Entergy

Entergy Nuclear Operations, Inc.
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August 10, 2007

10 CFR 50.55a

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Palisades Nuclear Plant
Docket 50-255
License No. DPR-20

Supplement to Request for Relief from ASME Section XI Code Requirements for Repair of Service Water Pipe

Dear Sir or Madam:

On July 31, 2007, Entergy Nuclear Operations, Inc. (ENO) submitted a relief request from ASME Section XI Code requirements for repair of a Palisades Nuclear Plant service water pipe. Enclosure 3 of the relief request letter contained a calculation of the service water piping flaw evaluation and flaw growth analysis. ENO subsequently discovered that the calculation was not the final calculation. The final calculation is provided herein as Enclosure 1. This final calculation replaces the one submitted earlier on July 31, 2007. The final calculation applied additional bending loads (moments) resulting in a change to the allowable circumferential flaw size from 35.87 inches to 25.58 inches. The allowable axial flaw size was not affected. The overall conclusion of the calculation was also not affected.

In parallel with the development of the request for relief, ENO began work on a permanent repair plan for the subject service water pipe. As suggested during conference calls with the NRC regarding this relief request, ENO is aggressively working to develop and implement the permanent repair plan on pace for completion during the upcoming 2007 refueling outage. ENO will provide updates on the progress of the permanent repair plan. If and when it is determined that the repair plan will be fully implemented in the 2007 refueling outage, the relief request will be withdrawn.

Summary of Commitments

This letter contains no new commitments and no revision to existing commitments.

Christopher J. Schwarz
Site Vice President
Palisades Nuclear Plant

Enclosure (1)

CC Administrator, Region III, USNRC
Project Manager, Palisades, USNRC
Resident Inspector, Palisades, USNRC

ENCLOSURE 1

SERVICE WATER PIPING FLAW EVALUATION AND FLAW GROWTH ANALYSIS CALCULATION

23 PAGES FOLLOW

Structural Integrity Associates, Inc. CALCULATION PACKAGE	File No.: PAL-13Q-301
	Project No.: PAL-13Q

PROJECT NAME:

Service Water Piping Flaw Evaluation and Flaw Growth Analysis

CONTRACT NO.:

00001007

CLIENT:	PLANT:
Entergy Operation, Inc.	Palisades

CALCULATION TITLE:

Flaw Evaluation Using ASME Code Case N-513-2 and Flaw Growth Analysis for Service Water Piping at Palisades Nuclear Plant

Document Revision	Affected Pages	Revision Description	Project Manager Approval Signature & Date	Preparer(s) & Checker(s) Signatures & Date
0	1 – 18 A1 – A5 Computer Files	Initial Issue	R. O. McGill 07/27/07	G. J. Licina 07/27/07 R. O. McGill 07/27/07 R. V. Perry 07/27/07

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1.0 INTRODUCTION

In July 2006, a pinhole leak was discovered approximately one foot downstream of control valve CV-0824 in the "Service Water Return from Containment" piping (HB-23-16) outside of the containment penetration MZ-13 [1]. This single pinhole is located on the bottom of the 16-inch carbon steel pipe in the 6 o'clock position [1]. The most recent NDE inspection data [2d] indicates that there are now 4 separate pinhole leaks in the same vicinity.

The initial leak was determined to be temporarily acceptable [3] per Code Case N-513-1 [4] at the time the leak was discovered (note the current 4 pinholes in combination would also be temporarily acceptable per the initial analysis); however, Palisades desires to implement repairs during the spring 2009 refueling outage which violates the provisions of the Code Case since repairs are not planned for the next scheduled outage (September 2007). The analysis contained herein is to provide technical justification for a planned relief request by the plant for postponing repair activity.

There are two objectives of the calculation. First, a flaw evaluation is performed to determine an allowable flaw size per Code Case N-513-2 [5], which provides specific guidance for through-wall nonplanar flaws. Second, a flaw growth analysis is performed based on NDE inspection data provided [2] to predict a bounding flaw size at the time of the spring 2009 outage. This flaw size is then compared to the allowable flaw size calculated.

2.0 METHODOLOGY

The flaw evaluation is based on the criteria prescribed in ASME Code Case N-513-2. Use of this Code Case has been authorized by the Nuclear Regulatory Commission (NRC) for use by Palisades through relief request approval [6]. The Code Case allows for the evaluation of nonplanar, through-wall or part-wall flaws in Class 2/3 moderate energy piping. The through-wall, nonplanar flaw is to be evaluated as planar, through-wall flaws in the axial and circumferential directions (as described in Section 3.0(f) of the Code Case). This evaluation is performed using criteria in ASME Section XI [7] as permitted by Code Case N-513-2.

The nonplanar, through-wall flaw evaluation herein was conducted using SI Pipe Eval software [8] developed by Structural Integrity Associates. SI Pipe Eval is an Excel based evaluation tool programmed in Visual Basic for Applications that performs the flaw evaluation procedure described in Code Case N-513-2. SI Pipe Eval has been verified through the SI software QA program by an independent third party.

The flaw growth analysis is based on NDE inspection data of the affected pipe region provided by Palisades. Those inspection results were acquired on October 27, 2006 [2a], February 14, 2007 [2b], May 9, 2007 [2c] and July 2, 2007 [2d]. More specifically, this inspected region is for the full circumference of the pipe for an axial distance of 9 inches downstream from the pipe-to-control valve weld on a one inch-by-one inch grid. Figures 2 through 5 depict the inspection data using contour plots. A trend and statistical analysis was performed to determine the flaw size at the time of the spring 2009 refueling outage, for comparison to the bounding flaw.

3.0 ASSUMPTIONS / DESIGN INPUTS

The following assumptions are made for the analysis:

1. Service Level A safety factors are conservatively applied per Section 4.0 of Code Case N-513-2 [5].
2. For the flaw growth projection, the spring 2009 outage is assumed to begin on May 1, 2009.

The following design inputs are used for the analysis (material properties are taken at the peak operating temperature):

1. Pipe OD = 16 inch [1].
2. Nominal wall thickness = 0.375 inch [1].
3. Maximum operating pressure = 50 psig [10].
4. Maximum operating temperature = 200°F [1].
5. Material toughness (for circumferential flaws)* = 45 lb/in [7, Table C-8321-1].
6. Material toughness (for axial flaws)* = 45 lb/in [7, Table C-8322-1].
7. Dead weight stress = 1.0749 ksi [9].
8. OBE stress = 1.498 ksi [9].
9. DBE stress = 2.996 ksi [9].
10. Thermal expansion stress = 1.888 ksi [9].
11. Pipe material is A53 Grade A [1].
12. Allowable design stress, S = 12 ksi [11, Appendix III, p.269].
13. Code yield strength, S_y = 30 ksi [12, p. 105].
14. Code tensile strength, S_u = 48 ksi [12, p. 105].
15. Young's modulus, E = 28,600 ksi [11, Appendix I, p. 129].

* Material toughness conservatively taken at lower shelf temperature.

4.0 CALCULATIONS AND RESULTS

4.1 Flaw Evaluation

The planar flaw characterization approach is illustrated in Figure 1. Planar flaw evaluations are performed to determine allowable flaw sizes for comparison to the predicted flaw sizes (analysis below) using the assumptions and design input listed above. Table 1 summarizes the calculated allowable flaw sizes. SI Pipe Eval input and output are provided in Appendix A.

Table 1: Calculated Allowable Flaw Sizes

Planar Direction	Allowable Flaw Size (in)
Axial	36.52
Circumferential	25.58

4.2 Flaw Growth Analysis

Figures 2 through 5 show that thinning is confined to approximately half of the circumference with the most serious thinning at the edge of the weld. Those same thickness results are shown in 2-dimensional profile representations in Figures 6 through 8. In Figure 8, the axial profile shows there is a dramatic difference between the minimum reported value for a given circumferential position and the average for that circumferential band.

Figure 9 is a statistical plot that shows the cumulative distribution of the measured thickness at each of the four inspections. Figure 10 is also a cumulative distribution plot of the apparent deltas, where delta is determined by the point-to-point difference at each grid between successive inspections. Note that negative delta values indicate that the thickness at that grid has increased.

Figure 9 shows that the cumulative distribution is basically bilinear. The best fit line at the higher thickness shows a very small variation in thickness that is near t_{nom}, and that the measured thickness is greater than t_{nom} for some measurements. The bilinear nature of Figure 9 demonstrates that there are actually two populations; one that is thinning (e.g., the lower half of the circumference), and one that is not. The lower thickness values, essentially all of which are at PHI values of -1 or less (PHI is essentially equivalent to the standard deviation of the observations). The differences between the best fit lines for different examinations provide an estimate of the rate of metal loss; at least since the first data set was collected in October 2006. The different data in Figure 9 show that not much thinning has occurred since February 2007. Best fit lines to the lower curves (i.e., where there is thinning) show that between October 2006 and July 2007 (248 days) that the rate of thinning is essentially 0.0273 inch/year (7.48×10^{-5} inch/day).

Figure 10 shows the same basic data in a different way. Figure 10 shows the same effect observed from Figures 6 through 8, but more quantitatively, using the apparent deltas as the measure. The advantage of evaluating delta is that effects show up directly and changes can be observed more readily. The primary disadvantage is that the error in measurements (each thickness measurement will have an error associated with it; typically ±0.010 inch for UT thickness measurements) will be magnified when the differences between subsequent individual measurements are compared. The means of all three data sets (i.e., the value at PHI = 0) are very close to zero, implying that the mean metal loss over the three measurements is very near zero. Figure 10 also shows that the vast majority of the metal loss occurred before the initial inspection in October 2006, with a much smaller amount of metal loss at any point between October 2006 and February 2007. Since February 2007, metal loss has been nil. The extremes of the apparent deltas were significant for the second data set, but have been much smaller in the two most recent inspections.

Extrapolating these results to May 2009 indicates the minimum thickness in at least one grid will be 0 (i.e., a leak is definitely predicted) and the smallest average thickness of any circumferential band where thinning is occurring (actually half of a circumference) will be of the order of 0.150 inch. Using the extreme values that the statistical plots permit predicts that the cumulative distribution of thickness in May 2009 will look like the plot in Figure 11. If it is assumed that all thinning occurs in the one inch grid closest to the weld, the band averages for that one inch grid will decrease from 0.292 inch (July 2007) to approximately 0.270 inch.

The UT thickness data have demonstrated that thinning was occurring prior to October 2006, that some thinning persisted between October 2006 and February 2007, but that essentially no thinning has occurred since that time. A key assumption in the projection to May 2009 is that the operative degradation mechanism that produced the thinning will be no more severe in the ensuing 22 months than it has been since October 2006. As such daily walkdowns and continued UT thickness determinations are recommended as discussed in Section 2.0(f) of the Code Case.

Note that calculation details are provided in the Excel file *PAL-13Q Analysis.xls* (included with the project files).

5.0 CONCLUSIONS

A flaw evaluation based upon Code Case N-513-2 has shown that the current condition of the piping downstream of control valve CV-0824 in the Service Water Return from Containment piping (HB-23-16) outside of the containment penetration MZ-13 will maintain structural integrity, even in the presence of a pinhole leak. The acceptable t_{min} (i.e., 360°) for this piping is 0.033 inch [3]. An allowable flaw size per Code Case N-513-2 and the loading to which this line is subjected is 36.52 inches (axial) by 25.58 inches (circumferential).

Regular inspections of the pipe have shown that there was minimal flaw growth after the leak was first discovered, then characterized in October 2006. Since February 2007, flaw growth has been nil. A projection of the flaw extent and depths based upon the entire history for which the pipe has been characterized using UT thickness measurements on one inch grids shows that at May 2009 the thinning will be larger than it is today; however, the predicted flaw will still be significantly smaller than the acceptable flaw size as calculated.

As noted above, the vast majority of the thinning occurred prior to October 2006, with some minimal thinning persisting between October 2006 and February 2007, but with essentially no thinning occurred since that time. A key assumption in the projection of these results to May 2009 is that the operative degradation mechanism that produced the thinning will be no more severe in the ensuing 22 months than it has been since October 2006. As such daily walkdowns and continued UT thickness determinations are recommended as discussed in Section 2.0(f) of the Code Case.

6.0 REFERENCES

1. NMC, "Operability Recommendation," CAP: 01041995, Rev. 0, July 30, 2006, SI File Number PAL-11Q-201.

2. Palisades NDE inspection data, SI File Number PAL-13Q-201:
    a. Ultrasonic Erosion Corrosion Examination Report, Work Order Number: 00294169 06, Examination Date: 10/27/06.
    b. Ultrasonic Erosion Corrosion Examination Report, Work Order Number: 00294169 10, Examination Date: 2/14/07.
    c. Ultrasonic Erosion Corrosion Examination Report, Work Order Number: 00294169 13, Examination Date: 5/09/07.
    d. Ultrasonic Erosion Corrosion Examination Report, Work Order Number: 00294169 15, Examination Date: 7/02/07.

3. SI Calculation Package PAL-11Q-301, "Flaw Evaluation for Service Water Piping at Palisades Nuclear Plant Using ASME Code Case N-513-1," Revision 0.

4. ASME Code Case N-513-1, "Evaluation Criteria for Temporary Acceptance of Flaws in Moderate Energy Class 2 or Class 3 Piping Section XI, Division 1," Cases of ASME Boiler and Pressure Vessel Code, March 28, 2001.

5. ASME Code Case N-513-2, "Evaluation Criteria for Temporary Acceptance of Flaws in Moderate Energy Class 2 or Class 3 Piping Section XI, Division 1," Cases of ASME Boiler and Pressure Vessel Code, February 20, 2004.

6. NRC Relief Request Approval Letter, "Safety Evaluation by the Office of Nuclear Regulation Use of ASME Code Case N-513-2," July 3, 2006, SI File Number PAL-13Q-202.

7. ASME Boiler and Pressure Vessel Code, Section XI, Appendix C, 2001 Edition (2002 Addenda).

8. SI Pipe Eval, Version 1.3, Structural Integrity Associates, 2007.

9. Excerpt from Stress Report EA-SP-3316-01, Revision 5, provided as email attachment from George Schrader (Entergy) to Bob McGill (Structural Integrity), "PDF.pdf," Dated July 24, 2007, 5:15 AM, SI File Number PAL-13Q-203.

10. Email from George Schrader (NMC) to Bob McGill (Structural Integrity), "FW: Service Water Piping Flaw Evaluation," Dated August 10, 2006, 8:55 AM, SI File Number PAL-11Q-204.

11. ASME Boiler and Pressure Vessel Code, Section III Appendices, 1989 Edition.

12. ASME Boiler and Pressure Vessel Code, Section II, Part A, 1989 Edition.

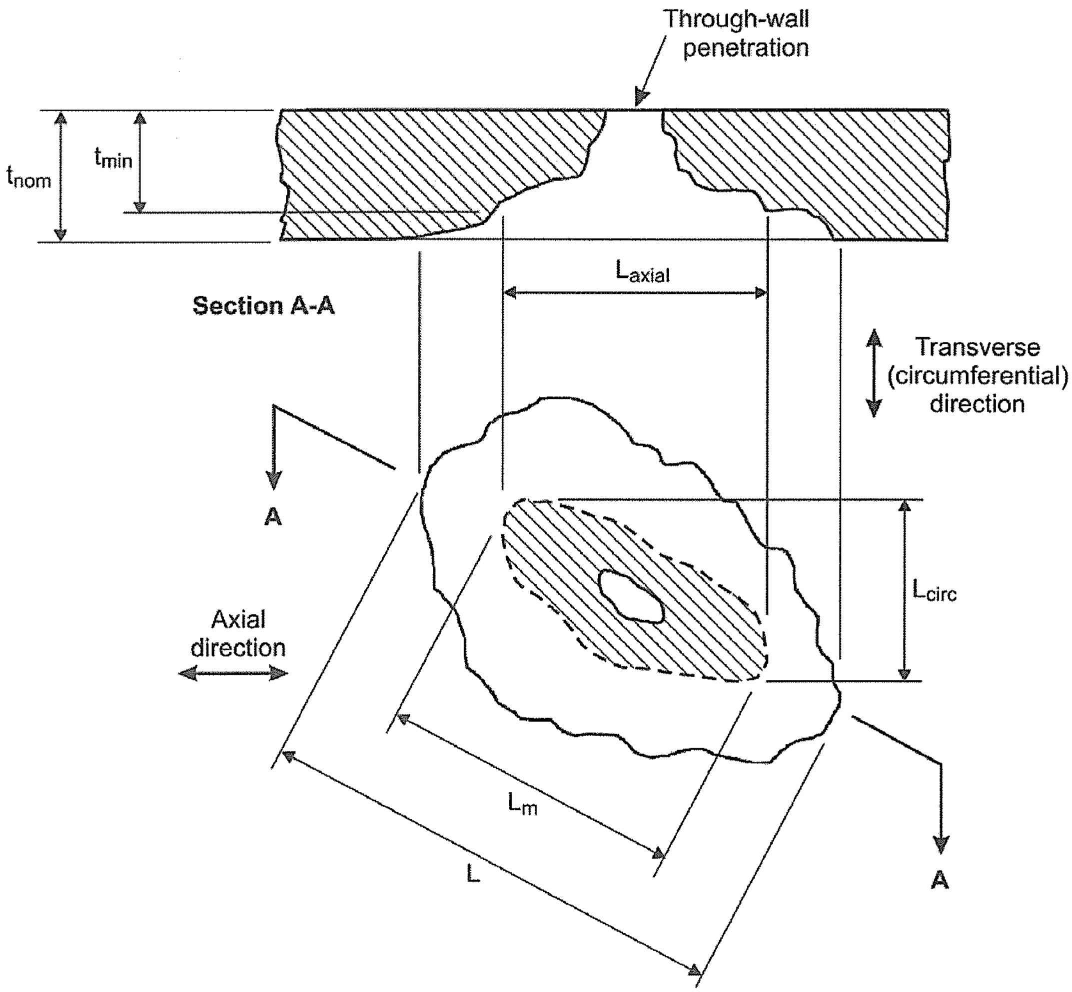

Figure 1. Planar Characterization of Through-wall, Nonplanar Flaw

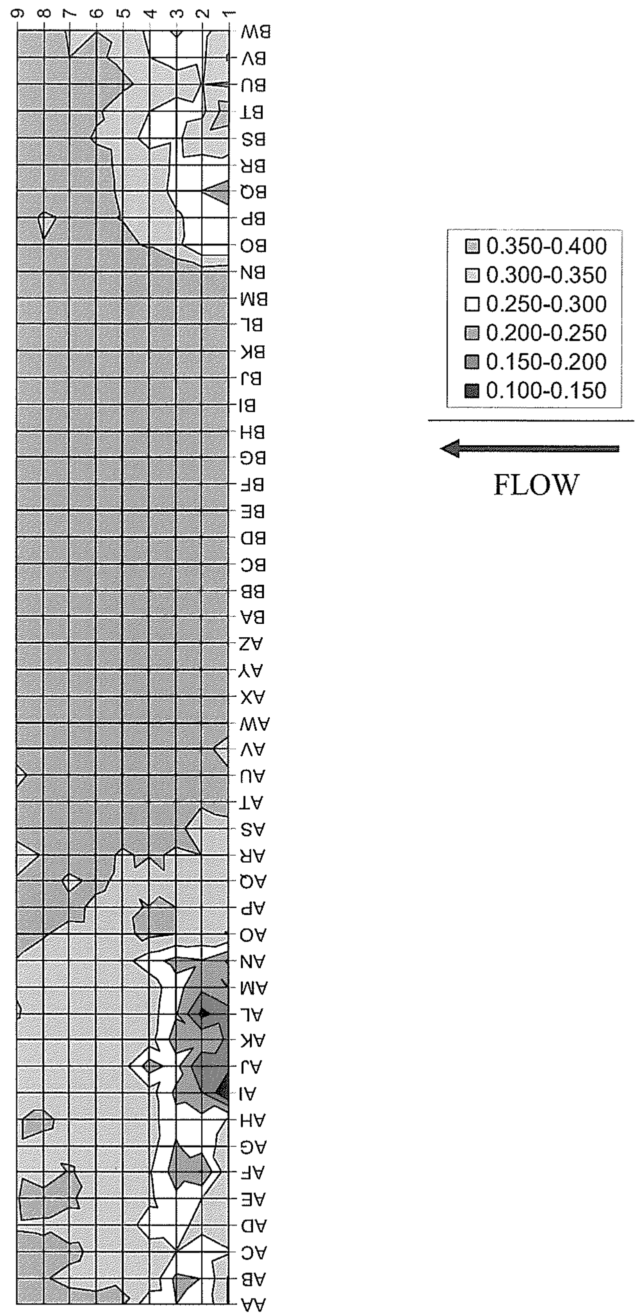

Figure 2. NDE Inspection Data of Effected Pipe Region from 10/27/06

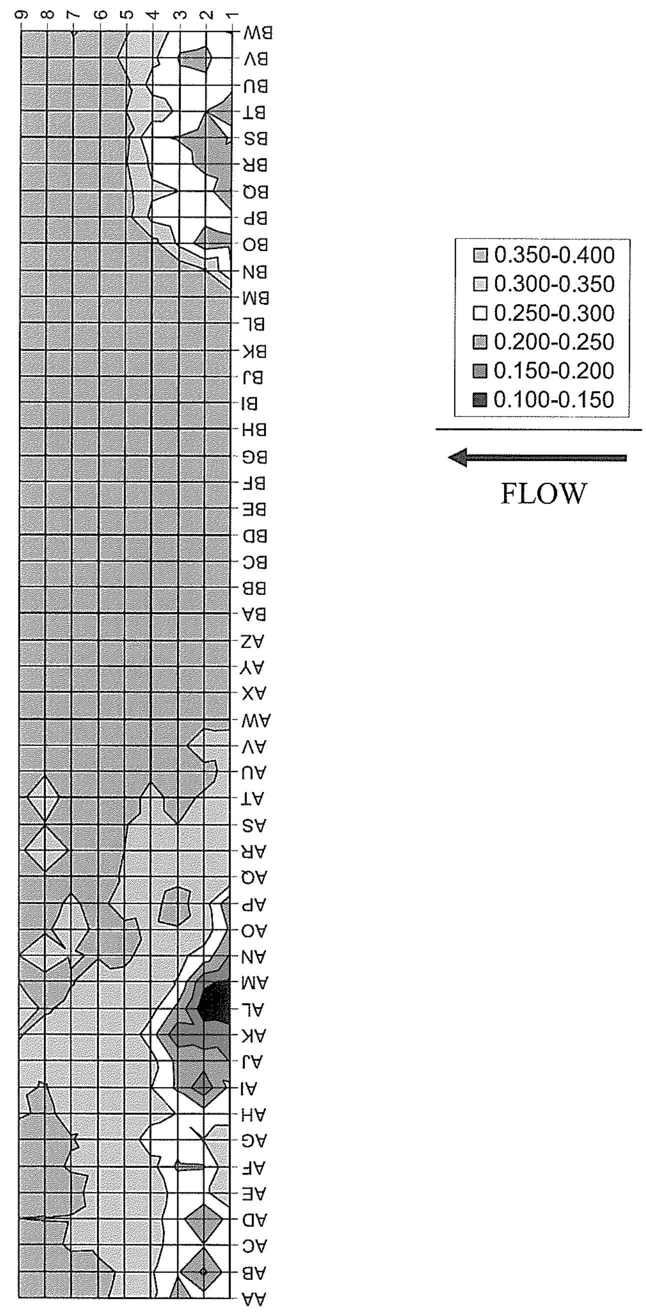

Figure 3. NDE Inspection Data of Effected Pipe Region from 2/14/07

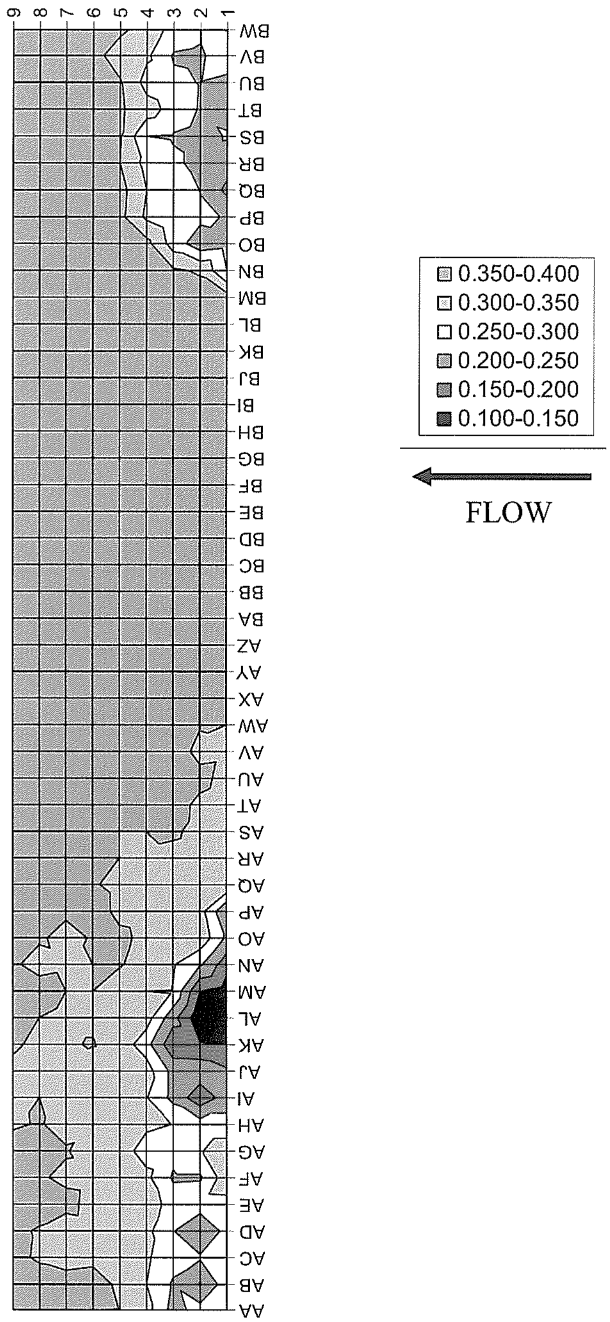

Figure 4. NDE Inspection Data of Effected Pipe Region from 5/09/07

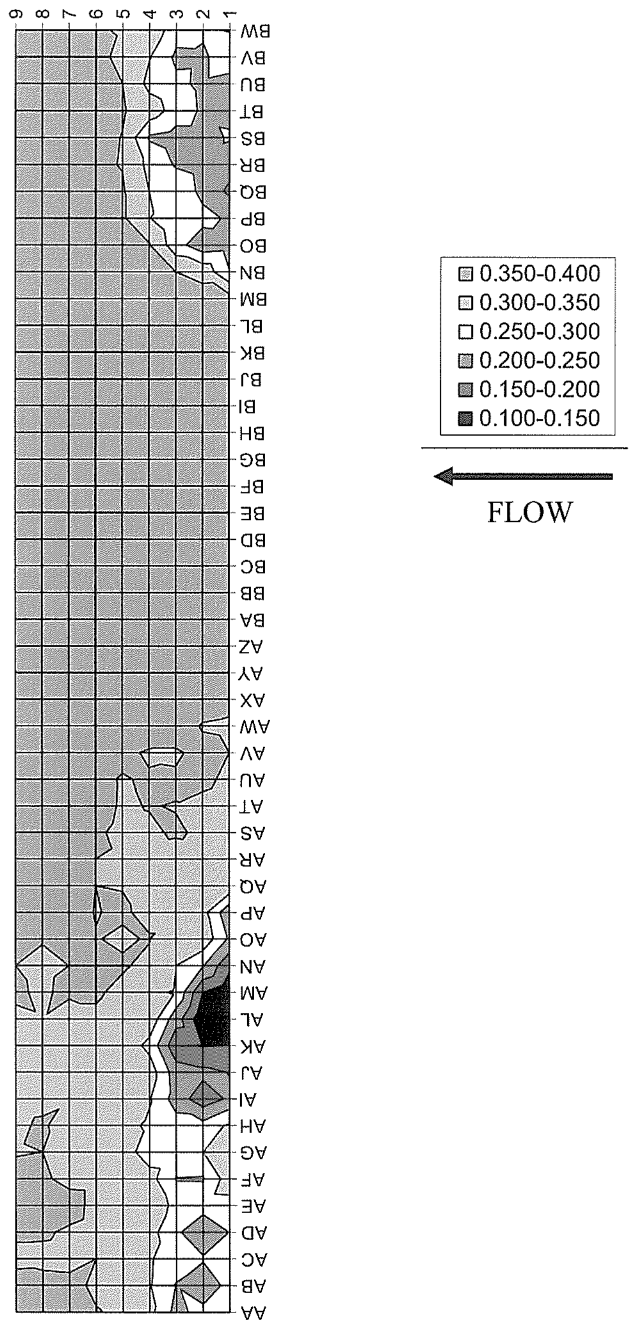

Figure 5. NDE Inspection Data of Effected Pipe Region from 7/02/07

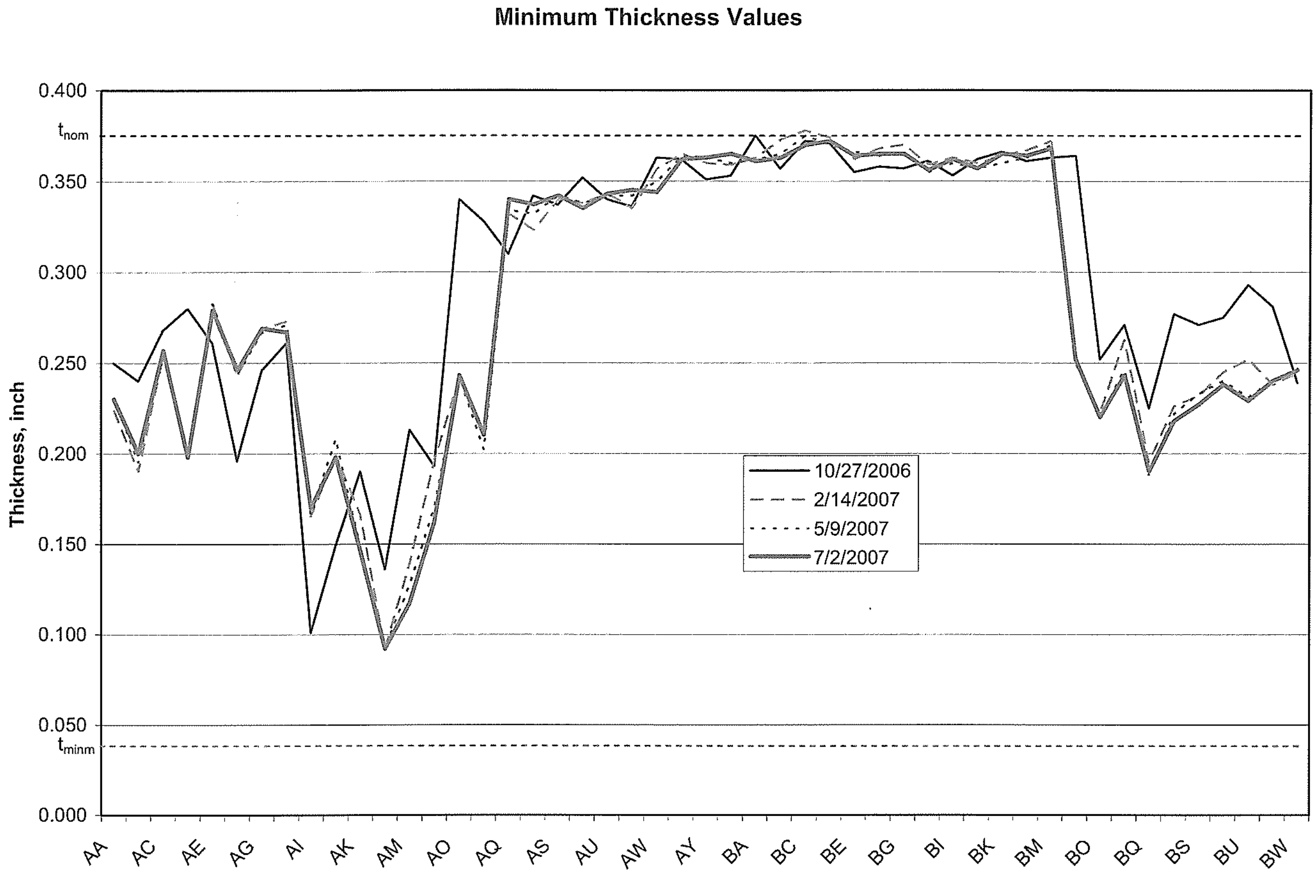

Figure 6. Circumferential Profile – Minimum Values

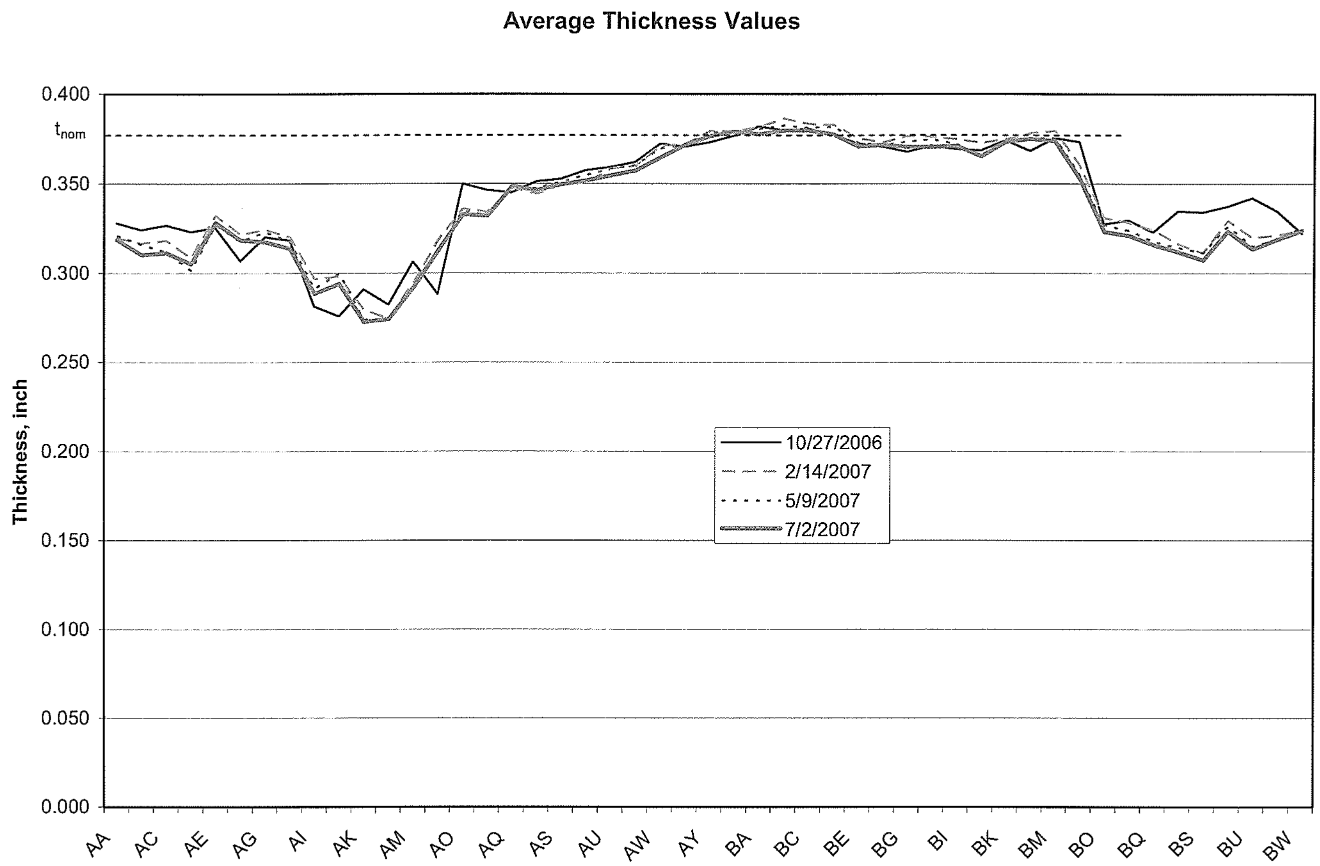

Figure 7. Circumferential Profile – Averages

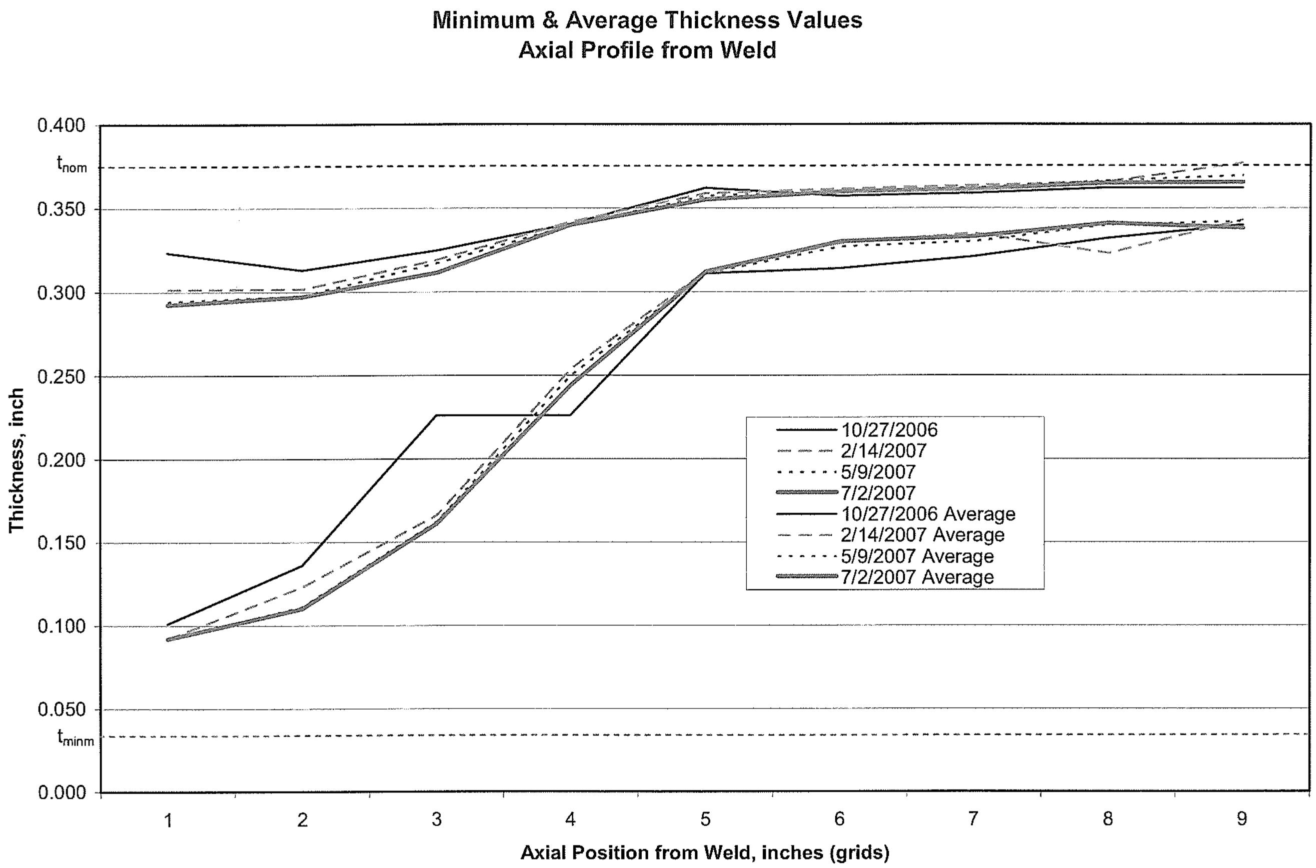

Figure 8. Axial Profiles

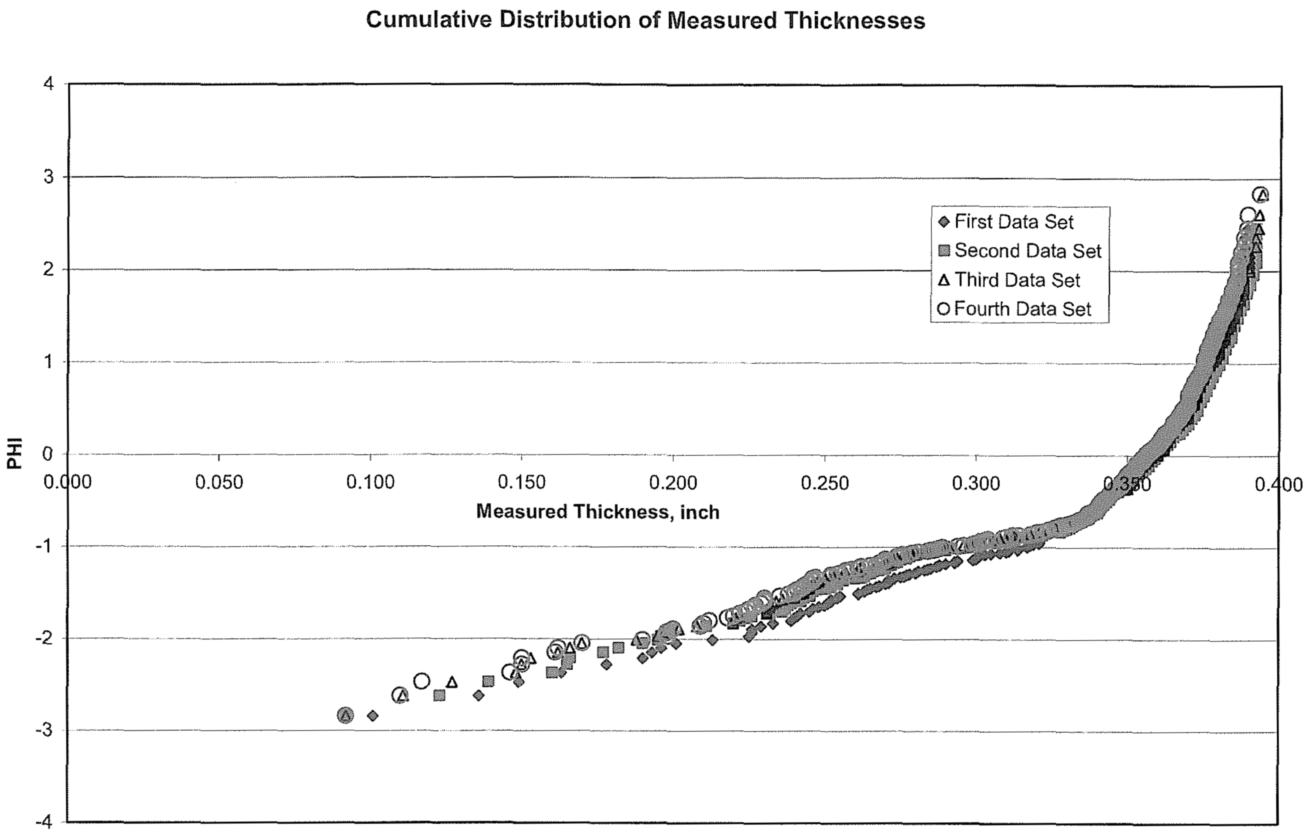

Figure 9. Cumulative Distribution of Measured Thickness

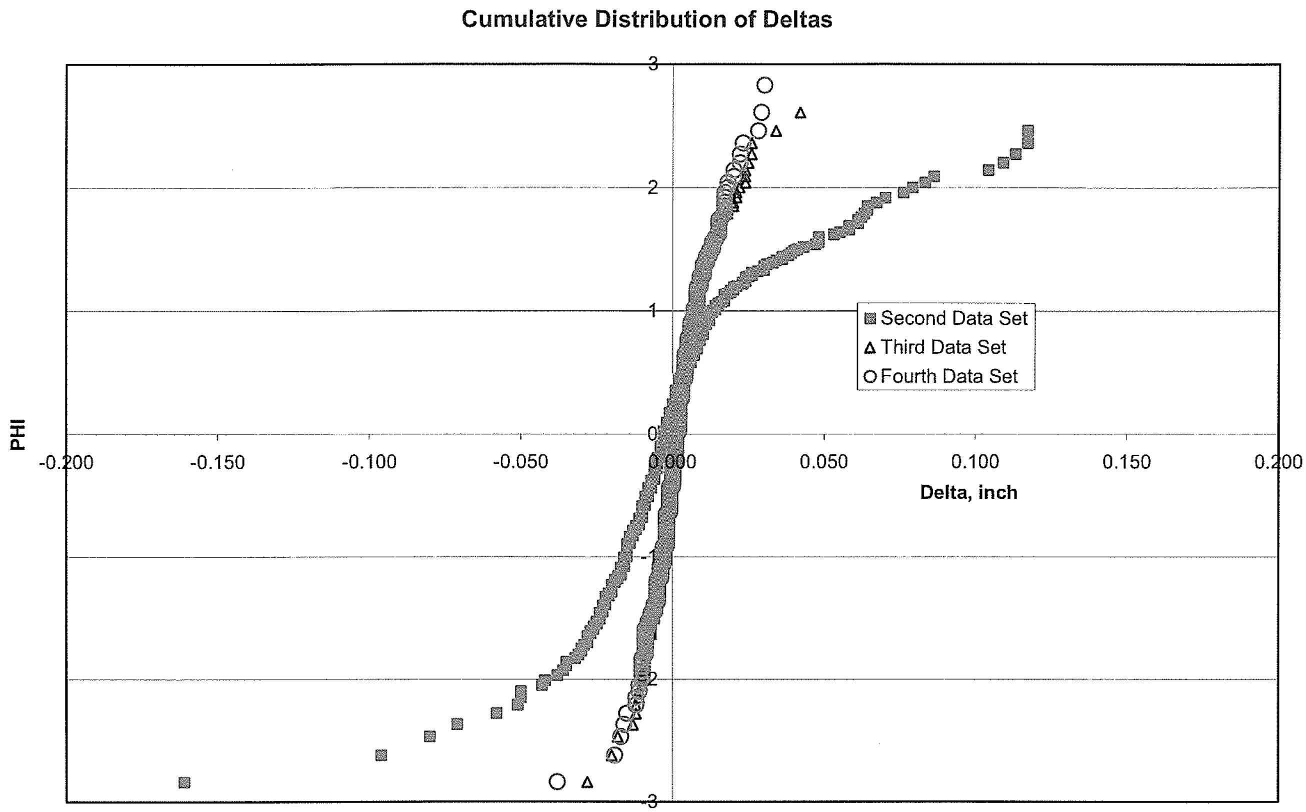

Figure 10. Cumulative Distribution of Deltas (point-to-point thickness differences from one examination to the next)

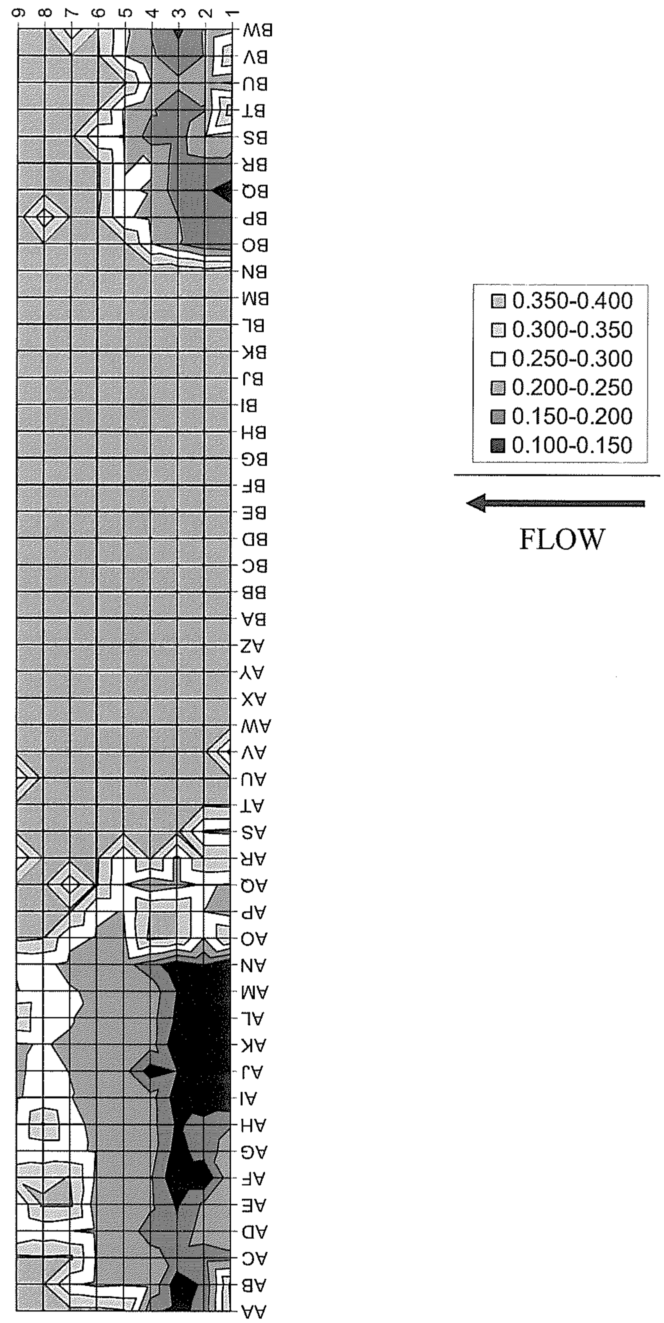

Figure 11. Predicted UT Thickness Map, May 2009

APPENDIX A

SI Pipe Eval Input and Output

Table A-1: SI Pipe Eval Input

Structural Integrity Associates, Inc.

Best Viewed with 1024 x 768 Screen Resolution

SI PIPE EVAL

Evaluation Criteria for Temporary Acceptance of Flaws in Moderate Energy Class 2 or 3 Piping Section XI, Division 1

INPUT OUTPUT

Pipe & Loading Input

Pipe OD =	16	in
Pipe Thickness =	0.375	in
Pipe Pressure =	50	psig
Operating Temperature =	200	°F
Resultant DW Moment =	75,523	in-lbs
Resultant Seismic OBE Moment =	105,250	in-lbs
Resultant Seismic DBE Moment =	210,501	in-lbs
Resultant Thermal Moment =	136,652	in-lbs
Select Service Level	A	

Flaw Description

Axial Nonplanar

Flaw Length =	4	in
Flaw to Thickness Ratio (a/t) =	1.00	

Through-wall Flaws (a/t = 1)

Evaluate Flaw

Allowable Flaw: 36.52 in

Code Case Evaluation: PASS

Material Properties

Austenitic

Ferritic

Allowable Design Stress, S =	12.0	ksi
Code Yield Strength, S_y =	30.0	ksi
Code Tensile Strength, S_u =	48.0	ksi
Young's Modulus =	28,600	ksi

NOTE: Results must be cleared prior to new run.

Clear Results

Help

Version 1.3

Execution Date: 7/27/2007

Notes:

1. Moments are derived from, $M = \frac{\sigma_b I}{R}$, where I = moment of inertia and R = outside pipe radius.

   See Excel file *Moment from Stress.xls* (included in project files) for calculation details.
2. Flaw length is arbitrarily chosen.

Table A-2: SI Pipe Eval Axial Evaluation Output

SI PIPE EVAL, SOLUTION SUMMARY: Axial Nonplanar, Ferritic
(Note: flaw is treated as an axial ***and*** circumferential planar flaw. Flaw must pass both conditions.)

Description of Solution Methodology:
A screening criteria [ASME Section XI Appendix C (2001), Section C-4300] must first be performed to determine the fracture analysis method. If the screening criteria calls for an EPFM or Limit Load analysis, then the inputs provided are used with the hoop stress and material flow stress calculated from Equations 2 and 3 of Code Case N-513-2 for use in Equation 1 to determine the allowable flaw length. If the screen criteria calls for an LEFM analysis, then the inputs provided are used with the evaluations procedures described in Section C-7200. An iterative process is used to determine the allowable flaw length.

SCREEN CRITERIA DETERMINATION

SC < 0.2	0.2 ≤ SC < 1.8	SC ≥ 1.8
Limit Load	EPFM	LEFM

Screening Criteria = 1.73 $SC = K_r' / S_r'$ Section XI Appendix C, Figure C-4220-1

K_r' = 0.067 $K_r' = \left[1000K_I^2 / E'J_{Ic}\right]^{0.5}$ Section XI Appendix C, Section C-4310

S_r' = 0.038 $S_r' = (pR_m / t)/\sigma_y$ Section XI Appendix C, Section C-4310 (Note: sigma y used instead of sigma l for through-wall flaw.)

Variables Used in Above Equations:

K_I = 2,502 psi-in$^{1/2}$ $K_I = (pR_m / t)(\pi a / Q)^{0.5} F$ Section XI Appendix C, Section C-4312

R_m = 7.8125 in $R_m = \dfrac{D_o - t}{2}$ Q = 1.09 $Q = 1 + 4.593(a/l)^{1.65}$ Section XI Appendix C, Section C-4312

F = 2.31 $F = 1.12 + 0.053\alpha + 0.0055\alpha^2 + (1.0 + 0.02\alpha + 0.0191\alpha^2)(20 - R_m/t)^2/1400$ Section XI Appendix C, Section C-4312

σ_y = 27,100 psi Section XI Appendix C, Figure C-4220-1

E' = 3.1E+07 psi $E' = E/(1-\upsilon^2)$ Section XI Appendix C, Section C-1300 J_{Ic} = 45 in-lb/in^2

LIMIT LOAD & EPFM ANALYSIS ***THIS ANAYSIS IS USED***

Flow Stress = 39,000 psi $\sigma_f = (S_y + S_u)/2$ Code Case N-513-2 Equation 3

Hoop Stress = 1,067 psi $\sigma_h = pD_o / 2t$ Code Case N-513-2 Equation 2

Structural Factor, Membrane = 2.7 Section XI Appendix C, Section C-2622

Allowable Flaw Length = 36.52 in $l_{all} = 1.58\sqrt{Rt}\left[\left(\dfrac{\sigma_f}{SF_m \sigma_h}\right)^2 - 1\right]^{\frac{1}{2}}$ Code Case N-513-2 Equation 1

Table A-3: SI Pipe Eval Circumferential Evaluation Output

SI PIPE EVAL, SOLUTION SUMMARY: Circumferential Nonplanar, Ferritic
(Note: flaw is treated as an axial ***and*** circumferential planar flaw. Flaw must pass both conditions.)

Description of Solution Methodology:
A screening criteria [ASME Section XI Appendix C (2001), Section C-4300] must first be performed to determine the fracture analysis method. If the screening criteria calls for a Limit Load analysis, then inputs provided are used with ASME Section XI Appendix C (2001), Section C-5320. An iterative approach is used on theta (half crack angle) to determine the allowable flaw size conforming to the allowable pipe bending stress ***and*** allowable pipe membrane stress. If the screening criteria calls for an EPFM analysis, then the inputs provided are used with Section C-6320. The analysis is identical to the Limit Load analysis except that a Z adjustment factor is used in determining the allowable pipe bending and membrane stresses. If the screen criteria calls for an LEFM analysis, then the inputs provided are used with the evaluations procedures described in Section C-7200. An iterative process is used to determine the allowable flaw length.

$\frac{R_m}{t} =$ 20.83 **The ratio of mean radius to thickness is greater than 20, thus the analysis will be conservative.** $R_m =$ 7.81 in $R_m = \frac{D_o - t}{2}$

SCREEN CRITERIA DETERMINATION

Screening Criteria = 1.85 $SC = K_r' / S_r'$ Section XI Appendix C, Figure C-4220-1

$\frac{SC < 0.2}{\text{Limit Load}}$ $\frac{0.2 \le SC < 1.8}{\text{EPFM}}$ $\frac{SC \ge 1.8}{\text{LEFM}}$

$K_r' =$ 0.280 $K_r' = \left[1000K_I^2 / E'J_{Ic}\right]^{0.5}$ Section XI Appendix C, Section C-4310

$S_r' =$ 0.151 $S_r' = (\sigma_b + \sigma_e)/\sigma_b'$ when $(\sigma_b + \sigma_e) \ge \sigma_m$ else $S_r' = \sigma_m / \sigma_m'$ Section XI Appendix C, Section C-4310

Variables Used in Above Equations:

$K_I =$ 37,488 psi-in$^{1/2}$ $K_I = K_{Im} + K_{Ib}$ Section XI Appendix C, Section C-4311

$K_{Im} =$ 7,789 psi-in$^{1/2}$ $K_{Im} = \left[P/(2\pi R_m t)\right](\pi a)^{0.5} F_m$ Section XI Appendix C, Section C-4311, where: $P =$ 9,133 lbs

$K_{Ib} =$ 29,699 psi-in$^{1/2}$ $K_{Ib} = \left[M/(\pi R_m^2 t)\right](\pi a)^{0.5} F_b$ Section XI Appendix C, Section C-4311, where: $M =$ 317,425 in-lbs

$F_m =$ 4.98 $F_m = 1.10 + x\left[0.15241 + 16.772(x\theta/\pi)^{0.855} - 14.944(x\theta/\pi)\right]$ Section XI Appendix C, Section C-4312

$F_b =$ 3.48 $F_b = 1.10 + x\left[-0.09967 + 5.0057(x\theta/\pi)^{0.565} - 2.8329(x\theta/\pi)\right]$ Section XI Appendix C, Section C-4312

$E' =$ 3.1E+07 psi $E' = E/(1-\upsilon^2)$ Section XI Appendix C, Section C-1300 $J_{Ic} =$ 45 in-lb/in^2

$\sigma_b =$ 2,573 psi $\sigma_e =$ 1,945 psi $\sigma_m =$ 533 psi
$\sigma_b = D_o M_b / 2I$ $\sigma_e = D_o M_e / 2I$ $\sigma_m = pD_o / 4t$ Section XI Appendix C, Section C-2500

$\sigma_b' =$ 29,878 psi $\sigma_b' = \frac{2\sigma_y}{\pi}\left[2\sin\beta - \frac{a}{t}\sin\theta\right]$ where $\beta = \frac{1}{2}\left[\pi - \frac{a}{t}\theta - \pi\frac{\sigma_m}{43.4}\right]$ when $(\theta + \beta) \le \pi$ Section XI Appendix C, Section C-4311

$\sigma_b' = \frac{2\sigma_y}{\pi}\left[\left(2 - \frac{a}{t}\right)\sin\beta\right]$ where $\beta = \pi\left(1 - \frac{a}{t} - \frac{\sigma_m}{43.4}\right) / \left(2 - \frac{a}{t}\right)$ when $(\theta + \beta) > \pi$

$\sigma_y =$ 27,100 psi Section XI Appendix C, Figure C-4220-1

$\sigma_m' =$ 22,804 psi $\sigma_m' = \sigma_y\left[1 - \frac{a}{t}\frac{\theta}{\pi} - \frac{2\varphi}{\pi}\right]$ where $\varphi = \arcsin\left[0.5\frac{a}{t}\sin\theta\right]$ Section XI Appendix C, Section C-4311

Table A-3: SI Pipe Eval Circumferential Evaluation Output (cont.)

SI PIPE EVAL, SOLUTION SUMMARY: Circumferential Nonplanar, Ferritic (continued)

LEFM ANALYSIS

Structural Factor, Membrane = 2.7 Structural Factor, Bending = 2.3 Section XI Appendix C, Section C-2621

σ_b = 2,573 psi σ_e = 1,945 psi σ_m = 533 psi

$\sigma_b = D_oM_b/2I$ $\sigma_e = D_oM_e/2I$ $\sigma_m = pD_o/4t$ Section XI Appendix C, Section C-2500

F_m = 4.98 $F_m = 1 + A_m(\theta/\pi)^{1.5} + B_m(\theta/\pi)^{2.5} + C_m(\theta/\pi)^{3.5}$ Code Case N-513-2 Appendix I-2.0

where:

$A_m = -2.02917 + 1.67763(R_m/t) - 0.07987(R_m/t)^2 + 0.00176(R_m/t)^3$

$B_m = 7.09987 - 4.42394(R_m/t) + 0.21036(R_m/t)^2 - 0.00463(R_m/t)^3$

$C_m = 7.79661 + 5.16676(R_m/t) - 0.24577(R_m/t)^2 + 0.00541(R_m/t)^3$

F_b = 3.48 $F_b = 1 + A_b(\theta/\pi)^{1.5} + B_b(\theta/\pi)^{2.5} + C_b(\theta/\pi)^{3.5}$ Code Case N-513-2 Appendix I-2.0

where:

$A_b = -3.26543 + 1.52784(R_m/t) - 0.072698(R_m/t)^2 + 0.0016011(R_m/t)^3$

$B_b = 11.36322 - 3.91412(R_m/t) + 0.18619(R_m/t)^2 - 0.004099(R_m/t)^3$

$C_b = -3.18609 + 3.84763(R_m/t) - 0.18304(R_m/t)^2 + 0.00403(R_m/t)^3$

K_{Im} = 7,789 $K_{Im} = (SF_m)F_m\sigma_m(\pi a)^{0.5}$ Section XI Appendix C, Section C-7300

K_{Ib} = 29,699 $K_{Ib} = [(SF_b)\sigma_b + \sigma_e]F_b(\pi a)^{0.5}$ Section XI Appendix C, Section C-7300

K_{Ir} = 0 K_I from residual stresses at the flaw location, Section XI Appendix C, Section C-7300

K_I = 37,488 psi-in$^{1/2}$ $K_I = K_{Im} + K_{Ib} + K_{Ir}$ Section XI Appendix C, Section C-7300

K_c = 37,607 psi-in$^{1/2}$ $K_c = (J_{Ic}E'/1000)^{0.5}$ Section XI Appendix C, Section C-7200

Allowable Flaw Length = 25.58 in Entered Flaw Length = 4.0 in

The half flaw length is incrementally increased up to the stability condition limit: $K_I \le K_c$