SASR 91-26
DRF 137-0010

FULL STRUCTURAL WELD OVERLAY DESIGN FOR PEACH BOTTOM UNIT 2 RWCU WELD 12-I-1D

April, 1991

Prepared For

Philadelphia Electric Company

By

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IMPORTANT NOTICE REGARDING

CONTENTS OF THIS REPORT

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1. INTRODUCTION

During ultrasonic examination of the Reactor Water Clean-Up (RWCU) piping system at Peach Bottom Unit 2 (PB2), the examiner located a circumferential indication at the inside surface of a 4-inch schedule 80 pipe. This indication was found March 9, 1991 near the weld to a check valve (weld 12-I-1D) as shown in Figure 1. The affected pipe is made of ASTM A-376 type 304 stainless steel. Details on the indication found are contained in the Reference 1 report. Further UT and radiography examinations were used to verify the existence of the flaw and to accurately characterize the flaw geometry. The flaw was determined to have a maximum depth of 0.14-inch with a pipe wall thickness of 0.40-inch in this region. This flaw is located an axial distance of about 0.8-inch from the weld centerline extending in length from about 1 to 3 inches clockwise from Top Dead Center (TDC).

To repair the pipe at this location, a full structural weld overlay is designed and applied at weld 12-I-1D. This full structural weld overlay is designed to support the entire pressure, dead weight and seismic loading in the pipe conservatively assuming that the crack extends through the wall of the original pipe for the entire circumference. The weld overlay is designed in accordance with Section XI of the ASME code to restore the pipe to meet ASME code structural margins.

2. SUMMARY

The weld overlay shown on Figure 2 has been designed to repair the indication in accordance with Section XI of the ASME code. The nominal overlay thickness is defined as 0.200 inches with a minimum thickness of 0.175 inches. The overlay must extend at least 1.5 inches past the indication on the side away from the valve to allow future UT measurements. On the valve side, the overlay should blend into the valve bevel as shown on Figure 2. The Reference 6 GE overlay procedure may be used to provide guidance in developing a site specific procedure.

3. WELD OVERLAY PROCESS

The weld overlay design consists of a continuous 360° band of weld metal deposited over the outside surface of the pipe directly over the crack indication. The overlay is made with high ferrite, low carbon Type ER308L stainless steel weld metal. This material has a very high toughness and is resistant to Intergrannular Stress Corrosion Cracking (IGSCC). The weld metal is deposited using an automatic Gas Tungsten Arc Welding (GTAW) technique with water cooling the inside surface of the pipe. Using this process, compressive residual stresses are created at the inside surface of the pipe which tends to arrest crack growth. The Reference 6 GE weld overlay procedure may be used to provide guidance in developing a site specific procedure for PECO.

4. WELD OVERLAY DESIGN METHODOLOGY

In designing a full structural weld overlay, the crack is conservatively assumed to extend through the original pipe wall thickness for the full circumference of the pipe. Making this assumption, the weld overlay design is independent of the size of the indication. This is conservative for the indication found which extends less than 40% through wall for less than 20% of the circumference. Also, the crack is unlikely to grow due to the compressive residual stresses created at the inner surface of the pipe using the heat sink weld overlay process.

The weld overlay effectively increases the pipe wall thickness with high ferrite, low carbon Type ER308L stainless steel material that is resistant to IGSCC. Therefore, a crack growing through the wall of the pipe will not extend into the overlay. This will be confirmed by future inspections.
The overlay thickness is designed such that a factor of safety of 3.0 is maintained against net section collapse for normal and upset condition loading per Paragraph IWB-3642 of Reference 2. A factor of safety of 1.5 must also be met for emergency and faulted loading.

4.1 Weld Overlay Thickness

An iterative process is used to determine the required weld overlay thickness. An initial overlay thickness, T, is first assumed. Considering the pressure, deadweight and seismic loading on the pipe, the membrane (P_m) and bending (P_b) stresses on the uncracked, overlaid section (Section A-A of Figure 3) are then calculated. The bending stress (P_{bc}) in the uncracked, overlaid section of the pipe (Section A-A) at the point of net section collapse of the cracked section of the overlay (Section B-B) is next calculated using the methodology described in Reference 3. The stress distribution shown for section B-B of Figure 3 is assumed at collapse. The flow stress, σ_f, is defined as 3 S_m as in Appendix C of Reference 2. For the membrane stress calculated previously, the neutral axis angle is determined by equation 3 of Reference 3 as

$$\beta = \pi (1 - d/t - Pm/\sigma_f) / (2 - d/t)$$

The bending stress in the uncracked section (A-A) at net section collapse of the cracked section (B-B) is then calculated according to equation 4 of Reference 3 as

$$P_{bc} = (2 \sigma_f / \pi) (2 - d/t) \sin(\beta)$$

The net section collapse stresses are then compared against the applied stresses to determine if factors of safety on collapse of 3 for upset loading and of 1.5 on faulted loading are achieved.

$$(P_m + P_{bc}) / (P_m + P_b)_{upset} \geq 3$$

$$(P_m + P_{bc}) / (P_m + P_b)_{faulted} \geq 1.5$$

If these condition are met, the assumed overlay thickness is sufficient. If these condition are not met, the assumed thickness must be increased and the calculations repaated until the required factors of safety are achieved.

4.2 Weld Overlay Width

After the required overlay thickness has been determined, the overlay width is considered. The overlay width is sized taking into account several considerations. First, the overlay must extend along the length of the pipe a distance great enough to ensure it will envelope the extent of cracking. For an axial crack, this overlay width must take into account the projected growth of the crack. For a circumferential crack, the extent of cracking is confined to a small axial region of the pipe. GE has completed studies into the minimum overlay width required to provide adequate structural reinforcement of the cracked area and to assure that the stresses in the overlay will be reasonably uniform. These studies have shown that an overlay width of $0.5\sqrt{Rt}$ to each side of the indication is adequate. This axial distance is also great enough to assure that the circumferential crack is fully enveloped by the overlay.

Another consideration is the inspectibility of the indication after the overlay is applied. The UT transducer must be placed flat on the outside surface of the overlay at some distance from the indication. This distance must be great enough to locate the crack tip with a 45° or 60° refracted wave. This requirement often exceeds the structural requirements for the overlay width described above. Finally, the overlay width may be dictated by geometric constraints if located near a tee, valve or other fitting.

5. WELD OVERLAY DESIGN

As stated previously, the weld overlay is designed using an iterative approach. The thickness is adjusted until the structural margins defined by the ASME code are achieved. For this analysis, the iterations made to arrive at the final overlay thickness are not shown. Only the calculations for the final overlay thickness are included to show that the designed thickness is sufficient. The calculations for this final weld overlay thickness, summarized in Table 1, are described in detail below.

5.1 Weld Overlay Thickness

The minimum overlay thickness was determined to be T = 0.175 inches. For this overlay thickness, the important dimensions and cross sectional properties are:

Pipe + Overlay Thickness, t = 0.400 + 0.175 = 0.575 inches
Pipe Inner Radius, R_i = 1.850 inches
Overlay Outer Thickness, R_o = 2.425 inches
Nominal Radius, R = 2.138 inches
Cross Sectional Area, A = 7.722 $inch^2$
Bending Inertia, I = 17.961 in^4

The actual UT measured thickness of the pipe (0.40") was used rather than the nominal thickness for a 4-inch schedule 80 pipe (0.337") because for the weld overlay design, the greater original pipe thickness conservatively leads to a greater overlay thickness.

Applied Stresses

Per Reference 4, the design pressure for this piping is 1800 psig. The primary membrane stress is thus

$$P_m = \pi R_i^2 P / A = \pi (1.850 \text{ in})^2 (1800 \text{ psig}) / 7.722 \text{ in}^2 = 2506 \text{ psi}$$

The maximum upset condition deadweight and OBE seismic bending stresses in the original 4-inch schedule 80 pipe are also given in Reference 4 as

σ_d = 5127 psi

and

σ_{OBE} = 4575 psi

The dimensions and cross sectional properties for the original 4-inch schedule 80 pipe are:

Pipe Wall Thickness, d = 0.400 inches,
Pipe Inside Diameter, ID = 3.700 inches,
Pipe Outside Diameter, OD = 4.500 inches, and
Pipe Bending Inertia, I_p = 10.929 inch^4.

Again, the actual UT measured thickness of 0.40" is conservatively used instead of the standard 4-inch schedule 80 nominal thickness of 0.337". Because the strength of the weld overlay is designed in relation to the strength of the original pipe, the use of the greater thickness is conservative and will lead to a greater overlay thickness. The applied moments can be calculated from the resulting stresses and the cross sectional properties as

$M_d = \sigma_d (I_p) / (OD/2)$ = 24905 inch-lbs

and

$M_{OBE} = \sigma_{OBE} (I_p) / (OD/2)$ = 22222 inch-lbs

for the deadweight and OBE seismic loading, respectively. Using these applied moments, the upset condition bending stress in the overlaid section is determined to be

$P_{bu} = (M_d + M_{OBE}) R_o / I = (24905 + 22222)\ 2.425 / 17.961 = 6363$ psi

For the faulted case, the SSE bending moment is conservatively assumed to equal twice the OBE moment

$$M_{SSE} = 2\ M_{OBE} = 44444 \text{ inch-lbs}$$

The faulted condition bending stress is then calculated as

$$P_{bf} = (M_d + M_{SSE})\ R_o\ /\ I = (14905 + 44444)\ 2.425\ /\ 17.961 = 9363 \text{ psi}$$

Net Section Collapse Stresses

The design stress intensity for this ASTM A-376 stainless steel pipe at 550°F is given in Table I-1.2 of Reference 5 as

$$S_m = 16950 \text{ psi}$$

The ER 308L stainless steel weld material has a greater strength. Therefore, the pipe material properties will conservatively be used. The flow stress is defined as three times the design stress intensity, or

$$\sigma_f = 3\ S_m = 50850 \text{ psi}$$

For the 2506 psi membrane stress calculated above, the neutral axis angle is calculated as

$$\beta = \pi(\ 1 - 0.400/0.575 - 2506/50850\ )\ /\ (\ 2 - 0.400/0.575\ ) = 0.6143 \text{ rad}$$

as described in Section 4.1. The bending stress in the overlaid pipe at net section collapse of the cracked section is

$$P_{bc} = [\ 2\ (50850)\ /\ \pi\ ]\ (\ 2 - 0.400/0.575\ )\ \sin(0.614) = 24339 \text{ psi}$$

Factor of Safety to Net Section Collapse

The ratio of net section collapse stresses in the uncracked, overlaid pipe over the applied stresses due to pressure, deadweight and an OBE seismic event, yields the factor of safety of

$$(P_m + P_{bc}) / (P_m + P_{bu}) = (2506 + 24339) / (2506 + 6363) = 3.03$$

This factor of safety exceeds the required factor of safety of 3.0 for normal operating and upset condition per Paragraph IWB-3642 of Reference 2.

For the faulted condition, the factor of safety is

$$(P_m + P_{bc}) / (P_m + P_{bf}) = (2506 + 24339) / (2506 + 9363) = 2.26$$

This exceeds the required factor of safety of 1.5 for faulted conditions per IWB-3642 of Reference 2. Both of the factor of safety requirements are met. Therefore, the minimum weld overlay thickness of 0.175 inches is sufficient. 25 mils are added to the minimum weld overlay thickness to obtain the nominal weld overlay thickness of 0.200 inches. No maximum overlay thickness is needed. The weld overlay repair is shown on Figure 2.

5.2 Weld Overlay Width

As described in section 4.2, the overlay must be applied for a width of at least

$$L = 0.5 \sqrt{R\ t} = 0.5 \sqrt{(2.138)\ (0.575)} = 0.55 \text{ inches}$$

beyond the indication on each side to meet structural requirements. However, to ensure the ability to conduct UT inspection of the indication after the overlay is made, an overlay width of 1.5 inches from the indication is recommended. The weld overlay repair is shown on Figure 2.

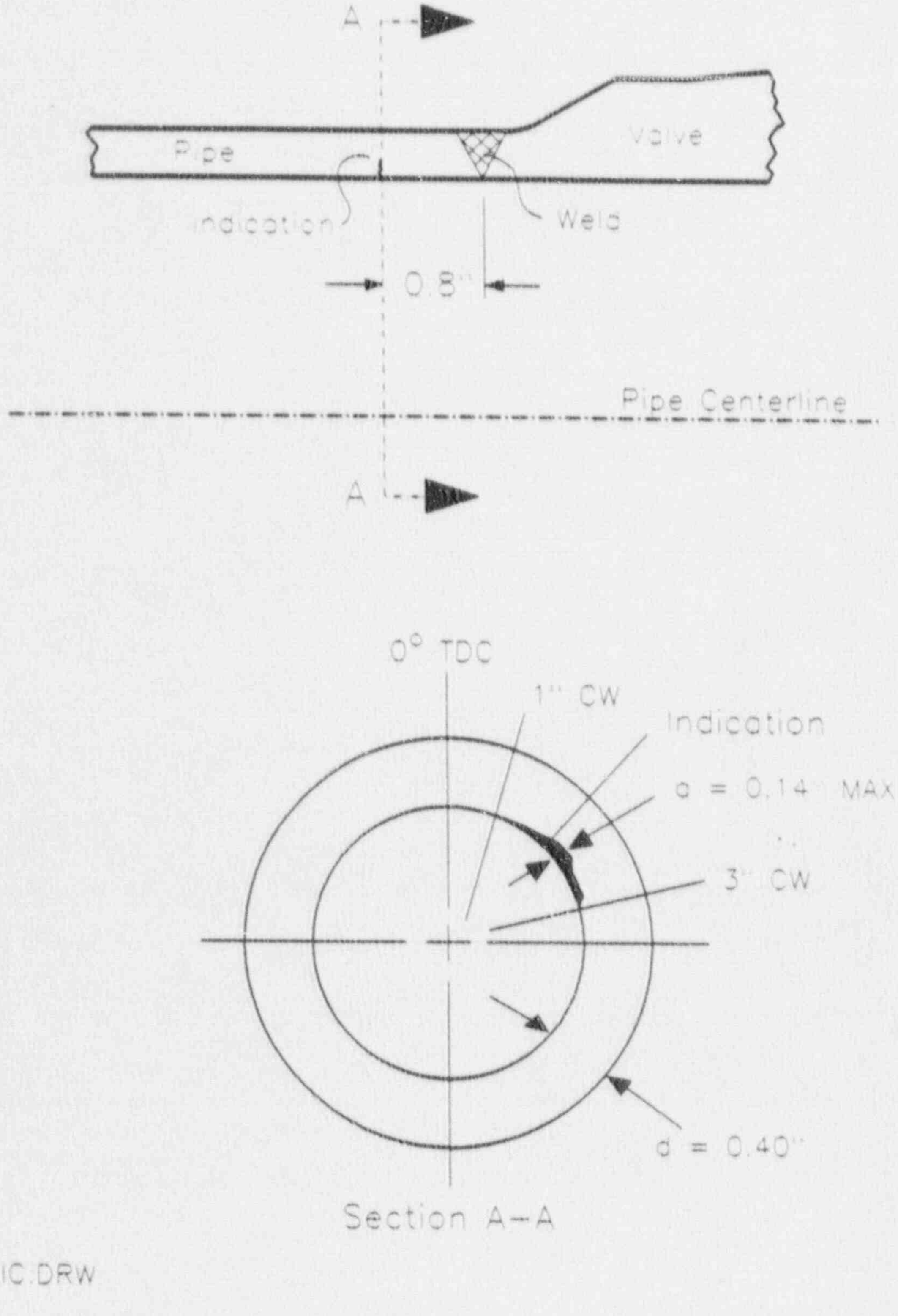

Figure 1 - Peach Bottom 2 RWCU Weld 12-I-1D Indication

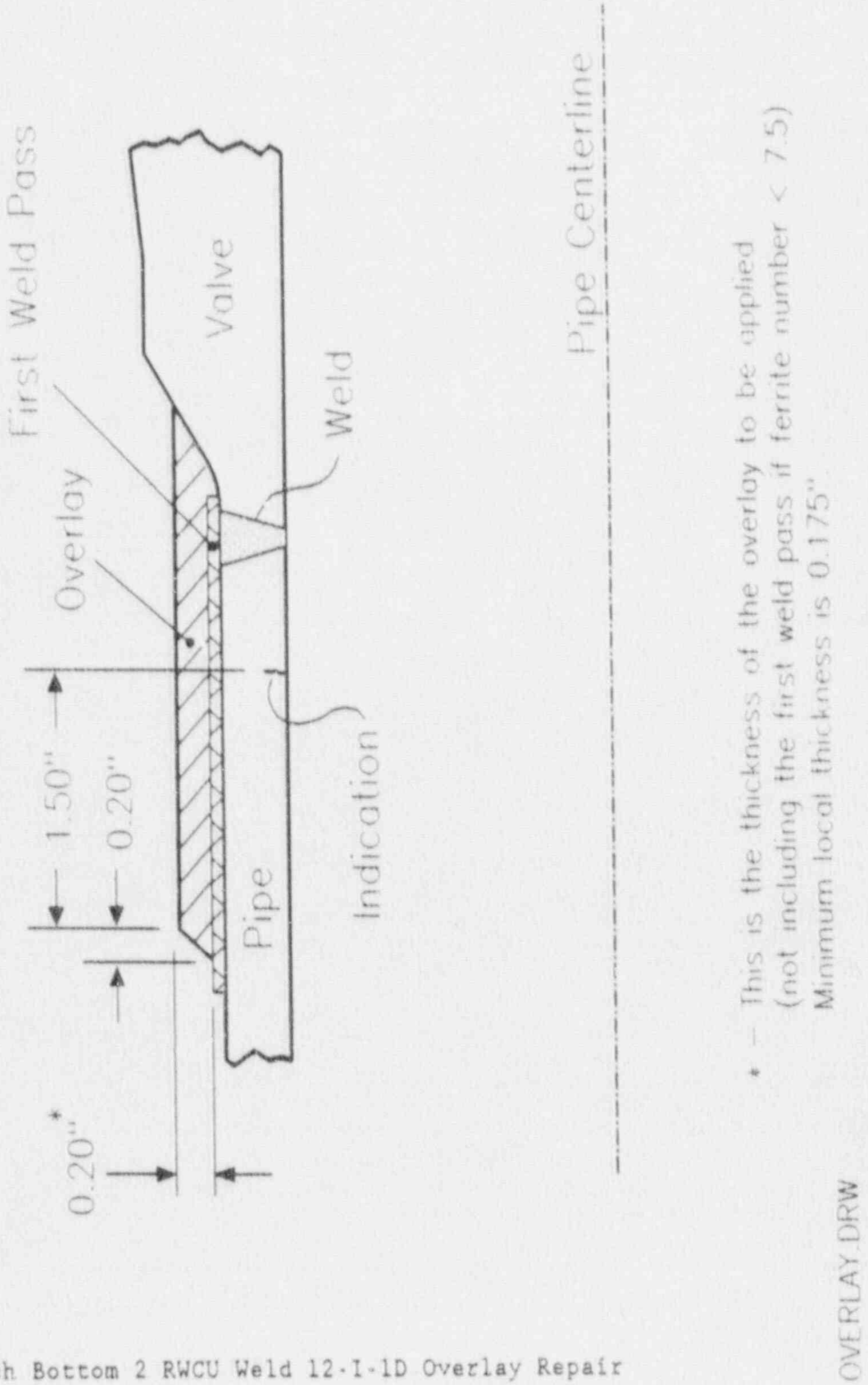

Figure 2 - Peach Bottom 2 RWCU Weld 12-I-1D Overlay Repair

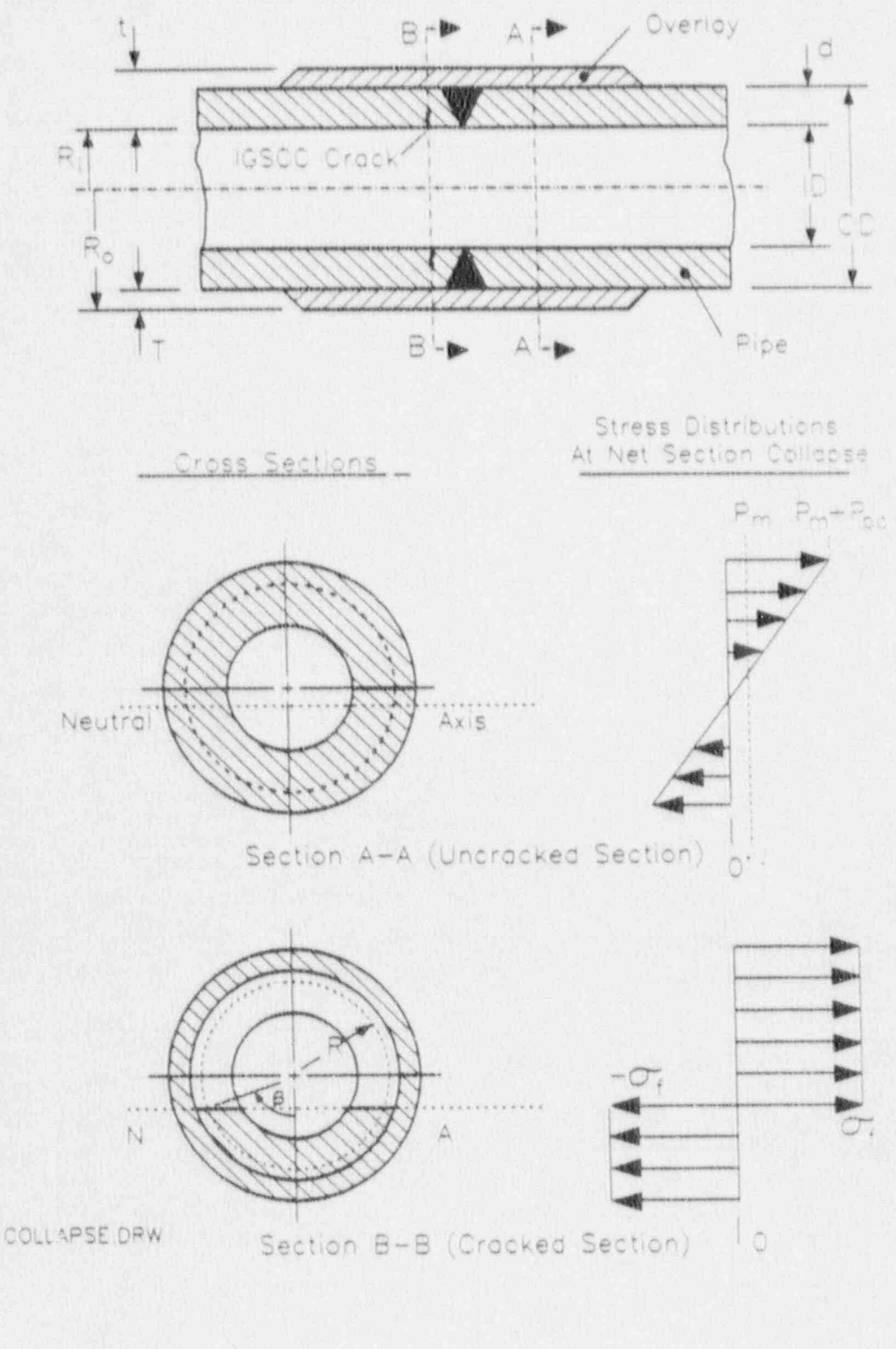

Figure 3 - Weld Overlay Stress Distributions at Net-Section Collapse

Table 1 - Weld Overlay Thickness Calculation Summary

Pipe and Flaw Dimensions:

Pipe ID:	3.700 (in)
Wall Thickness, d:	0.400 (in)
Pipe OD:	4.500 (in)
Pipe Area, Ap:	5.152 (in^2)
Pipe Inertia, Ip:	10.929 (in^4)
1) Assumed Flaw Depth, a:	0.400 (in)

Piping Loads:

	Pressure, p:	1800 (psi)
Axial Loads:	Deadweight, Fd:	0 (lbs)
	OBE Seismic, Fs:	0 (lbs)
Moments:	Deadweight, Md:	24905 (in-lbs)
	OBE Seismic, Ms:	22222 (in-lbs)

Overlay Dimensions:

Overlay Thickness, T:	0.175 (in)
Min. Overlay Length, L:	1.109 (in)
[L= $\sqrt{Rt}$ on each side of indication]	

Piping Stresses:

Membrane, Pmp:	3756 (psi)
[Pmp = (p(PI/4)ID^2+Fd+Fs) / Ap]	
Bending, Pbp:	9702 (psi)
[Pbp = (Md+Ms) OD / (2 Ip)]	

Pipe + Overlay Dimensions:

Wall+Ovrly Thickness, t:	0.575 (in)
[t = T + d]	
Pipe Inner Radius, Ri:	1.850 (in)
Overlay Outer Radius, Ro:	2.425 (in)
Nominal Radius, R:	2.138 (in)
Cross Sectional Area, A:	7.722 (in^2)
Bending Inertia, I:	17.961 (in^4)

Pipe Overlay Stresses:

Membrane, Pmo:	2506 (psi)
[Pmo = (p(PI)Ri^2+Fd+Fs) / A]	
Bending, Pbo:	6363 (psi)
[Pbo = (Md+Ms) Ro / I]	
Factor of Safety, FS:	3.00
MIN Critical Bending Stress:	24101 (psi)
[Pbc > FS (Pmo+Pbo) - Pmo]	

Material Properties:

Pipe Material: TP 304 SS, ASTM A-376
Overlay Material: Type 308L SS

Design Stress, Sm:	16950 (psi)
Flow Stress, Sf = 3 Sm:	50850 (psi)

Critical Bending Stress Calculation:

Neutral Axis Angle, B:	0.6143 (rad)
[B = PI (1-a/t-Pmo/Sf) / (2-a/t)]	
Critical Bending Stress, Pbc:	24339 (psi)
[Pbc = 2 (Sf/PI) (2-a/t) sinB]	

Critical Bending Stress, Pbc = 24339 (psi)
is greater than the Required
Critical Bending Stress of 24101 (psi)
Therefore, the Overlay Design
Thickness of T = 0.175 (in)
and Length of L = 1.109 (in)
is Sufficient.

Notes:

1) The pipe is conservatively assumed to have a 360 degree through-wall crack for this full structural overlay design.

OVERLAY.WK1 19-Mar-91

6. REFERENCES

1) Indication Notification Report (INR) # PB2-91-INR-02, Prepared for Philadelphia Electric Company by EBASCO, March 11, 1991.

2) 1989 ASME Boiler and Pressure Vessel Code, Section XI.

3) S. Ranganath and H.S. Mehta, "Engineering Methods for the Assessment of Ductile Fracture Margin in Nuclear Power Plant Piping, "Elastic-Plastic Fracture: Second Symposium, Volume II, Fracture Resistance Curves and Engineering Applications," 1983, (ASTM STP-803), pp. 309-330.

4) Non-Conformance Report (NCR) # P-90407, Prepared for Philadelphia Electric Company by Bechtel, July 12, 1990, Sheet XVII - 4.

5) 1989 ASME Boiler and Pressure Vessel Code, Section III.

6) G.E. Document# P50YP225, Rev. 3, "Process Specification for Weld Overlay for Austenitic Stainless Steel Piping Welds," July 1987.

ATTACHMENT 2

GE Nuclear Energy

General Electric Company
175 Curtner Avenue, San Jose, CA 95125

SASR 91-26
DRF 137-0010

April 15, 1991

To: A.R. Diederich (PECO)
Manager of Projects, Peach Bottom

cc: S. MacNichol
P. Tutton
S. Ranganath

From: C.D. Frederickson (GE)

Subject: Full Structural Weld Overlay for PB2 RWCU Weld 12-I-1D

I have reviewed the records for the full structural weld overlay completed on Weld 12-I-1D at Peach Bottom unit 2 and have concluded that the final overlay applied by Philadelphia Electric Company (PECO) meets the overlay design specified in the Reference 1 report. Also, the weld overlay process was controlled in accordance with the Reference 2 weld overlay procedure. Specifics of the final weld overlay and the process control information are discussed below.

The final weld overlay thickness ranged from a minimum of 0.270 inch to a maximum of 0.380 inch as determined by 20 UT thickness measurements taken before and after the overlay. These measurements were taken for 0°, 90°, 180° and 270° azimuths at five axial locations ranging from 1 inch upstream to 1 inch downstream of the indication. The weld overlay thickness exceeds the nominal thickness of 0.20" given in Reference 1 for a length exceeding $0.5\sqrt{Rt}$ (0.55 inch) on each side of the indication.

The weld overlay thicknesses described above include the first weld pass. Ferrite measurements were taken for the first weld pass with values ranging from 7.7FN to 12FN. The average ferrite measurement for this pass is 9.6FN. These measurements meet the ferrite acceptance criteria of 5FN minimum and 8FN average given in paragraph 4.4.2 of Reference 2. Therefore, the first pass may be included in the total overlay thickness. The average of the ferrite measurements for the second, third and fourth passes are 9.5FN, 9.4FN and 9.1FN, respectively.

The total overlay width was approximately 4 inches. The shrinkage was measured at four azimuths to be:

Azimuth	Shrinkage (inch)
0°	0.325
90°	0.245
180°	0.270
270°	0.311

These shrinkage values range from 0.245" to 0.325" for a maximum variation of 0.08". This variation matches the distortion control guideline of 0.02 x 4" = 0.08" for a 4 inch wide overlay as defined in paragraph 3.7.4 of Reference 2 to assure uniform shrinkage.

To achieve favorable compressive residual stresses at the inside surface for this weld overlay, the inside surface of the pipe was water cooled during the weld overlay process. The temperature of the cooling water was measured upstream of the overlay at a point between the pump discharge and the regenerative heat exchanger. This temperature ranged from 105 to 120°F. The coolant temperature at the weld overlay region will be somewhat below the indicated temperatures due to heat loss through the regenerative and non-regenerative heat exchangers. Pipe surface temperatures were also monitored just upstream of the overlay. These surface temperatures ranged from 88 to 94°F. The inlet coolant water temperature was thus maintained well below the 120°F maximum requirement specified in paragraph 3.6.3 of Reference 2. The flow maintained through this pipe during the overlay process was 125 gpm (0.279 ft^3/sec). This translates to a flow velocity of approximately 3.7 ft/sec for the 4 inch schedule 80 pipe. This flow rate is within 5% of the minimum flow rate recommended in paragraph 3.6.2 of Reference 2. The water cooling technique was also verified by conducting a mockup. The mockup test confirmed that the water cooling provided during the overlay procedure was acceptable. Water cooling for the overlay thus met the requirements given in the Reference 2 specification.

The 1:1 slope for the blend of the overlay to the pipe was recommended by GE. This slope provides a reasonably smooth transition, preventing significant stress concentration. A 1:1 slope was used rather than the 3:1 slope specified in Reference 2 to provide the maximum flat surface for UT measurements while maintaining the minimum overall length of the overlay and thus also the least possible shrinkage.

As described in this letter, the overlay applied by PECO meets all structural requirements defined by GE in the Reference 1 report. The weld overlay process was also well controlled by PECO within he guidelines given by the Reference 2 weld overlay procedure. All design records for this overlay are contained in DRF#137-0010, SASR# 91-26.

Sincerely,

C.D. Frederickson
Senior Engineer,
Structural Analysis Services
(408) 925-2699

References:

1) G.E. Report# SASR 91-26, DRF 137-0010, "Full Structural Weld Overlay Design for Peach Bottom Unit 2 RWCU Weld 12-I-1D," C.D. Frederickson, April 1991.

2) G.E. Document# P50YP225, Rev. 3, "Process Specification for Weld Overlay for Austenitic Stainless Steel Piping Welds," July 1987.