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December 14, 1984

Docket No. 50-278

Mr. John F. Stolz, Chief
Operating Reactors Branch #4
Division of Licensing
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

SUBJECT: Peach Bottom Atomic Power Station - Unit 3 Corrective Actions for Intergranular Stress Corrosion Cracking (IGSCC) during Spring 1985 Refueling Outage

REFERENCE:
1. Confirmatory Order, J. F. Stolz, USNRC, to E. G. Bauer, Jr., PECo, September 7, 1983
2. NRC Generic Letter 84-11, "Inspections of BWR Stainless Steel Piping
3. Letter, S. L. Daltroff, PECo, to D. G. Eisenhut, USNRC, Response to Generic Letter 84-11, June 4, 1984
4. Letter, S. L. Daltroff, PECo, to D. G. Eisenhut, USNRC, Supplemental Response to Generic Letter 84-11, October 5, 1984
5. Meeting with NRC Staff, October 9, 1984, Bethesda, MD

Dear Mr. Stolz:

This letter provides our plans for mitigation of Intergranular Stress Corrosion Cracking (IGSCC) in primary system piping during the Peach Bottom Unit 3 Spring 1985 refueling outage in accordance with the Reference 1 Confirmatory Order. This inspection plan is submitted for your review and is the basis for our justification to return Unit 3 to full power for a minimum of one additional cycle following the 1985 outage.

During the 1983 refueling outage on Peach Bottom Unit 3, augmented inservice inspection of welds in the recirculation and residual heat removal systems was performed in accordance with the requirements of I.E. Bulletin 83-02, "Stress Corrosion Cracking in Large-Diameter Stainless Steel Recirculation System

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Piping at BWR Plants." A total of 112 welds or 75% of all welds in these systems were examined after ultrasonic (UT) indications were discovered in the original sampling. The welds which were not inspected were of conforming material as specified in NUREG-0313, Rev. 1, or were not practicable to inspect due to high radiation or physical inaccessibility. The results of the inspections, including crack growth analysis and corrective actions taken by Philadelphia Electric Company, were reported to the NRC in letters dated August 9, 1983; August 22, 1983; August 24, 1983 and August 30, 1983. The corrective actions taken by Philadelphia Electric Company were found acceptable by the NRC in the Reference 1 Confirmatory Order.

The following describes the inspection plan to be performed during the Spring 1985 Unit 3 refueling outage.

CONFORMANCE WITH GENERIC LETTER 84-11 INSPECTIONS

Philadelphia Electric Company will perform weld inspections in response to Generic Letter 84-11, "Inspections of BWR Stainless Steel Piping", dated April 19, 1984. The Generic Letter was issued as a result of Bulletin 83-02 inspection results, and the NRC concluded that certain actions to be taken by Licensees, in accordance with the Generic Letter, would be considered as acceptable responses to current IGSCC concerns. These actions were specified in Section 5.4.2 of NUREG-1061 (Draft) as an appropriate reinspection program and were derived from SECY-83-267c, "Staff Requirements for Reinspection of BWR Piping and Repair of Cracked Piping" (Commission paper), November 7, 1983. The Philadelphia Electric Company response of June 4, 1984 (Reference 3) to Generic Letter 84-11 was reviewed by S. D. Reynolds of the NRC Region I Staff during Inspection 50-277, 278/84-21, 84-17, and found to meet the requirements of the Generic Letter. Based on our ongoing effort concerning IGSCC mitigation, certain specific weld locations specified in that response were modified. These welds were identified along with the technical justification for the changes in the Reference 4 letter. We believe these changes enhance our conformance to Generic Letter 84-11. A summary of the welds to be examined specified in the Reference 3 and 4 letters is included as Attachment 1. The Generic Letter 84-11 inspection plan was presented to the NRC Staff at the Reference 5 meeting.

ADDITIONAL INSPECTION

As a result of indications discovered in welds in the Unit 2 reactor coolant primary boundary piping systems during the current Unit 2 outage, Philadelphia Electric Company will perform additional inspections of welds in the reactor

nozzle-safe end areas on Unit 3, beyond the requirements of Generic Letter 84-11. These weld locations are specified in Attachment 2.

QUALIFICATION OF EXAMINERS

All Level II and Level III personnel utilized for the ultrasonic examination of IGSCC susceptible welds will have successfully completed the EPRI NDE Center's IGSCC UT detection program. All Level I personnel utilized for these exams will have received training and familiarization in the techniques and unique requirements of UT scanning for IGSCC.

Additionally, any IGSCC indications detected will be sized by personnel who have successfully completed the EPRI NDE Center's "UT Operator Training for Planar Flaw Sizing."

SUMMARY

Attachment 3, "Technical Justification for Multi-Cycle Operation of Peach Bottom Unit 3 Recirculation and RHR Piping", October 1984, prepared by the General Electric Company, in conjunction with the reinspection program, supports the deferment of piping replacement based on the weld overlay repairs and induction heating stress improvement (IHSI) treatment on primary system welds during the 1983 Unit 3 outage. The reinspection scope will be expanded in accordance with I.E. Bulletin 83-02 if new indications are discovered.

Section 6.0 of NUREG-1061 (Draft) provides guidance on the decision and criteria to evaluate for replacement, repair, or continue operation without repair such as leak-before-break criteria and stress corrosion crack growth rates. Evaluations for continued operation with or without repairs and the criteria for crack repairs must be sufficient to provide full ASME Section XI IWB-3640 margin during the operating period. NUREG-1061 (Draft) acknowledges that "operating experience and fracture mechanics evaluations indicate that leak-before-break is the most likely mode of piping failure." During the 1983 outage, appropriate leak detection procedures were implemented and will be continued following conclusion of the Spring 1985 weld reinspection program. This includes moisture sensitive tape installed on selected welds and revised Technical Specifications regarding Limiting Conditions for Operation and Surveillance Requirements on the drywell sump pumpout rate regarding unidentified drywell leakage.

All crack indications discovered during the last outage were weld overlay repaired which, based on the compressive stresses induced by the overlay, should be effective in preventing the initiation of new IGSCC cracks and inhibiting the growth of existing flaws. Permanent utilization of Hydrogen Water Chemistry (HWC) is being investigated, and an Amendment to the Technical Specifications to allow testing of HWC injection was issued by the Commission on November 14, 1984. Based on the results of this testing at Peach Bottom (and at Dresden Unit 2), PECo will make an evaluation on a permanent HWC injection program for Peach Bottom Units.

CONCLUSION

The plans for weld reinspection, during the Spring 1985 Unit 3 outage, satisfy the NRC requirements of Generic Letter 84-11, are supported by General Electric Company, and are substantiated by the issuance by NRC Staff of NUREG-1061 (Draft). Acceptance of weld overlay repair, the beneficial effects of IHSI treatment and HWC control implementation, as supported by NUREG-1061, have indicated that weld reinspection on Unit 3 is appropriate at this time.

Very truly yours,

Attachments

cc: J. H. Williams, Resident Inspector

Attachment 1

Generic Letter 84-11 Category	Planned Actions
2.(a) -	
- Inspect 20% of welds in each pipe size not previously inspected.	Recirculation System: 22 inch piping - Inspect 2 welds: 2-BM-2 2-BM-3 28 inch piping - Inspect 4 welds: 2-AS-9 2-BS-8 2-AD-13 2-BD-16
- Inspect 20% of welds previously inspected and found not cracked	Recirculation System: 12 inch piping - Inspect 6 welds: 2-AHK-4 2-BHE-3 2-AHH-3 2-BHC-4 2-AHF-3 2-BHA-3 22 inch piping - Inspect 2 welds: 2-BM-4 2-BM-5 28 inch piping - Inspect 5 welds: 2-AS-5 2-BS-6 2-AD-17 2-BD-15 2-BS-4 RHR Shutdown Cooling System: 20 inch piping - Inspect 2 welds: 10-0-3 10-0-2 24 inch piping - Inspect 4 welds: 10-IA-7 10-IB-4 10-IA-10 10-IB-11
2.(b) -	
- Inspect all unrepaired cracked welds.	No inspection; all cracked weld locations were weld overlay repaired.

2.(c) -

- Inspect all weld overlays on welds where circumferential crack length is greater than 10% of the circumference.	RHR System: 20 inch piping - Inspect 5 welds: 10-0-5 10-0-6 10-0-7 10-0-10 10-0-15* *Note: The circumferential crack length at this location is less than 2% of the circumference. Nuclear Steam Supply System: 4 inch piping - Inspect 1 weld: The N8-B Jet Pump Instrument Seal Safe-End to Reducer weld.

2.(d) -

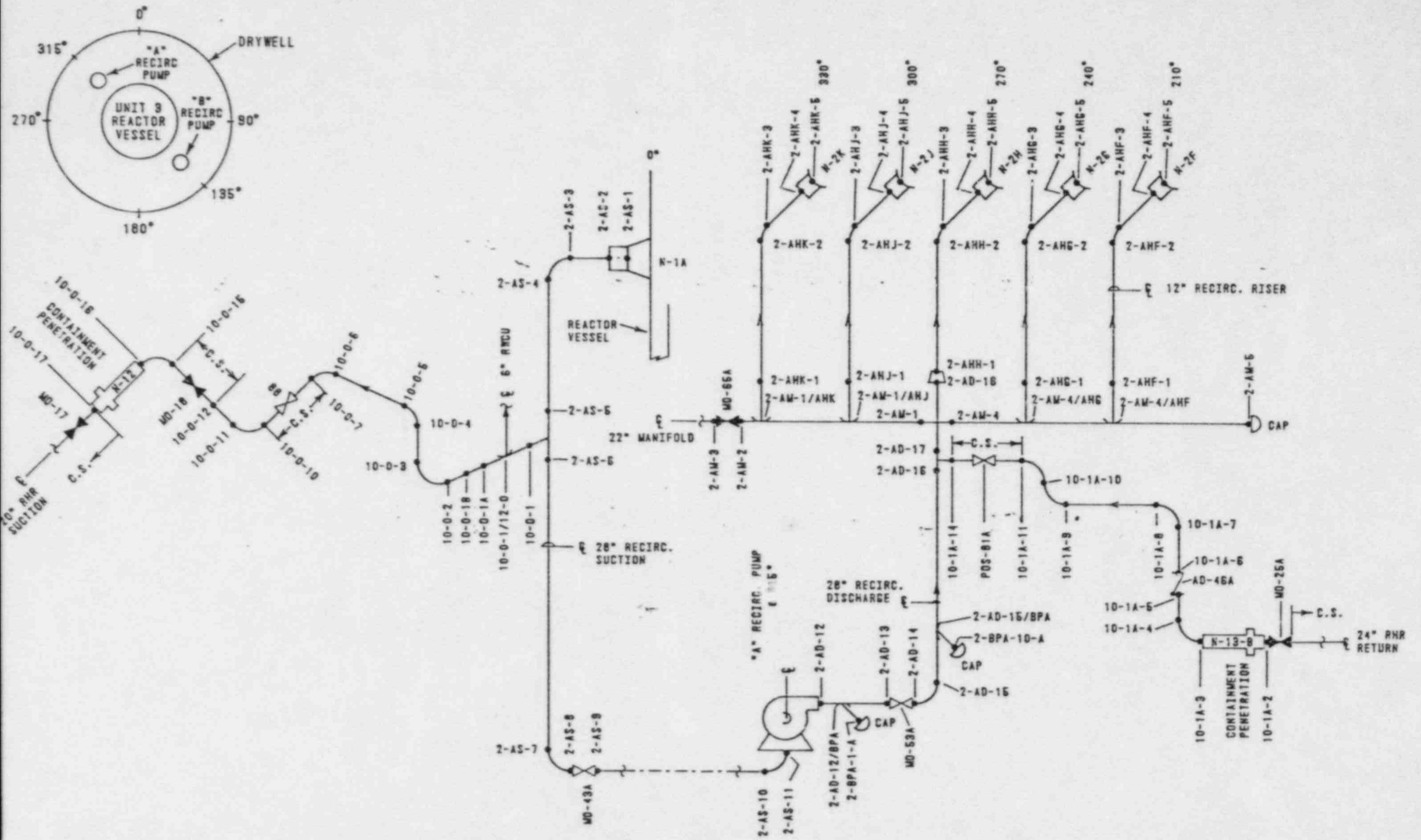
- Inspect IHSI treated welds which had not been post-IHSI UT acceptance tested.	No inspection; all 91 IHSI treated welds were post-IHSI NDE.

2.(e) -

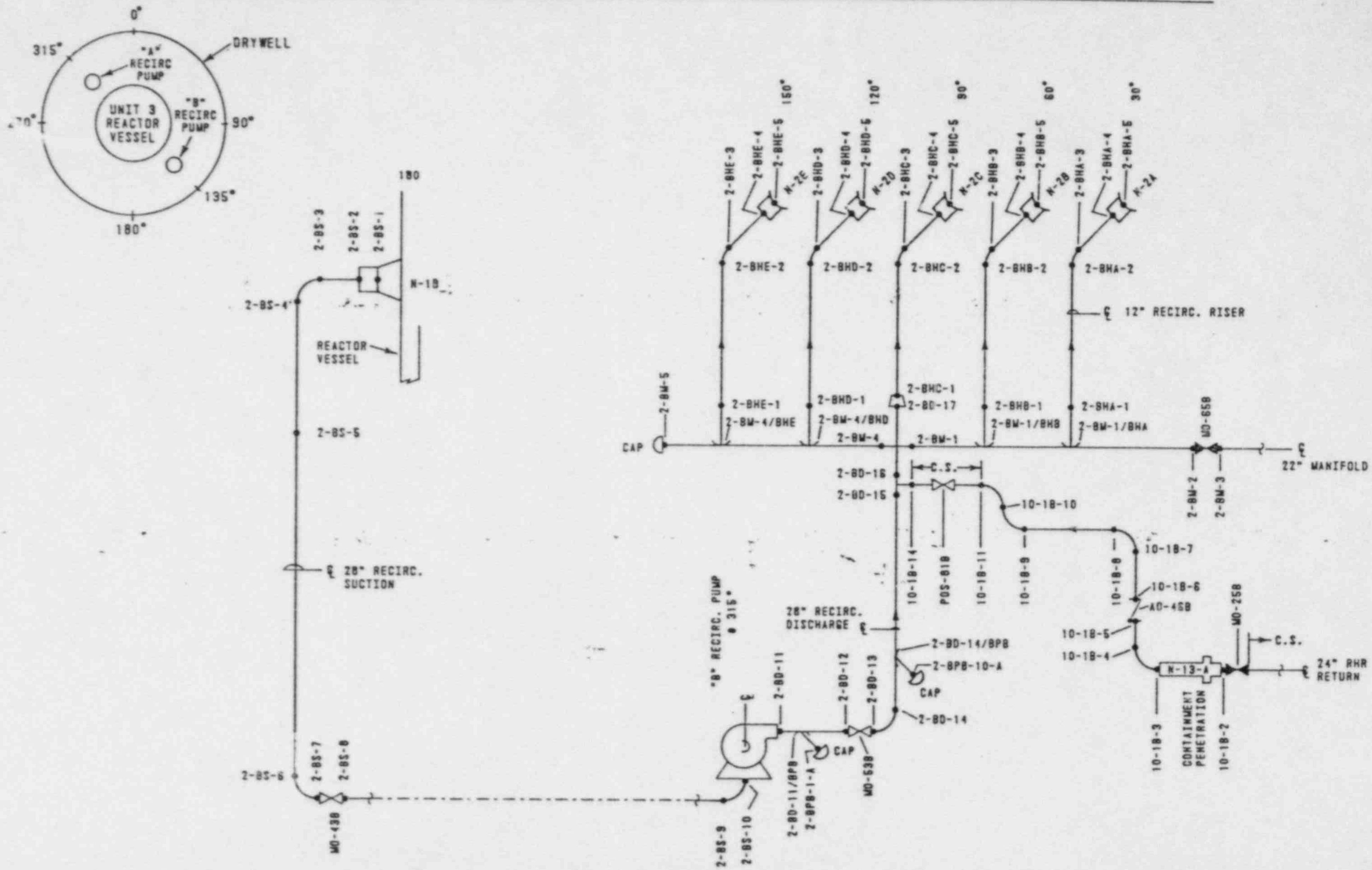
- If new cracks or significant growth of old cracks is detected, expand inspection scope in accordance with NRC I.E. Bulletin 83-02.	Will address as required.

Attachment 1-2

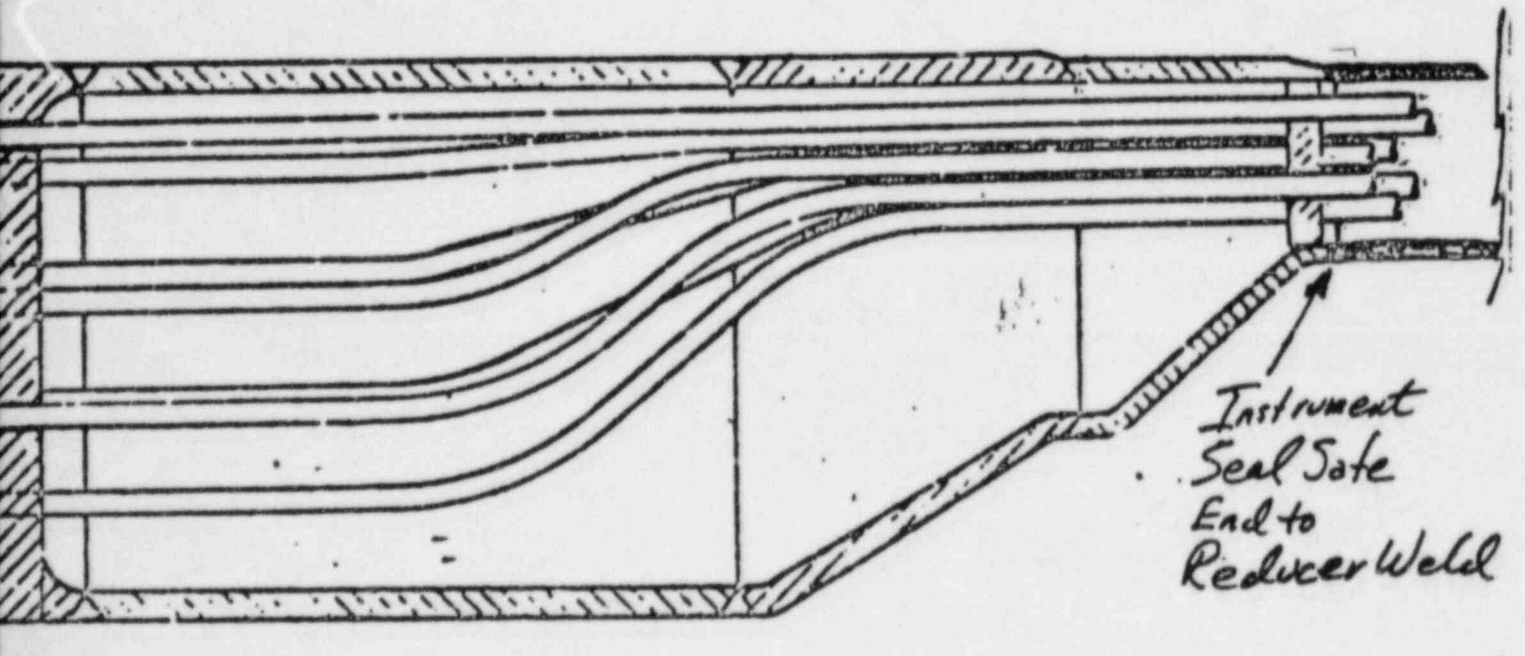
PBAPS-UNIT 3 "A" RECIRCULATION PIPING & RHR SHUTDOWN COOLING SUCTION/RETURN PIPING



PBAPS-UNIT 3 "B" RECIRCULATION PIPING & RHR SHUTDOWN COOLING SUCTION/RETURN PIPING



Attachment 1C



JET PUMP INSTRUMENT SEAL

Attachment 2

Additional Inspections

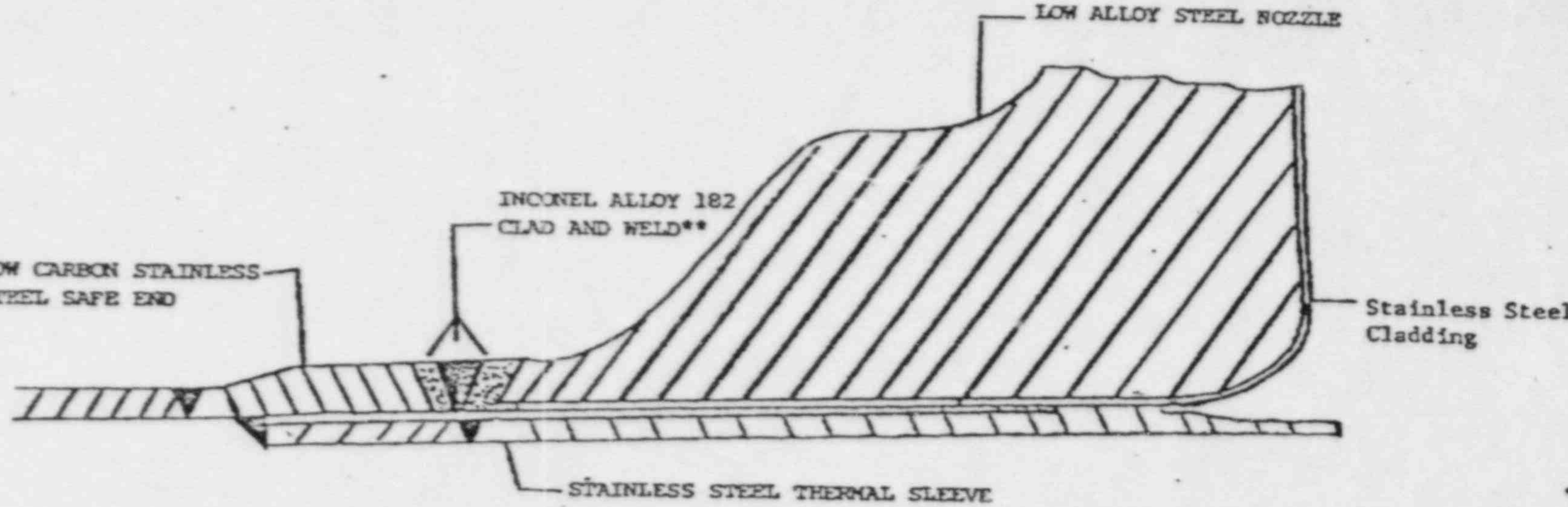
Weld Locations	Planned Inspections Beyond Generic Letter 84-11 Requirements
1) N-1 RPV Outlet Nozzle to Safe-End (2 locations).	UT examine minimum of 1 weld location.
2) N-2 RPV Inlet Nozzle to Safe-End (10 locations)	UT examine 5 weld locations.
3) Internal Attachment weld of Thermal Sleeve to N-2 Nozzle Safe-End (10 locations)	Perform best effort UT examination at these 10 locations.
4) Other weld locations in containment piping systems.	Perform inspections required to meet ISI Program requirements.

Attachment 2a

FIGURE 3

PEACH BOTTOM UNIT 3

RECIRCULATION INLET NOZZLE TO SAFE END DESIGN*



* RECIRCULATION OUTLET DESIGN DOES NOT CONTAIN A THERMAL SLEEVE

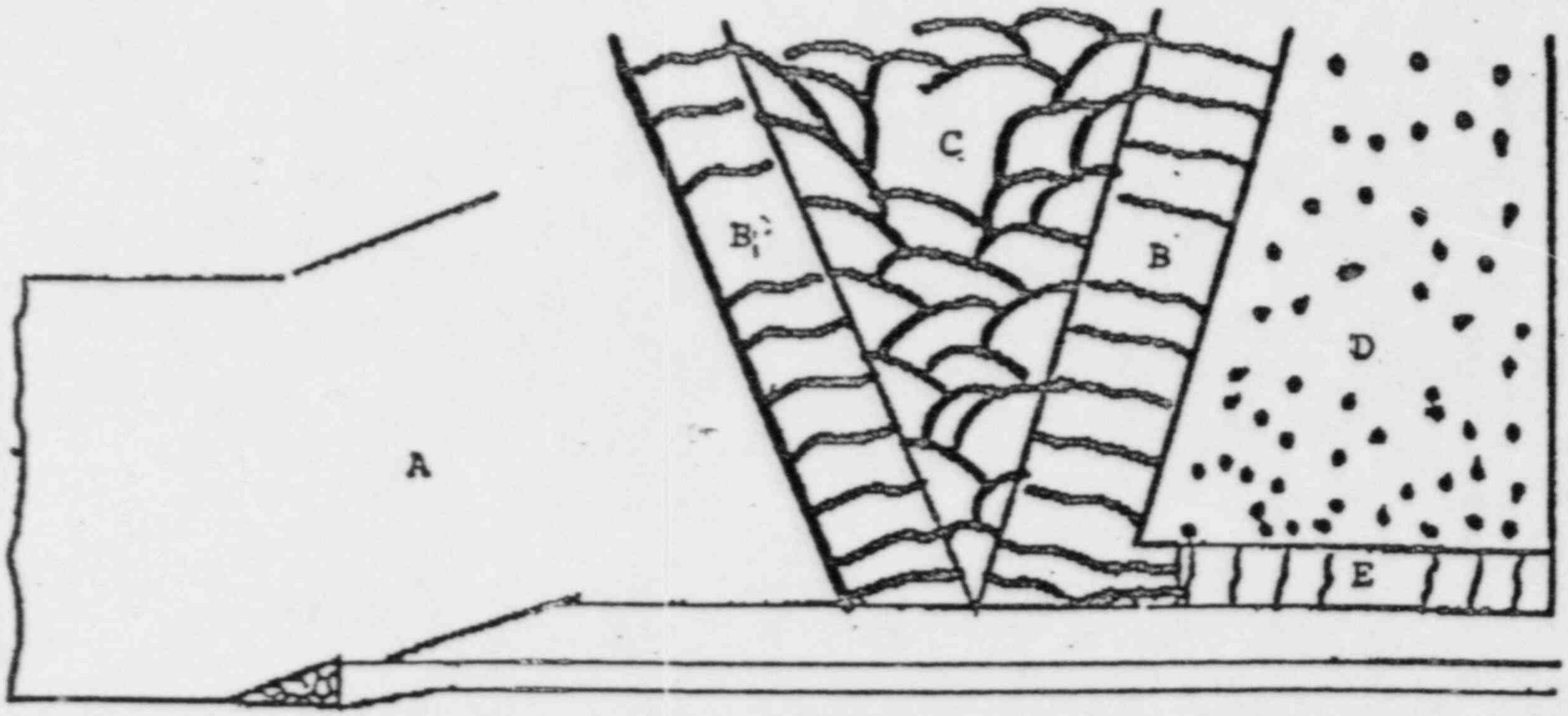
** ID ALLOY 182 CLAD MAY BE DILUTED WITH TYPE 308 WELD BUTTER FROM ORIGINAL FABRICATION (BEFORE SAFE END REPLACEMENT)

FIGURE 4

METALLURGICAL CONDITION OF PEACH BOTTOM UNIT 3

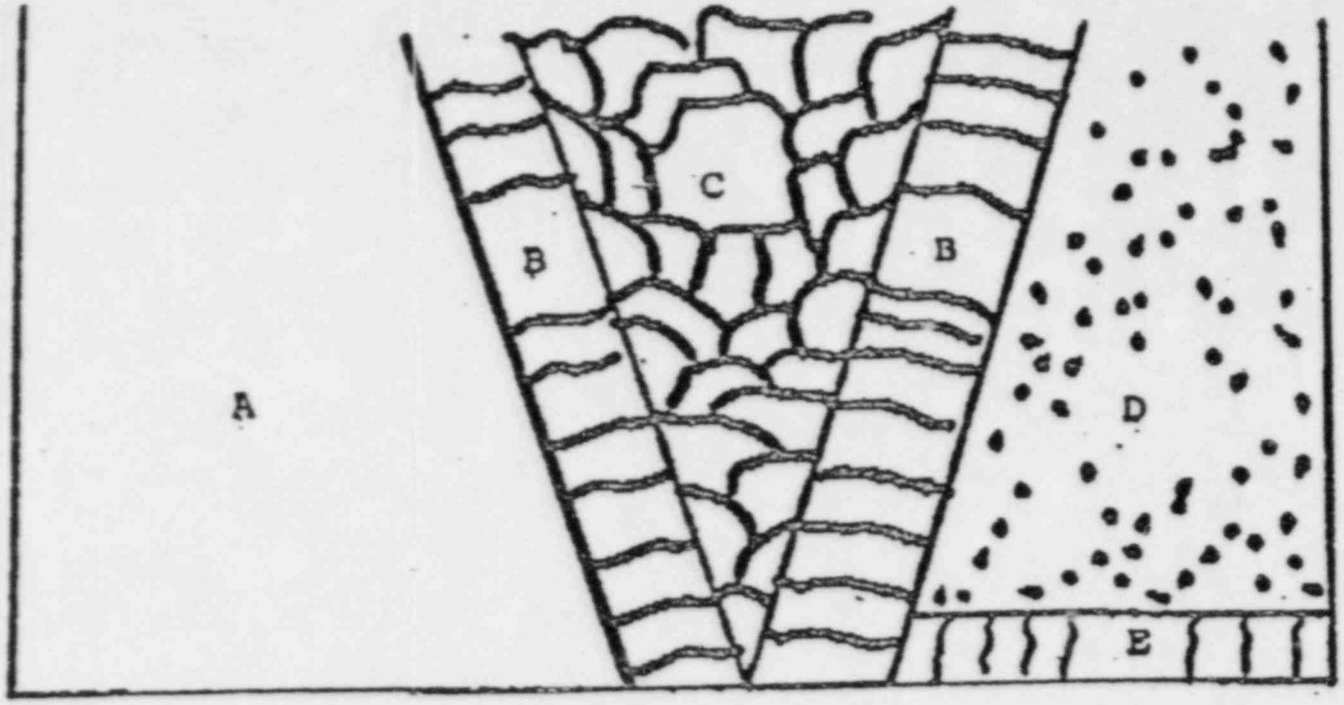
SAFE END TO NOZZLE ATTACHMENTS

• RECIRCULATION INLET



Attachment 26

• RECIRCULATION OUTLET



A) LOW CARBON STAINLESS STEEL SAFE END

B) INCONEL ALLOY 182 WELD CLAD (ID ON NOZZLE SIDE MAY BE DILUTED WITH TYPE 308 FROM ORIGINAL FABRICATION)

C) INCONEL ALLOY 182 WELD METAL

D) LOW ALLOY STEEL NOZZLE

E) STAINLESS STEEL NOZZLE CLAD

Attachment 2C

ATTACHMENT 3

GE Report No. 137-0010, MAR 84-21 (Rev. 2)

Technical Justification for Multi-Cycle Operation of
Peach Bottom Unit 3 - Recirculation and RHR Piping

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DRF #137-0010
MAR 84-21 (Rev. 2)
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TECHNICAL JUSTIFICATION FOR MULTI-CYCLE OPERATION OF PEACH BOTTOM UNIT 3 RECIRCULATION AND RHR PIPING

October 1984

Prepared for Philadelphia Electric Company

H. S. Mehta

S. Ranganath

General Electric Company

1. INTRODUCTION

During the 1983 outage, Peach Bottom Unit 3 recirculation/RHR piping was inspected for IGSCC and the appropriate remedial actions such as IHSI and weld overlays were taken by Philadelphia Electric in conformance with the requirements of IE Bulletin 83-02. A summary of the number of welds examined and the remedial actions is given in Table 1. A total of 149 welds was involved, of which 125 welds were considered as susceptible to IGSCC based on a susceptibility matrix evaluation. Ninety-one welds were IHSI treated, out of which 15 had IGSCC indications. Weld overlay repair was performed at all 15 locations. Also, in June 1984, weld overlays were applied on the 4-inch jet pump instrumentation nozzle/safe end. At the present time, these corrective actions have been accepted by the NRC for one cycle operation.* This report documents the technical bases to justify continued operation beyond one fuel cycle.

*NUREG 1061 presently under review in draft form recommends approval of plant operation with overlays for at least two fuel cycles. If additional mitigation measures are implemented, extended operation beyond two fuel cycles may be permitted.

2. WELD OVERLAY DESIGN

This section first describes the structural design basis for the weld overlays. Specific aspects of Peach Bottom 3 weld overlays are then discussed.

2.1 Structural Integrity Aspects of Weld Overlay

The discussion in this section has been essentially excerpted from Reference 1. Peach Bottom Unit 3 recirculation and RHR piping were designed to meet the requirements of ANSI B-31.1. Specifically, the requirements of this Code are intended to provide design margins against excessive plastic deformation and ductile rupture and to assure that fatigue failure will not occur as a result of cyclic loadings. Section XI of the ASME Code applies to in-service evaluations of these components. A weld overlay on a cracked piping component designed to meet Section XI, IWB-3640 (Reference 2) requirements assures that the same minimum construction Code margins are maintained after accounting for the initial overdesign of the component and for the loss in structural capability due to the presence of the crack, and considering the crack growth during the projected future period of operation. In the following sections the design stress levels in overlays and the associated design margins are discussed in greater detail.

2.1.1 Design Stress Levels

Applied stresses in piping are classified into three categories: primary, secondary, and peak stress. Primary stresses are developed by imposed loading (e.g., pressure, dead weight, and seismic) and are not self-limiting. Secondary stresses are displacement-governed stresses resulting from self constraint of the structure. They must satisfy the local strain continuity requirements and are inherently self-limiting. An important feature of a secondary stress is that the associated strain discontinuity can be accommodated by yielding in ductile materials. Therefore, the secondary stresses do not affect the limit load of the structure. Peak stress is a local stress, occurring mainly in regions of geometric discontinuity or temperature non-linearity, and is of concern only in fatigue life evaluation.

Primary membrane and bending stress limits in piping are:

$$P_m \leq S_m$$

$$P_m + P_b \leq 1.5\ S_m$$

where P_m is the membrane stress component (due mainly to pressure) and P_b is the bending stress (due to weight and seismic moments). S_m is the ASME design stress intensity equal to the lesser of 0.9 S_y at 550°F or 1/3 S_u. ANSI B31.1 imposes similar limits on primary stresses which assure essentially the same design margins. The Section III Primary plus Secondary stress (P + Q) limit is 3 S_m. The P + Q limit assures elastic shakedown and minimizes plastic deformation. The P + Q limit does not directly affect design margins in ductile materials. They may be exceeded provided that the effects of plasticity are properly accounted for as they may affect fatigue analysis and incremental deformation. There are no specific limits on peak stresses apart from their effect on the fatigue analysis.

Based on the above discussion, it is clear that the important requirement in weld overlay design is to limit the primary stress. The limit on primary membrane stress applies mainly to the hoop stress. In general, pipes are sized such that the hoop stress for normal conditions is less than or equal to S_m. Therefore, the hoop stress for normal conditions is less than S_m and the corresponding axial pressure stress (which is of interest for circumferential cracks) is less than 0.5 S_m. In general. the main contribution to the axial stress is the pressure stress. Other primary stresses (dead weight and seismic) are usually much smaller. In BWR primary piping the total axial stress including contributions of pressure, dead weight, and seismic loads is well below S_m. It is clear that weld overlay thickness required to maintain full Code margins is less than the full pipe thickness, even if the structural capability of the original pipe material is not considered in determining the stress capability of the overlayed pipe. In fact, for normal and upset conditions, the $P_m + P_b$ in the axial direction is often less than 0.6 S_m, and the Code design margins can be maintained with overlay thickness less than half the original pipe wall thickness. Specifically, the overlay thickness is determined based on the IWB-3640 requirements for the overlayed pipe

configuration (thickness equal to original pipe wall plus the overlay) and with stresses adjusted for the new thickness. As discussed later, IWB-3640 requirements provide a safety margin of approximately 2.8 based on limit analysis. This is comparable to the margins for uncracked piping designed to ANSI B31.1 requirements and subjected to stress levels corresponding to the maximum allowable Code loadings.

The three overlays on welds 10-0-05, 10-0-06, and 10-0-07 in the RHR system were sized without taking credit for the uncracked portion of the original pipe. This is defined commonly as a full structural overlay. The IWB-3640 requirements are satisfied assuming a 360° circumferential crack of depth equal to the original pipe thickness t. The weld overlay thickness, h, is determined such that the non-dimensional crack depth t/(t + h) meets the acceptance criteria of IWB-3640 for a 360° crack under the applied stresses corresponding to the weld overlayed configuration. The IWB-3640 margins on limit loads are maintained at levels corresponding to minimum Code values. Since the uncracked ligament is not considered, the weld overlay thickness is independent of both the UT measured length and depth of the original crack. Thus, uncertainties on UT sizing capabilities do not affect the design.

Cracking on welds 10-0-10 and 10-0-15 was shallow. With conservative depth estimates it was shown that operation 'as-is' without repair was acceptable, even after accounting for IGSCC growth. However, a weld overlay of 0.25 inch thickness was applied to provide additional margin. In fact, based on the applied stresses, the 0.25 inch thick overlay is for all practical purposes a full structural overlay.

Overlays on riser welds have been applied on axial cracks in weld heat affected zones (HAZ). Axial cracks in general are short since the weld HAZ is limited to a narrow circumferential band near the weld. Welds with axial cracks of this length can be shown to retain acceptable design margin even if they are assumed to be through-wall. Thus, for axial cracks, required structural design margins can be maintained regardless of the crack depth since the length is inherently limited by the HAZ width. For axial cracks, overlays (0.25 inch thick) were applied mainly to prevent leakage from through-wall or nearly through-wall cracks.

In addition, a weld overlay of 0.125 inch thickness (excluding the first layer) was applied on the 4-inch diameter jet pump instrumentation nozzle/safe end weld. A combination of circumferential and axial cracking was detected in this weld.

Fatigue. When a weld overlay is applied on a piping component with a crack, IGSCC crack growth is not expected to be significant since the weld overlay produces compressive residual stresses on the inside surface and in the inner portion of the wall of the pipe, thereby preventing new IGSCC initiation or retarding existing IGSCC crack growth. This subject is discussed in detail in Section 5. Fatigue crack growth can generally be shown to be small since the recirculation and RHR piping where overlays have been applied do not experience significant fatigue cycling.

An alternate approach which can be used to demonstrate fatigue margin is to perform a Section III fatigue analysis considering crack initiation from the IGSCC defect. In accordance with ASME Code practice, a maximum fatigue strength reduction factor of 5 is used and the fatigue usage is shown to be less than 1.0.

2.1.2 Margin to Collapse or Fracture

The methodology used in developing the IWB-3640 acceptance flaw size is to first determine the critical flaw size for the applied loading conditions. The acceptance flaw size is then determined by requiring a suitable design margin on the critical flaw conditions. The critical flaw size is determined using limit-load concepts. It is assumed that a pipe with a circumferential crack is at the point of incipient failure when the net section at the crack develops a plastic hinge. Plastic flow is assumed to occur at a critical stress level, σ_f, called the flow stress of the material. The criterion is simple to apply and has been shown to be effective in predicting failure of stainless steel pipes containing circumferential cracks (References 3, 4). Using this method, critical flaw parameters can be represented in the form of a failure diagram defining the combination of critical crack depth and length

at which collapse occurs for a given applied stress. Figure 1 shows a typical failure diagram defining the flaw parameters at failure for stress level $P_m + P_b = S_m$. The allowable flaw size is determined by applying a safety factor of 2.77 on the failure line. This is comparable to the minimum ASME Code design margin in uncracked piping (Reference 5) subject to maximum allowable loadings.

The IWB-3640 flaw assessment procedure used in the weld overlay design explicitly assures adequate margins against collapse but implicitly assumes margin on failure by tearing instability. The toughness of the austenitic stainless base material is high enough to assure that the acceptance flaw sizes in IWB-3640 also provide equivalent margins on tearing instability. Since most IGSCC cracks are in the base metal near the weld, the fracture properties in the immediate region of cracking are adequate. However, recent data on stainless steel weldments have shown that the toughness of some heats of submerged arc weldments (SAW) can be significantly lower than that of base metal. Parametric studies using the lower bound SAW data have shown that the factor of safety on tearing instability can be lower than that implied by the Code (approximately 2.0 compared to the Code value of 2.77). Data from the same programs, however, show that GTAW weldments have substantially higher toughness than the SAW and are therefore not substantially affected by these weld metal toughness concerns. Since weld overlays on cracked piping are made using GTAW weldment, the design based on IWB-3640 as described above also provides adequate margin on tearing instability. Detailed fracture evaluations of the overlays are presented in Section 6.

3. PEACH BOTTOM UNIT 3 WELD OVERLAY CONFIGURATIONS

Of the total of 15 weld overlays on piping, 10 are located on the recirculation risers, one on each riser. These were designed as repair measures for the axial flaws which were conservatively assumed as through-wall. The maximum axial flaw length was 1.0 inch. The weld overlay thickness was 0.25 inch. As noted in Section 2.1, the required structural margin can be maintained even if a 1.0 inch long through-wall axial crack is present. Thus the main function of the riser overlays was to prevent leakage from through-wall or essentially through-wall cracks.

The overlays on welds 10-0-05, 10-0-06, and 10-0-07, located on the 20-inch RHR suction piping were also sized without taking credit for the uncracked ligament in the original pipe. Thus, the IWB-3640 requirements were satisfied assuming a 360° circumferential crack of depth equal to the original pipe thickness. Thus uncertainties in crack sizing by UT did not affect the weld overlay design. The overlay thickness at welds 10-0-05 and 10-0-06 was 0.5 inch and that at weld 10-0-07 was 0.35 inch. The cracking on welds 10-0-10 and 10-0-15 was shallow and shown to be acceptable for operation without repair. Nevertheless, a 0.25 inch thick overlay was applied on these welds. This was very close to the thickness (0.280 inch) required for a full structural overlay.

Finally, full structural overlays were also applied on the two jet pump instrumentation nozzle/safe end welds.

4. RESIDUAL STRESS IMPROVEMENT

One of the essential factors in IGSCC initiation is the presence of tensile stress in excess of the local yield stress. In the as-welded condition, the predicted residual stresses on the inside surface of a pipe are highly tensile. Both the IHSI and weld overlays produce compressive residual stress at the inside surface of the pipe, thus promoting crack growth retardation or arrest. As indicated in Table 1, 91 welds in the Peach Bottom 3 recirculation and RHR lines have been treated with IHSI, out of which 15 welds were subsequently weld overlayed. This section presents the technical support information on the beneficial residual stresses induced by IHSI and weld overlay processes.

4.1 Induction Heating Stress Improvement (IHSI)

In this process, compressive residual stresses at the inside wall surface (and subsurface) are produced by induction heating the outer surface of a pipe weldment while simultaneously cooling the inside surface with water [Reference 7]. Analytical predictions of residual stresses from IHSI have been presented in Reference 8.

A similar analysis has been presented in Reference 9 for operating plant pipe welds in which undetected IGSCC crack may already exist. Figure 2 from Reference 9 shows the predicted IHSI induced residual stress pattern for both an uncracked pipe and for pipes containing circumferential cracks of depths equal to 6% to 40% of thickness. It is seen that compressive residual stresses are still produced, even in the presence of moderately deep cracks.

4.2 Residual Stresses Resulting from Weld Overlays

Both analytical and experimental results on the weld overlay induced residual stress patterns are discussed.

4.2.1 Analytical Prediction of Residual Stress Distributions Resulting From Weld Overlay Repairs

The analytical procedure is essentially similar to that for IHSI. The only difference is in the temperature analysis where heat flow calculations are now performed either by using a moving point source or by nugget area heating method. Figure 3 from Reference 1 presents a typical calculated axial stress distribution through the wall of a 12-inch pipe in the heat affected zone, following the application of a 0.25 inch weld overlay with a heat input of approximately 25 KJ/in.

4.2.2 Experimental Bases for Weld Overlay Residual Stress. Extensive residual stress measurements have been made with weld overlays made using typical field practice. These measurements include

- o Measurements done at Argonne National laboratory on overlays simulating the geometry of the Hatch 1 and Hatch 2 piping (Figures 4, 5).
- o EPRI/BWR Owners' Group program on large diameter pipe overlays done at the J. A. Jones Applied Research Center.
- o GE data on weld overlayed 16-inch diameter pipe.

The results of the different programs confirm that weld overlays produce compressive residual stresses on the ID surface and through a substantial portion of the inner pipe wall. The magnitude and distribution of the residual stress is dependent on the specific details of the welding process, number of layers, heat input, and pipe thickness. The effect of the favorable residual stress is to produce a negative (compressive) stress intensity factor which inhibits crack growth. The beneficial effect of the compressive stress applies even for relatively deep cracks. Therefore, in addition to the structural reinforcement from the overlay, there is also additional benefit from the residual stress.

In overlays which also consider the original pipe wall (the so-called mini-overlay), the benefit of the compressive stress is included in the crack growth calculations and subsequent decisions on crack acceptability. However, in a full structural overlay, the sizing already assumes a 360° through-wall crack in the original pipe wall. Therefore, the overlay design does not count on the benefit of the residual stresses in limiting crack growth. This is important, since differences in the welding parameters or other overlay application variables are not significant when the benefit of residual stress is not included in the design basis.

5. CORROSION CRACKING RESISTANCE OF WELD MATERIAL

The application of duplex stainless steel weld overlay to austenitic stainless steel pipe joints results in the deposition of several layers of weld metal over an existing girth weld containing a defect. The weld overlay material is selected to be highly resistant to IGSCC in BWR environments. In the following section, the criteria used to select the weld overlay material are discussed, based upon the inherent IGSCC resistance of austenitic base microduplex stainless steels.

5.1 IGSCC Resistance of Weld Metal

The susceptibility of austenitic stainless steels to IGSCC in oxidizing environments is understood to be the result of a reduction in the level of chromium at grain boundaries to below approximately 12 wt%, the level which confers passivity upon stainless steels in these environments. This 'chromium depletion' is generally the result of thermal or thermo-mechanical processing (such as welding) which causes the material to precipitate chromium-carbides at these continuous austenitic grain boundaries thereby 'depleting' the adjacent matrix material in chromium. Two straightforward approaches which can effectively prevent this chromium depletion at grain boundaries resulting from the thermo-mechanical processing are (1) increasing the chromium level in the alloy and (2) reducing the carbon level in the alloy.

In general, the IGSCC resistance of microduplex stainless steels of the Type 308 or 316 stainless steel types (or interdendritic stress corrosion cracking resistance) is derived from the fact that these steels contain ferrite, a phase rich in chromium. The chromium level in this phase is generally of the order of 25 wt%, while in the austenite phase the chromium level is typically of the order of 16-18 wt%. Unlike the fully austenitic Types 304 or 316 stainless steel pipe in which the chromium is depleted from the austenite grain boundary vicinity, in the microduplex stainless steels the intergranular chromium carbide precipitation occurs predominantly along austenite-ferrite grain boundaries during thermal processing. The ferrite grain typically provides the additional chromium required for the precipitation since this

phase has a significantly higher composition of chromium than austenite and the chromium diffusivity at 1100°F is approximately three orders of magnitude greater in ferrite than in austenite. A small amount of precipitation may occur from the austenite side of the ferrite-austenite grain boundary, thus resulting in some small amount of sensitization. The potential for sensitization and susceptibility to interdendritic stress corrosion cracking are dependent primarily on the carbon content and the ferrite content of the weld metal. These two factors are interdependent since ferrite content generally increases as the carbon content is reduced. Thus, both factors favor IGSCC resistance. A number of investigations, laboratory tests and field service evaluations have been performed and used to establish the basis of requirements for carbon level and ferrite levels of weld overlay materials that will provide the required IGSCC resistance of the weld overlay buildup. This work will be discussed below.

5.2 Carbon and Ferrite Levels Required to Provide IGSCC Resistance

In the extensive pipe test programs used to evaluate the behavior of Type 304 stainless steel as well as the different mitigation techniques (such as IHSI, LPHSW, solution heat treatment, and the alternate materials 316NG and 304NG), the weld metal used to join the test pieces was made of Type 308L with 0.035 percent maximum carbon and a minimum of 8 Ferrite Number (FN). The weld metal in those tests was always resistant to IGSCC even with the high residual stresses which generally peak near the weld centerline. Secondly, in tests on shop applied corrosion resistant cladding (CRC) with maximum 0.035% carbon and minimum ferrite 8 FN, no IGSCC was observed (Reference 10). The IGSCC resistance of weld metal is consistent with laboratory studies performed by Devine (Reference 10). He evaluated the influence of carbon level, ferrite content, and ferrite distribution in duplex stainless steel alloys and weld metals on IGSCC resistance in copper-copper sulphate solution. His results confirm that if the carbon level is less than 0.015%, IGSCC immunity was assured and that Type 308L with 8 FN weld metal would also be expected to be resistant to IGSCC.

Laboratory experience also has established that weld metal with low carbon and high ferrite content will arrest propagating intergranular stress corrosion cracks as well. As part of an EPRI/General Electric study investigating crack growth rates in Type 304 SS pipe material, precracked fracture mechanics specimens containing welds of Type 308 or 308L stainless steel with different ferrite levels were tested in a laboratory simulation of the BWR environment under slow cyclic loading (Reference 11). The high carbon Type 308 SS welds exhibited significant intergranular penetration into the weld metal at ferrite levels up to 8.5%. Arrest was observed at a ferrite level of 11.5%. However, the Type 308L SS welds, fabricated from 0.025 wt% carbon material and containing from 5.5 to 11.5% ferrite always exhibited arrest of the IGSCC cracks, which had initiated in the adjacent sensitized heat affected zone. The intergranular branches of the primary crack continued in the wrought, sensitized Type 304 SS along the base metal weld heat affected zone parallel to the weld/base metal interface, demonstrating that the IGSCC mechanism continued to be active in the specimen.

In another EPRI-sponsored study, investigators at Ishikawajima-Harima Heavy Industries (IHI) fabricated and tested girth welded Type 304 SS pipe processed to produce nearly through-wall IGSCC (Reference 12). One intergranular crack penetrated the weld metal and extended several millimeters into the weld. The weld metal crack which penetrated in high carbon Type 308 SS of approximately 5% ferrite appeared to terminate where the ferrite level had increased to approximately 9% ferrite.

One additional study sponsored by EPRI and performed by General Electric provided striking evidence of the ability of microduplex stainless steel weld metal to resist IGSCC in BWR-like environments (Reference 13). In that study, fatigue precracked, plate welded fracture mechanics specimens were bolt loaded and tested for an extended period of time in simulated BWR water. All of the austenitic materials, including Types 304NG and 316NG stainless steel exhibited significant intergranular crack growth in this very severe test. In two samples where the fatigue precrack inadvertently terminated in the weld metal, no crack extension was observed in the weld. Type 308L stainless steel containing 8FN minimum and 0.035 wt% carbon maximum was specified for these tests.

Finally, in tests run as part of the degraded pipe study, Type 308L high ferrite (8 FN minimum) weld overlays demonstrated complete crack arrest at the weld interface (Reference 14).

The field data is similar to the laboratory data. In general, all weld metals, whether Type 308 or 308L, have exhibited excellent IGSCC resistance. There are only a few incidences where growing IGSCC cracks have penetrated low ferrite high carbon weld metals. In all cases the cracks appeared to arrest when the ferrite level increased to ~6%. In most cases arrest occurred in weld metal with a ferrite content as low as 3%. Details of the field data are described here.

Evaluation of the IGSCC failure at KRB showed that the IGSCC always appeared to arrest at ferrite levels of 3% when the cracks penetrated the weldment (Reference 15). A second instance of weld metal cracking was in a a section of the core spray line at Quad Cities Unit 2 (Reference 16). Metallurgical analysis of the weld revealed the cracking to be interdendritic in 0.064% carbon Type 308 stainless steel containing approximately 5% ferrite. Finally, at Nine Mile Point Unit 1 selected metallurgical analyses were performed on pipe specimens removed from the recirculation system (Reference 17). The environmentally assisted cracking had grown through the base metal (Type 316 SS) into the weld metal in two of the pipe joints. The cracking in the weld metal appeared to be interdendritic, although the photomicrographs provided did not contain sufficient detail to conclusively document that observation. The weld filler is believed to have been Type 308 or 316 stainless steel and was determined to contain between 3% and 6% ferrite. This result is similar to the GE/EPRI results.

All these field observations provide clear evidence that in instances of weld metal IGSCC cracking, there was either high carbon or low ferrite content or a combination of both.

5.3 First Layer Weld Overlay Dilution

Due to weld penetration and mixing with the pipe base material, some reduction in the ferrite level and increase in carbon content will occur in the first layer. Except for very localized microstructural and fusion line diffusion effects, each overlay weld layer is a homogeneous fused structure of uniform carbon and ferrite composition. The automatic GTAW process applied to weld overlay will result in base metal to total fused weld metal dilution of 20-30%. This low level of dilution would still produce a first layer overlay that would be highly resistant to IGSCC when a 308L high ferrite weld material is used for the overlay. The second or subsequent layers are essentially undiluted, so that the bulk overlay material has IGSCC resistance equivalent to that of the weld material. This is confirmed by the results of the GE/EPRI degraded pipe program, Reference 14, (described in Section 7) where crack arrest was observed at the base metal interface with overlays made of 308L SS with 8 FN ferrite content (Figure 17).

5.4 Peach Bottom Unit 3 Overlay Material Specification

Because of the importance of ferrite to the IGSCC resistance of 308L material, GE specifications require ferrite determination using calibrated magnetic measurement of weld deposits for each heat of material. This technique has been found to be more reliable and conservative than chemical composition (Schaffler or DeLong diagrams) or microstructural measurements of ferrite. Magnetic measurement using the actual weld deposit eliminates potential errors due to estimated weld material nitrogen content which must be assumed for the chemical analysis methods. Using the magnetic measurement procedure, a minimum ferrite content of 8.0 FN was applied for the Peach Bottom weld overlay welding material. Carbon content requirements were in accordance with ASME SFA 5.9 requirements for Type ER308L. This welding material specification requirement provides a weld overlay (including the first layer) that is highly resistant to IGSCC. The actual heats of material applied at Peach Bottom 3 were typically 0.020% maximum carbon and 10-12 FN, providing even further IGSCC margin for the overlay.

6. FRACTURE MECHANICS MARGIN

Weld overlay designs for the cracks at the riser and RHR welds, and the Jet Pump instrumentation nozzle at Peach Bottom Unit 3 were based on Paragraph IWB-3640 of Section XI, ASME Code. The allowable flaw size tables in IWB-3640 are based on the net section collapse theory. With implied safety margin of 2.8 for normal (Level A) and upset (Level B) conditions and 1.4 for emergency (Level C) and faulted (Level D) conditions.

Maximum load and allowable flaw size predictions of this theory have been shown to be in good agreement with both the experimental results (References 13 and 18) and the calculations using the currently available elastic-plastic fracture mechanics (EPFM) techniques (Reference 19). Since most of the attention was directed toward stainless steel pipes with IGSCC, the experimental studies were focused on cracks in the heat affected zone (HAZ) or the base material. EPFM evaluations of the tests used the base metal fracture toughness properties. The implied assumption was that the stainless steel weld metal in all cases would have essentially the same toughness as the base metal and that due to its ferrite content requirements, the IGSCC cracks are unlikely to propagate in the weld metal. However, recently available toughness data on the stainless steel welds seem to suggest that the welds produced by some processes such as the submerged arc welding (SAW) may have considerably lower toughness than that of the base metal or the HAZ. On the other hand, the welds produced by TIG, the process used in the weld overlays, shows considerably higher toughness.

The fracture mechanics analysis presented in this section addresses these weld toughness concerns as they relate to Peach Bottom Unit 3. It is shown that the safety margins implied in IWB-3640 are exceeded even when the low weld toughness properties are factored in. The evaluation was conducted using EPFM techniques.

The weld overlay toughness was characterized in terms of a lower bound J-resistance curve based on a review of the available technical literature.

For each distinct overlay configuration, an allowable stress magnitude was calculated corresponding to the elastic-plastic instability. The design or the actual primary stress, $P_m + P_b$, at the same location was obtained from the overlay design report. The ratio of these two stresses determines the factor of safety based on EPFM calculations. These are compared with the IWB-3640 factors of safety.

6.1 Weld Toughness Data Evaluation

Recent data from References 20 through 23 indicate that in some cases the stainless steel weld metal toughness may be lower than the base material. The difference appears to be a strong function of the welding process. The welds produced by the SAW process appear to show the lowest toughness. On the other hand, the welds produced by TIG, the process used in weld overlays, shows considerably higher toughness, almost approaching that of the base metal. Figure 6 shows conservative representations of the (J_{mat}, T_{mat}) curves for two types of welds. Curve 1 from Reference 23 is for a submerged arc weld. Curve 2 also from Reference 23 is for gas tungsten arc weld (GTAW) similar to the overlay welds. Curves 1 and 2 may not be the absolute lower bounds for the rspective weld categories, but were considered as representative lower bounds and were used in the EPFM evaluation.

6.2 EPFM Calculation Methodology and Parameters

The J-integral and the applied tearing modulus, T, were evaluated as a function of applied loading using the estimation scheme procedure given in Elastic-Plastic Fracture Handbook (Reference 24). The intersection of ($J_{applied}$,$T_{applied}$) curve and the appropriate (J_{mat},T_{mat}) curve gave the value of J-integral at instability. The applied stress at instability was determined corresponding to the J value (see schematic in Figure 7).

A key input in the evaluation of J_{app} and T_{app} is the Ramberg-Osgood characterization of the material stress-strain behavior:

$$\frac{\varepsilon}{\varepsilon_o} = \left(\frac{\sigma}{\sigma_o}\right) + \alpha \left(\frac{\sigma}{\sigma_o}\right)^n$$

$$\varepsilon_o = \frac{\sigma_o}{E}$$

Where σ_o, α, n are parameters determined by fitting the equation to the true stress-strain curve.

Variations in the stress-strain behavior of austenitic stainless steels may occur due to such factors as welding process, heat input rate, filler metal composition, thermal boundary conditions, etc. Since a detailed study of these aspects was beyond the scope of this report, the evaluations were performed for one set of these parameters. The following Ramberg-Osgood parameters from Reference 23 based on an experimentally-determined true stress-true strain curve of a GTAW weldment were used:

$\alpha = 2.83$, $n = 11.84$, $\sigma_o = 53{,}900$ psi

6.3 RHR Weld Overlay Evaluation

The RHR supply line weld overlays 10-0-05, 10-0-06, and 10-0-07 are full structural type; i.e., the overlays were sized without taking credit for the uncracked portion of the original pipe. The IWB-3640 requirements were satisfied assuming a 360° circumferential crack of depth equal to the original pipe thickness. The overlay thickness at welds 10-0-05 and 10-0-06 is 0.5 inch and that at weld 10-0-07 is 0.35 inch.

For the assumed 360° crack geometry, the J-integral and T_{app} values were calculated using the following estimation scheme formulas:

$$J = f_1 (a_o, R_i/R_o) \frac{P^2}{E} + \alpha \sigma_o \varepsilon_o c \left(\frac{a}{b}\right) h_1 \left(\frac{P}{P_o}\right)^{n+1}$$

$$T = \frac{E}{\sigma_o^2} \cdot \frac{dJ}{da}$$

The estimation scheme parameters for bending loading are currently unavailable and, therefore, only the pure tension loading case was evaluated.

Figure 8 shows a plot of J-integral versus applied axial stress for overlay configurations on weld 10-0-05. Since the crack tip for this case would advance essentially in a GTAW weld metal, GTAW J-T (Curve 2) was used to determine the value of J-integral at instability. The instability stress was calculated as 31.1 ksi and is shown in Table 2 along with the actual primary membrane (P_m) and bending (P_b) stress based on the piping stress report. The ($P_m + P_b$) stress at weld 10-0-05 is 5.96 ksi and, thus, the calculated factor of safety is 31.1/5.96 or 5.2. Results of similar calculations for overlays on welds 10-0-06 and 10-0-07 are shown in Table 2.

Indications in weld 10-0-10 and 10-0-15 were relatively shallow and were acceptable as is. Nevertheless, a 0.25 inch thick overlay was applied. The fracture margin evaluation for welds 10-0-10 and 10-0-15 was conducted based on the following conservative assumptions:

(i) The flaw depth was taken as two times that reported by UT inspection

(ii) Submerged arc (J-T) properties, Curve 1, was used in the instability stress evaluation.

(iii) The reinforcing benefit of the 0.25 inch thick overlayed was conservatively neglected.

The results for these two welds and the corresponding factor of safety are also listed in Table 2.

6.4 Riser Weld Overlays

All of the UT-detected cracks near the riser welds in the Peach Bottom Unit 3 recirculation line were short (<1 inch) and were oriented in the axial direction. The applied minimum weld overlay thickness was 0.25 inch. This overlay thickness was based on the conservative assumption that the crack depth is equal to the original pipe thickness. Figure 9 shows the dimensions of this overlay.

Currently, the J-integral estimation scheme formulas for part-through wall axial flaws in cylinders are not available and, therefore, the EPFM calculations were performed assuming a through-wall flaw. The J-integral was estimated using the solution for a crack in an infinite plate by Shih and Hutchinson [25] and a curvature correction factor from Reference [26]:

$$\frac{J}{Y^2 \sigma_o \varepsilon_o a} = \pi\left[1 + \frac{1}{2}\left(\frac{n-1}{n+1}\right)\left(\frac{\sigma}{\sigma_o}\right)^2\right]\left(\frac{\sigma}{\sigma_o}\right)^2$$

$$+ \alpha\left[3.85\ \ n\left(1-\frac{1}{n}\right) + \frac{\pi}{n}\right]\left(\frac{\sigma}{\sigma_o}\right)^{n+1} \quad \text{for } \sigma \leq \sigma_o$$

$$= \pi\left[1 + \frac{1}{2}\left(\frac{n-1}{n+1}\right)\right]\left(\frac{\sigma}{\sigma_o}\right)^2$$

$$+ \alpha\left[3.85\ \ n\left(1-\frac{1}{n}\right) + \frac{\pi}{n}\right]\left(\frac{\sigma}{\sigma_o}\right)^{n+1} \quad \text{for } \sigma \geq \sigma_o$$

where $Y^2 = (1 + 1.25\ \lambda^2)$ for $\lambda \leq 1.0$

$= (0.6 + 0.9\ \lambda^2)$ for $1.0 \leq \lambda \leq 5.0$

Figure 10 shows a plot of J-integral as a function of nominal hoop stress. The instability hoop stress was determined to be ~52 ksi. The nominal hoop stress in the riser pipes for the Level A and B conditions is 10.9 ksi. The corresponding factor of safety is 4.8 and is shown in Table 2.

6.5 Discussion on Fracture Margins

The calculated factors of safety in Table 2 for the riser and RHR weld overlays are well in excess of the implied safety margins in IWB-3640. Even higher margins are expected for the jet pump instrumentation nozzle overlays since the applied loads on the nozzle are low. Based on these results, it is concluded the Code-implied safety margins are maintained at the subject locations in the Peach Bottom Unit 3 recirculation and RHR lines, even when the lower bound material toughness properties are factored in.

7. RESULTS FROM DEGRADED PIPE PROGRAM

Under EPRI sponsorship, GE is conducting a test program on degraded piping subjected to remedies like IHSI or weld overlay. The purpose of this program is to provide the experimental basis to define the design life of the remedies. The initial goal was to confirm weld overlay life for 1-2 cycles. Results of this test program to date are described here.

The first result on weld overlayed piping was on a 4-inch Schedule 80 pipe with a full structural overlay. The weld overlay specified 308L stainless steel material with ferrite number 8 FN. The specimens were precracked by IGSCC mechanism and were subsequently overlayed. Testing was at a nominal stress level of 16.9 ksi (S_m) in 8 ppm oxygenated water at 550°F. To obtain an early assessment of life for the weld overlay, specimen RSP-14 was removed after 1000 hours exposure in the test environment to perform a destructive evaluation of crack growth under the overlay. Weld 'D' of the specimen was chosen for evaluation. HAZ 'D-2' had a through-wall crack, which caused a small blowhole when penetrated by the weld overlay and required a repair procedure similar to procedures used in the field for this occurrence. Since this crack was of known depth, terminating at the weld overlay interface, it afforded an opportunity of evaluating crack growth under the overlay.

Since the weld overlay provides full structural reinforcement of the pipe, the primary concerns to be resolved were: (1) whether the crack would penetrate through the weld overlay, and (3) whether the crack would extend in a circumferential direction.

A dye penetrant examination was made on the ID of the pipe at weld 'D' to determine the circumferential length of the crack and compare this to the length of the crack before the remedy was applied as determined by UT examination. No PT indication could be obtained. This could be due to the high compressive stress on the ID surface which caused the crack to close up and prevent absorption of the dye.

The circumferential length of one of the cracks was measured after bending the pipe wall to open up the crack. Comparison of this length to the original length as measured by UT before overlay application showed no growth.

Two longitudinal metallographic pipe sections were made through weld HAZ 'D' at two different locations where blowholes occurred when penetrated by the weld overlay. Both of these sections showed complete arrest of the crack at the weld overlay metal interface. Figure 11 shows metallography of the crack section confirming crack arrest. Based on the observation of no measurable crack growth in any direction, a lifetime of several fuel cycles can be predicted. This provides definitive proof, under simulated field conditions, that the weld overlay provides crack arrest even under 8 ppm oxygenated water at 550°F. Exact determination of the factor of improvement is not possible since the stress and environment in the pipe test were more severe than that in the field. One measure of the improvement may be deduced from the fact that the average time to failure in pipe tests on unmitigated 304 stainless steel welds in 8 ppm oxygenated water is 100 hours (compared to crack initiation time in the field of 2-3 years). The fact that no crack growth occurred in 1000 hours suggests that the weld overlays should be good for several fuel cycles.

Similar results were also obtained on precracked IHSI pipe tests. Successful operation of up to 2000 hours has been confirmed. This shows that in welds with IHSI, even if undetected cracking exists, crack propagation would not occur and the benefit of IHSI would be maintained.

8. IHSI TREATED WELDED JOINTS WITHOUT CRACKING

Since IHSI is considered an IGSCC mitigating measure, a reexamination of these welds may not be necessary. As an alternative, a sample of such welds may be reexamined. The number of welds to be inspected and the frequency of inspection will depend on the regulatory requirements at the time of inspection.

9. CONCLUSIONS

The report presents the technical basis to justify continued operation of Peach Bottom Unit 3 recirculation and RHR lines for more than one fuel cycle. Various elements of the technical justification include:

a. Structural margin evaluation and discussion of IGSCC resistance of weld overlays.

b. Residual stress improvement due to IHSI and weld overlay processes.

c. Results of GE experimental programs for weld overlays.

Based on the results presented here, continued operation with overlays can be extended well in excess of two fuel cycles.

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Table 1

Peach Bottom 3
RHR/Recirculation Piping Repair Summary

Total number of welds to first isolation valve outside primary containment (Recirculation System and RHR Shutdown Cooling Suction and Return Piping)	149 (Note 1)
Number of weld locations thought not susceptible to IGSCC	24 (Note 2)
Number of weld locations susceptible to IGSCC	125
Number of weld locations IHSI treated	91
Number of weld locations where IGSCC was detected	15
Number of weld locations weld overlay repaired	15
Number of weld locations with IGSCC and not weld overlay repaired	2
Number of weld locations not examined and not IHSI treated	17
Number of weld locations examined but not IHSI treated	17

1. This total does not include 3 susceptible RWCU weld locations which were not inspected.

2. 4 sweepolets to manifold locations were examined and found acceptable; 4 other sweepolet to manifold weld locations were not inspected.

Table 2

EPFM Based Safety Factor Evaluation for Weld Overlays

Weld ID	Pipe Diameter/ Thickness	Crack Geometry	Weld Overlay Thickness (in.)	Stresses Accounting for Overlay Thickness P_m	P_b	$P_m + P_b$	EPFM Calculated Failure Stress	Factor of Safety
10-0-05	20 in./0.85 in.	.35 in. deep 172°	0.50	4.3	1.66	5.96	31.1[1]	5.2
10-0-06	20 in./0.95 in.	.4 in. deep 183°	0.50	4.03	2.76	6.79	29.2[1]	4.3
10-0-07	20 in./0.95 in.	.35 in. deep 109°	0.35	4.2	2.5	6.7	23.7[1]	3.5
10-0-10	20 in./0.90 in.	.20 in. deep 132°	0.25[2]	5.83	2.2	8.03	38.8	4.8[2]
10-0-15	20 in./0.95 in.	.3 in. deep 29°	0.25[2]	5.5	2.41	7.91	27.1	3.4
Riser Welds	12 in./0.69 in.	1 inch long.	0.25	10.9	—	10.9	52.0	4.8

[1]Based on a 360° circumferential flaw with a depth equal to the original pipe thickness.

[2]Welds 10-0-10 and 10-0-15 contained shallow flaws and were shown to be acceptable for continued operation and repair. Nevertheless, an 0.25 inch thick weld overlay was applied to provide additional margin. Safety factors shown here assumed twice the UT measured flaw depth and did not consider the additional reinforcement due to the overlay. Lower bound toughness properties corresponding to submerged arc weldments were used.

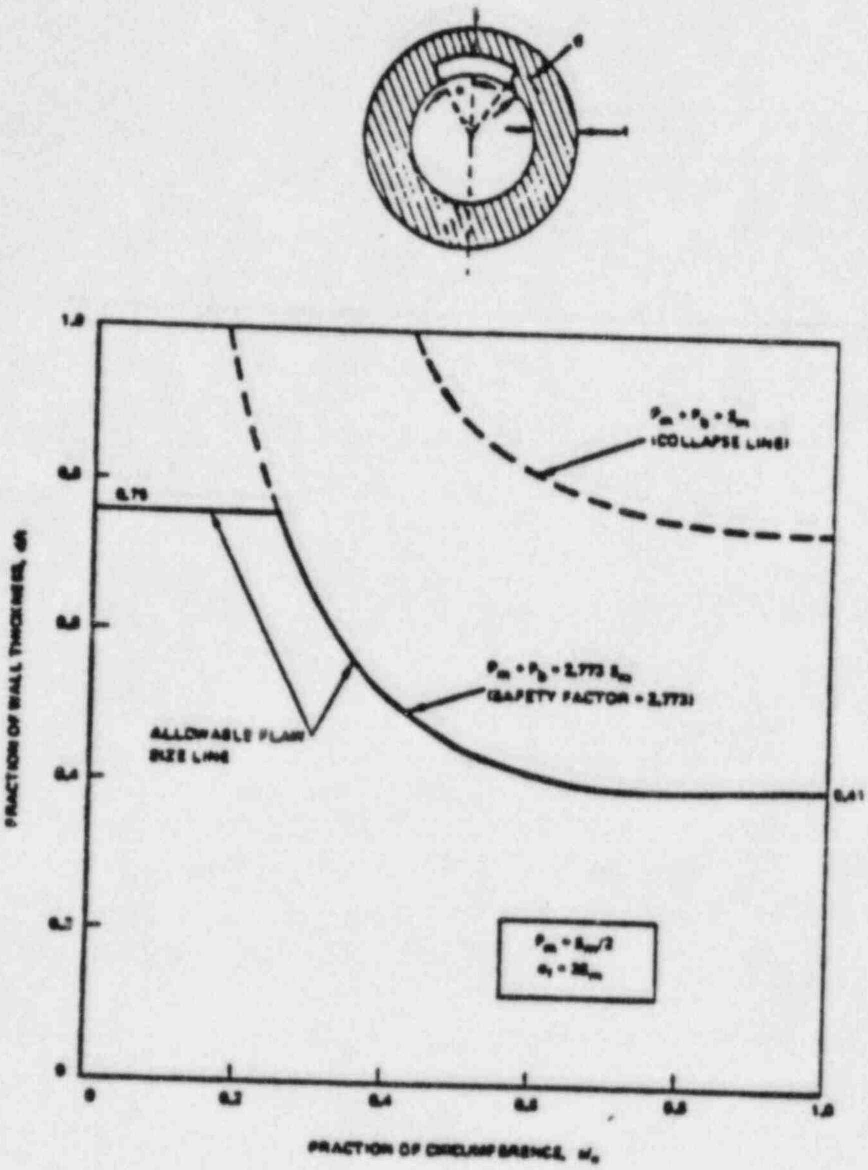


FIGURE 1. Determination of al[illegible]able flaw sizes with a safety factor of 2.773 for normal [illegible]ditions.

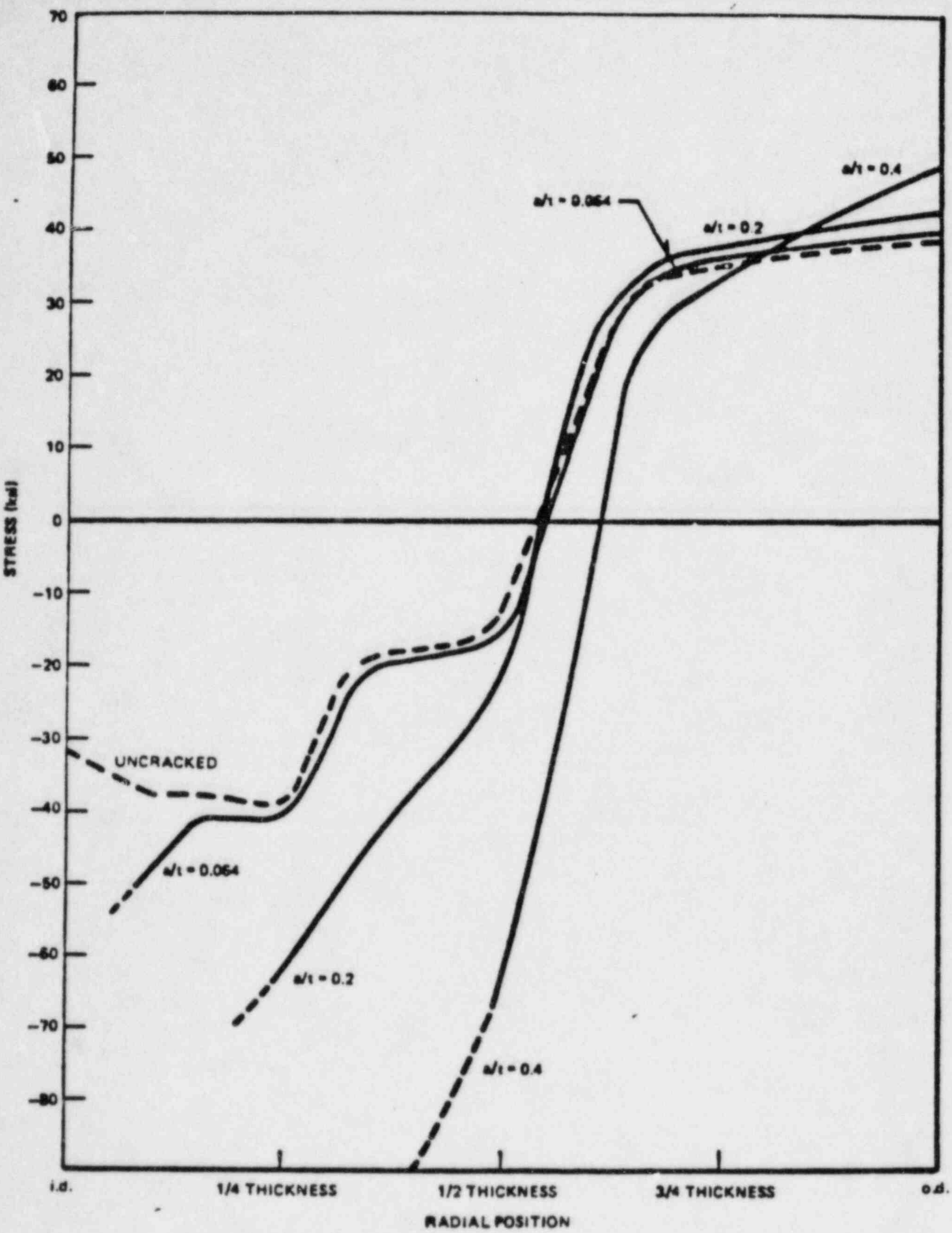


Figure 2. IHSI Through-Wall Axial Stress Distribution at Weld Center Line for Preexisting Cracks

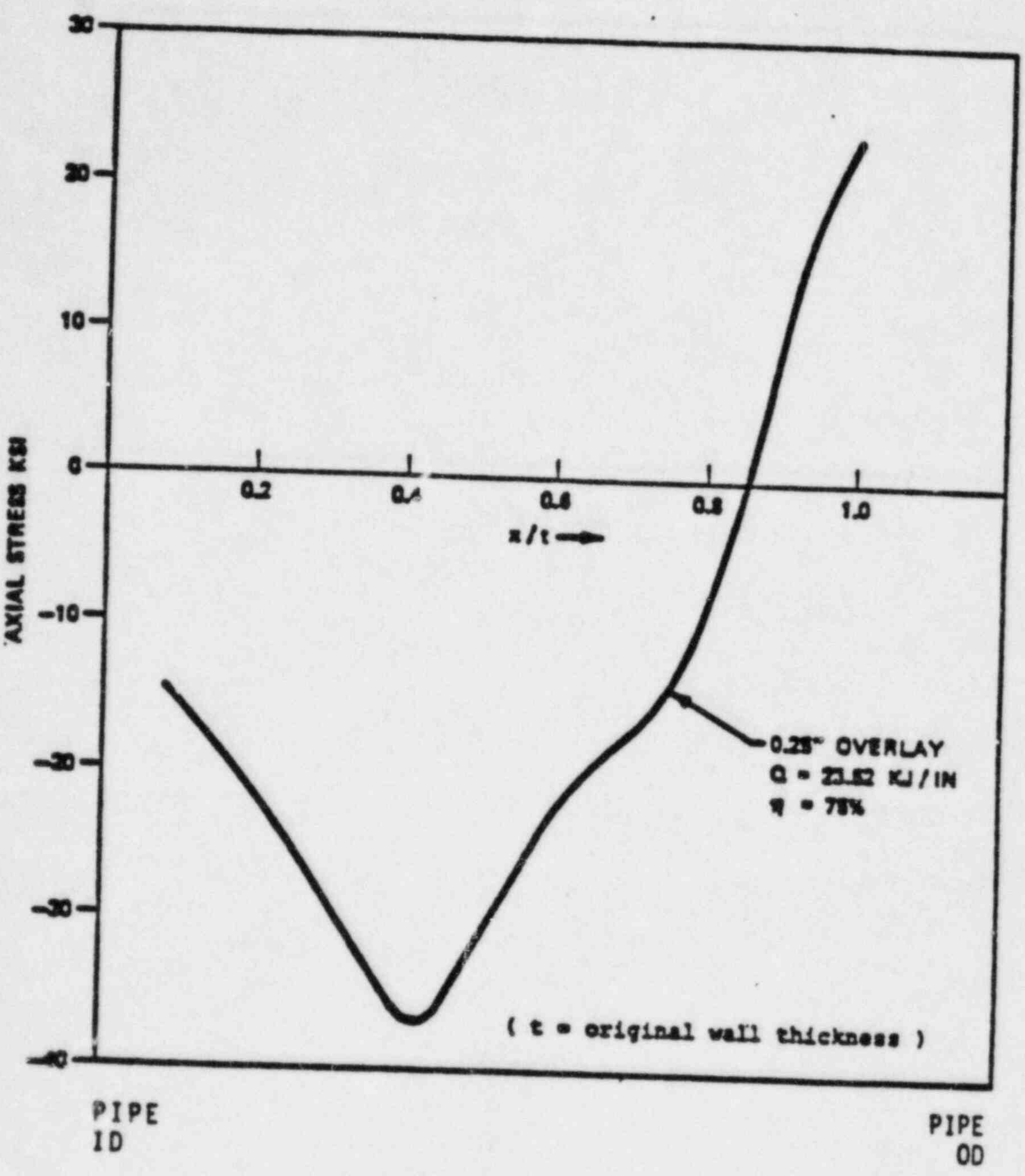


Figure 3. Typical Axial Weld Residual Stress Distribution After Overlay

.20" OVERLAY WELD ON 12" SCH. 100 PIPE

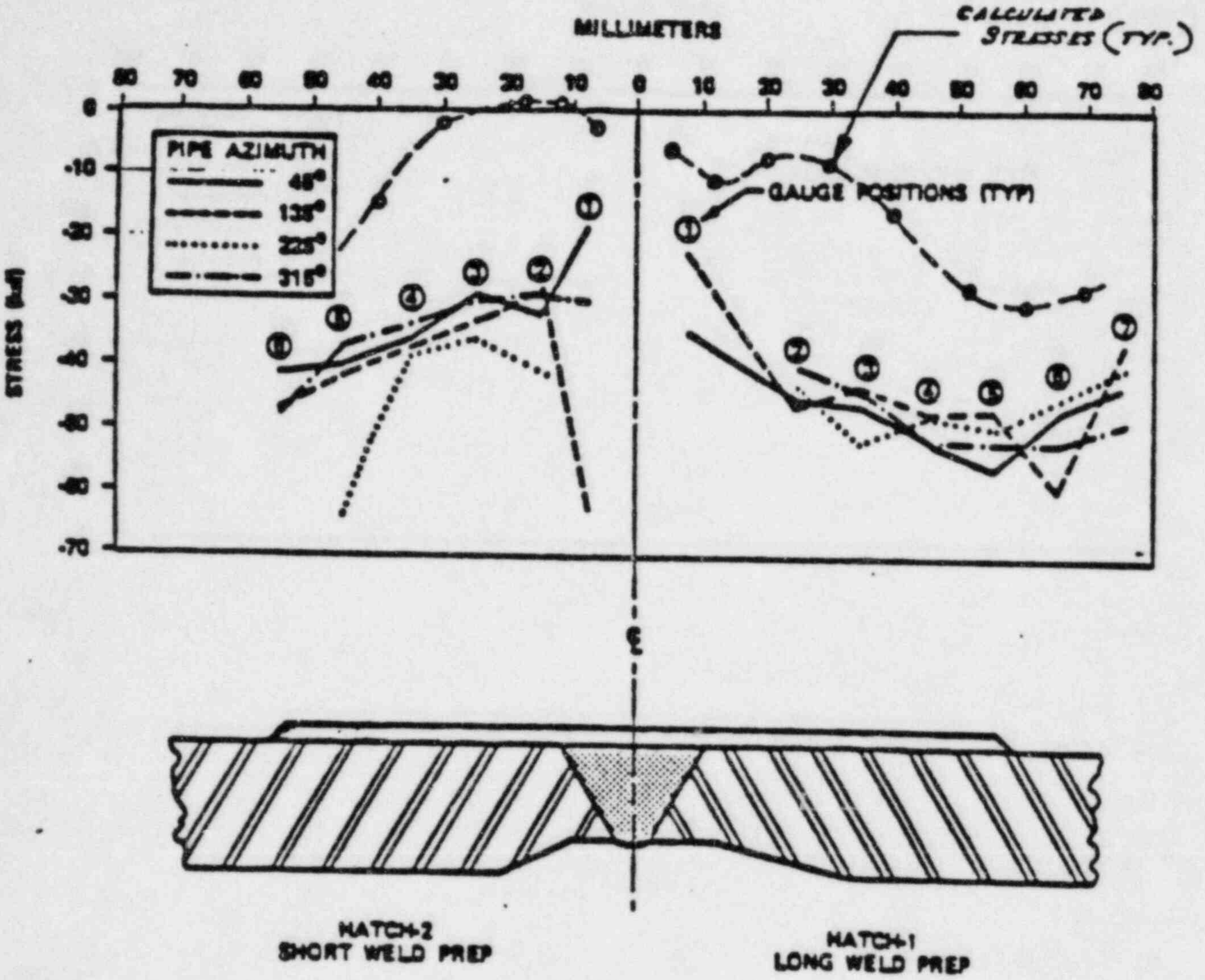
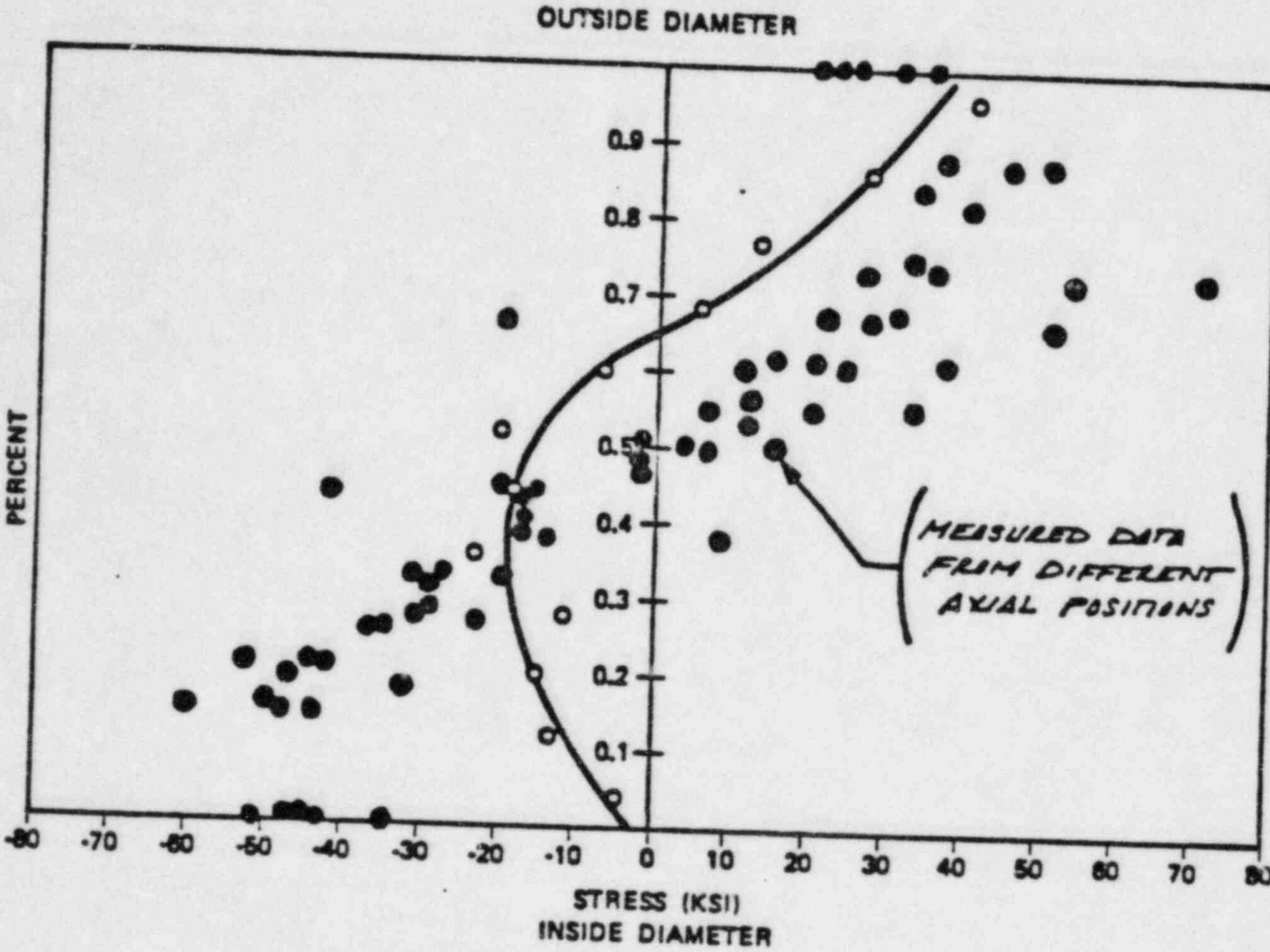


Figure 4. ID Surface Axial Residual Stress

WELD OVERLAY TESTS



.20" OVERLAY
HATCH-1 (LONG) WELD PREP

CALCULATED AXIAL RESIDUAL STRESS
THROUGH-WALL OF 12" SCH. 100 PIPE

Figure 5. Through-Wall Residual Stresses

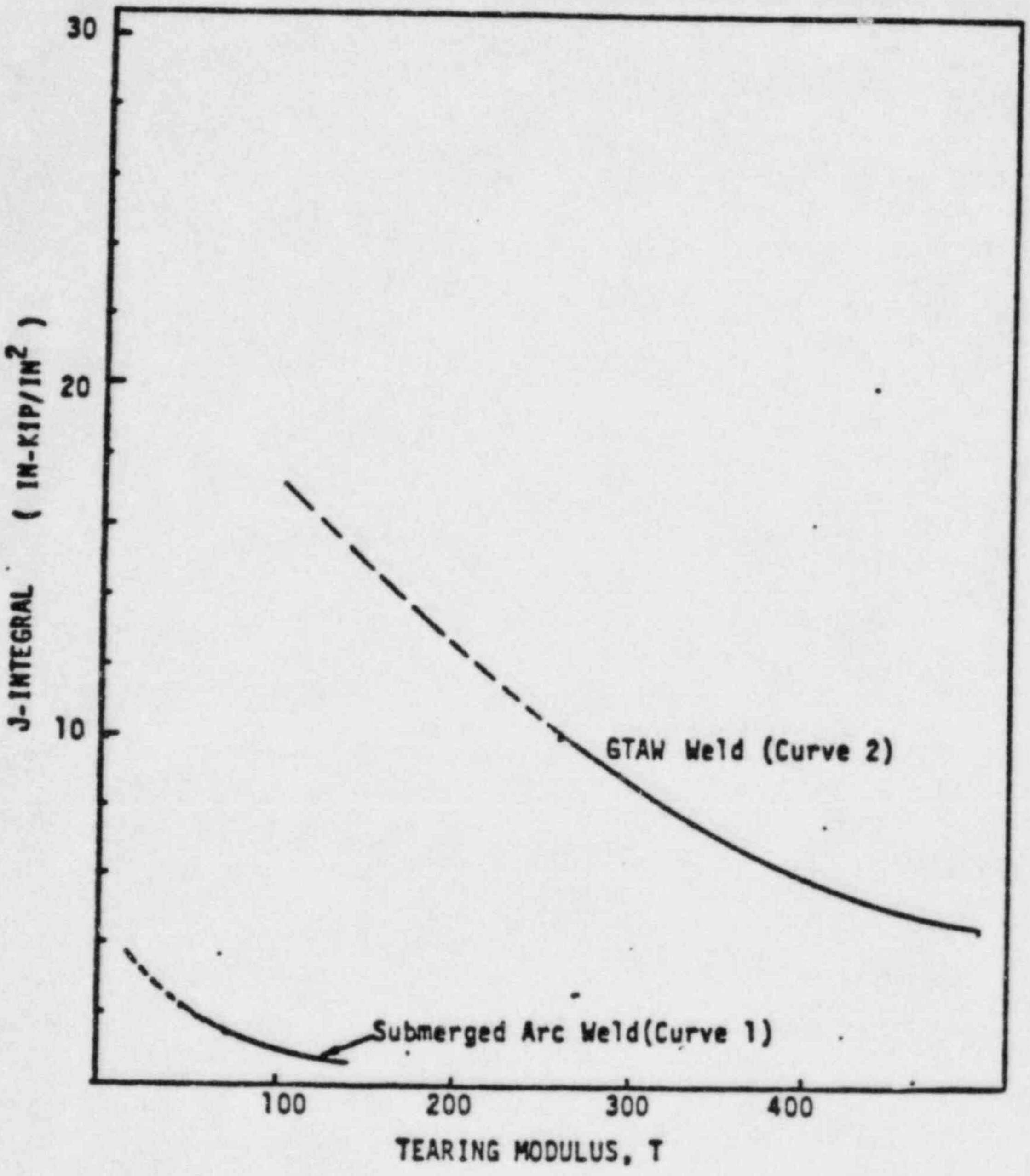


Figure 6. Selected (J_{mat}, T_{mat}) Curves For Welds

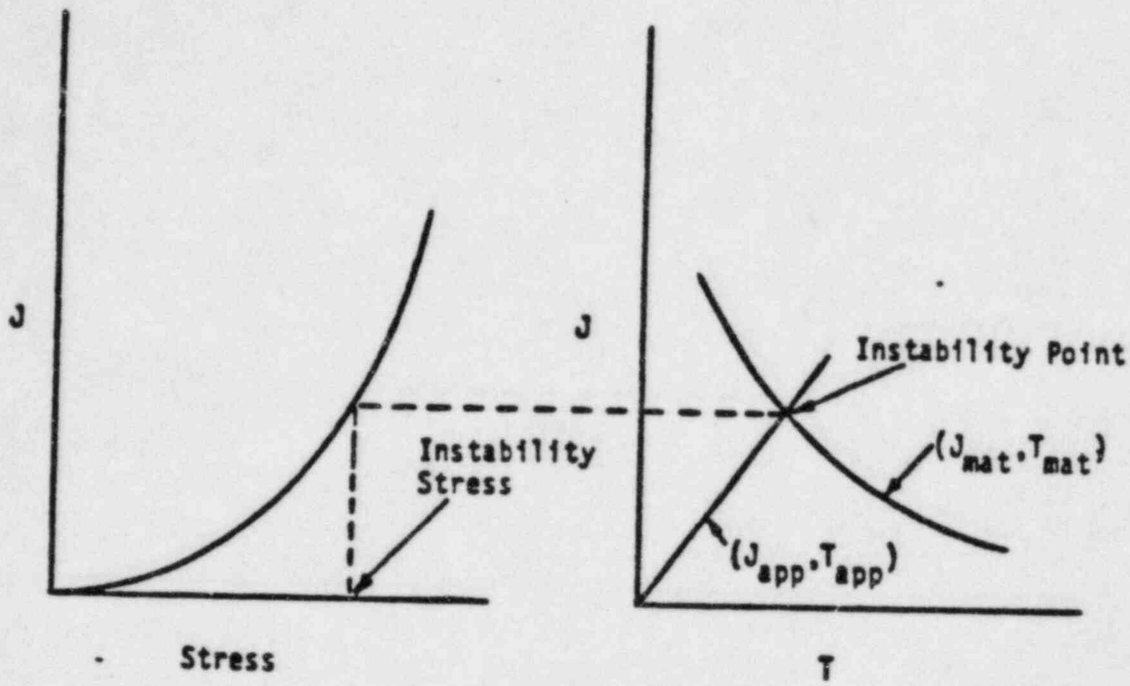


Figure 7. Illustration of Method For Instability Stress Determination

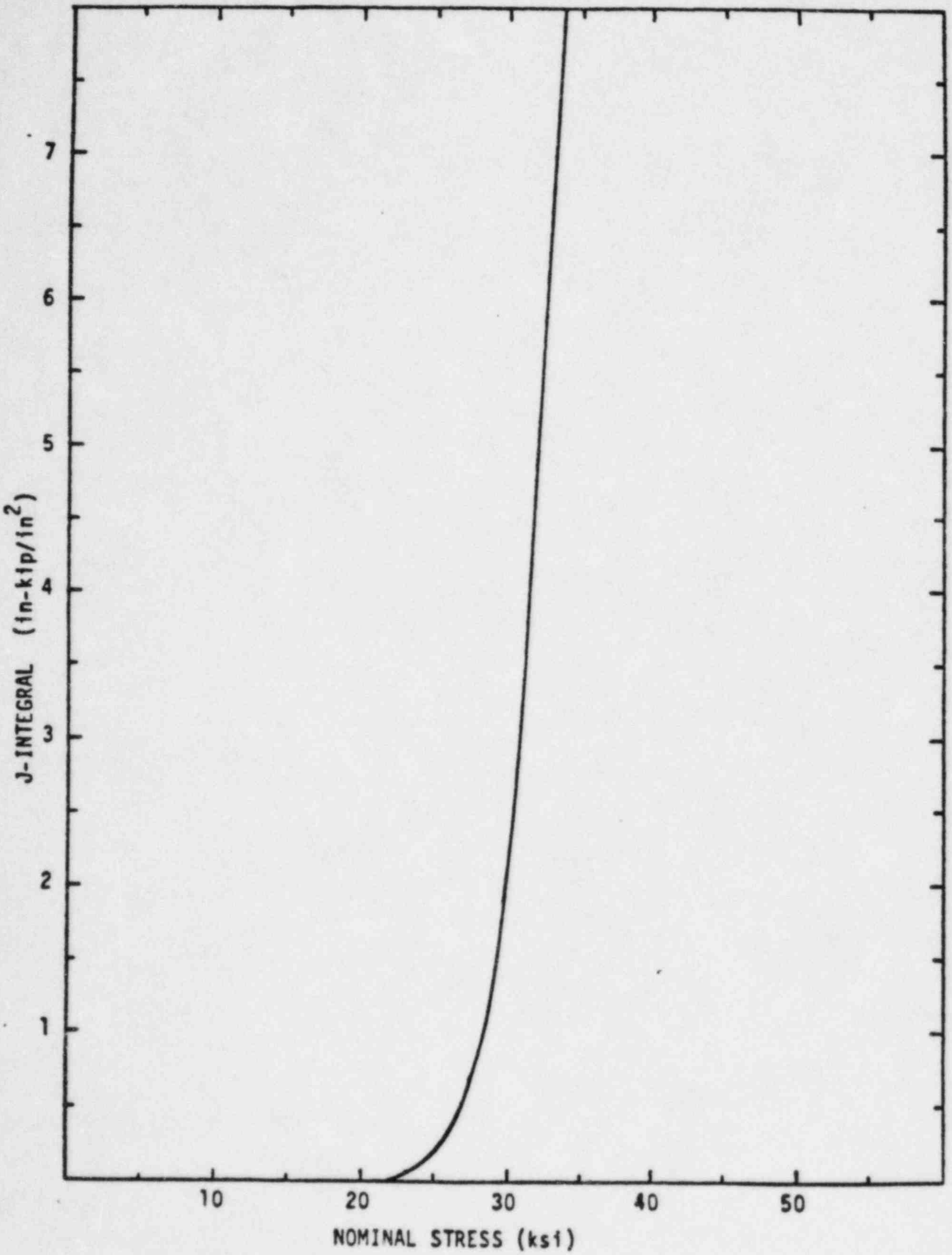
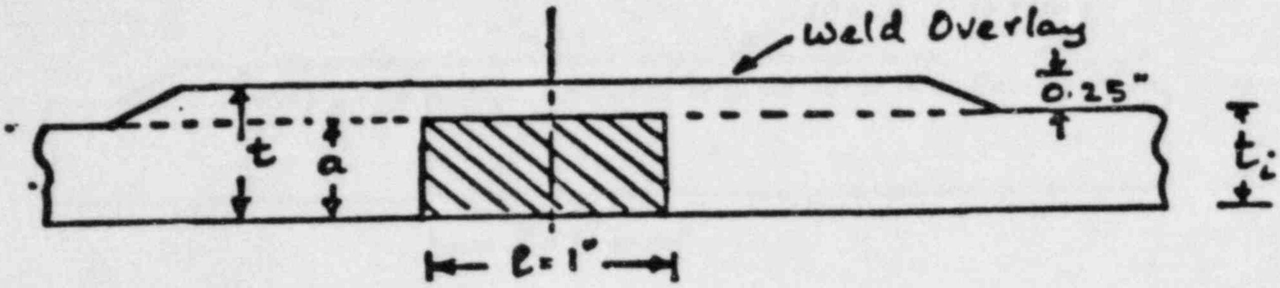


Figure 8. J-Integral Versus Axial Stress for Weld 10-0-05



Pipe Side

t_i = 0.7 in.

t = 0.95 in.

a = 0.7

$\frac{a}{t}$ = 0.74

Elbow Side

t_i = 0.8 in.

t = 1.05 in.

a = 0.8

$\frac{a}{t} = \frac{0.8}{1.08} = 0.76$

FIGURE 9.

Schematic of Riser

Axial Flaw with Weld Overlay

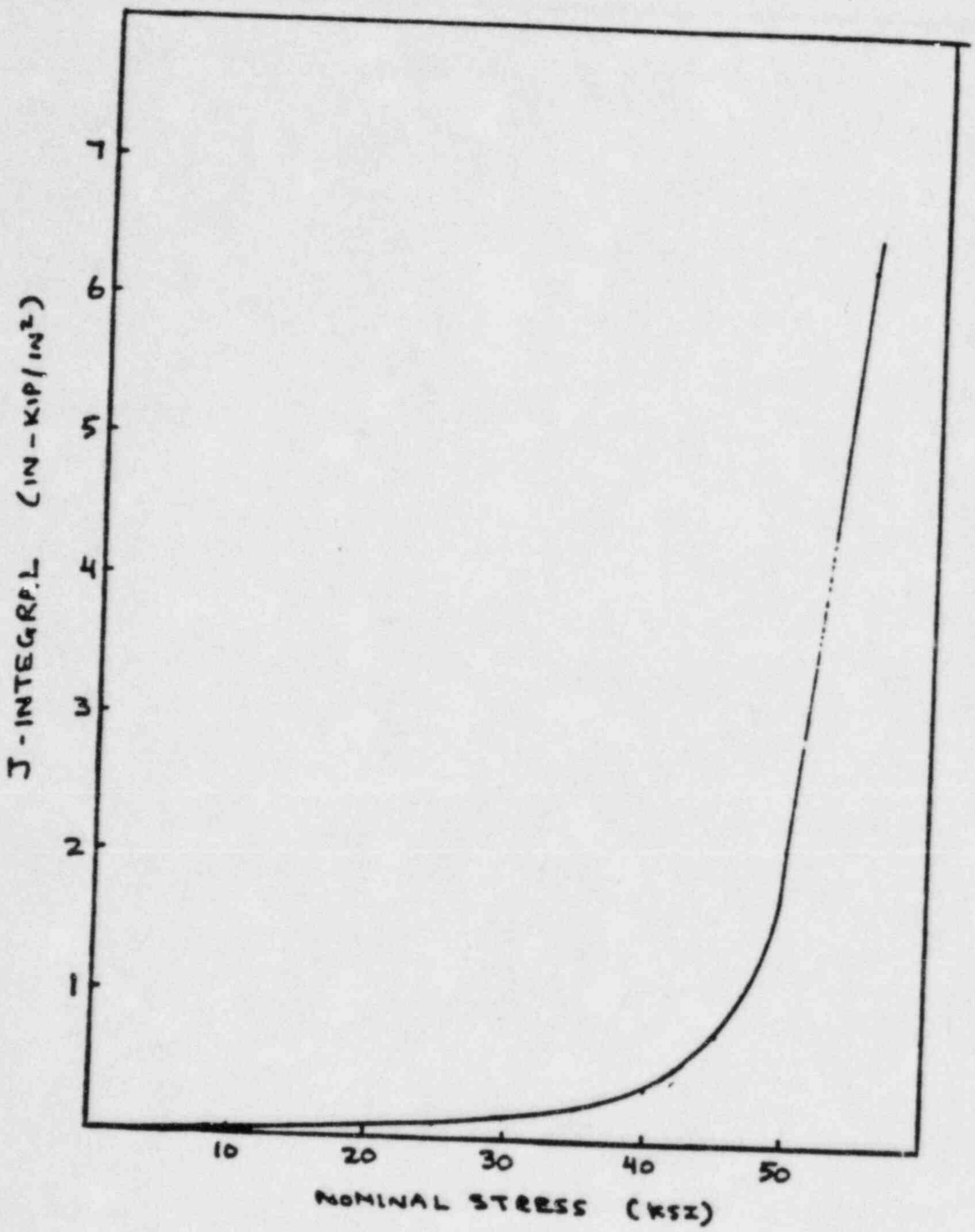
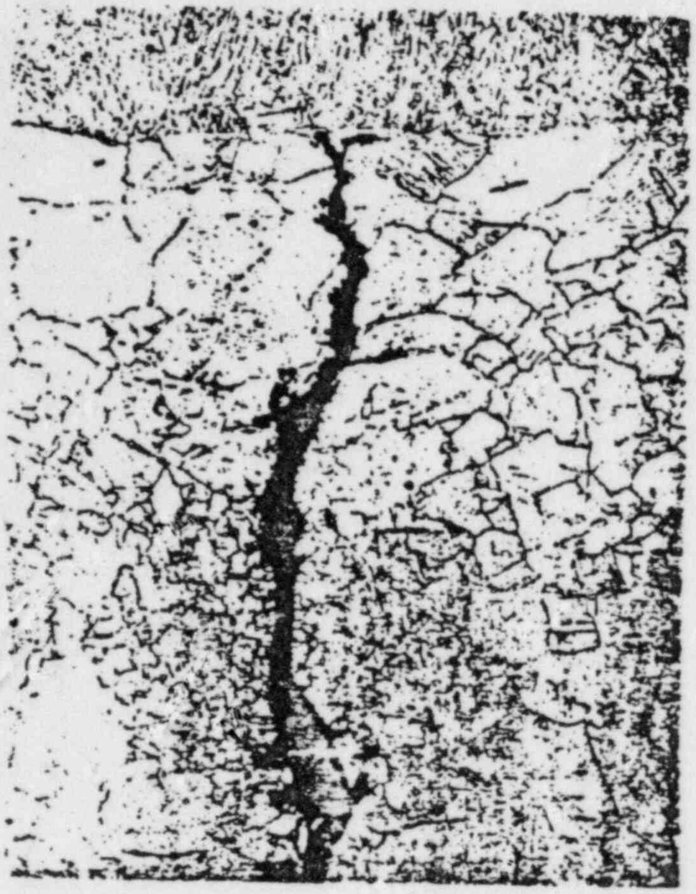


Figure 10 J-Integral versus nominal Stress for Axial Flaw in 12 Inch Sch. 80 Pipe



200X

Figure 11. Crack Under Weld Overlay, Specimen RSP-14 After 1000 Hours Exposure