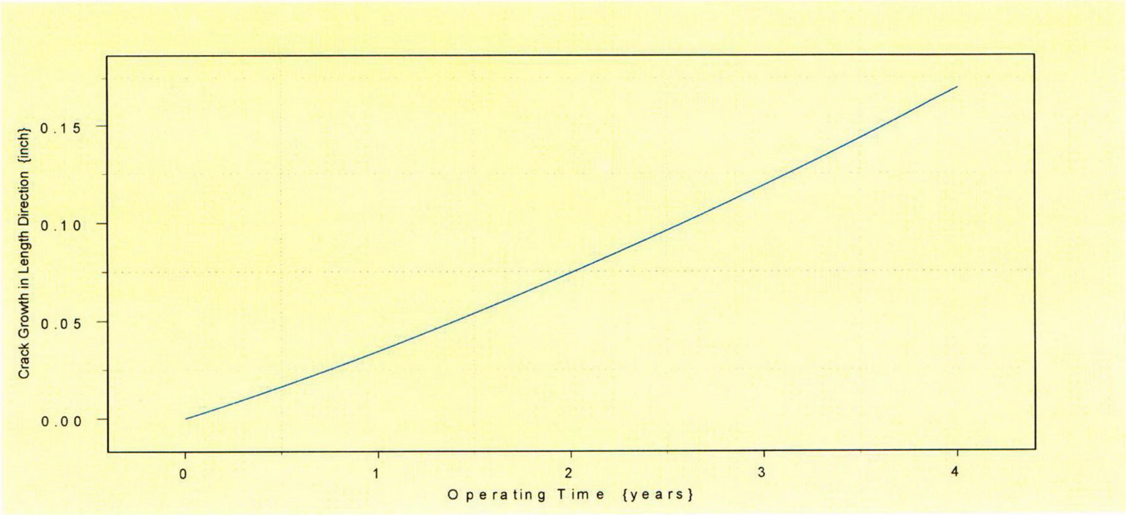
| |
|---|
| 16.561 |
| 16.414 |
| 16.42 |
| 16.426 |
| 16.433 |
| 16.439 |
| 16.445 |
| 16.451 |
| 16.457 |
| 16.463 |
| 16.469 |
| 16.475 |
| 16.482 |
| 16.488 |
| 16.494 |
| 16.5 |

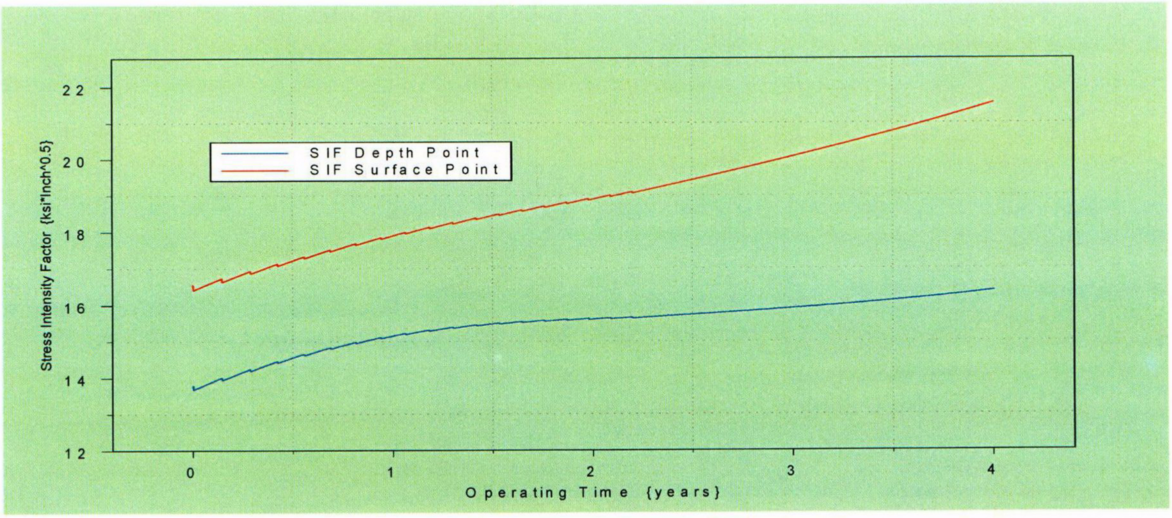
$CGR_{sambi_{(k,5)}} =$

| |
|---|
| 13.786 |
| 13.676 |
| 13.682 |
| 13.688 |
| 13.695 |
| 13.701 |
| 13.708 |
| 13.714 |
| 13.721 |
| 13.727 |
| 13.733 |
| 13.74 |
| 13.746 |
| 13.753 |
| 13.759 |
| 13.765 |


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


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


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


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