NUTECH
CONTROLLED
COPY

CPL-17-103
Revision 0
March 1984
CPL017.0103

STATISTICAL EVALUATION OF POSTULATED FLAWS AT BRUNSWICK STEAM ELECTRIC PLANT UNIT 1

Prepared for:
Carolina Power and Light Company

Prepared by:
NUTECH, Engineers, Inc.
San Jose, California

Prepared by:

J. E. Charnley, P.E.
Project Engineer

Issued by:

H. J. Sund
Project Manager

Approved by:

T. J. Wenner, P.E.
Engineering Manager

Date March 28, 1984

nutech
ENGINEERS

REVISION CONTROL SHEET

TITLE: Statistical Evaluation of Postulated Flaws at Brunswick Steam Electric Plant Unit 1

DOCUMENT FILE NUMBER: CPL-17-103

NAME / TITLE	INITIALS
J. E. Charnley/Staff Engineer	IDM for JEC
H. L. Gustin/Senior Engineer	HLG
D. C. Talbott/Associate Engineer	DCT
T. Lem/Associate Engineer	TL

AFFECTED PAGE(S)	DOC REV	PREPARED BY / DATE	ACCURACY CHECK BY / DATE	CRITERIA CHECK BY / DATE	REMARKS
1	0	IDM for JEC 3/28/84	TL 3/28/84	HLG 3-28-84	
2	0	↓	↓	↓	
3	0				
4	0				
5	0				
6	0				
7	0				
8	0				
9	0				
10	0				
11	0				
12	0				
13	0				
14	0				
15	0				
16	0		↓		
17	0		TL 3/28/84		
18	0		DCT 3-28-84		
19	0		↓		
20	0				
21	0		↓		
22	0		DCT 3-28-84		
23	0				
24	0		TL 3/28/84		
25	0	↓	↓	↓	
26	0	IDM for JEC 3/28/84	TL 3/28/84	HLG 3-28-84	

PAGE ____ OF ____

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

The purpose of this report is to document the results of a statistical evaluation of postulated intergranular stress corrosion crack (IGSCC) growth in the Brunswick Unit 1 recirculation piping system. The evaluation consisted of reviewing the cracks detected in the Brunswick Unit 2 recirculation piping system following full UT-inspection during late 1983, performing crack growth calculations using that data, and then applying those results to the Brunswick Unit 1 recirculation piping system. This approach is creditable in that the two units exhibit similar characteristics pertaining to material composition, geometric configuration, system loads, and operational conditions.

The results of the evaluation show that the probability of circumferential cracks growing to an unacceptable size (Reference 1) before the scheduled refueling outage for Brunswick Unit 1 in November 1984 is very low.

2.0 BACKGROUND

Brunswick Unit 1 has only had a limited number of welds examined per IE Bulletin 83-02 and is not scheduled for another such examination until the next refueling outage scheduled for November 1984.

Inspections per IE Bulletin 83-02 were performed at Brunswick Unit 2 during an outage in November 1983. During that outage, 131 welds were examined in the recirculation, residual heat removal (RHR) and reactor water cleanup (RWCU) systems. Ultrasonic (UT) inspection indications were found in 19 of the 131 welds that were judged to be due to IGSCC. Eight of those welds were repaired with weld overlays while the remaining eleven were shown to be acceptable without repair for at least one fuel cycle (Reference 2).

3.0 ASSUMPTIONS

The following assumptions were used in the statistical evaluation of IGSCC data from Brunswick Unit 2 for application to a Brunswick Unit 1 prediction of unacceptable IGSCC by November 1984.

3.1 Crack Orientation

Only circumferential cracks were considered. Axial IGSCC is limited in length to the width of the weld heat affected zones. Axial IGSCC will not lead to a pipe failure either by plastic collapse or tearing instability. Thus, axial cracks are not structurally limiting.

3.2 Initial Crack Depth

Table 3.1 presents a comparison between Brunswick Units 1 and 2 of the relevant factors which contribute to IGSCC. Inspection of Table 3.1 shows that Units 1 and 2 have approximately equal propensity for IGSCC after an equal number of operating hours. As of February 28, 1984, Unit 2 had accumulated 8,300 more hot critical hours than Unit 1. Assuming uninterrupted operation,

Unit 1 should have an equivalent amount of IGSCC in November 1984 as Unit 2 had in December 1983, when it was examined. During the Unit 1 examination that was performed in November 1983, two welds had UT indications that were already sized at depths comparable to those observed in Unit 2 in December 1983. Therefore, to be conservative, it was assumed in this evaluation that Units 1 and 2, as of December 1983, had similar IGSCC depths.

3.3 Crack Length

All cracks in large diameter pipes were conservatively assumed to be 360°. This assumption allows the use of the nonlinear stress distributions which are analytically predicted for large pipe. All cracks in small diameter pipe were assumed to have a crack length equal to ten times the maximum crack depth. This assumption is justified because the appropriate residual stress distributions are linear. Therefore finite length cracks may be analyzed.

Table 3.1

COMPARISON OF RELEVANT IGSCC PARAMETERS OF BRUNSWICK UNITS 1 AND 2

Parameter	Brunswick Unit 1	Brunswick Unit 2
Material	304 stainless steel	304 stainless steel
Designer	General Electric	General Electric
Fabricators	Associated Piping M. W. Kellog	Associated Piping M. W. Kellog
Installers	General Electric Brown and Root	General Electric Brown and Root
Carbon Content	0.04% - 0.075%	0.04% - 0.075%
Water Chemistry	No significant difference between the Units	No significant difference between the Units
Hot Critical Hours	37,760	46,065

4.0 CONCLUSIONS

The following conclusions can be made from the evaluation results:

a) There are no flaws in piping with diameters greater than 12 inches which are predicted to reach an unacceptable depth (Reference 1) by November 1984. With 99 percent confidence, the deepest flaw in large diameter pipe at that time will be less than 0.60 inch with an allowable depth of 0.79 inch (based upon a wall thickness of 1.26").

b) For 12" and under welds, with the entire range of values of the crack growth law, weld residual stress, applied stress and initial crack size, the statistical results indicate that two welds could have unacceptable flaws by November 1984. However, the following additional considerations offset those results:

1. Although it was assumed that Brunswick Units 1 and 2 are identical from an IGSCC perspective, Unit 1 has operated 8300 fewer hours.

2. Those cases that resulted in unacceptable crack sizes were based on very conservative analyses, i.e., high crack growth rates and other conservative assumptions.

3. A total of 24 12" and smaller welds, including those welds with the highest applied stress (the 12" pipe-to-safe end welds), were inspected by UT in January 1983, and no circumferential cracks were discovered. The unit has operated only 7 months since then.

Therefore, for 12" and smaller piping, the probability that unit operation until November 1984 will result in unacceptable cracks is very low.

5.0 ANALYSIS

IGSCC growth is a function of four major variables; initial crack size, weld residual stress, applied stress and crack growth law. The calculation of the expected size of IGSCC in Brunswick Unit 1 by November 1984 is based on determining the expected range of each of these variables and then performing many crack growth analyses to obtain a distribution of final crack depths. Because of the significantly different weld residual stress patterns in pipe diameters equal to or less than 12" as compared to diameters greater than 12", two separate final crack size distributions were calculated.

5.1 Initial Crack Depth

Table 5.1 contains the maximum reported depth of the eighteen circumferential indications from the Brunswick Unit 2 inspections (Reference 2) and the two circumferential indications from the Brunswick Unit 1 inspection (Reference 3).

From Table 5.1, it can be seen that of the welds examined in pipes with a diameter less than or equal to 12", 8 had circumferential cracks with a mean ($\bar{X}$) depth of 11.2% of wall and a standard deviation (s) of 3.45%

of wall. Similarly, for pipe with a diameter greater than 12", 12 had circumferential cracks with a mean depth of 19% of wall and a standard deviation of 4.48% of wall. For each size of pipe, three initial crack sizes were chosen to represent the expected crack distribution in Unit 1 as of December 1983. Those sizes were $\overline{X}$-2S, $\overline{X}$, and $\overline{X}$+2S. Thus, for 12" pipe with a wall thickness of 0.568", the initial sizes were 0.025", 0.064", and 0.10". Similarly, for 28" pipe with a wall thickness of 1.26", the initial sizes were 0.13", 0.24", and 0.35".

5.2 Weld Residual Stress

The variation in weld residual stress is difficult to quantify. The NUTECH standard weld residual distributions for both 12" and 28" pipe (Reference 9) were used as the conservative (high growth rate) distributions.

For 28" pipe, the best estimate and the optimistic distributions were obtained from Reference 4. The best estimate distribution was identified as the average case in Reference 4 and the optimistic case was identified as the Harris case in Reference 4. All three distributions are shown on Figure 5.1.

For 12" pipe, it was conservatively assumed that all distributions are linear. The best estimate and optimistic distributions were obtained from the Reference 9 conservative distribution by reducing the maximum stress by 5 ksi and 15 ksi, respectively. All three distributions are shown in Figure 5.2.

5.3 Applied Stress

The applied stresses that are important for crack growth in a given weld are those that exist during normal operation, such as dead weight, pressure, steady state thermal expansion and bending stress due to shrinkage of weld overlays at other locations. Dead weight and pressure stresses were obtained from Reference 5. Steady state thermal and weld overlay shrinkage stresses were obtained from Reference 3.

For pipe larger than 12", maximum values of stress due to pressure plus dead weight, steady state thermal, and weld shrinkage are 8500 psi, 6200 psi and 300 psi, respectively. Even though these stresses do not occur at the same location, it was conservatively assumed that the highest stress was equal to their sum (15,000 psi). The minimum stress was obtained by adding the pressure stress of 5800 psi and the minimum thermal

nutech ENGINEERS

expansion stress of 600 for a total stress of 6400 psi. The mean stress was judged to be 8300 psi.

For 12" and smaller pipe, the maximum stress due to pressure plus dead weight, steady state thermal and weld shrinkage are 12,200 psi, 11,300 psi and 3400 psi, respectively. Again these stress values do not occur at the same locations. Since the maximum thermal stress was abnormally high, it would have been overly conservative to add all the maximum stress values. The location with the highest total stress is in the N2C recirculation inlet safe end to pipe weld with a pressure plus dead weight stress of 11,100 psi, a steady state thermal stress of 7,300 psi and a small weld shrinkage stress assumed to be 400 psi. Thus, the worst case total stress is 18,800 psi. The minimum stress was obtained by adding the minimum pressure stress of 7000 psi to the minimum steady state thermal stress of 500 for a total stress of 7500 psi. The mean stress was judged to be 11,000 psi.

5.4 Crack Growth Law

The typical steady state conditions during IGSCC growth are welding sensitization, 0.2 ppm oxygen water chemistry and constant load. An extensive search of

nutech ENGINEERS

existing crack growth information was performed. However, only one set of data was found (Reference 6) which meets the above conditions. These data are shown in Figure 5.3. Upper bound, best estimate and lower bound crack growth equations were determined as follows:

Upper Bound

$$\frac{da}{dt} = 8.23 \times 10^{-9} K^{2.537}$$

Best Estimate

$$\frac{da}{dt} = 2.50 \times 10^{-9} K^{2.537}$$

Lower Bound

$$\frac{da}{dt} = 9.091 \times 10^{-10} K^{2.537}$$

Where:

da = Differential Crack Depth (inches)

dt = Differential Time (hours)

K = Stress Intensity Factor (ksi $\sqrt{\text{inches}}$)

5.5 Crack Growth Calculations

For both sizes of pipe, crack growth calculations for an eleven-month period (December 1983 - November 1984) were performed with the three different values for each of the four major variables. Thus, 81 crack growth cases for each size of pipe were performed. The computer program NUTCRAK (Reference 7) was used for the 28" pipe with assumed 360° cracks and the computer program NUFLAW (Reference 8) was used for the 12" pipe with assumed crack lengths of ten times their depths. The results of each case are given in Tables 5.2 and 5.3.

Examination of Table 5.2 (28" pipe) reveals the following:

a) The largest predicted crack size after 11 months is 0.74 inch

b) The mean predicted crack size is 0.27 inch

c) The standard deviation is 0.11 inch

Due to the large number of crack growth calculations and the method that was used to select the input variables, the actual mean crack size (μ) can be calculated by using the τ distribution.

nutech ENGINEERS

$$\overline{X} - T \frac{s}{\sqrt{n}} < \mu < \overline{X} + T \frac{s}{\sqrt{n}}$$

Where:

$\overline{X}$ = sample mean = 0.27

s = sample standard deviation = 0.11

n = number of calculations = 81

T = value of the T distribution at the appropriate confidence level and number of degrees of freedom.

With a confidence level of 99% and number of degrees of freedom greater than 29, the actual mean crack size is between 0.24 inch and 0.30 inch.

The allowable crack size for a 360° crack in 28" pipe is 63% of the pipe wall (0.79 inches) per Reference 1 (stress ratio = 0.6). All calculated crack sizes as of November 1984 are less than the allowable. The mean calculated crack size and the three standard deviation extreme crack size are below the allowable crack size.

Examination of Table 5.3 (12" pipe) reveals the following:

a) 17 of the 81 cases result in a through wall crack within eleven months. Two additional cases result in a crack larger than the allowable depth (47% of wall) for a 360° crack within eleven months. It should be noted that the prediction of a through wall crack does not indicate a safety concern for several reasons. First, a conservative initial crack was postulated to exist and to exist in combination with the worst case values of the other major variables. Second, Brunswick Unit 1 has instituted augmented leakage monitoring. Third, high growth rates can only occur adjacent to welds with high applied bending stress. Such bending stress will cause significant asymmetry, thus, assuring leak before break.

b) 16 of the 19 cases that result in an unacceptable crack occur with the upper bound crack growth law. The remaining 3 cases result from a combination of the highest applied stress coupled with the largest initial defect or the worst case residual stress.

c) The remaining 62 cases result in a maximum crack depth after 11 months (November 1984) of 0.26 inch with a mean value of 0.10 inch.

Thus, based on the above and on the fact that approximately 10 percent of the 12-inch and smaller welds examined at Brunswick Unit 2 were cracked in December 1983, the number (N) of welds which would be expected to have cracks of depth greater than that permitted by Reference 1 can be defined with the following equation:

$$N = .10 \left(\frac{21}{81}\right) N' = 0.026N'$$

Where:

N' = Number of 12 inch and smaller welds

Since N' is approximately equal to 74, two welds in the 12 inch and smaller piping could have flaws larger than those allowed by Reference 1. Since Unit 1 has operated for 8300 fewer hours than Unit 2, it is likely that no unacceptable cracks will exist in Unit 1 by November 1984.

Table 5.1

CIRCUMFERENTIAL CRACK DEPTHS

Weld Number	Maximum Crack Depth for Pipe Diameter of ≤ 12"	> 12"
2-B32-28-A-8		17%
2-B32-28-A-14		20%
2-B32-28-A-4		19%
2-B32-28-B-4		11%
2-B32-28-B-5		22%
2-B32-28-B-3		16%
2-B32-28-A-13		19%
2-B32-28-B-9		17.6%
1-B32-28-A-14		20%
1-B32-28-B-8		30%
2-B32-22-AM-5		20%
2-B32-22-BM-1		16%
2-B32-12-G-4	14%	
2-B32-12-K-3	5%	
2-B32-12-J-3	11%	
2-B32-12-K-2	11%	
2-B32-12-J-2	12%	
2-G31-6-10	13%	
2-G31-6-15	16%	
2-G31-6-16	8%	
Average Depth ($\overline{X}$)	11.2%	19.0%
Standard Deviation (S)	3.45%	4.48%

Table 5.2

28" PIPE CRACK GROWTH RESULTS

Case	Initial Crack Depth (inches)	Weld Residual Stress	Applied Stress (psi)	Crack Growth Law	Final Crack Depth in 11 months (inches)
1	.13	Cons.	15,000	Upper Bound	.3918
2	.24				.5478
3	.35				.7390
4	.13	Best			.2054
5	.24				.2790
6	.35				.3583
7	.13	Opt.			.1532
8	.24				.2364
9	.35				No Growth
10	.13	Cons.	8,300		.2518
11	.24				.3529
12	.35				.4387
13	.13	Best			.1600
14	.24				.2437
15	.35				No Growth
16	.13	Opt.			.1332
17	.24				No Growth
18	.35				No Growth
19	.13	Cons.	6,400		.2268
20	.24				.3239
21	.35				.4064
22	.13	Best			.1512
23	.24				.2393
24	.35				No Growth
25	.13	Opt.			.1298
26	.24				No Growth
27	.35				No Growth
28	.13	Cons.	15,000	Best Estimate	.1958
29	.24				.3233
30	.35				.4378
31	.13	Best			.1517
32	.24				.2508
33	.35				.3493
34	.13	Opt.			.1348
35	.24				.2361
36	.35				No Growth
37	.13	Cons.	8,300		.1620
38	.24				.2740
39	.35				.3752
40	.13	Best			.1366
41	.24				.2385

Table 5.2

28" PIPE CRACK GROWTH RESULTS
(Concluded)

Case	Initial Crack Depth (inches)	Weld Residual Stress	Applied Stress (psi)	Crack Growth Law	Final Crack Depth in 11 months (inches)
42	.35				No Growth
43	.13	Opt.			.1277
44	.24				No Growth
45	.35				No Growth
46	.13	Cons.	6,400		.1552
47	.24				.2648
48	.35				.3652
49	.13	Best			.1512
50	.24		6,400		.2370
51	.35				No Growth
52	.13	Opt.			.1266
53	.24				No Growth
54	.35				No Growth
55	.13	Cons.	15,000	Lower Bound	.1488
56	.24				.2671
57	.35				.3779
58	.13	Best			.1349
59	.24				.2416
60	.35				.3466
61	.13	Opt.			.1287
62	.24				.2360
63	.35				No Growth
64	.13	Cons.	8,300		.1381
65	.24				.2500
66	.35				.3563
67	.13	Best			.1293
68	.24				.2369
69	.35				No Growth
70	.13	Opt.			.1260
71	.24				No Growth
72	.35				No Growth
73	.13	Cons.	6,400		.1358
74	.24				.2467
75	.35				.3525
76	.13	Best			.1282
77	.24				.2364
78	.35				No Growth
79	.13	Opt.			.1256
80	.24				No Growth
81	.35				No Growth

Table 5.3

12" PIPE CRACK GROWTH RESULTS

Case	Initial Crack Depth (inches)	Weld Residual Stress	Applied Stress (psi)	Crack Growth Law	Final Crack Depth in 11 months (inches)
1	.025	Cons.	18,800	Upper Bound	thru 6.3 mo.
2	.064				thru 3.6 mo.
3	.10				thru 2.4 mo.
4	.025	Best			thru 7.8 mo.
5	.064				thru 4.4 mo.
6	.10				thru 2.9 mo.
7	.025	Opt.			.180
8	.064				thru 7.2 mo.
9	.10				thru 4.6 mo.
10	.025	Cons.	11,000		.255
11	.064				thru 7.2 mo.
12	.10				thru 4.9 mo.
13	.025	Best			.135
14	.064				thru 9.3 mo.
15	.10				thru 6.3 mo.
16	.025	Opt.			.060
17	.064				.164
18	.10				.353
19	.025	Cons.	7,500		.135
20	.064				thru 10.0 mo.
21	.10				thru 6.9 mo.
22	.025	Best			.085
23	.064				.244
24	.10				thru 9.2 mo.
25	.025	Opt.			.045
26	.064				.119
27	.10				.198
28	.025	Cons.	18,800	Best Estimate	.085
29	.064				.304
30	.10				thru 7.9 mo.
31	.025	Best			.065
32	.064				.199
33	.10				thru 9.7 mo.
34	.025	Opt.			.040
35	.064				.124
36	.10				.223
37	.025	Cons.	11,000		.055
38	.064				.129
39	.10				.243

Table 5.3

12" PIPE CRACK GROWTH RESULTS
(Continued)

Case	Initial Crack Depth (inches)	Weld Residual Stress	Applied Stress (psi)	Crack Growth Law	Final Crack Depth in 11 months (inches)
40	.025	Best			.040
41	.064				.109
42	.10				.183
43	.025	Opt.			.035
44	.064				.084
45	.10				.143
46	.025	Cons	7,500		.040
47	.064				.114
48	.10				.178
49	.025	Best			.040
50	.064				.094
51	.10				.153
52	.025	Opt.			.030
53	.064				.079
54	.10				.123
55	.025	Cons.	18,800	Lower Bound	.040
56	.064				.104
57	.10				.188
58	.025	Best			.035
59	.064				.094
60	.10				.158
61	.025	Opt.			.035
62	.064				.084
63	.10				.133
64	.025	Cons.	11,000		.035
65	.064				.084
66	.10				.138
67	.025	Best			.030
68	.064				.079
69	.10				.128
70	.025	Opt.			.030
71	.064				.074
72	.10				.118
73	.025	Cons.	7,500		.030
74	.064				.079
75	.10				.128
76	.025	Best			.030
77	.064				.074
78	.10				.123

Table 5-3

28" PIPE CRACK GROWTH RESULTS
(Concluded)

Case	Initial Crack Depth (inches)	Weld Residual Stress	Applied Stress (psi)	Crack Growth Law	Final Crack Depth in 11 months (inches)
79	.025	Opt.			.030
80	.064				.069
81	.10				.113

nutech
ENGINEERS

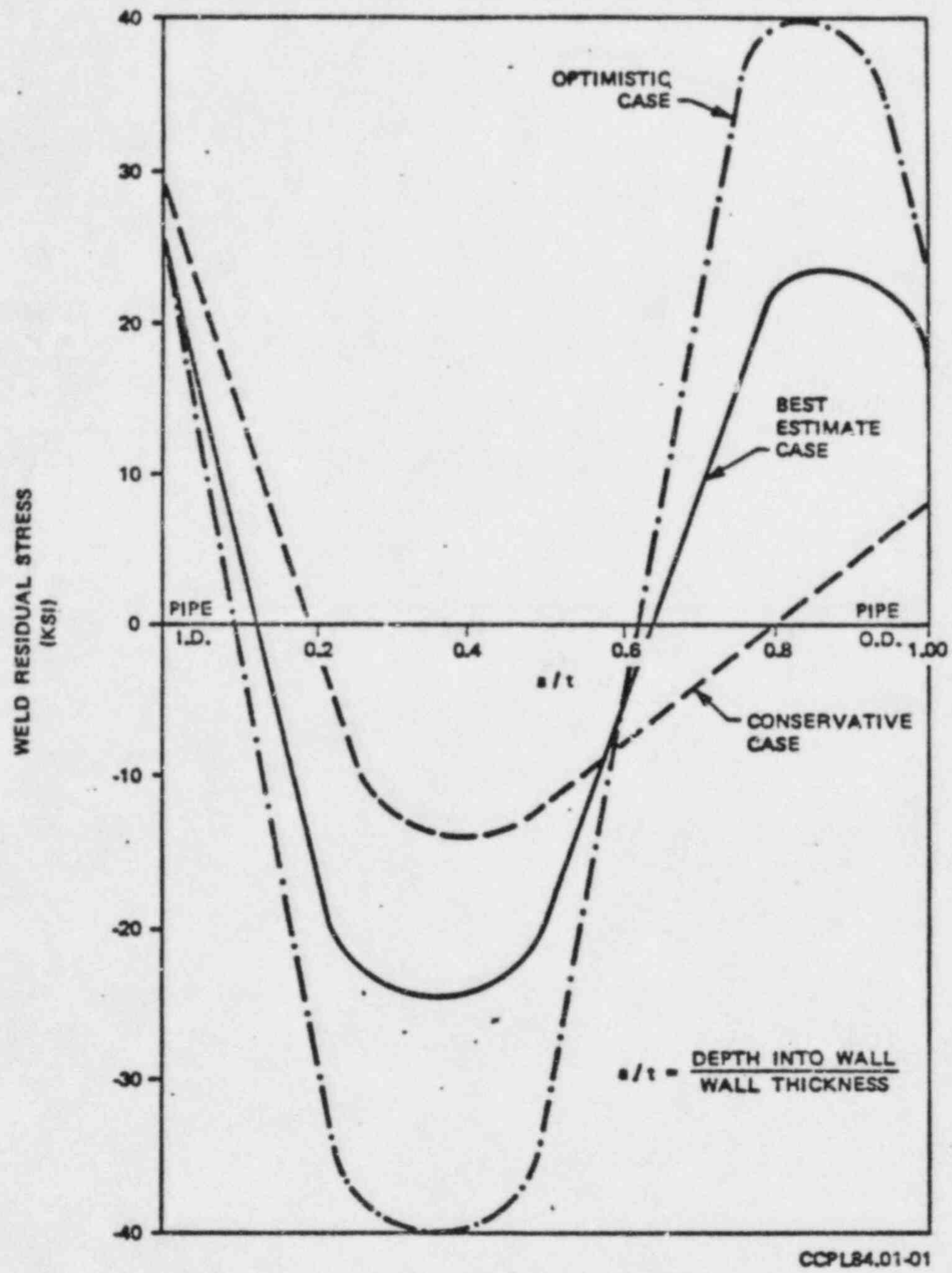


Figure 5.1

RESIDUAL AXIAL STRESS
IN LARGE DIAMETER PIPE

(> 12" Φ)

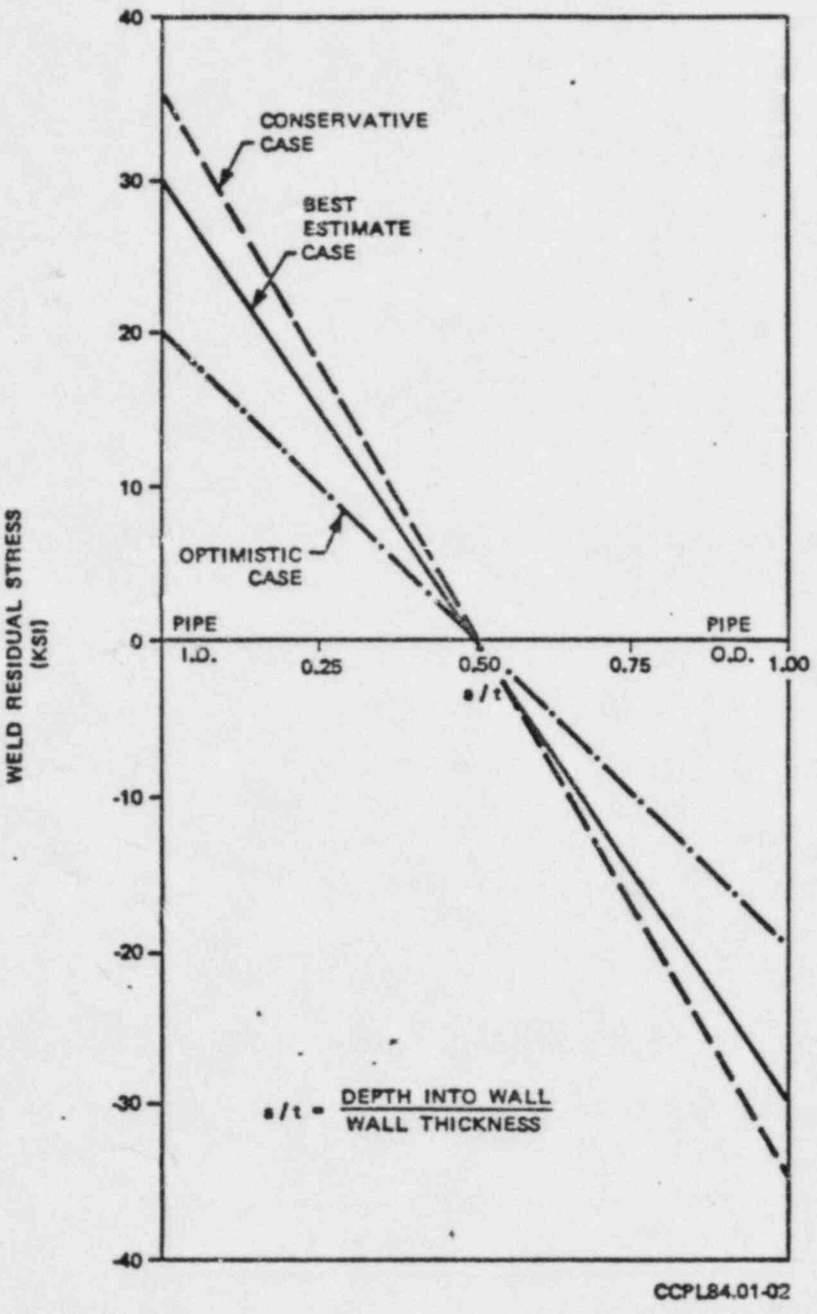
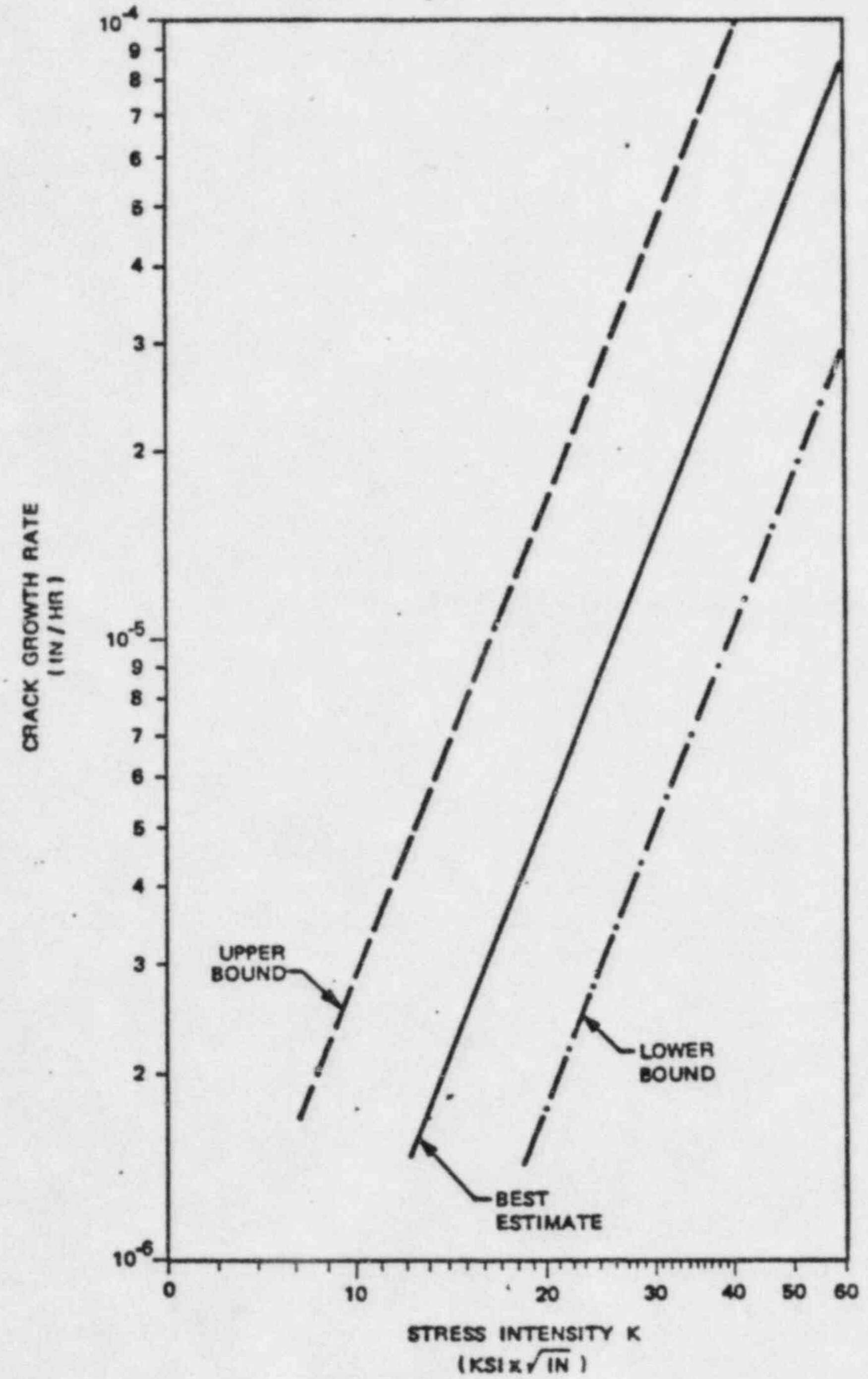


Figure 5.2

RESIDUAL AXIAL STRESS IN SMALL DIAMETER PIPE

($\leq$ 12" Φ)



CCPL84.01-03

Figure 5.3

CRACK GROWTH LAWS

6.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section XI, Paragraph IWB-3640, 1983 Edition, Winter 1983 Addenda.

2. NUTECH Report CPL-13-104, Revision 1, Design Report for Weld Overlay Repairs at Brunswick Steam Electric Plant, Unit 2.

3. NUTECH Report CPL-13-103, Revision 0, Design Report for Recirculation System Weld Overlay Repairs at Brunswick Steam Electric Plant, Unit 1.

4. CNSI Meeting on the Regulatory Basis for Actions on BWR Pipe Cracks, February 7-9, 1984, "Analysis of the Remaining Life of Flawed Piping Weldments in BWRs," by William Shack.

5. General Electric Letter G-KB1-1-193, December 30, 1981, "Transmittal of GE Design Memo 170-17 Revision 1, "Seismic Reevaluation of Recirculation Piping System for Brunswick Units 1 and 2".

6. EPRI Report NP-2472 Volume 2, Section H-8, July 1982.

7. NUTECH Computer Program NUTCRAK, Revision 2.0.2, December 1983, File No. 08.039.0005.

8. NUTECH Computer Program NUFLAW, Revision 0, November 1983.

9. "Weld Residual Stress Data Base for IGSCC Crack Growth Calculations," NUTECH Internal Memo HLG-84-001, January 10,1984.