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WELD OVERLAY DESIGN
FOR THE INDICATIONS IN THE DUANE ARNOLD
RECIRCULATION RISER PIPE

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Prepared by: Gary L. Stevens 5/20/85
G. L. Stevens, Engineer
Structural Analysis Services

Verified by: T. A. Caine 5/20/85
T. A. Caine, Senior Engineer
Structural Analysis Services

Approved by: S Ranganath 5/21/85
S. Ranganath, Manager
Structural Analysis Services

Approved by: S Ranganath For AER 5/21/85
A. E. Rogers, Manager
Application Engineering Services

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1. ABSTRACT

During an in-service inspection at the Duane Arnold site, an axial crack indication and a lamination indication were discovered in the recirculation riser pipe weld #RRDJ7. The indications were located in the loop B riser pipe adjacent to the weld joining the riser pipe to the transition piece (Figure 1).

It was decided to perform a weld overlay repair. The weld overlay was designed to provide full structural reinforcement and maintain ASME Code safety margins. The minimum recommended weld overlay total thickness is .19 inch. Although based on analysis an acceptable width would be 1.8 inches, a 6.5 inch width overlay is recommended for application to the actual joint and overlay onto the pipe. This design was selected to overlay the area of the axial crack and lamination indications and to provide a configuration suitable for future in-service inspection of the riser pipe to transition piece weld. The weld overlay repair meets GE recommended minimum thickness requirements for weld overlays and also the requirements for being a Type 1 full structural overlay for a 360° through-wall circumferential crack.

2. INTRODUCTION

During an in-service inspection at the Duane Arnold site, an axial crack indication and a lamination indication were discovered in the recirculation loop B riser pipe.The indications were located in the riser pipe adjacent to the weld joining the riser pipe to the transition piece.

It was decided to perform a weld overlay repair of this joint. The weld overlay consists of a continuous 360° band of weld metal applied to the outside surface of a pipe directly above the crack and lamination indications. The overlay weld metal is Type 308L stainless steel containing low carbon and high ferrite, deposited using a high quality gas tungsten arc welding technique (GTAW) with water inside the pipe. This process deposits a high toughness weld consisting of material resistant to IGSCC and typically produces a compressive residual stress at the inside surface of the pipe and through a substantial portion of the inner wall.

Due to the fact that the crack indication is axial in nature, calculations show that the weld overlay thickness required for the joint is minimal (to prevent leakage) since the flaw size is well within acceptable limits from a structural margin standpoint. Reference 4 provides analysis results to show that weld overlay is not required for the lamination which is not considered IGSCC. However, it was decided that overlay of the entire area would be applied as the most conservative repair for this condition. The overlay design also meets the requirements for a full structural (Type 1) overlay and maintains the ASME Code intended safety margins for a 360° through-wall circumferential flaw. This report provides the basis for the overlay design and the detailed geometric considerations.

3. WELD OVERLAY DESIGN ANALYSIS

Axial cracks due to IGSCC are of minimal concern since they are generally confined to the narrow sensitized heat affected zone (HAZ). Beyond the HAZ the crack tip would be in the annealed base material and would not be susceptible to IGSCC. For such short axial cracks it can be shown that even a through-wall crack can be tolerated while maintaining the code safety margin. For example, for an axial through wall crack, the critical crack length corresponding to the applied hoop stress is given by

$$\sigma_h = 3 S_m / M$$

where

S_M = allowable ASME Code design stress intensity equal to one third of the flow stress.

and $M = (1 + 1.61 \ell^2 / 4 Rt)^{\frac{1}{2}}$

ℓ = crack length

R = mean radius of pipe

t = pipe thickness

For the pipe where the axial crack indication has been found, t = 0.58 in., R = 5.1 in. The hoop stress corresponding to design pressure is 12.4 ksi. Substituting this, the critical crack length for a through-wall crack is 10.7 in. This confirms that large through-wall axial cracks can be tolerated.

The reported axial crack indication is located approximately 1" from the riser pipe to transition piece weld centerline and extends 0.5" downstream in the riser pipe. The indication was sized at approximately 26% through the pipe wall from the inside surface. The overlay thickness is selected such that GE minimum thickness requirements for weld overlays are met. This minimum thickness is typically two layers after the first layer. For axial flaws, the length of the flaw rather than the depth of the flaw through the pipe wall is the controlling dimension from a fracture mechanics standpoint. The actual flaw length (0.5") is much less than the maximum acceptable through-wall length of 10.7". Therefore the two layer recommended minimum thickness after the first layer is adequate since the overlay need only provide protection for leakage in the event the crack extends through the wall. The selection of IGSCC-resistant material assures that IGSCC crack growth into the weld overlay material beyond the first layer does not occur.

The overlay location and width are selected primarily to allow for future in-service inspections. Consideration was also given to the lamination discovered subsequent to the original axial indication. The overlay width was chosen to assure coverage and full structural reinforcement to both indications. Figure 3 shows the dimensions of the final weld overlay design. The position of the overlay (only on the pipe) was chosen to allow future in-service inspection of the adjacent transition piece to manifold weld. The minimum width of the overlay was calculated to be 1.8" for structural reinforcement of the axial crack indication region. A length of 6.5" was specified to properly cover the crack and lamination indications and to allow future in-service ultrasonic examination of the pipe to transition piece weld through the overlay. The following section describes additional considerations included in the overlay design for added protection against cracks which are circumferential in nature.

4. DESIGN CONSIDERATIONS FOR CIRCUMFERENTIAL CRACKS

Another consideration in the design of the weld overlay joint is the potential for circumferential cracking. An allowance for circumferential cracks in the weld overlay design would be beneficial. This section analyzes the subject joint from a circumferential crack viewpoint and demonstrates that the overlay design of Figure 3 meets the requirements for a full structural (Type 1) overlay which maintains the ASME Code intended safety margins for a 360° through-wall circumferential flaw.

4.1 Methodology for Determining the Minimum Required Weld Overlay Thickness

The minimum weld overlay thickness necessary to achieve full structural reinforcement is that thickness which provides the appropriate factor of safety against net section collapse of the adjacent material for a postulated 360° through-wall crack. The depth at which net section collapse occurs is a function of the material flow stress, the overall wall thickness including the weld overlay, and the applied primary membrane and bending stresses. The primary membrane stress is produced by pressure, and the primary bending stress is the sum of the dead weight and seismic stresses.

Paragraph IWB-3642 of the ASME Code, Section XI (Reference 1) can be used to determine the allowable flaw size using a safety factor of 3.0 on applied loading. Assuming that the indication is fully circumferential, the method described in Reference 2 can be used. In the reference report a relationship between the applied loads, the flow stress, and the critical crack depth to thickness ratio is defined by Equations (1) and (2).

$$B = \frac{\pi(1 - \frac{a}{t} - \frac{P_m}{\sigma_f})}{2 - \frac{a}{t}} \tag{1}$$

$$P_b = \frac{2\sigma_f}{\pi} (2 - \frac{a}{t}) \sin B \tag{2}$$

where

σ_f = Material Flow Stress = 3 S_m

P_m = Primary Membrane Stress

P_b = Primary Bending Stress

a = Crack Depth

t = Total thickness (pipe wall + weld overlay thickness)

These equations cannot be solved directly for the allowable flaw depth to thickness ratio, so an iterative approach must be used. In the iteration scheme, a weld overlay thickness is assumed and the primary stresses are adjusted to the new total thickness. The iteration is performed until the minimum required weld overlay thickness is determined. A factor of safety of 3.0 is used in accordance with IWB-3642.

4.2 Applied Stresses at the Weld Overlay Location

Stresses were determined using the Duane Arnold Recirculation System stress report (Reference 3). The pressure at normal operation of 1325 psi results in a primary membrane stress of 5.23 ksi. The primary bending stress is the sum of the dead weight and seismic stress. The dead weight stress is 0.38 ksi and the OBE seismic stress is 3.67 ksi, giving a total $P_m + P_b$ value of 9.28 ksi.

4.3 Weld Overlay Thickness

The iterative calculations described in Section 4.1 were performed using the stresses described in Section 4.2. The thickness generated by this calculation is the minimum necessary for the overlay to maintain the required safety factor of 3.0. Figure 2 shows the results of the iterative analysis to determine the overlay thickness. As shown in Figure 3, a minimum total thickness of .19 inch is recommended.

4.4 Weld Overlay Width

Unlike the thickness requirements for weld overlay designs which are based on satisfying the safety margins of the ASME Code, there are no specific requirements for the weld overlay widths. General Electric has performed finite element studies which determined that a minimum weld overlay structural width of $\sqrt{Rt}$ provides the required reinforcement to the joint. Even though the width based on the criteria of $\sqrt{Rt}$ would be 1.8 inches, the minimum width was chosen as 6.5 inches. This additional width assures that the overlay covers the weld, heat affected zone, axial flaw and lamination, and provides sufficient width for ultrasonic testing for circumferential indications as discussed in Section 3.

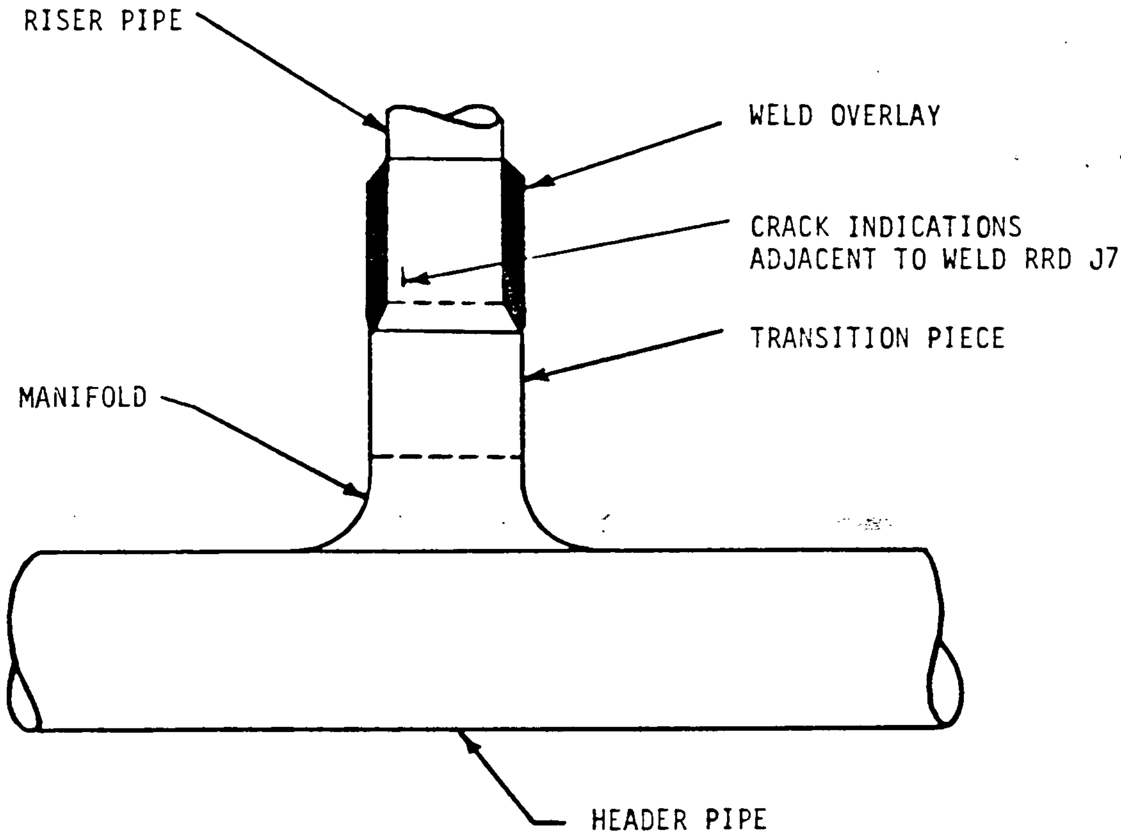
4.5 Weld Overlay Design

The specific overlay design shown in Figure 3 considered such factors as the relative thicknesses of the butt welded members, the weld crown geometry, the extent of the original heat affected zone, the proximity to transition area, and the consideration of ultrasonic testing. The slope of the overlay end was set to one-to-one (thickness-to-width) to reduce stress concentration effects. In the event that the thickness of the weld overlay rises above the transition piece outer diameter, a minimum slope requirement of 4 to 1 which does not extend beyond the weld crown edge is necessary to provide for ultrasonic examination of the pipe to transition piece weld from the transition piece side of the joint. Therefore, the weld overlay design recommended provides conservative safety margins which satisfy the requirements for a typical full structural (Type I) overlay.

5. ACCEPTABILITY FOR MULTIPLE CYCLE OPERATION

The weld overlay design recommended here is based on the conservative assumption of a through-wall crack. Furthermore, the weld overlay design accounts for a potential circumferential indication by providing adequate thickness for an assumed 360° circumferential crack. Thus the weld overlay sizing considers all potential crack sizes and orientations and still provides the required Code margins. This, coupled with the fact that the overlay is made of a high ferrite low carbon weld material resistant to IGSCC, provides assurance for satisfactory long term performance. The results of the recent GE/EPRI degraded type program have confirmed that weld overlays of the type described here provide structural and IGSCC margins for several cycles. Recognizing this, the NRC has stated in NUREG 1061 that weld overlays for circumferential cracks are acceptable for two fuel cycles. Overlays for axial cracks are acceptable for longer periods of time. Based on this it can be concluded that the overlay is acceptable for more than two operating cycles.

FIGURE 1 - LAYOUT OF RECIRCULATION PIPE AND OVERLAY



Note: Not to scale.

FIGURE 2 - WELD OVERLAY CALCULATIONS FOR DUANE ARNOLD
(360° through-wall circumferential crack)

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************************************************************************
*                                                                      *
*                                                                      *
*                   WELD ID:  DUANE ARNOLD                             *
*                                                                      *
*                                                                      *
*               PIPE THICKNESS =  0.58 INCH                            *
*               PIPE DIAMETER  = 10.77 INCH                            *
*                                                                      *
*          PRIMARY LOADS (STRESS):                                     *
*                 PRESSURE    =  5.23 KSI                              *
*                 DEAD WEIGHT =  0.38 KSI                              *
*                 SEISMIC     =  3.67 KSI                              *
*                                                                      *
*                                                                      *
*                                                                      *
*                                 PB (KSI)        PM+PB     PM+PB      *
*             __I__     PM     ------------        SM        3SM       *
*     WOT     T+WOT    (KSI)   ACTUAL   CALC    (ACTUAL)  (CALC)       *
*    -----------------------------------------------------------       *
*                                                                      *
*    0.190    0.752    3.859   3.044   16.925    0.408     0.410       *
*                                                                      *
*                                                                      *
*                                                                      *
*          PRIMARY STRESS RATIOS (ADJUSTED):                           *
*                      PM/SM    = 0.228                                *
*                   (PM+PB)/SM = 0.408                                 *
*                                                                      *
*                                                                      *
*    MINIMUM REQUIRED WELD OVERLAY THICKNESS = 0.190 INCH              *
*    MINIMUM REQUIRED WELD OVERLAY WIDTH     =  1.8  INCH              *
*                                                                      *
*                                                                      *
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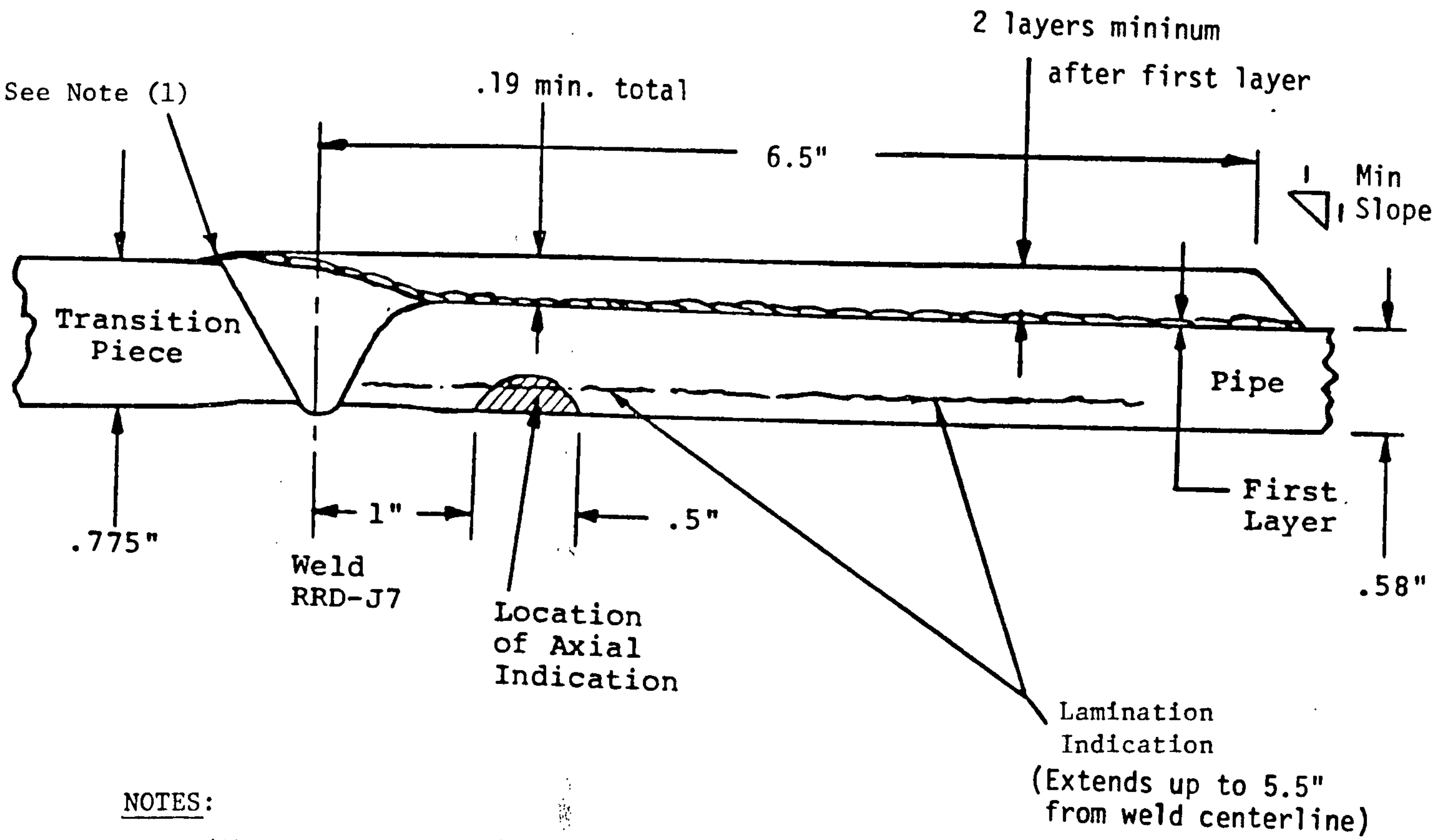
FIGURE 3 - RECIRCULATION PIPE WELD OVERLAY DESIGN



NOTES:

(1) Do not overlay beyond weld crown edge. If overlay thickness rises above transition piece O.D., grind edge with a 4 to 1 minimum slope.

6. REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section XI, 1980 Edition, including Appendix X, "Acceptance Criteria for Flaws in Austenitic Piping," approved April 1983.

2. Ranganath, S. and Mehta, H.S., "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, ASTM STP-8-3, 1983, pp. 309-330.

3. G.A. Randall, "Duane Arnold Energy Center Piping Stress Analysis - Recirculation Loop B," Volumes 1-3, Nuclear Services Corporation, Campbell, CA, 10-6-72, (NSC-IOW-4).

4. Ranganath, S., "Evaluation of the Lamination in the Region of Weld RRD-J7 of the Duane Arnold Recirculation Line," SASR 85-33, MDE-72-0485, Rev. 0, April 1985.

WELD OVERLAY DESIGN
FOR WELDS

RRH-J4A
RRG-J4A
RRF-J4A
RRE-J4A
RRD-J4A
RRD-J4
RRB-J4A
RRA-J4A
RRA-J4
RHB-J1