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GPC-07-102  
Revision 1  
September 1983  
GPC007.0102

DESIGN REPORT  
FOR  
WELD OVERLAY REPAIRS  
AND FLAW EVALUATIONS  
IN  
RECIRCULATION AND RHR SYSTEMS  
AT  
E. I. HATCH NUCLEAR POWER PLANT  
UNIT 2

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# REVISION CONTROL SHEET

TITLE: Design Report for Weld Overlay Repairs and Flaw Evaluations in the Recirc and RHR Systems at Plant Hatch Unit 2

DOCUMENT FILE NUMBER: GPC007.0102

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AFFECTED PAGE(S)	DOC REV	PREPARED BY / DATE	ACCURACY CHECK BY / DATE	CRITERIA CHECK BY / DATE	REMARKS
ii	0	HLD 6-7-83	JEC 6.7.83	JFC/6-7-83	
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3.4					
4.1					
4.2					
5.1		HLD 6-7-83	JEC 6.7.83	JFC/6-7-83	

REVISION CONTROL SHEET  
(CONTINUATION)

TITLE: Design Report for Weld Overlay DOCUMENT FILE NUMBER: GPC007.0102  
Repairs and Flaw Evaluations in  
the Recirc and RHR Systems at Plant Hatch Unit 2

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5.4			JFC 6-7-83		
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5.40			YSW 6-7-83		
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5.42			AKR 6-7-83		
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5.49			JFC 6-7-83		
5.50		NLS 6-7-83	KC 6-7-83	JFC/6-7-83	



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TITLE: Design Report for Weld Overlay Repairs and Flaw Evaluations in the Recirc and RHR Systems at Plant Hatch Unit 2  
DOCUMENT FILE NUMBER: GPC007.0102

AFFECTED PAGE(S)	DOC REV	PREPARED BY / DATE	ACCURACY CHECK BY / DATE	CRITERIA CHECK BY / DATE	REMARKS
5.51	0	NLS 6-7-83	YSW 6-7-83	JFC/6-7-83	
5.52			PCP 6-7-83		
5.53			KC 6-7-83		
5.54			YSW 6-7-83		
5.55			JFC 6-7-83		
5.56			JFC 6-7-83		
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vi			JFC 9-14-83	JFC 9-14-83	
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CERTIFICATION BY REGISTERED PROFESSIONAL ENGINEER

I hereby certify that this document and the calculations contained herein were prepared under my direct supervision, reviewed by me, and to the best of my knowledge are correct and complete. I am a duly Registered Professional Engineer under the laws of the State of California and am competent to review this document.

Certified by:



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This report summarizes evaluations performed by NUTECH to assess weld overlay repairs and unrepaired flaws in the Recirculation and Residual Heat Removal (RHR) systems at Georgia Power Company's E. I. Hatch Nuclear Power Plant Unit 2 (Hatch 2). Weld overlay repairs have been applied to address ultrasonic (UT) examination results believed to be indicative of intergranular stress corrosion cracking (IGSCC) in the vicinity of the welds. The purpose of each overlay is to arrest any further propagation of the cracking, and to restore original design safety margins to the weld. The unrepaired welds which had UT examination indications have been shown by analysis to still have the original design safety margins.

The required design life of each weld overlay repair is at least five years. The amount that the actual life exceeds five years will be established by a combination of future analysis and testing.

UT indications have been detected adjacent to nine 28" elbow-to-pipe welds, eighteen 12" elbow-to-pipe welds, four recirculation pipe-to-safe end welds, one 12" pipe-to-pipe weld, two 20" RHR pipe-to-elbow welds,



one 24" RHR pipe-to-elbow weld, and four 22" end cap to header welds. As part of a program to verify UT sizing techniques, Georgia Power Company elected to remove an end cap with large UT indications for metallurgical evaluation, and to install a new end cap in its place. The 28", 24", and 20" welds were found to be acceptable without repair. All other welds with indications as shown in Table 1.1 were repaired with weld overlay designs which are described and evaluated in this report.

Figure 1.1 shows all the welds in relation to the Reactor Pressure Vessel and other portions of the Recirculation and RHR systems. Table 1.1 lists the welds evaluated in this report, describes the indications found at each location, and identifies the type of repair (as defined in Section 2) performed. All of the existing affected RHR and Recirculation system materials are Type 304 stainless steel.

Table 1.1

Identification of Observed UT Indications  
(Continued)

<u>Weld Identification Number</u>	<u>Orientation</u>	<u>Flaw Description Maximum Depth</u>	<u>Maximum Length*</u>	<u>Flaw Disposition</u>
2B31-1RC-12BR-C-3	Circumferential	30%	360°I	Weld Overlay per Fig. 2.1
2B31-1RC-12BR-C-4	Circumferential	32%	360°I	Weld Overlay per Fig. 2.1
2B31-1RC-12BR-D-2	Circumferential	14%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12BR-D-3	Circumferential	17%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12BR-E-3	Circumferential	22%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12BR-E-3A	Circumferential	21%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12BR-E-4	Circumferential	18%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-F-2	Circumferential	25%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-F-3	Circumferential	10%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-G-2	Circumferential	14%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-G-3	Circumferential	15%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-H-2	Circumferential	10%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-H-3	Circumferential	30%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-J-2	Circumferential	23%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-J-3	Circumferential	20%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-J-4	Circumferential	28%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-K-2	Circumferential	19%	360°I	Weld Overlay per Fig. 2.2
2B31-1RC-12AR-K-3	Circumferential	6%	360°I	Weld Overlay per Fig. 2.2

\* The designation 360°I means that the UT indication extended intermittently for 360°

Table 1.1

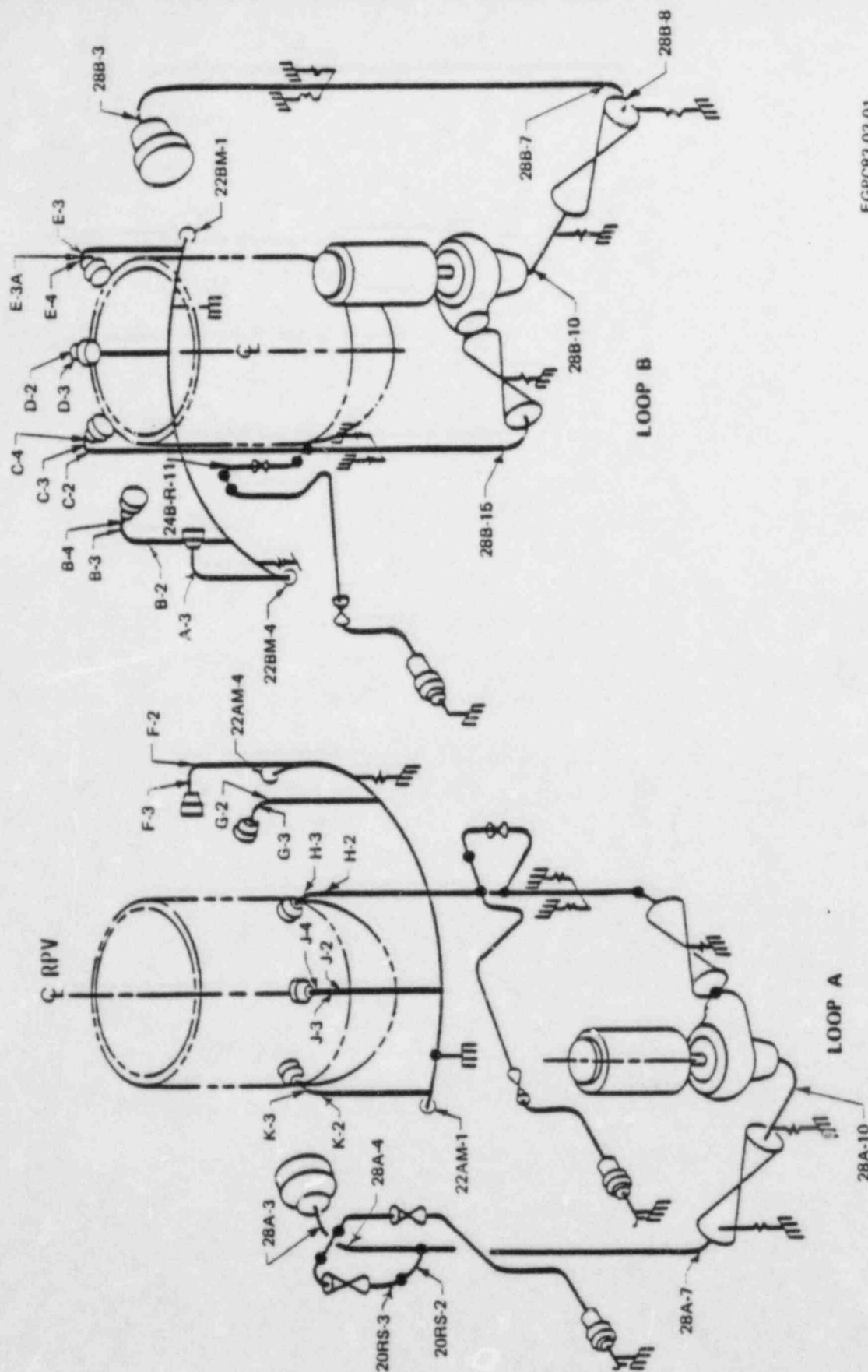
## Identification of Observed UT Indications

Weld Identification Number	Orientation	Flaw Description Maximum Depth	Maximum Length*	Flaw Disposition
2B31-IRC-22AM-1	Circumferential	42%	53"	Weld overlay per Fig. 2.3
2B31-IRC-22AM-4	Circumferential	19%	60"	Weld overlay per Fig. 2.3
2B31-IRC-22BM-1	Circumferential	40%	25-1/2"	Weld overlay per Fig. 2.3
2B31-IRC-22BM-4	Circumferential	37%	360°I	Replace End Cap
2B31-IRC-28A-3	Circumferential	12%	5-1/2"	Acceptable by analysis
2B31-IRC-28A-4	Circumferential	17%	360°I	Acceptable by analysis
2B31-IRC-28A-7	Circumferential	8%	360°I	Acceptable by analysis
2B31-IRC-28A-10	Circumferential	10%	1-1/2"	Acceptable by analysis
2B31-IRC-28B-1	Circumferential	15%	360°I	Acceptable by analysis
2B31-IRC-28B-7	Circumferential	18%	360°I	Acceptable by analysis
2B31-IRC-28B-8	Circumferential	7%	360°I	Acceptable by analysis
2B31-IRC-28B-10	Circumferential	20%	360°I	Acceptable by analysis
2B31-IRC-28B-15	Circumferential	23%	360°I	Acceptable by analysis
2E11-IRHR-20RS-2	Circumferential	13%	360°I	Acceptable by analysis
2E11-IRHR-20RS-3	Circumferential	14%	360°I	Acceptable by analysis
2E11-IRHR-24B-A-11	Circumferential	18%	10-9/16"	Acceptable by analysis
2B31-IRC-12BR-A-3	Circumferential	25%	360°I	Weld Overlay per Fig. 2.2
2B31-IRC-12BR-B-2	Circumferential	26%	360°I	Weld Overlay per Fig. 2.2
2B31-IRC-12BR-B-3	Circumferential	22%	360°I	Weld Overlay per Fig. 2.2
2B31-IRC-12BR-B-4	Circumferential	23%	360°I	Weld Overlay per Fig. 2.2
2B31-IRC-12BR-C-2	Circumferential	28%	360°I	Weld Overlay per Fig. 2.2

\* The designation 360°I means that the UT indication extended intermittently for 360°

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Figure 1.1  
CONCEPTUAL DRAWING OF RECIRCULATION SYSTEM

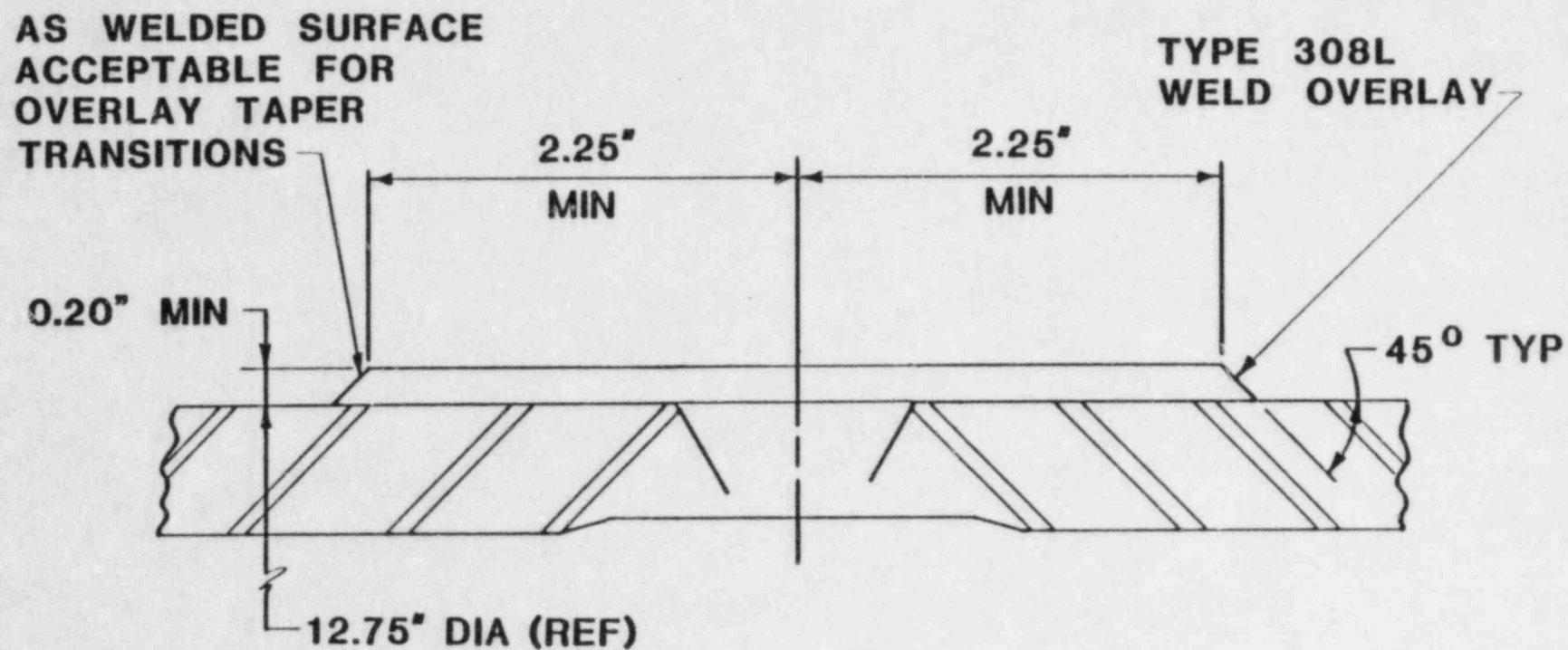


The indications in the pipe side of the safe ends, 12" elbows, 12" pipes, and three of the four end cap weld heat-affected zones have been repaired by establishing additional "cast-in-place" pipe wall thickness from weld metal deposited 360 degrees around and to either side of the existing weld, as shown in Figures 2.1 through 2.3. The fourth end cap was cut off and replaced with a new end cap. The weld-deposited band over the cracks provides wall thickness equal to that required to provide the original design safety margins. In addition, the weld metal deposition produces a favorable compressive residual stress pattern. The deposited weld metal is type 308L stainless steel, which is resistant to propagation of IGSCC cracks.

The non-destructive examination of the weld overlays consisted of:

- 1) Surface examination of the completed weld overlay by the liquid penetrant examination technique in accordance with ASME Section III.

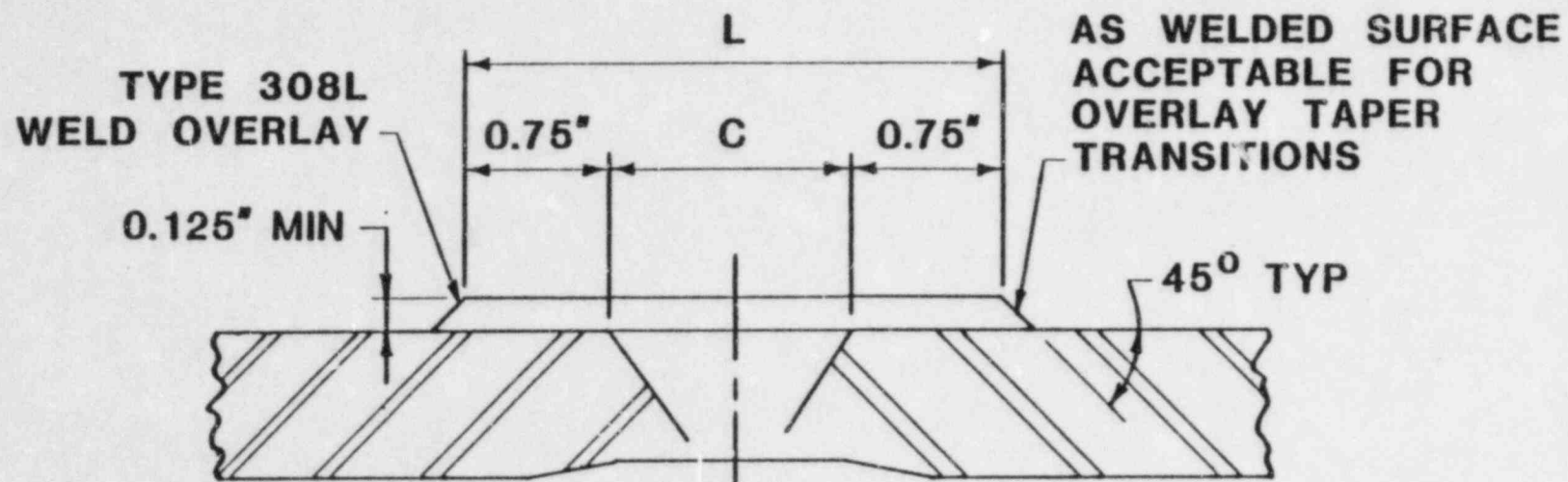
- 2) Volumetric examination of the completed weld overlay by the ultrasonic examination technique in accordance with ASME Section XI.
- 3) Volumetric baseline examination of the weld overlay and existing circumferential pipe weld by the ultrasonic examination technique in accordance with ASME Section XI.



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Figure 2.1

STANDARD OVERLAY DESIGN 12" RECIRCULATION PIPING



$$L_{\text{MINIMUM}} = 1.5" + C$$

C = WELD CROWN WIDTH

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Figure 2.2

MINI - WELD OVERLAY 12" RECIRCULATION PIPING



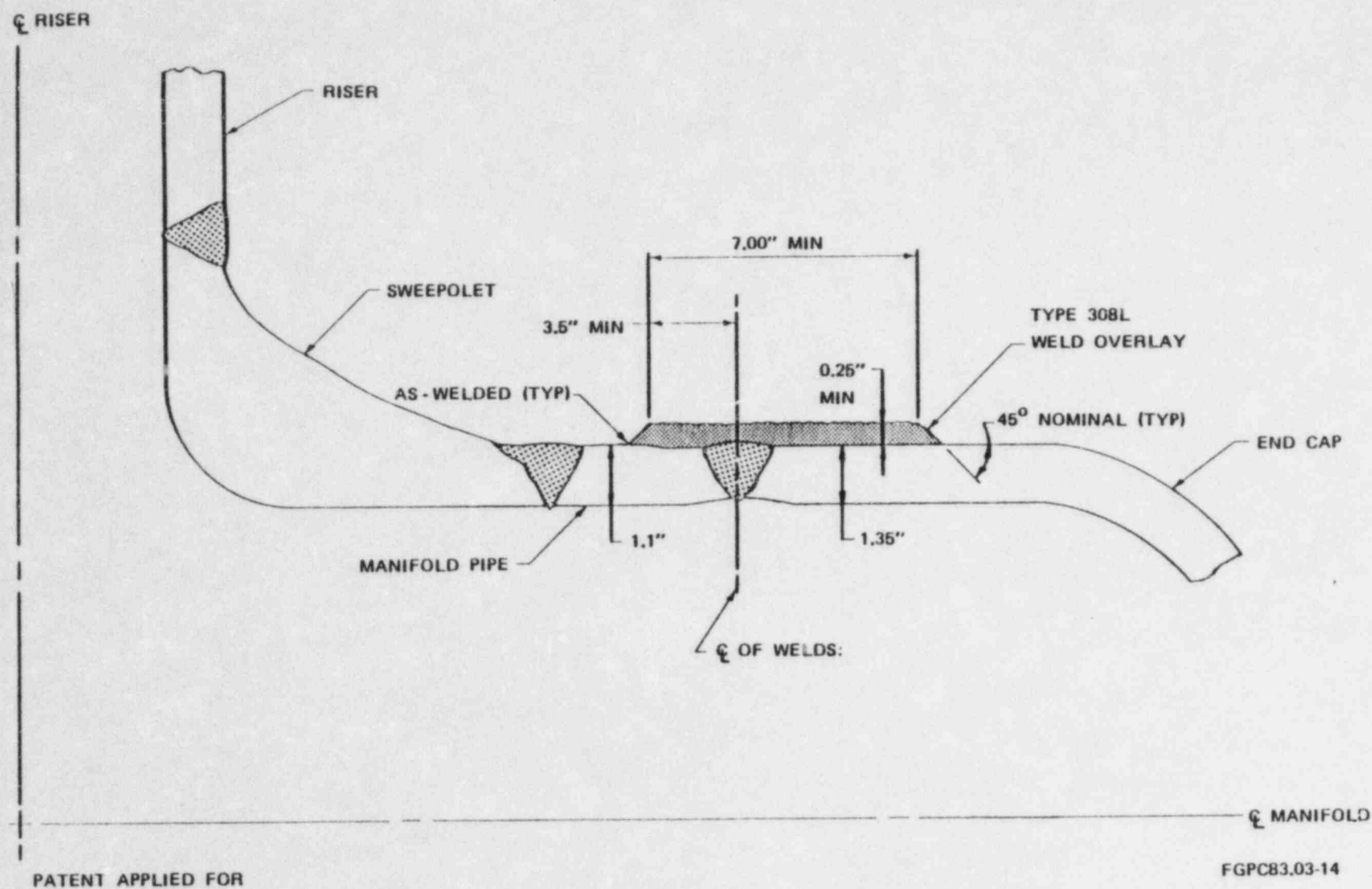


Figure 2.3  
CONFIGURATION OF END CAP WELD OVERLAY

### 3.0 EVALUATION CRITERIA

#### 3.1 Weld Overlay Evaluation

This section describes the criteria that are applied in this report to evaluate the acceptability of the weld overlay repairs described in Section 2.0. Because of the nature of these repairs, the geometric configuration is not directly covered by Section III of the ASME Boiler and Pressure Vessel Code, which is intended for new construction. However, materials, fabrication procedures, and Quality Assurance requirements are in accordance with applicable sections of this Construction Code, and the intent of the design criteria described below is to demonstrate equivalent margins of safety for strength and fatigue considerations as provided in the ASME Section III Design Rules. In addition, because of the IGSCC conditions that led to the need for repairs, IGSCC resistant materials have been selected for the weld overlay repairs. As a further means of ensuring structural adequacy, criteria are also provided below for fracture mechanics evaluation of the repairs.

### 3.1.1 Strength Evaluation

Adequacy of the strength of the weld overlay repairs with respect to applied mechanical loads was demonstrated by the following methods:

1. An ASME Boiler and Pressure Vessel Code Section III, Class 1 (Reference 1) analysis of the weld overlay repairs was performed.
2. The ultimate load capacity of the weld overlay repairs was calculated with a tearing modulus analysis. The ratio between failure load and applied loads was required to be greater than that required by Reference 1.

### 3.1.2 Fatigue Evaluation

The stress values obtained from the above strength evaluation were combined with thermal and other secondary stress conditions to demonstrate adequate fatigue resistance for the design life of each repair. The criteria for fatigue evaluation included:

1. The maximum range of primary plus secondary stress was compared to the secondary stress limits of Reference 1.
2. The peak alternating stress intensity, including all primary and secondary stress terms, and a fatigue strength reduction factor of 5.0 to account for the existing crack underneath weld overlays, was evaluated using conventional fatigue analysis techniques. The total fatigue usage factor, defined as the sum of the ratios of applied number of cycles to allowable number of cycles at each stress level, must be less than 1.0 for the design life of each repair. The allowable number of cycles was determined from the stainless steel fatigue curve of Appendix I of Reference 1.

### 3.1.3 Crack Growth Evaluation

Crack growth due to both fatigue (cyclic stress) and IGSCC (steady state stress) was calculated. The allowable crack depth was established based on net section limit load for each cracked and repaired weld (Reference 2). The design life of each repair was

established as the minimum of either the predicted time for the observed crack to grow to the allowable crack depth or five years.

### 3.2 Unrepaired Flaw Evaluation

Crack growth due to both fatigue (cyclic stress) and IGSCC (steady state stress) was calculated. The allowable crack depth was established based on the net section collapse load for the cracked welds (Reference 2).

The life of the unrepaired welds with observed flaws was established as the time for the flaw to grow to the allowable depth.

### 3.3 End Cap Replacement

The BM-4 end cap was replaced with an end cap which satisfies all of the design requirements of the original end cap (References 3 and 4). In addition, because of the IGSCC conditions that led to the need for replacement, the end cap was installed with welding procedures which minimize the potential for future IGSCC.



The loads considered in the evaluation of the repaired, replaced and unrepaired welds were mechanical loads, internal pressure, differential thermal expansion loads, and welding residual stresses. The mechanical loads and internal pressures used in the analysis are described in Section 4.1, and an explanation of the thermal transient conditions which cause differential thermal expansion loads is presented in Section 4.2. Welding residual stresses are considered in the crack growth analyses and are discussed in Sections 5.1 and 5.4.

The design pressures of 1450 psi for the pump discharge and 1250 psi for the pump suction portions of the Recirculation system were obtained from Reference 3. The dead weight and seismic loads applied to each weld were also obtained from Reference 3. The design stresses for the RHR system were obtained from Reference 5.

The thermal expansion loads for each weld were obtained from Reference 3 for the Recirculation system and from Reference 4 for the RHR system. Reference 4 defines several types of transients for which the Hatch 1 Recirculation and RHR systems were designed. It is assumed in this report that the Hatch 1 and Hatch 2 design transients are similar. These transients were conservatively grouped into three composite transients. The first composite transient is a startup/shutdown transient with a heatup or cool down rate of 100°F per hour. The second composite transient consists of a 50°F step temperature change with no change in pressure. The third composite transient is an emergency event with a 416°F step temperature change and a pressure change of 1325 psi. In the five year overlay design life, there are 38 startup/shutdown cycles, 25 small temperature change cycles, and one emergency cycle.

The evaluation of the welds consisted of a code stress analysis per Section III (Reference 1) and a fracture mechanics evaluation per Section XI (Reference 6).

## 5.1

Weld Residual Stress Calculation and Measurement

## 5.1.1

## Residual Stress Calculation

The residual stresses that exist in the weld heat-affected zone after application of the weld overlays were calculated using the methodology of Reference 7 for each repair geometry.

The analysis consists of four steps:

1. Temperature analysis for welding the original butt weld.
2. Residual stress analysis for the original butt weld.
3. Temperature analysis for welding the overlay.
4. Residual stress analysis for the overlay weld.

The temperature analysis is based on heat flow from a point source moving in a straight line in an infinite

solid. Boundary conditions are imposed by superimposing auxiliary heat sources to simulate insulated pipe surfaces. The temperature profiles generated for each weld pass, both in the heating and cooling phases, then serve as input to the finite element residual stress analysis model. The welding parameters assumed for the analysis of the original butt welds are shown in Table 5.1 (Reference 8), and are representative of those used in practice. The weld overlay parameters are also shown in Table 5.1.

The residual stress analyses utilize axisymmetric finite element models. Material properties are temperature dependent and the stress-strain behavior is elastic-plastic. Elastic unloading is allowed from a yielded element. Deformation and stress profiles are computed at selected steps during welding.

An axisymmetric finite element mesh was generated for each stress analysis. The stress analysis uses temperature dependent material properties and a bilinear stress strain curve. The Prandtl-Reuss equations for plasticity are used. Residual forces are applied at the end of each incremental solution. At the beginning of each heating or cooling phase, an iteration on the stiffness

matrix is made to take into account the non-proportional loading due to an abrupt change in the load path.

Because of the results of previous analyses, the crack is not included in the models. Inclusion of a 40% of pipe wall thickness, 360° crack with a small axial length has been shown to have little effect on the residual stress pattern. Furthermore, inclusion of a crack produces results which are physically unrealistic: the crack surfaces tend to move through each other. To correctly model a crack, a finite element type allowing only compression would be required.

The transient thermal loading from the welding process was imposed on the structural model by applying the temperature distributions from the thermal analysis in several piecewise linear changes.

Using the above method and models, the residual stress distributions due to the original butt welds were calculated and used as input to the residual stress analysis of the overlay welds.

The resulting axial stress distributions in the heat-affected zone due to the overlay welds are presented in Figures 5.1 through 5.6. From these figures it is seen



that the weld overlay produces significant axial compressive stress in the original pipe cross section. These stress profiles will prevent or mitigate the growth of cracks, as shown in Section 5.2. Only axial residual stress profiles are presented, since all of the observed cracks are circumferentially oriented.

#### 5.1.2 Residual Stress Measurements

In order to empirically confirm the analytical residual stress calculations described above, Georgia Power Company is planning to conduct a test program to measure the effect that application of a weld overlay has on residual stresses. This test program is described in detail in References 9 and 10.

The test will attempt to monitor temperatures and stresses (via thermocouples and strain gages) at various locations on a 12" stainless steel pipe during application of a weld overlay.

The results will be compared with the analytical predictions similar to those described in Section 5.1.1.

## 5.2 Weld Repair and Evaluation

### 5.2.1 12" Recirculation Inlet Safe End Evaluation

UT indications were detected in the heat-affected zones on the pipe side of the weld between four recirculation inlet safe ends and the recirculation piping. Three of the indications had maximum depths of less than 30% of the wall thickness. The mini overlay shown in Figure 2.2 was used to repair these locations. The 12BR-C-4 weld had an indication with a maximum depth of 32% of the wall thickness (see Table 1.1). The standard overlay shown in Figure 2.1 was used to repair this location.

#### 5.2.1.1 Code Stress Analysis

The ASME Code stress analyses of the four repaired safe end welds were performed with ANSYS (Reference 11) finite element models. The models were based on the design minimum overlay thicknesses of 0.20 inch and 0.125 inch (standard and mini, respectively). Figures 5.7 and 5.8 show the models. The stresses in the overlaid safe ends due to design pressure and applied moments (Sections 4.1 and 4.2) were calculated with the finite element models.

The weld overlay thermal model was taken to be axisymmetrical (Figure 5.9). The exterior boundary was assumed to be insulated. The temperature distribution in the weld overlay subject to the thermal transients defined in Section 4.2 can be readily calculated using Charts 16 and 23 of Reference 12. The maximum through-wall temperature difference was determined to be less than 2°F for the normal startup cycle, 40°F for the small temperature cycle and 329°F for the emergency transient.

The maximum thermal stress for use in the fatigue crack growth analysis was calculated as follows:

(Reference 1)

$$\sigma = \frac{Ea\Delta T_1}{2(1-\nu)} + \frac{Ea\Delta T_2}{1-\nu}$$

Where:

E = 28.3 x 10<sup>6</sup> psi (Young's Modulus)

a = 9.11 x 10<sup>-6</sup>°F<sup>-1</sup>

(Coefficient of Thermal Expansion)

ΔT<sub>1</sub> = Equivalent Linear Temperature Difference (°F)

ΔT<sub>2</sub> = Peak Temperature Difference (°F)

The values of  $\Delta T_1$ ,  $\Delta T_2$ , and  $\sigma$  are given in Table 5.2 for all three thermal transients.

The results of Code stress analyses of the standard and the limiting mini-overlays per Reference 1 are given in Table 5.3. The allowable stress values from Reference 1 are also given. The weld overlay repairs satisfy the Reference 1 requirements.

A conservative fatigue analysis per Reference 1 was performed. In addition to the stress intensification factors required per Reference 1, an additional fatigue strength reduction factor of 5.0 was applied due to the crack. The fatigue usage factor was then calculated assuming 38 startups, 25 small temperature change cycles and one emergency cycle every five years. The results are summarized in Table 5.3.

#### 5.2.1.2 Fracture Mechanics Evaluation

Three types of fracture mechanics evaluations were performed. The allowable crack depth was calculated based on Reference 2. Crack growth due to both fatigue and IGSCC was calculated using the NUTECH computer program NUTCRAK (Reference 13) with material constants and methodology from References 14 and 15. Finally, the

ultimate margin to failure for a crack assumed to propagate all the way through the original pipe material to the weld overlay was calculated per References 16 and 17.

The allowable crack depth for a 360° circumferential crack in the overlaid welds was determined based on Reference 2. The allowable crack depth is 46% of the mini-weld overlaid thickness, and is 57% of the standard weld overlaid thickness. Thus, the allowable crack depth for a 360° circumferential crack in a location with a mini-weld overlay is 0.34 inch, and in a location with a standard weld overlay is 0.50 inch.

The existing cracks could grow due to both fatigue and stress corrosion. Fatigue crack growth due to the three types of thermal transients defined in Section 4.2 was calculated using the material properties from Reference 14. The fatigue cycles considered are shown in Figure 5.10. The fatigue crack growth for 5 years was calculated to be less than 0.01 inch.

IGSCC crack growth was calculated using the overlay residual stress distributions shown in Figures 5.1 and 5.2 and the upper bound crack growth law for weld-



sensitized stainless steel (Figure 5.11). The steady state loads of pressure, dead weight, thermal expansion and axial weld shrinkage (Section 5.4) were also applied. The results are shown in Figure 5.12.

Inspection of Figure 5.12 will show that the maximum depth achieved after five years by a 360° circumferential crack is approximately 0.23 inch, which is well below the allowable size.

Thus, the safe end weld overlay designs are acceptable for at least five years.

#### 5.2.1.3 Tearing Modulus

The largest size to which the existing crack could reasonably be expected to grow was postulated to be a 360° circumferential crack of depth equal to that given in Section 5.2.1.2. A tearing modulus evaluation was then performed for this postulated crack. The applied loads were pressure, weight, and seismic.

The evaluation was performed using the methodology of Reference 16 with material properties from Reference 17.

The postulated flaw and the results are shown in Figure 5.13. The upper dotted line represents the inherent material resistance to unstable fracture in terms of J-integral and Tearing Modulus,  $T$ . The line originating at the origin represents the applied loading. Increasing load results in applied J-T combinations moving up this line, and unstable fracture is predicted at the intersection of this applied loading line with the material resistance line.

Figure 5.13 shows that the predicted failure load is in excess of 4 times the normal applied loads. Thus, there is a safety factor on normal loads (including OBE seismic) of at least 4, which is well in excess of the safety factor inherent in the ASME Code, even in the presence of this worst case assumed crack.

#### 5.2.2 12" Elbow and Pipe-to-Pipe Evaluation

The heat-affected zone of the weld between eighteen recirculation inlet elbow and risers have UT indications. In addition, one 12" pipe-to-pipe weld has indications. To ensure a conservative overlay design, it was assumed that a 360° circumferential crack exists in the welds, with maximum depths as shown in Table 1.1. Eighteen of the nineteen welds were repaired

with the mini-overlay design (Figure 2.2) and one elbow weld, 12BR-C-3, was repaired with the standard overlay design (Figure 2.1).

#### 5.2.2.1 Code Stress Analysis

Analyses of the standard weld overlay and mini-weld overlay designs (Figures 2.1 and 2.2) for the 12" elbows were based on an ANSYS three dimensional finite element model (Figure 5.14). This model was used to develop correlation equations for axisymmetric models of 12" elbows. Axisymmetric models of both overlay designs were developed using the BOSOR4 finite element program (Reference 23). A representative model (standard overlay) is shown in Figure 5.15. The BOSOR4 results were factored to account for the three dimensional effects.

The stress in the overlaid elbow due to design pressure and applied moments as described in Sections 4.1 and 4.2 was calculated with the finite element models. The thermal analysis was performed in the same manner as for the safe end (Section 5.2.1), with appropriate dimensional changes.

The results of a code stress analysis per Reference 1 are given in Table 5.4. The allowable stress values from Reference 1 are also given. The weld overlay repairs satisfy the Reference 1 requirements.

A conservative fatigue analysis per Reference 1 was performed. A fatigue strength reduction factor of 5.0 was applied due to the crack. The fatigue usage factor was then calculated assuming 38 startups, 25 small temperature change cycles and one emergency cycle every 5 years. The results are summarized in Table 5.4.

#### 5.2.2.2 Fracture Mechanics Evaluation

Three types of fracture mechanics evaluations were performed. The allowable crack depth was calculated based on Reference 2. Crack growth due to both fatigue and IGSCC was calculated using the NUTECH computer program NUTCRAK (Reference 13) with material constants and methodology from References 14 and 15. Finally, the ultimate margin to failure for the assumed crack was calculated per References 16 and 17.

The allowable crack depth for a 360° circumferential crack in the repaired welds was determined based upon Reference 2. The allowable crack depth for a 360° crack

with a standard overlay thickness of 0.20 inch is 0.50 inch. The allowable crack depth for a 360° crack with a mini-overlay thickness of 0.125 inch is 0.34 inch.

IGSCC crack growth was calculated using the overlay residual stress patterns shown in Figures 5.3 and 5.4. The steady state loads of pressure, dead weight, thermal expansion and axial weld shrinkage (Section 5.4) were also applied. The results are shown in Figure 5.16. The fatigue crack growth due to five years of the cycles shown in Figure 5.10 is less than 0.01 inch. Inspection of Figure 5.16 will show that maximum crack depth after five years is predicted to be 0.22 which is less than the allowable crack depth. The weld overlay repairs are therefore acceptable for at least 5 years.

#### 5.2.2.3 Tearing Modulus

A tearing modulus evaluation was performed for a 360° crack of depth equal to that calculated above. The normal operating loads of OBE seismic, pressure, and dead weight were applied.

The evaluation was performed using the methodology of Reference 16 with material properties from Reference 17. The postulated flaw and the results are



shown in Figure 5.17. The upper dotted line represents the inherent material resistance to unstable fracture in terms of J-integral and Tearing Modulus, T. The line originating at the origin represents the applied loading. Increasing load results in applied J-T combinations moving up this line, and unstable fracture is predicted at the intersection of this applied loading line with the material resistance line.

Figure 5.17 shows that the predicted failure load is in excess of 4 times the normal operating loads. Thus, there is a safety factor on normal operating loads, including OBE seismic, of at least 4, which is in excess of the safety factor inherent in the ASME Code, even in the presence of this worst case assumed crack.

#### 5.2.3 22" End Cap Repair Evaluation

The heat-affected zones of four of the welds between the 22" pipe and the end cap have several circumferential UT indications. The largest of the indications was estimated to have a depth of approximately 42% percent of the wall thickness. Although at least one of the end cap welds could have been shown to be acceptable without repair, Georgia Power Company conservatively decided to repair or replace all four welds.

#### 5.2.3.1 Code Stress Analysis

A finite element model of the repaired end caps was prepared using ANSYS as above. This model is shown in Figure 5.18. The stress in the end cap due to design pressure as described in Section 4.1 was calculated with the finite element model. The thermal analysis was performed in the same manner as for the safe end (Section 5.2.1), with appropriate dimensional changes.

The results of a Code stress analysis per Reference 1 are given in Table 5.5. The allowable stress values from Reference 1 are also given. The repaired end cap configuration satisfies the Reference 1 requirements.

A conservative fatigue analysis per Reference 1 was performed. A fatigue strength reduction factor of 5.0 was applied due to the assumed crack. The fatigue usage factor was then calculated assuming 38 startups, 25 small temperature change cycles and one emergency cycle every five years. The results are summarized in Table 5.5.

#### 5.2.3.2 Fracture Mechanics Evaluation

Three types of fracture mechanics evaluations were performed. The allowable crack depth was calculated based on Reference 2. Crack growth due to both fatigue and IGSCC was calculated using the NUTECH computer program NUTCRAK (Reference 13) with material constants and methodology from References 14 and 15. Finally, the ultimate margin to failure for the assumed crack was calculated per References 16 and 17.

The existing cracks could grow due to both fatigue and stress corrosion. Fatigue growth due to the three types of thermal transients defined in Section 4.2 was calculated using the material properties from Reference 14. The fatigue crack growth for five years of the cycles shown in Figure 5.10 was calculated to be less than 0.01 inch.

IGSCC crack growth was calculated using the upper bound crack growth law shown in Figure 5.5. The residual stress was based on both the original butt weld residual stress and that due to the overlay as shown in Figure 5.5. The crack growth analysis was performed with the NUTECH computer program NUTCRAK (Reference 13). Crack growth as a function of time is

shown in Figure 5.19. Inspection of Figure 5.19 will show that maximum crack depth after five years is predicted to be 0.48 inch which is well below the allowable of 0.89 inches.

The end cap weld overlay repair is acceptable for at least 5 years.

#### 5.2.3.3 Tearing Modulus

A tearing modulus evaluation was performed for a 360° crack of depth equal to that calculated in Section 5.2.3.2. The normal operating loads of OBE seismic, pressure, and dead weight were applied. The evaluation was performed using the methodology of Reference 16 with material properties from Reference 17.

The postulated flaw and the results are shown in Figure 5.20. The upper dotted line represents the inherent material resistance to unstable fracture in terms of J-integral and Tearing Modulus,  $T$ . The line originating at the origin represents the applied loading. Increasing load results in applied J-T combinations moving up this line, and unstable fracture is predicted at the intersection of this applied loading line with the material resistance line.

Figure 5.20 shows that the predicted failure load is in excess of 4 times the normal operating loads. Thus, there is a safety factor on normal operating loads, including OBE seismic, of at least 4, which is in excess of the safety factor inherent in the ASME Code, even in the presence of this worst case assumed crack.

#### 5.2.4 End Cap Replacement Evaluation

The BM-4 end cap could have been repaired with a weld overlay. However, Georgia Power Company chose to remove and metallurgically examine it. The BM-4 end cap was replaced with an end cap of similar design which was fabricated from the same material (304 stainless steel) as the original end cap. The replacement end cap was welded with water-backed (heat sink) welding.

A welding residual stress analysis using the method described in Reference 7 was performed. The actual welding parameters used in the end cap replacement were used in the analysis. The resulting residual stress distribution is shown in Figure 5.6. Inspection of Figure 5.6 shows that the axial residual stress on the inside surface of the weld heat-affected zones is compressive. The new end cap design is therefore



significantly more resistant to IGSCC than the original end cap design.

The new end cap is equivalent to the original end cap in all aspects except its resistance to IGSCC, which is superior. Thus the replacement end cap is acceptable.

### 5.3 Evaluation of Unrepaired Flaws

UT examination of the large diameter piping of the Recirculation and RHR systems at Hatch 2 has revealed twelve welds which have reportable indications. Nine of the welds with reportable indications are in the 28" Recirculation piping, one is in the 24" RHR piping, and two are in the 20" RHR piping. The location of each of these indications is shown in Figure 1.1. All of these indications are circumferentially oriented.

IGSCC crack growth in large diameter piping is different than IGSCC crack growth in small diameter piping due to a significant difference in the original butt weld residual axial stress. In large diameter piping, there is a significant portion of the pipe thickness near the inside surface which is in compression as shown in Figure 5.21. Typically in small diameter piping, the inside one-half of the pipe thickness experiences axial

residual tensile stress. Thus, shallow circumferential flaws in large diameter piping will generally grow significantly slower than similar flaws in small diameter piping. The following Sections provide the results of crack growth analyses of the flaws in large diameter Recirculation and RHR piping.

#### 5.3.1 28" Recirculation Piping

Nine welds in the 28" Recirculation piping have reportable UT indications. All the welds with reportable UT indications are pipe-to-elbow welds. All UT indications are circumferentially oriented. The flaws are tabulated in Table 1.1 and their location is shown in Figure 1.1.

Weld number 28B-15 has the highest value of primary stress and contains the largest UT indication. Thus, the allowable crack depth for weld 28B-15 will be bounding for any of the crack indication locations in the 28" Recirculation piping. The allowable crack depth for weld 28B-15 was determined based on the primary stress values from Reference 3, and on the method in Reference 2.

$$P_m + P_b = \frac{PR}{2T} + \frac{M}{Z}$$

where:

- P = Design Pressure = 1450 psi  
R = Outside Radius = 14.0 inches  
T = As-built "c" Dimension Thickness = 1.384 inches  
M = Bending Moment due to Dead Weight and OBE

$$M = \sqrt{M_1^2 + M_2^2} = 448,920 \text{ inch-pounds}$$

where:

- $M_i = M_{DWi} + M_{OBEi}$   
 $M_{DWi}$  = Dead Weight Moment about Axis i  
 $M_{OBEi}$  = OBE Moment about Axis i  
Z = Section Modulus = 734. inches<sup>3</sup>

so:

$$P_m + P_b = 7945 \text{ psi}$$

The stress ratio may be determined as:

$$\text{Stress Ratio} = \frac{P_m + P_b}{S_m} = \frac{7945}{16,800} = 0.47$$

From Reference 2 for a 360° circumferential crack, the allowable depth is greater than 63% of the pipe thickness. (The table in Reference 2 does not have allowable depths for stress ratios less than 0.6.) Based on a three-dimensional finite element analysis of a 28" elbow-to-pipe joint, no stress intensification factor is included in the above calculation for  $P_m + P_b$ .

The prediction of crack growth for each of the existing UT indications requires several inputs:

- 1) Steady state applied stress
- 2) Weld residual stress
- 3) Flaw characterization
- 4) Crack growth model
- 5) Crack growth law

The approach was to use conservative input for applied stress, residual stress, crack growth model and crack growth law. Thus, the result of the analysis is a very conservative prediction of crack size versus time.

The steady state moments at each crack location due to operating pressure, dead weight and thermal expansion were obtained from Reference 3. In addition, the moment due to the axial weld shrinkage of the overlays

(Section 5.4) was added to the other steady state moments. The steady state stresses were then calculated based on design minimum weld preparation wall thickness ("C" dimension) at each specific location, as described above.

The weld residual stress was obtained from a set of NUTECH standard residual stress curves (Reference 18). The residual axial stress curve for large bore piping from Reference 18 is shown in Figure 5.21. This residual stress curve was used for each crack growth analysis.

The flaw sizes are tabulated in Table 1.1. It was conservatively assumed that each crack was full depth for the entire crack length.

The crack growth law is the upper bound law from Reference 14 and is given below (Figure 5.11):

$$\frac{da}{dT} = 4.116 \times 10^{-12} K^{4.615}$$



where:

da = Differential crack size

dT = Differential time

K = Applied stress intensity factor

The crack growth model is a linear interpolation between an inside diameter (I.D.) cracked cylinder and an edge-cracked plate. The magnification factors for both an I.D. cracked cylinder with  $T/R = 0.1$  and an edge-cracked plate ( $T/R = 0.0$ ) were obtained from Reference 19. It was conservatively assumed that each magnification factor for  $0 \leq T/R \leq 0.1$  could be obtained by linear interpolation between  $T/R = 0$  and  $T/R = 0.1$ . The value of  $T/R$  for weld 28B-15 is  $T/R = 1.384/14 = 0.099$  while the smallest value of  $T/R$  for any of the unrepaired 28" welds is  $T/R = 1.089/14 = 0.078$  (for weld 28A-4).

The predicted crack growth of each of the nine cracked welds was calculated with the NUTECH computer program NUTCRAK (Reference 13). Figure 5.22 is a plot of the stress intensity factor for both applied and residual stresses versus crack depth for weld 28B-15 which has the largest flaw at present. Figure 5.23 is a plot of the predicted crack depth as a function of time for weld 28B-15. Examination of Figure 5.23 will show that the

UT indication will not grow to the allowable size for at least 290 months.

Another way of expressing the same margin is to determine the crack size that would grow to the allowable crack size in the next 18 month fuel cycle. From Figure 5.23 for weld 28B-15, a crack size of 60% would grow to the allowable of 63% in 18 months. Thus, the currently allowable crack size is 60%, which is 2.5 times the largest measured crack size. The predicted crack growth for all nine UT indications are tabulated in Table 5.6. Inspection of Table 5.6 shows that none of the nine unrepaired indications will grow to the allowable size in less than 5 years. The crack which is predicted to grow to the allowable size in the shortest time is in weld 28A-4. This crack could grow to the allowable size in 218 months. Alternatively, the allowable present flaw depth in weld 28A-4 is 55%, while the measured depth is 17%.

#### 5.3.2 24" RHR Piping

One weld (24B-R-11) in the 24" RHR piping has reportable UT indications. The weld with reportable UT indications is a pipe-to-elbow weld. The UT indications are

circumferentially oriented. The flaws are tabulated in Table 1.1 and their location is shown in Figure 1.1.

The allowable crack depth for weld 24B-R-11 was determined based on the method in Section 5.3.1 to be 63% of the pipe wall thickness.

The predicted crack growth of weld 24B-R-11 was calculated using the method described in Section 5.3.1. The results are tabulated in Table 5.6. The indication in the 24" piping will not grow to the allowable size in less than 5 years.

#### 5.3.3 20" RHR Piping

Two welds in the 20" RHR piping have reportable UT indications. Both of the welds with reportable UT indications are pipe-to-elbow welds. All UT indications are circumferentially oriented. The flaws are tabulated in Table 1.1 and their location is shown in Figure 1.1.

Weld number 20RS-3 has the highest value of primary stress and contains the largest UT indication. Thus, the allowable crack depth for weld 20RS-3 will be bounding for both of the crack indication locations in the 20" RHR piping. The allowable crack depth for weld

20RS-3 was determined based on the method in Section 5.3.1 to be 63% of the pipe wall thickness.

The predicted crack growth for each of the cracks was calculated using the method described in Section 5.3.1. The results are tabulated in Table 5.6. Neither indication in 20" piping will grow to the allowable size in less than 5 years.

#### 5.4 Effect on Recirculation and RHR Systems

Installation of the weld overlay repairs caused a small amount of radial and axial shrinkage underneath the overlay. Based on measurements of the weld overlays, the maximum axial shrinkage was 0.33 inch.

The effects of the radial shrinkage are limited to the region adjacent to and underneath the overlay. Based on Reference 20, the stresses due to the radial shrinkage are less than yield stress at distances greater than 4" from the ends of the overlay. Weld residual stresses are steady state secondary stresses and thus are not limited by the ASME Code (Reference 1).

The effect of the axial weld shrinkage on the Recirculation and RHR systems was evaluated with the NUTECH computer program PISTAR (Reference 21) and the piping model shown in Figure 5.24.

The measured axial shrinkages of all weld overlays were imposed as boundary conditions on this model. Since the ASME Code does not limit weld residual stress, all stress indices were set equal to 1.0.

The maximum calculated stress was 6.9 ksi. The location of this stress is shown on Figure 5.24. Steady state secondary stresses of 6.9 ksi are judged to have no deleterious effect on the Recirculation or RHR systems.



Case	Location	Energy Input (KJ/in.)	Welding Speed (in/min.)
Original Butt Weld	End Cap Root	9.5	3
	End Cap Fill	34.3	6
	12" Pipe & Safe End		
	Layer 1	20.0	3
	"    2	35.0	6
	"    3	40.0	6
	"    4	40.0	6
	"    5	45.0	6
Replacement Butt Weld	End Cap Root	39.38	2
	End Cap Fill	27.31	3.2
Weld Overlays	All	23.52	3

Table 5.1  
WELDING PARAMETERS

PARAMETER	NORMAL STARTUP CYCLE (CYCLE 1)	SMALL TEMPERATURE CHANGE CYCLE (CYCLE 2)	EMERGENCY CYCLE (CYCLE 3)
EQUIVALENT LINEAR TEMPERATURE $\Delta T_1$	2°F	32°F	265°F
PEAK TEMPERATURE $\Delta T_2$	0	8°F	64°F
THROUGH WALL THERMAL STRESS $\sigma$	368 PSI	8,840 PSI	72,370 PSI

FGPC83.03-29

Table 5.2  
THERMAL STRESS RESULTS

CATEGORY	EQUATION NUMBER	ACTUAL STRESS OR USAGE FACTOR	SECTION III NB ALLOWABLE
S	N/A	N/A	$S_m = 16,700$ PSI
PRIMARY	(9)	10,200 PSI	25,050 PSI
PRIMARY + SECONDARY	(10)	26,300 PSI	50,100 PSI
PEAK CYCLE 1 CYCLE 2 CYCLE 3	(11)	(37,300)5* (13,000)5* (143,300)5*	N/A
USAGE FACTOR (5 YR)	N/A	0.049	1.0

\* THE FACTOR OF 5 IS THE CONSERVATIVELY ASSUMED FATIGUE STRENGTH REDUCTION FACTOR.

FGPC83.03-10

Table 5.3  
SAFE END CODE STRESS RESULTS

CATEGORY	EQUATION NUMBER	ACTUAL STRESS OR USAGE FACTOR	SECTION III NB ALLOWABLE
S	N/A	N/A	$S_m = 16,700$ PSI
PRIMARY	(9)	9,600 PSI	25,050 PSI
PRIMARY + SECONDARY	(10)	25,200 PSI	50,100 PSI
PEAK CYCLE 1 CYCLE 2 CYCLE 3	(11)	(20,300) 5* (13,300) 5* (126,200) 5*	N/A
USAGE FACTOR (5 YR)	N/A	0.024	1.0

\* THE FACTOR OF 5 IS THE CONSERVATIVELY ASSUMED FATIGUE STRENGTH REDUCTION FACTOR.

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Table 5.4  
12" ELBOW CODE STRESS RESULTS

CATEGORY	EQUATION NUMBER	ACTUAL STRESS OR USAGE FACTOR	SECTION III NB ALLOWABLE
S	N/A	N/A	$S_m = 16,700 \text{ PSI}$
PRIMARY	(9)	19,300 PSI	25,050 PSI
PRIMARY + SECONDARY	(10)	25,200 PSI	50,100 PSI
PEAK CYCLE 1 CYCLE 2 CYCLE 3	(11)	(23,700)5* (13,000)5* (129,700)5*	N/A
USAGE FACTOR (5 YR)	N/A	0.023	1.0

\* THE FACTOR OF 5 IS THE CONSERVATIVELY ASSUMED  
FATIGUE STRENGTH REDUCTION FACTOR.

FGPC83,03-30

Table 5.5

22" END CAP CODE STRESS RESULTS



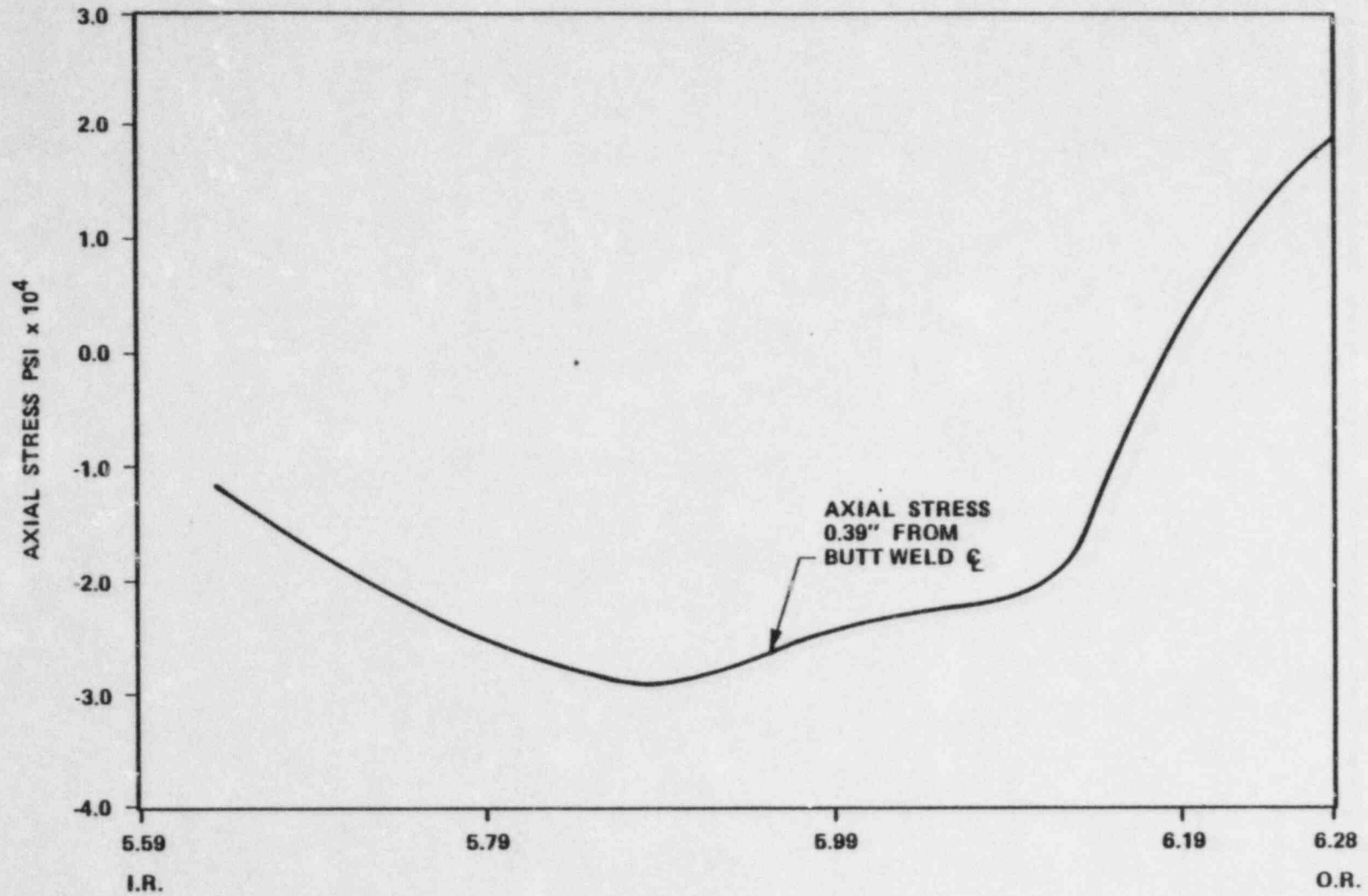
Table 5.6

Crack Growth of Unrepaired Flaws

<u>Weld Identification Number</u>	<u>Flaw Depth</u>		<u>Margin</u>	<u>Number of Months Required to Grow to Allowable Depth</u>
	<u>Current</u>	<u>Allowable for 360° Crack</u>	<u>Allowable Current Flaw Depth</u>	
2B31-1RC-28A-3	12%	63%	57%	293
2B31-1RC-28A-4	17%	63%	55%	218
2B31-1RC-28A-7	8%	63%	57%	332
2B31-1RC-28A-10	10%	63%	58%	349
2B31-1RC-28B-3	15%	63%	58%	359
2B31-1RC-28B-7	18%	63%	57%	264
2B31-1RC-28B-8	7%	63%	57%	347
2B31-1RC-28B-10	20%	63%	59%	384
2B31-1RC-28B-15	23%	63%	60%	290
2E11-1RHR-20RS-2	13%	63%	56%	248
2E11-1RHR-20RS-3	14%	63%	56%	256
2E11-1RHR-24B-R-11	18%	63%	56%	574

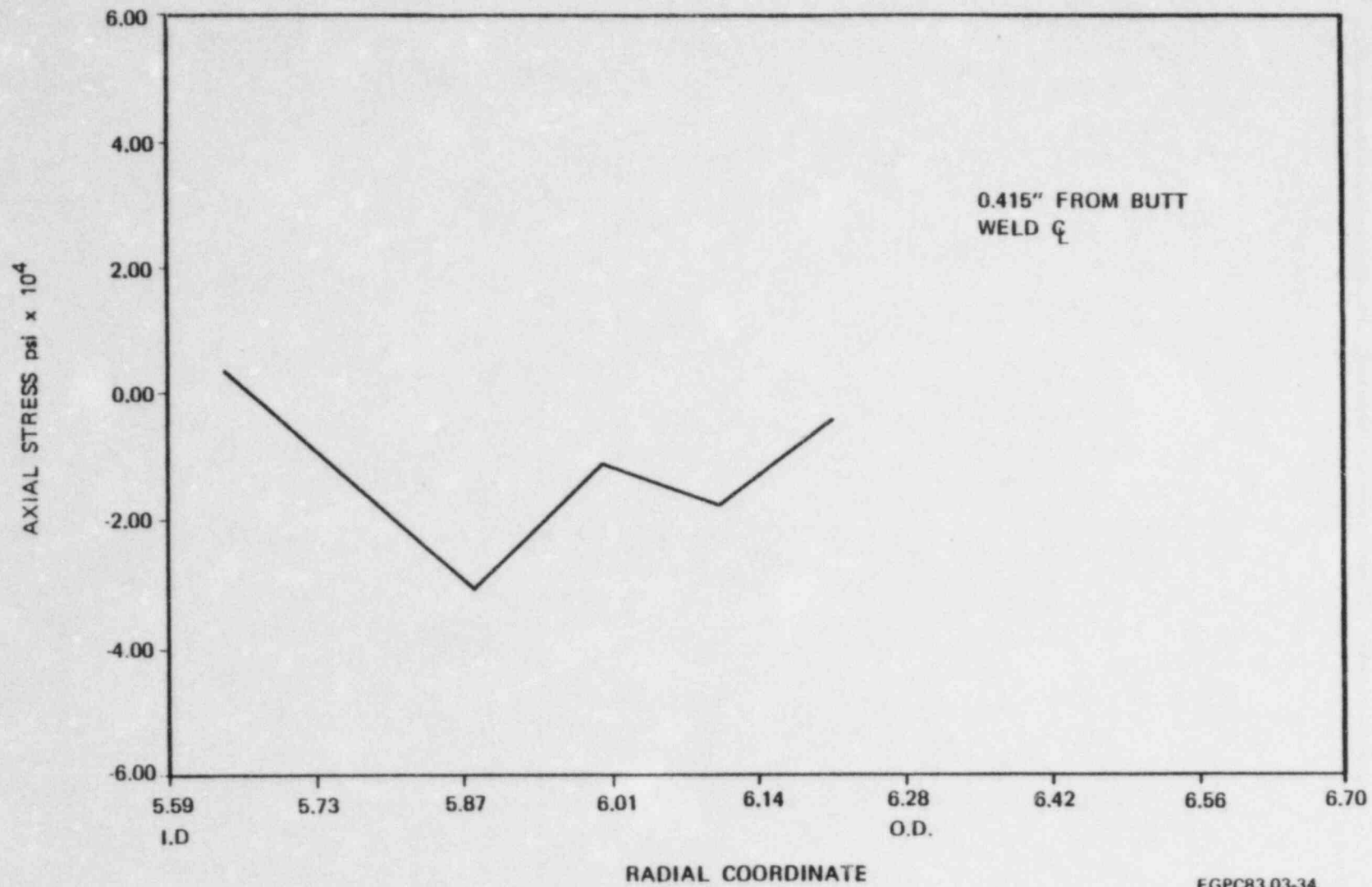
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Revision 1

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Figure 5.1  
WELDING RESIDUAL STRESS FOR SAFE END  
STANDARD WELD OVERLAY



FGPC83.03-34

Figure 5.2  
WELDING RESIDUAL STRESS FOR SAFE END  
MINI WELD OVERLAY

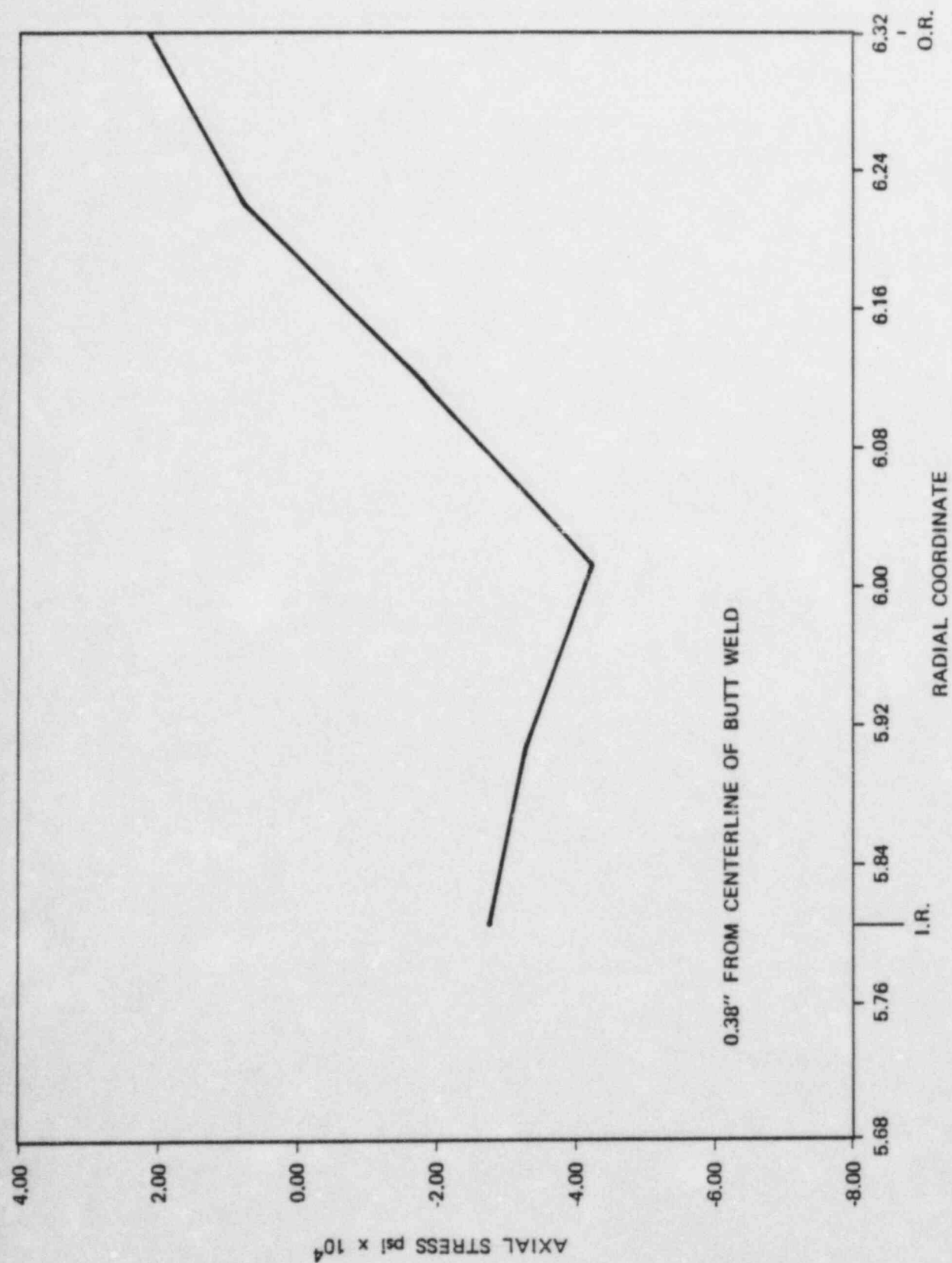


Figure 5.3

WELDING RESIDUAL STRESS FOR ELBOW STANDARD WELD OVERLAY

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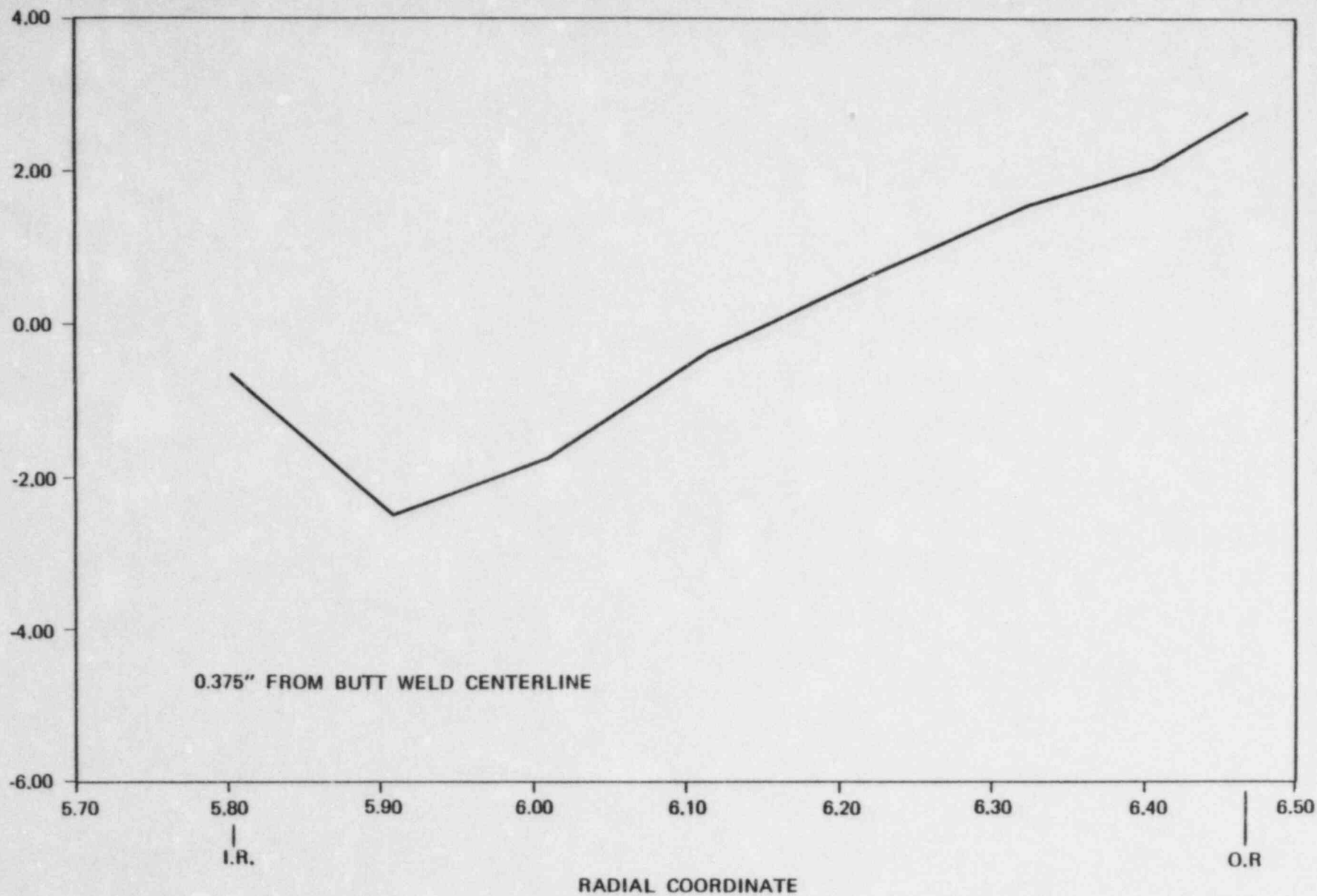


Figure 5.4

WELDING RESIDUAL STRESS FOR ELBOW MINI-WELD OVERLAY

FGPC83.03-19



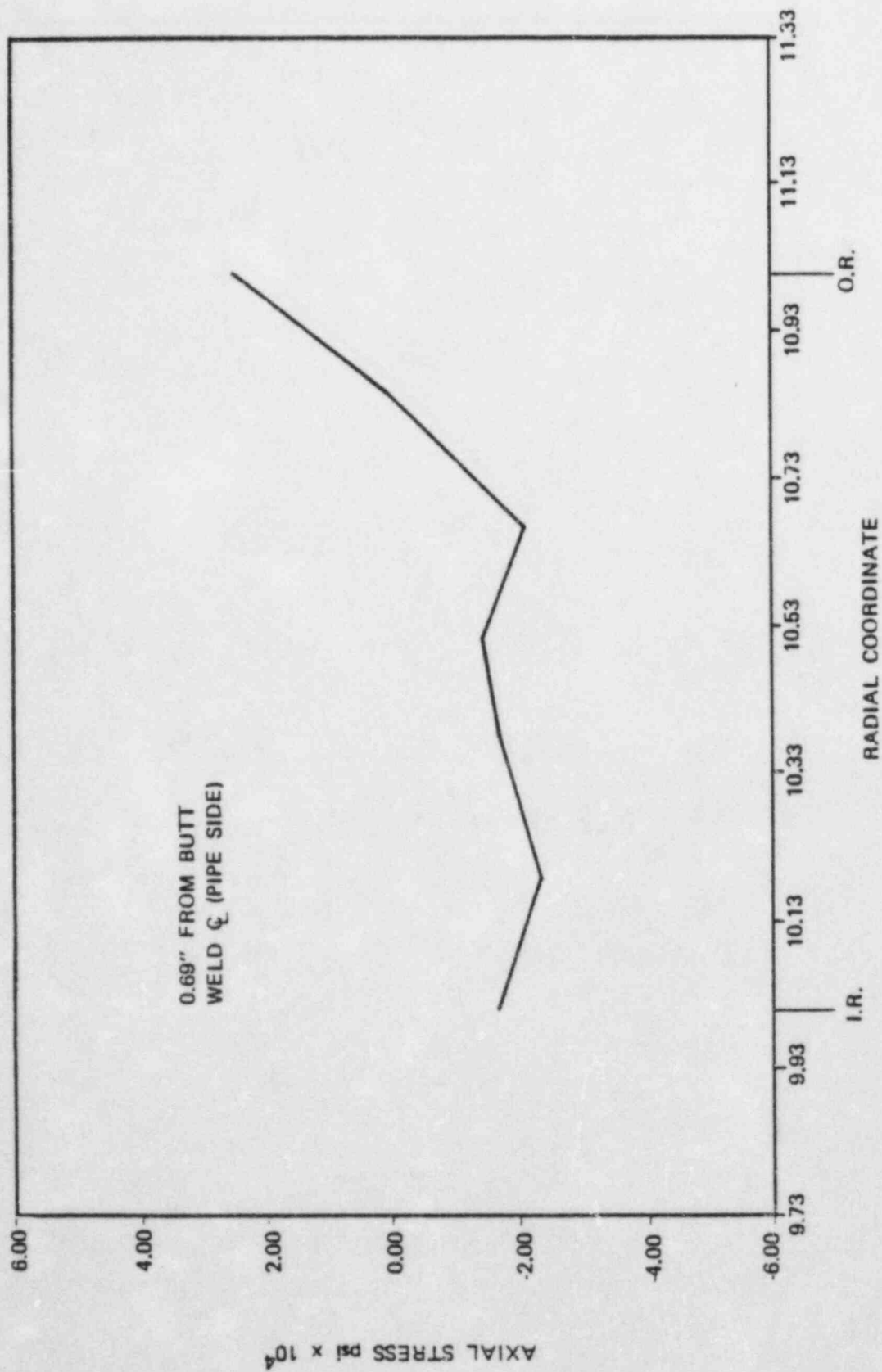
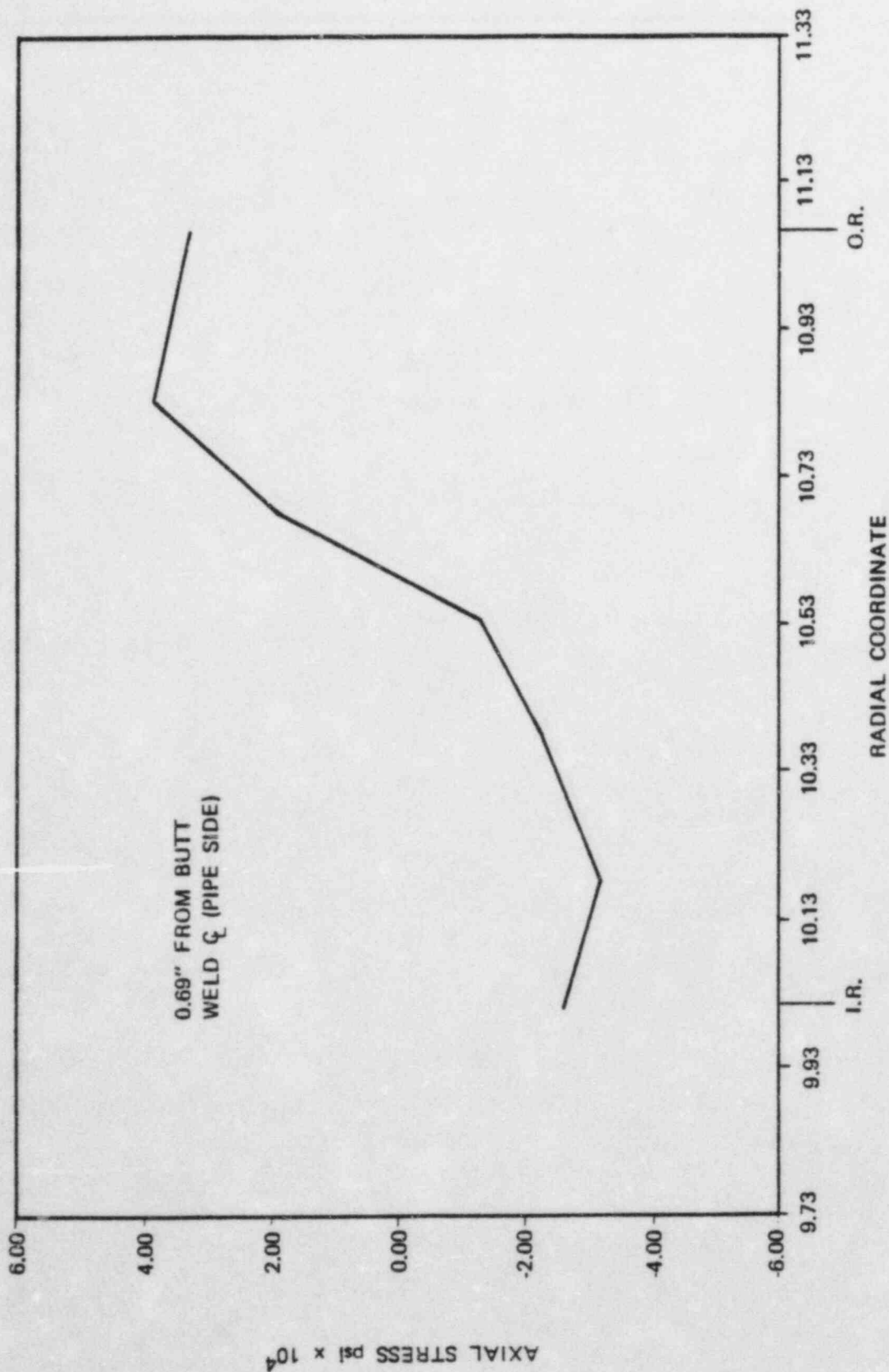


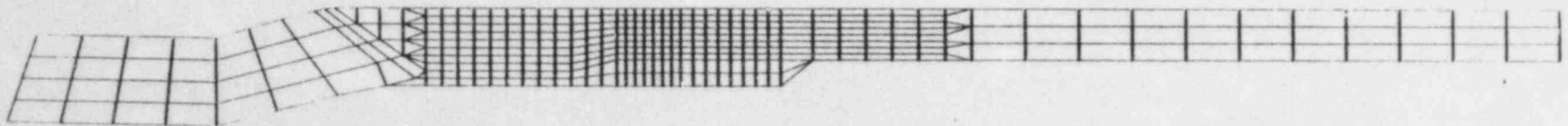
Figure 5.5  
WELDING RESIDUAL STRESS FOR END  
CAP WELD OVERLAY

FGPC83,03-24



FGPC83.03-25

Figure 5.6  
WELDING RESIDUAL STRESS FOR END  
CAP REPLACEMENT



5.41

Figure 5.7

SAFE END STANDARD OVERLAY FINITE ELEMENT MODEL

FGPC83.03-05

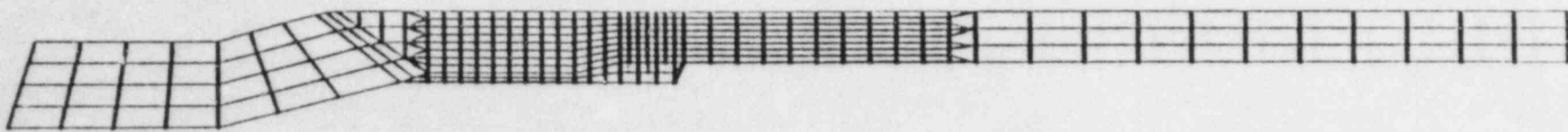
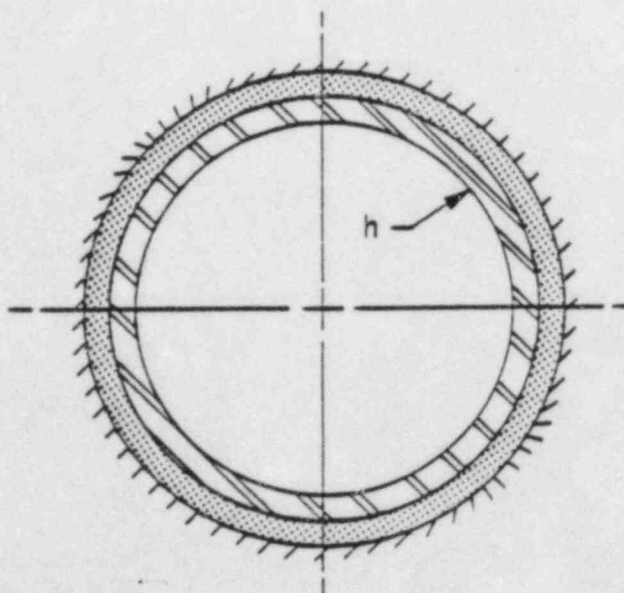
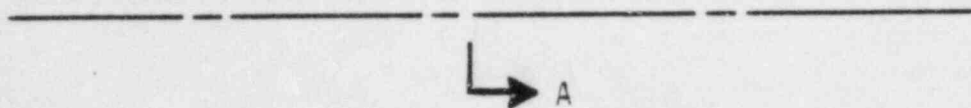
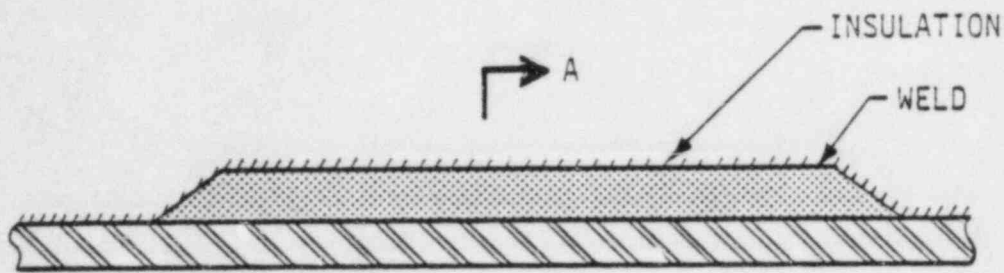


Figure 5.8

SAFE END MINI - OVERLAY FINITE ELEMENT MODEL

FGPC83.03-35



SECTION A-A

$$h = 738 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$$

$$k = 10 \text{ BTU/hr-ft-}^\circ\text{F}$$

Figure 5.9

WELD OVERLAY THERMAL MODEL

FGPC83.03-06



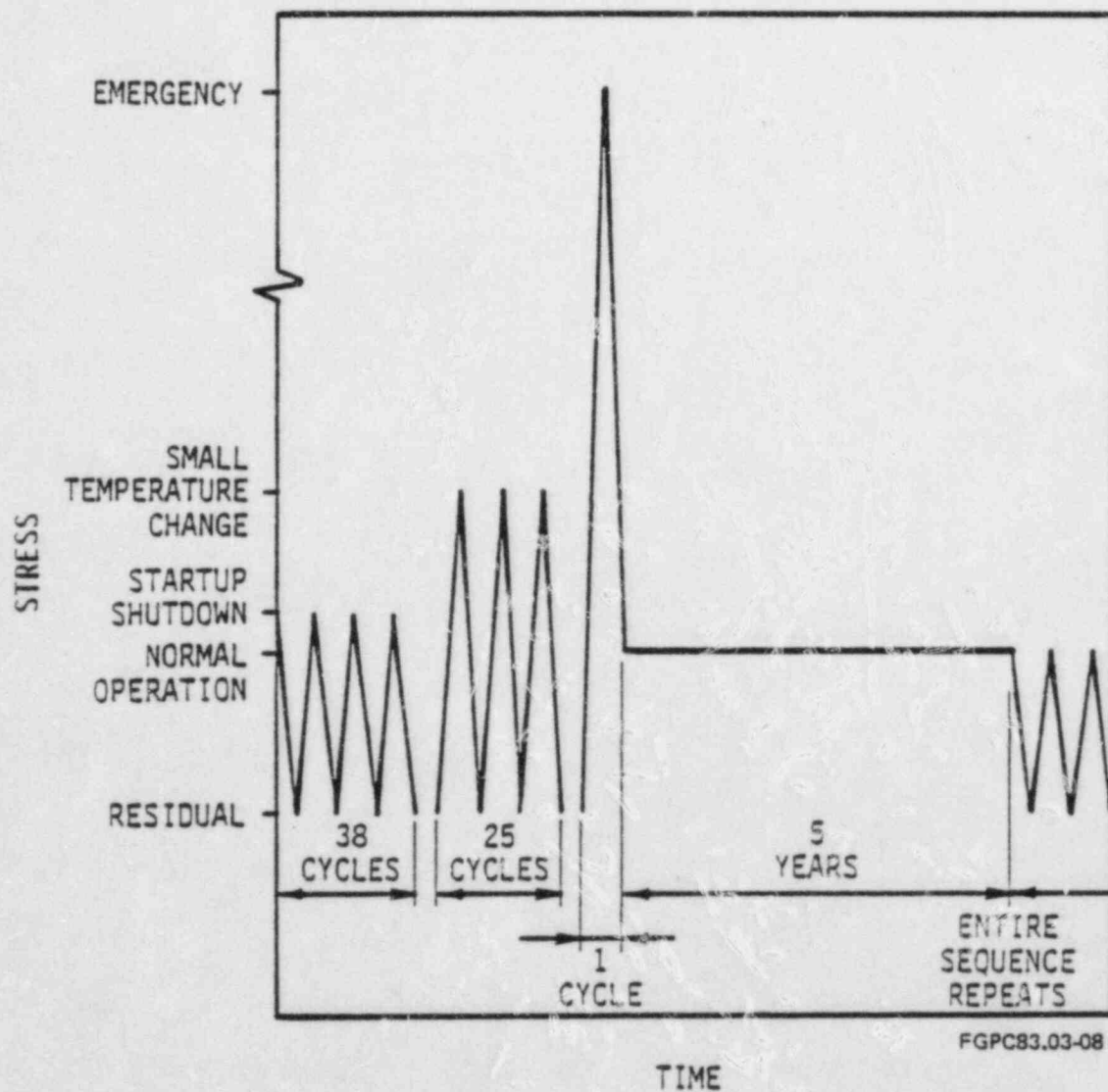
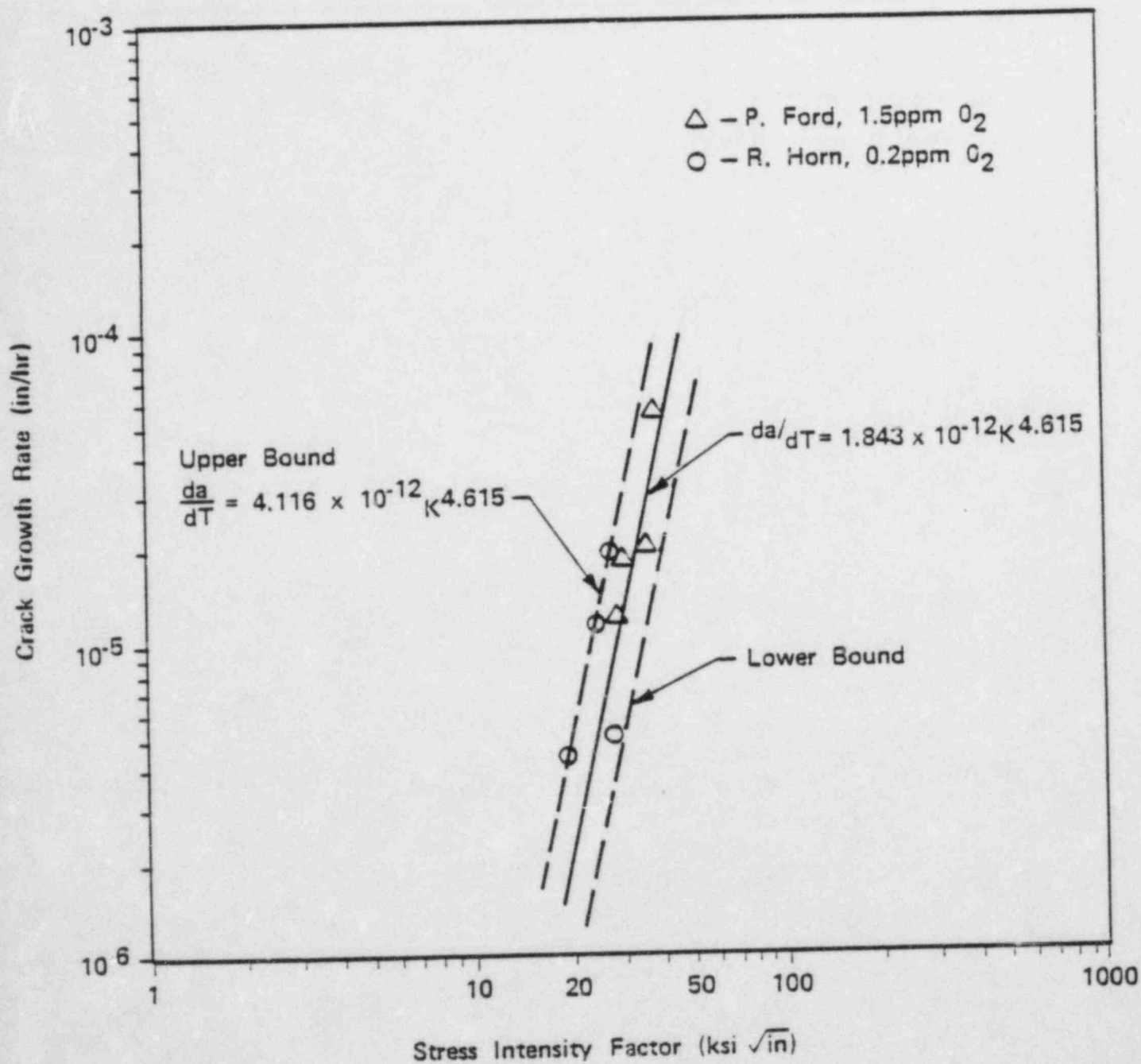
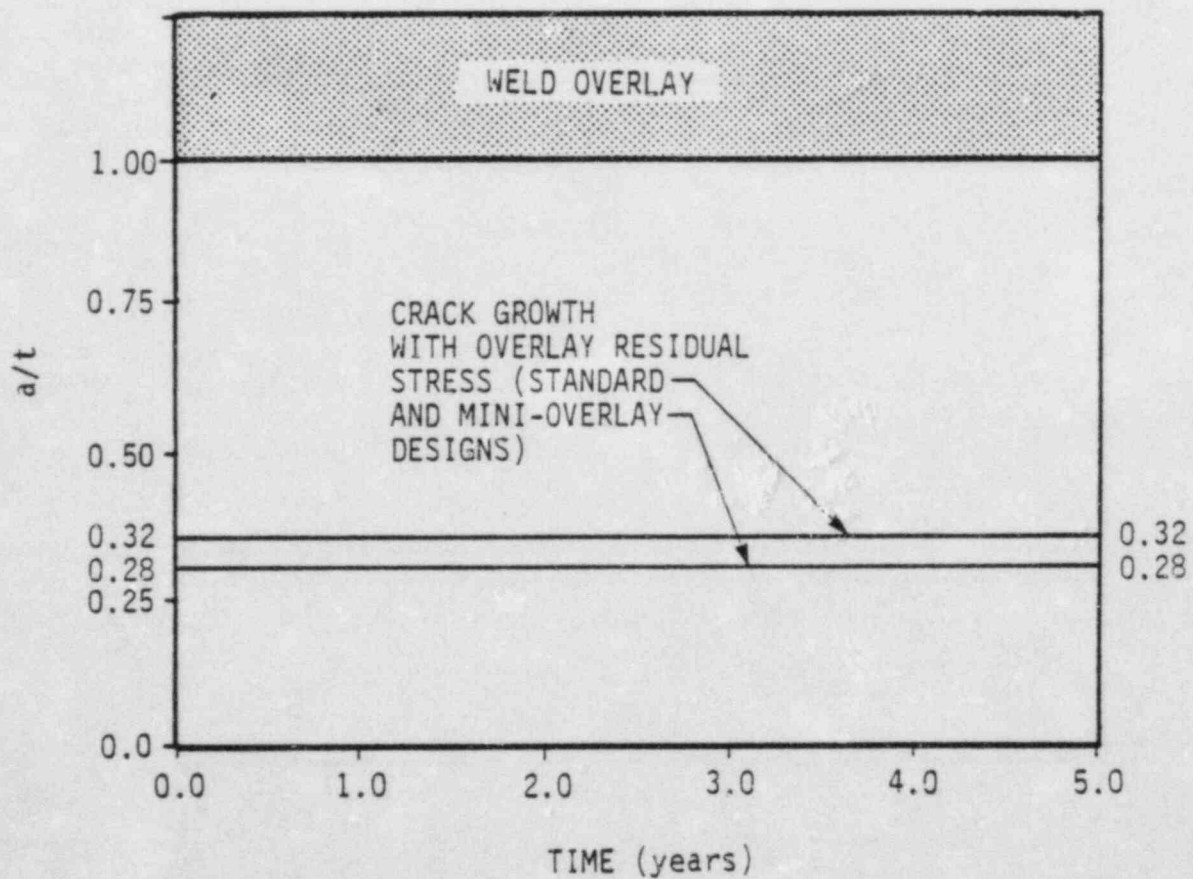
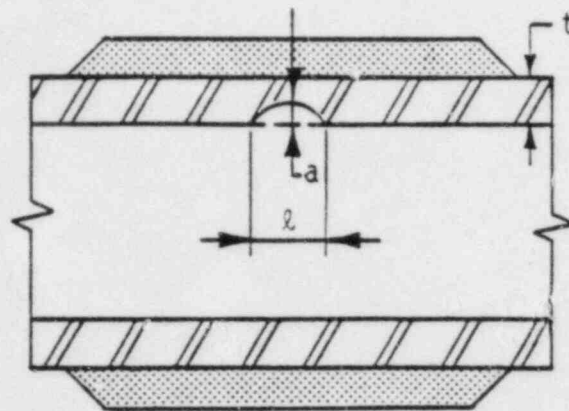


Figure 5.10  
THERMAL TRANSIENTS



FGPC83.03-25

Figure 5.11  
 TYPICAL IGSCC CRACK GROWTH DATA  
 (WELD SENSITIZED 304SS IN BWR ENVIRONMENT)



FGPC83.03-36

Figure 5.12

SAFE END CRACK GROWTH

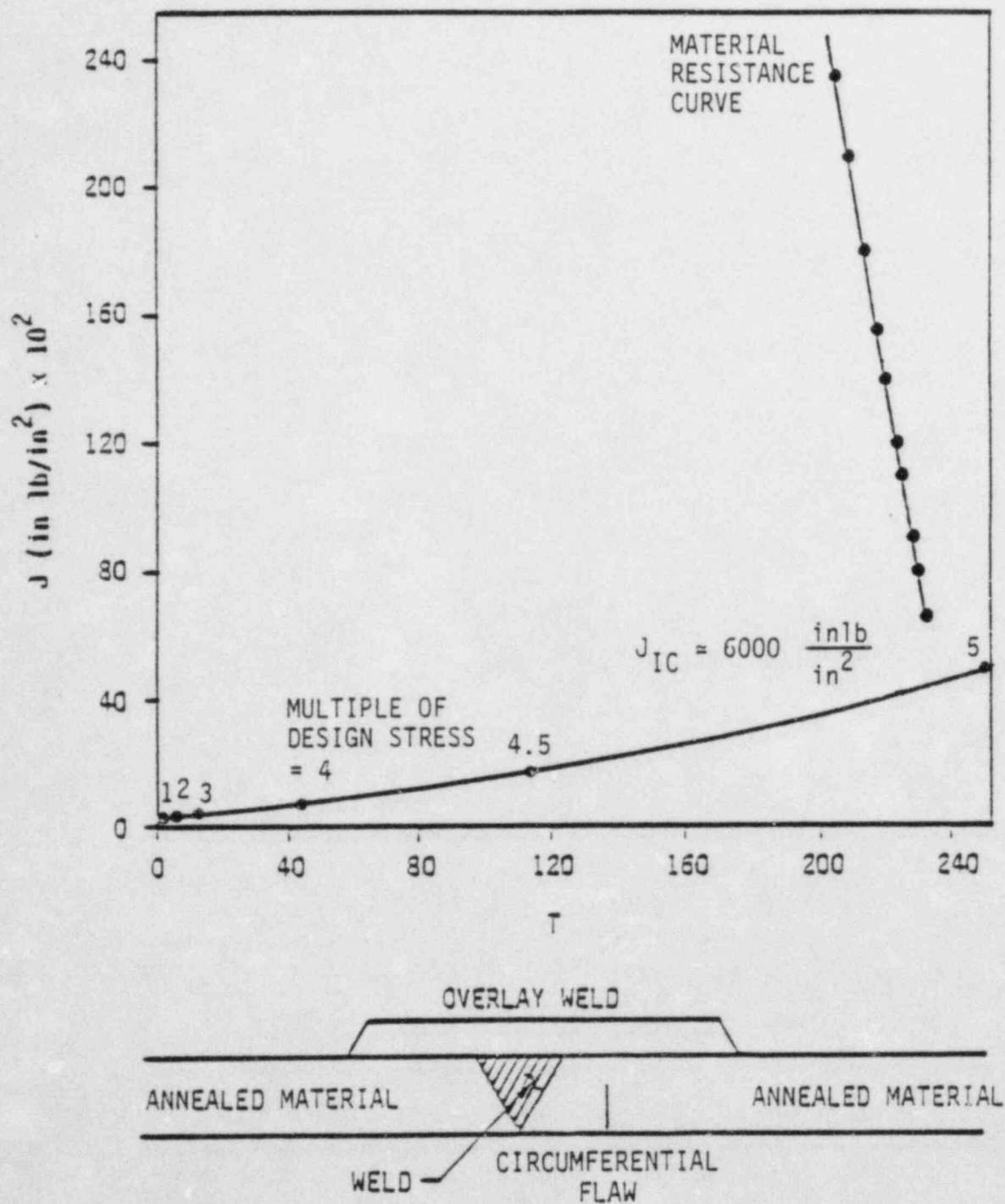


Figure 5.13

# SAFE END TEARING MODULUS

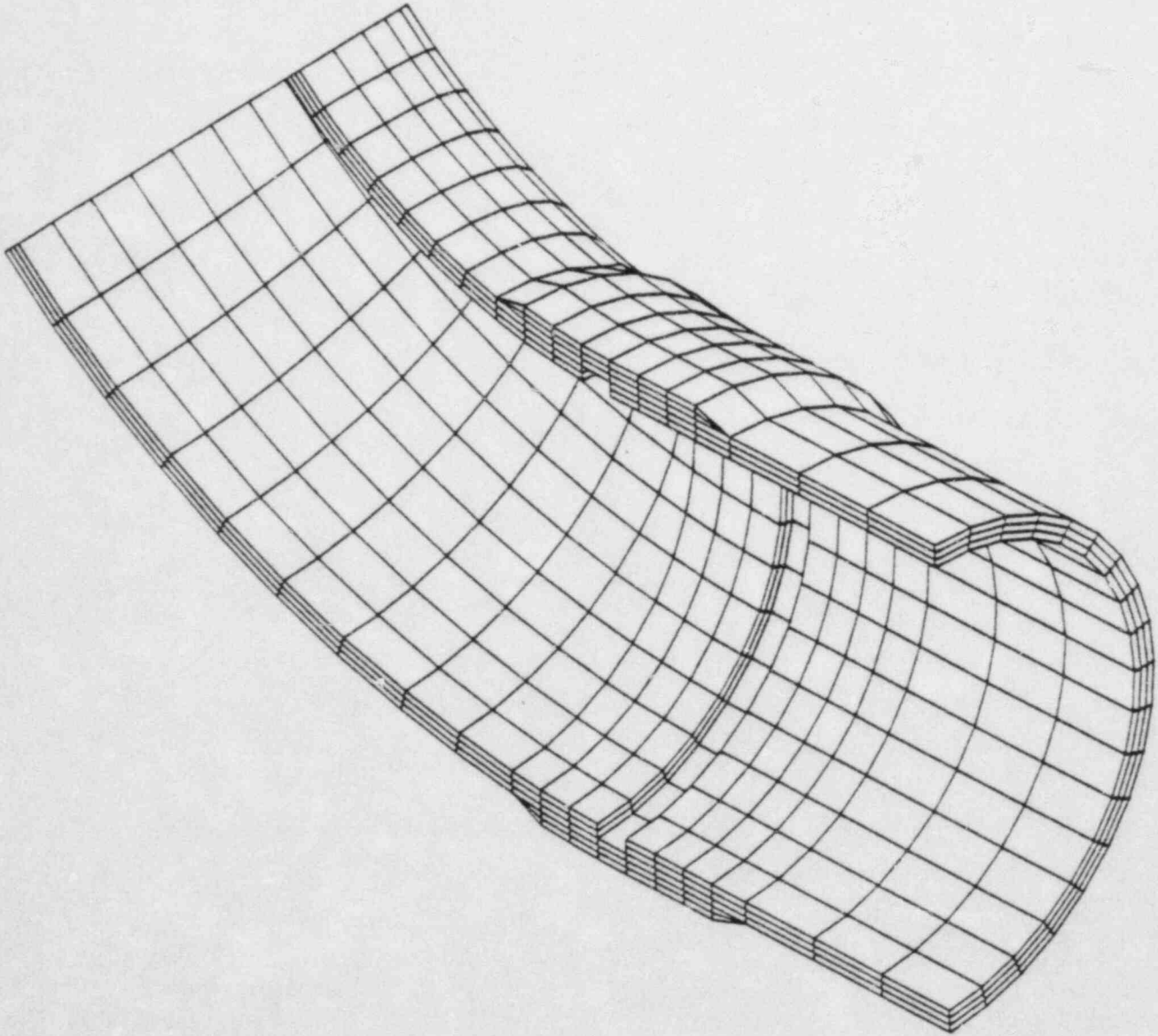


Figure 5.14  
THREE DIMENSIONAL 12"  
ELBOW FINITE ELEMENT MODEL

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$a = \text{FLAW DEPTH} = 0.32t$   
 $a = 0.220''$   
 $\text{FLAW LENGTH} = 2a$   
 $2a = 0.440''$

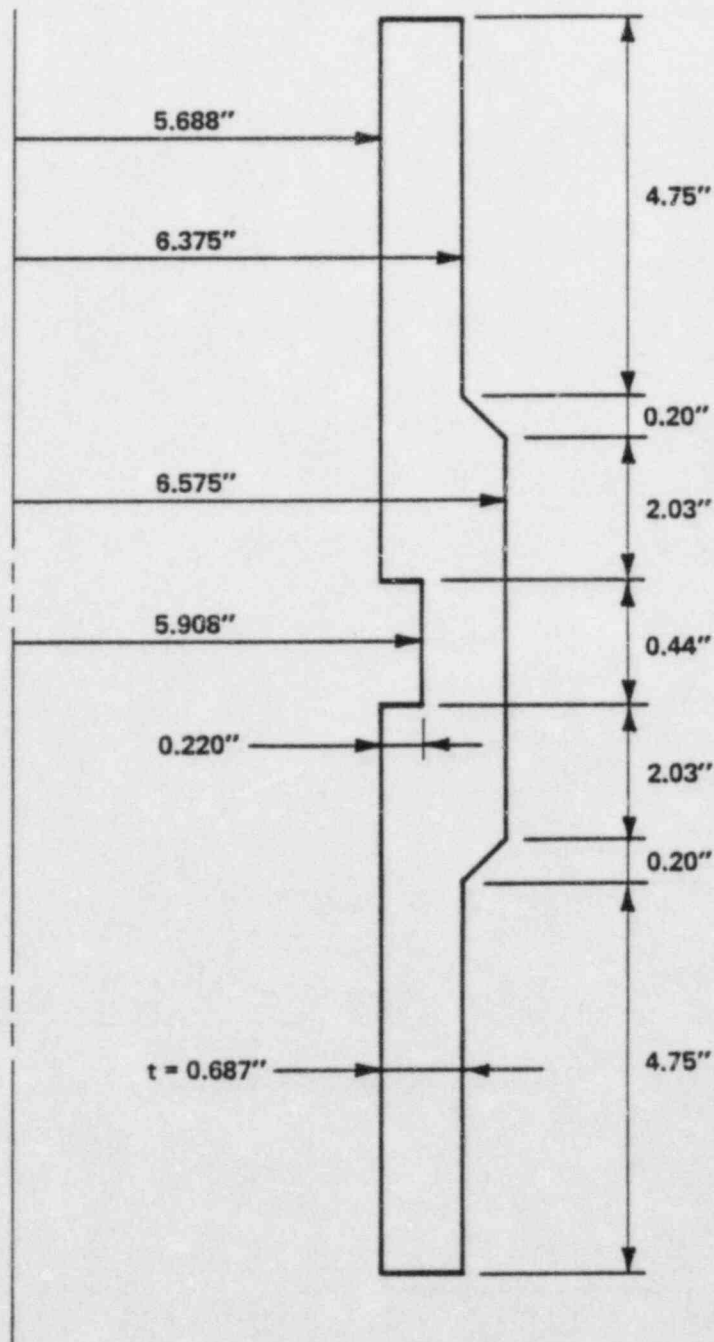
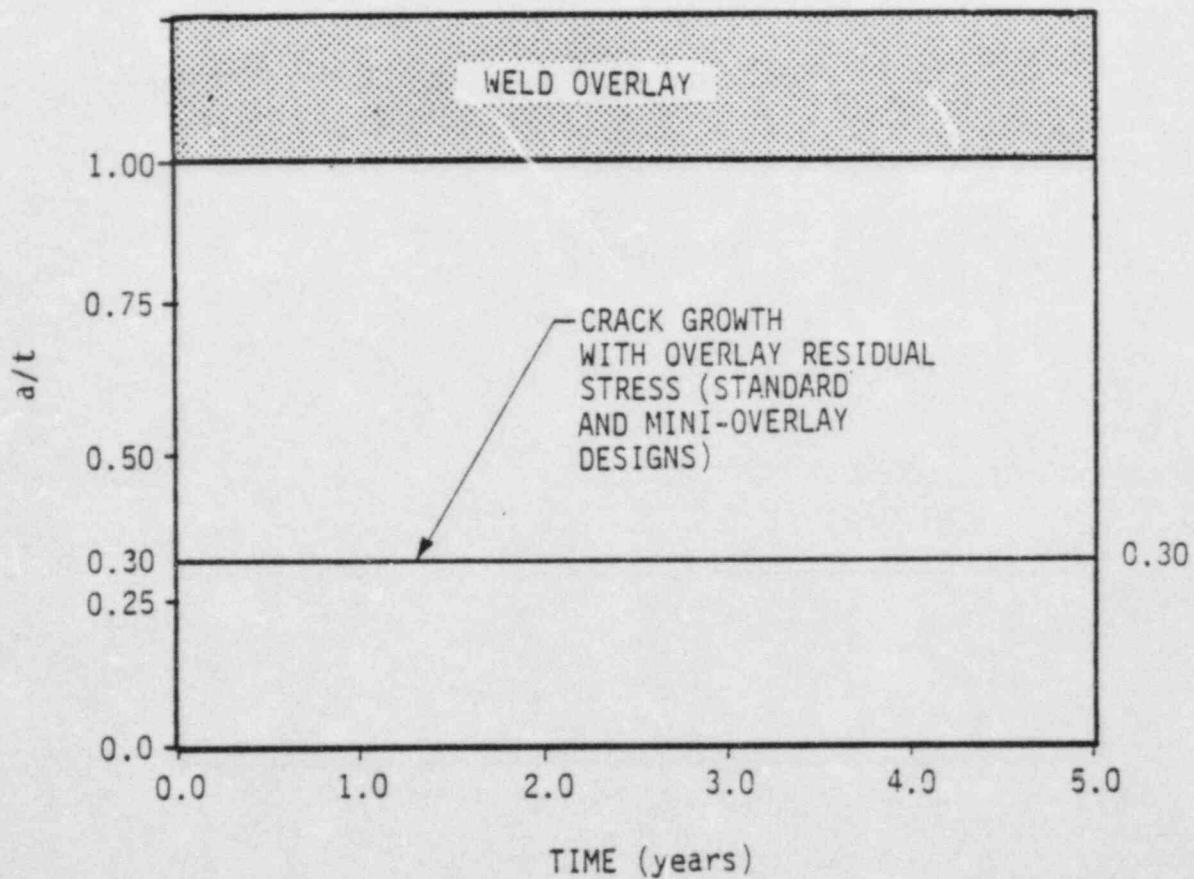
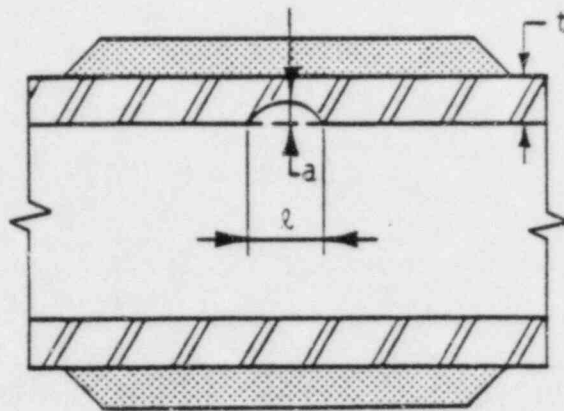


Figure 5.15

BOSOR 4 MODEL FOR 12" ELBOW  
 STANDARD WELD OVERLAY DESIGN

FGPC83,03-31



FGPC83.03-32

Figure 5.16

12" ELBOW CRACK GROWTH

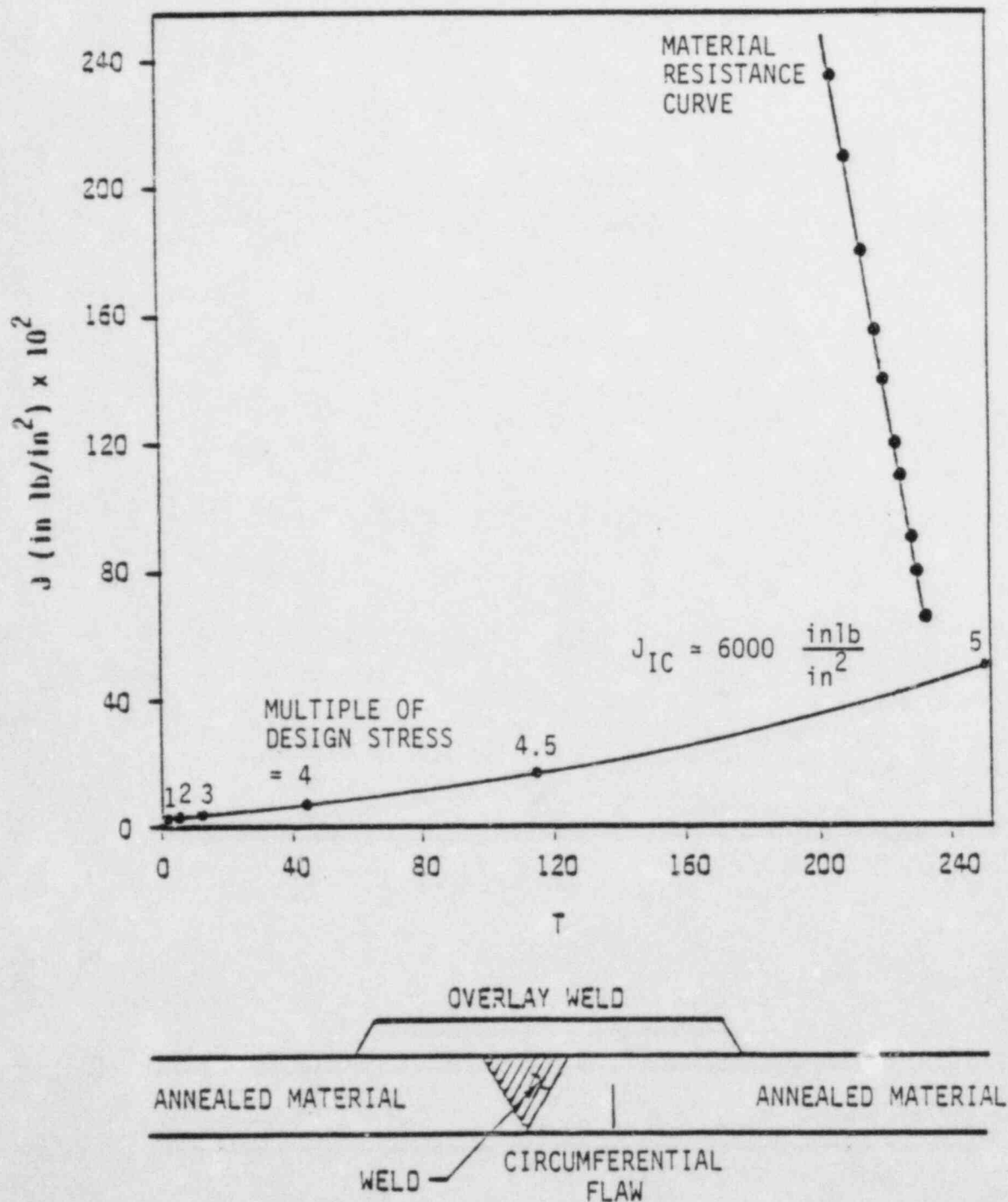


Figure 5.17

12" ELBOW TEARING MODULUS

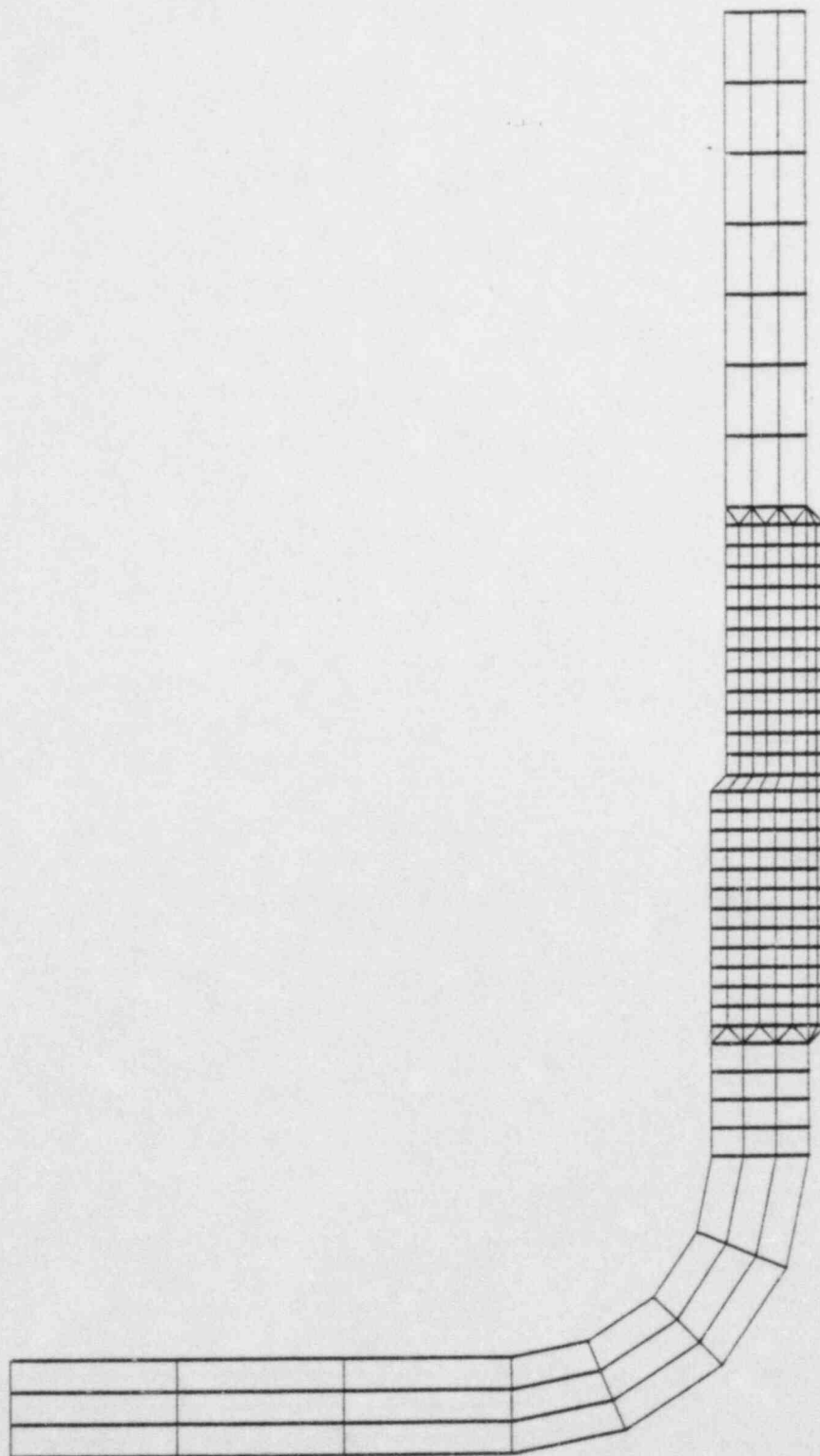
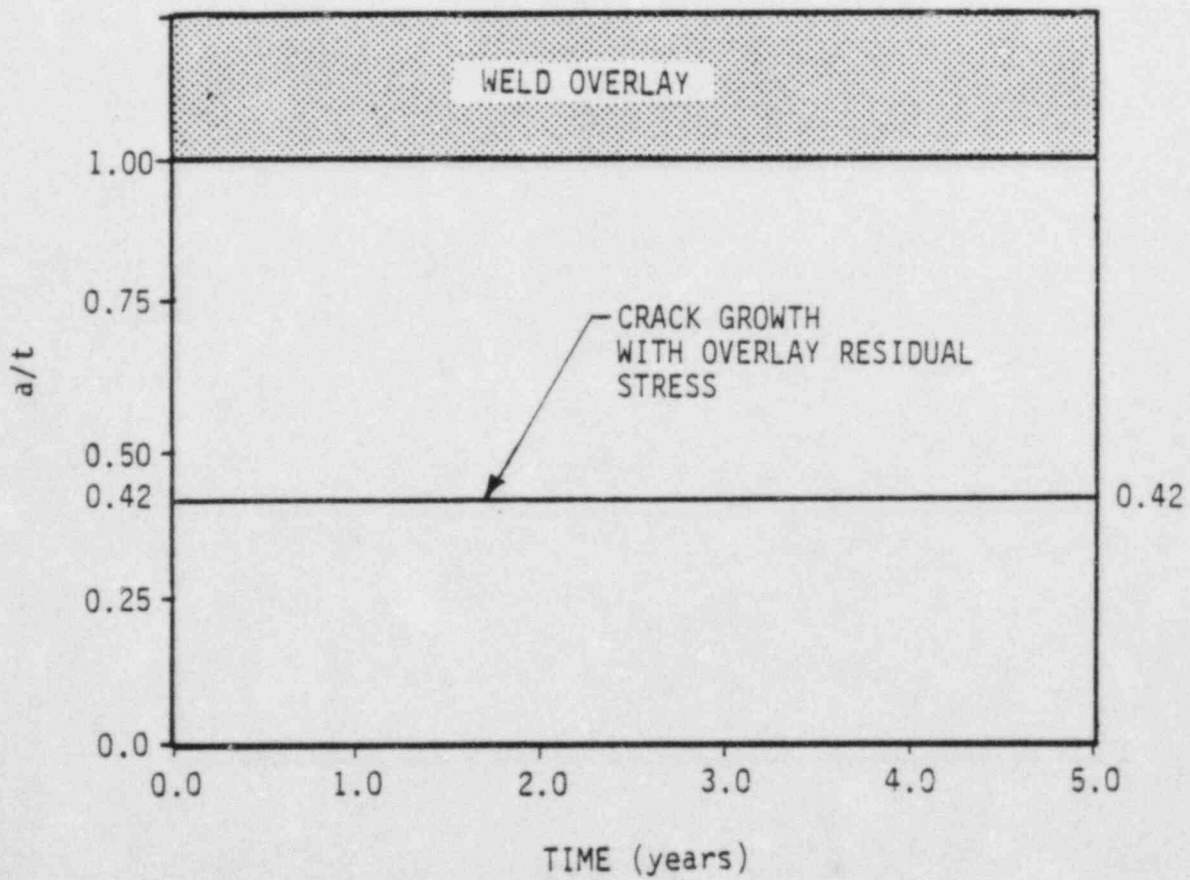
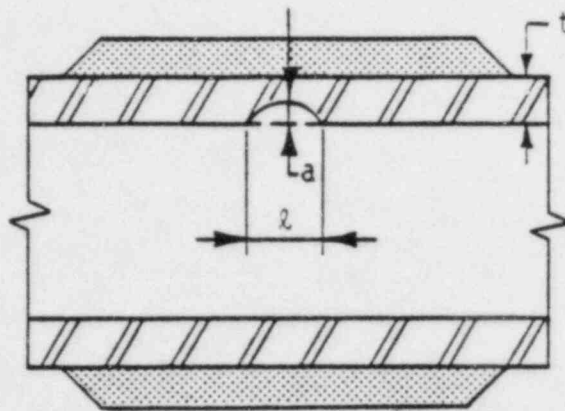


Figure 5.18

END CAP FINITE ELEMENT MODEL

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FGPC83.03-33

Figure 5.19

### END CAP CRACK GROWTH

GPC-07-102  
Revision 1



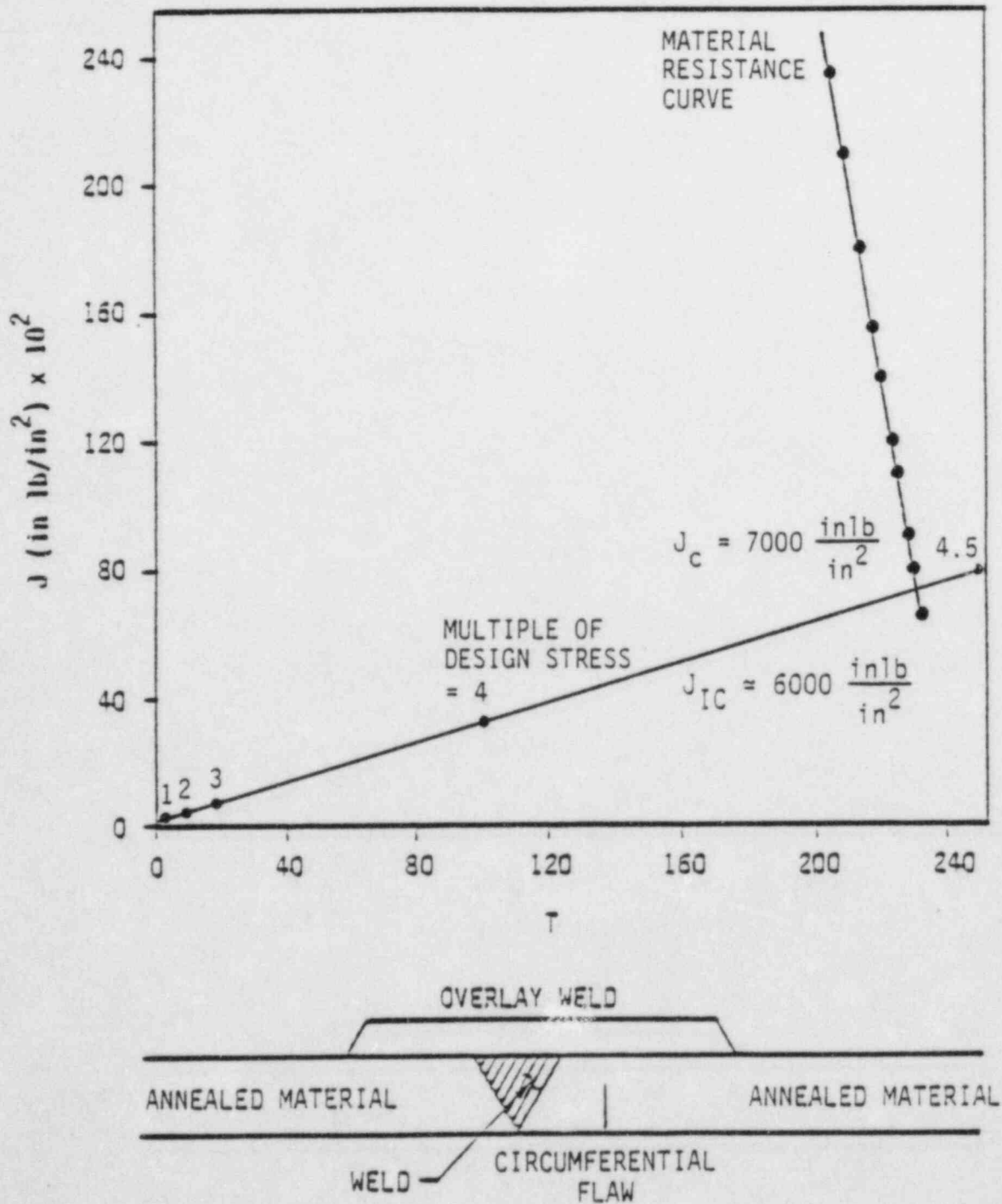
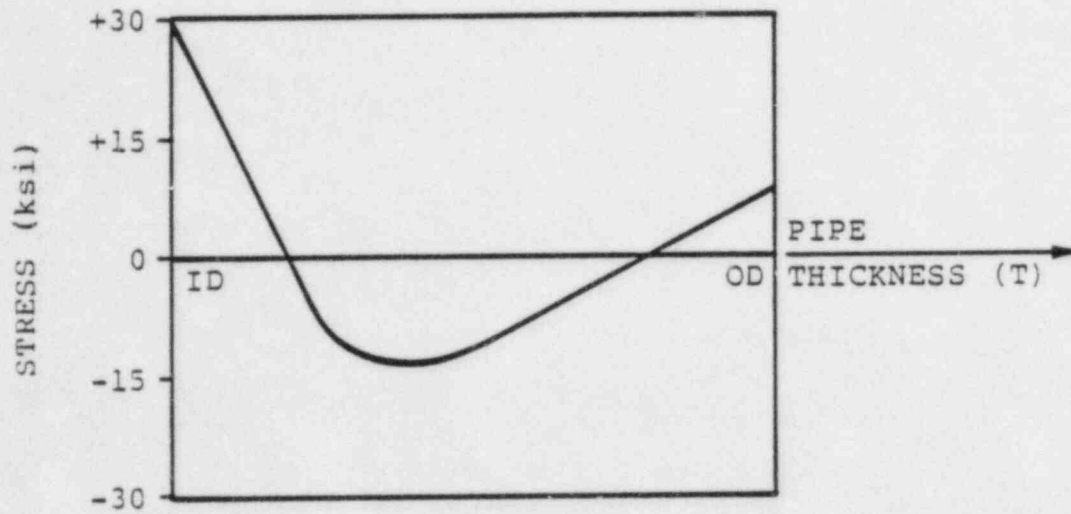


Figure 5.20

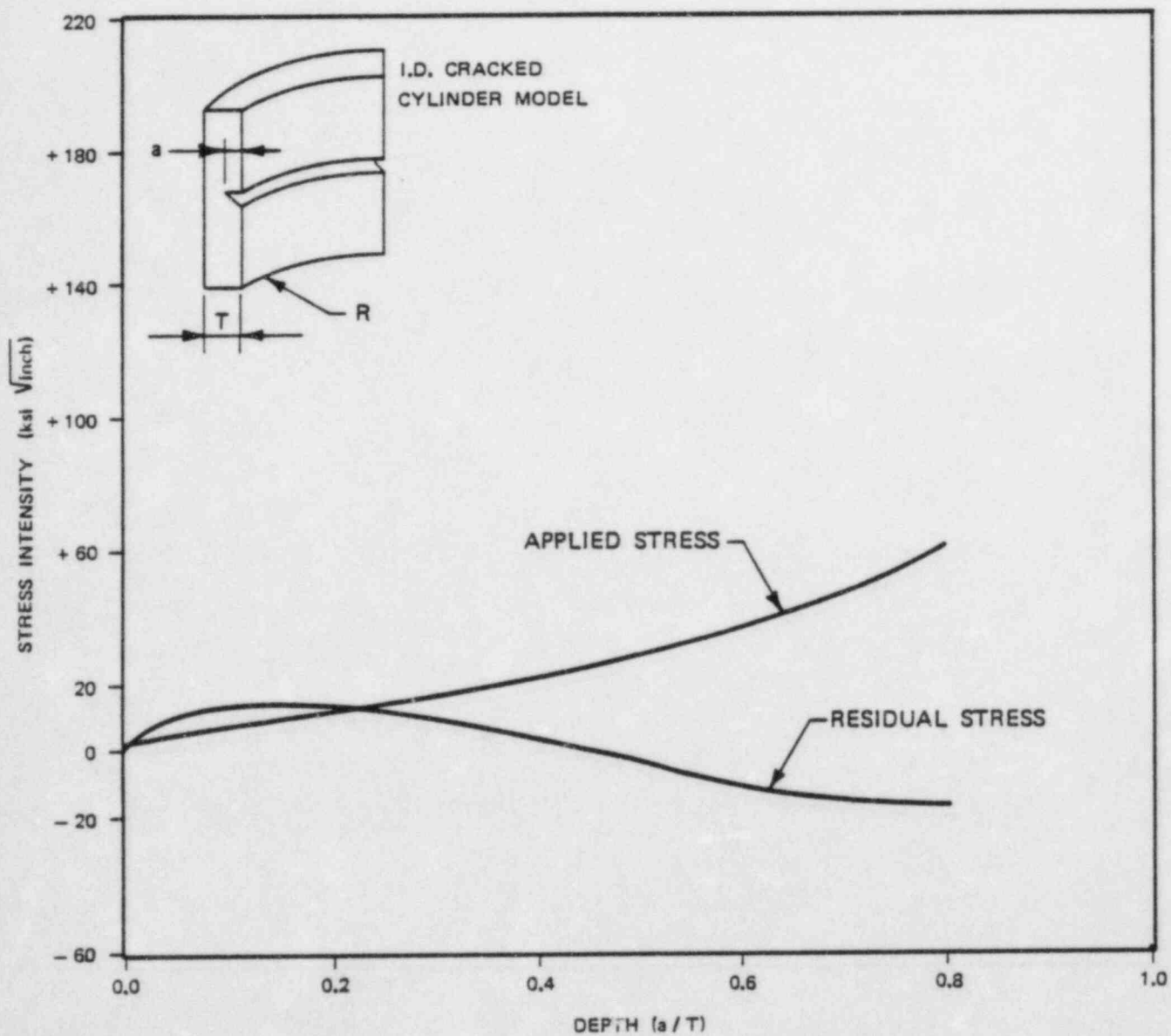
# END CAP TEARING MODULUS



T%	STRESS (ksi)
0	+30.0
19	0.0
25	- 9.9
59	-14.2
50	-12.0
81	0.0
100	+ 8.1

FGPC83.02

Figure 5.21  
AXIAL RESIDUAL STRESS  
PIPE DIAMETER OF 20" TO 28"



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Figure 5.22  
STRESS INTENSITY FACTOR FOR  
RECIRCULATION SYSTEM WELD 28B - 15

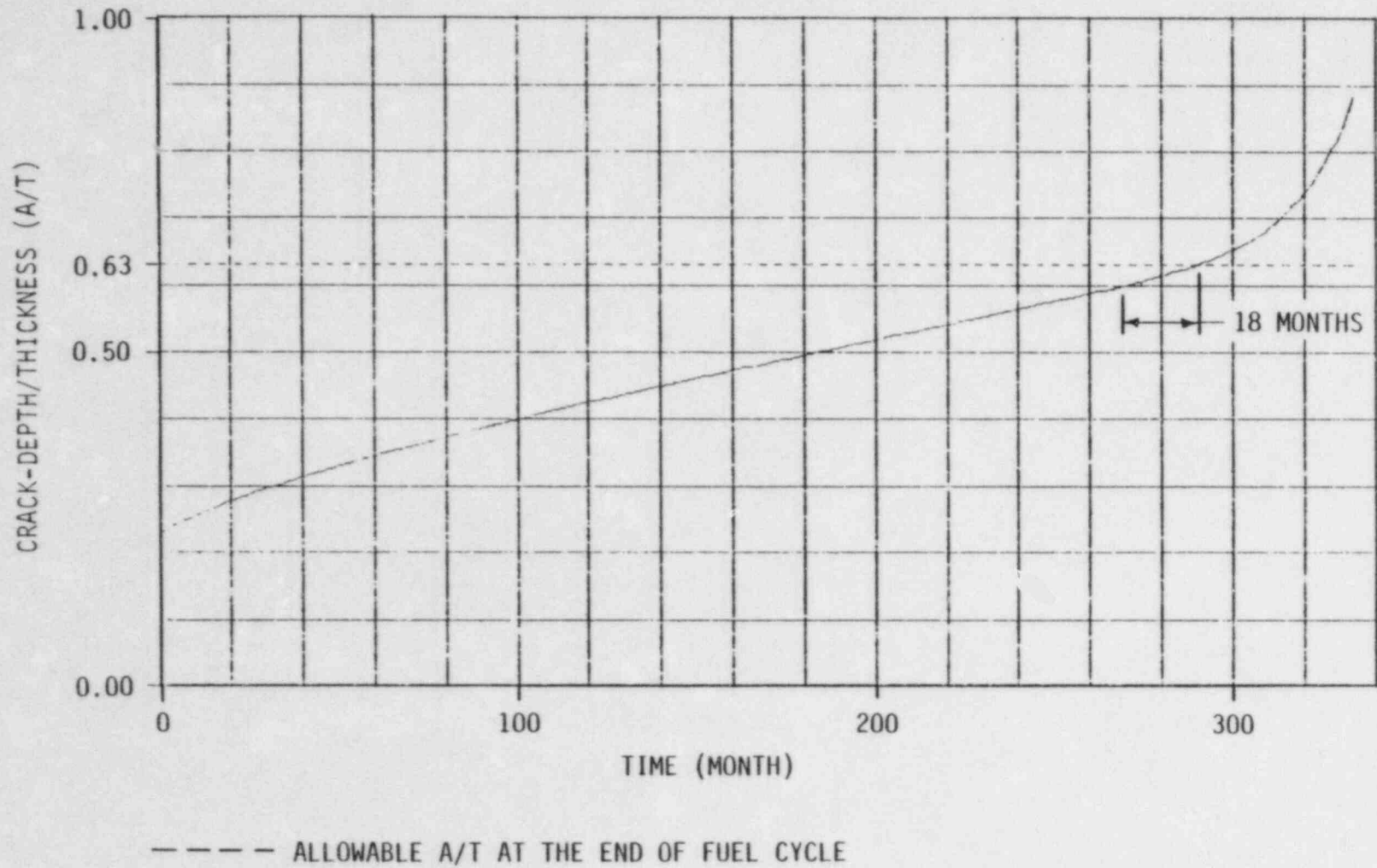


Figure 5.23

CRACK GROWTH FOR RECIRCULATION SYSTEM WELD 28B-15

FGPC83.03-26

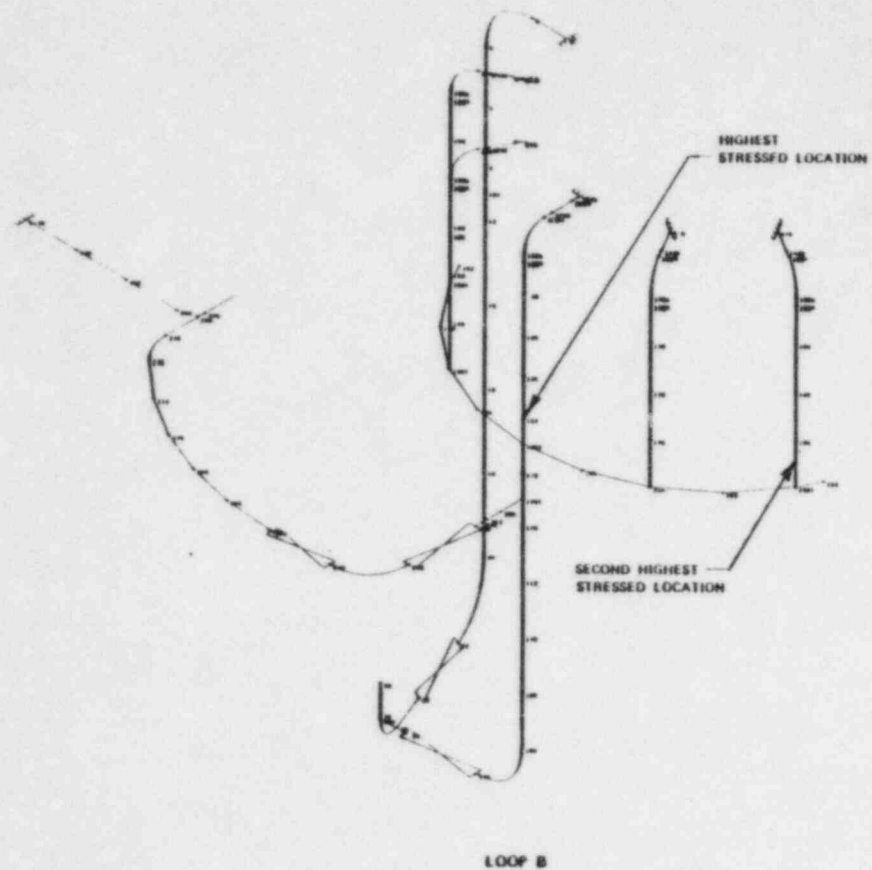
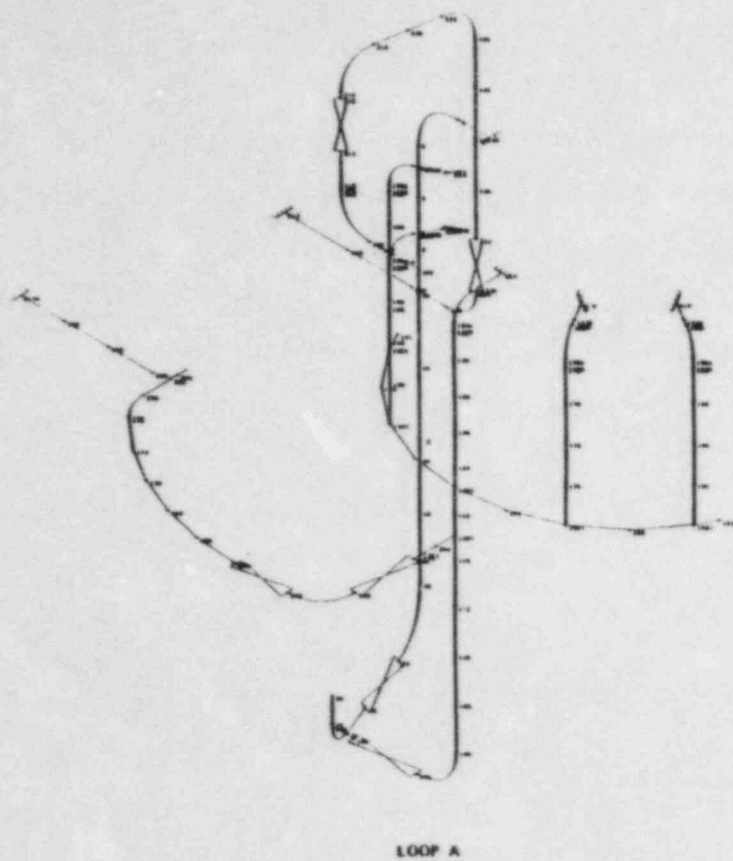


Figure 5.24  
PIPING MODEL

FGPC83,03-22



## 6.0 LEAK-BEFORE-BREAK

### 6.1 Net Section Collapse

The simplest way to determine the effect of IGSCC on the structural integrity of piping is through the use of a simple "strength of materials" approach to assess the load carrying capacity of a piping section after the cracked portion has been removed. Studies have shown (References 15 and 17) that this approach gives a conservative, lower-bound estimate of the loads which would cause unstable fracture of the cracked section. Typical results of such an analysis are indicated in Figure 6.1 (Reference 15). This figure defines the locus of limiting crack depths and lengths for circumferential cracks which are predicted to cause failure by the net section collapse method. Curves are presented for both typical piping system stresses and stress levels equal to ASME Code limits. Note that a very large percentage of the pipe wall can be cracked before reaching these limits (40% to 60% of circumference for through-wall cracks, and 65% to 85% of wall thickness for 360° part-through cracks), depending on the stress level and material flow stress.

Also shown in Figure 6.1 is a sampling of cracks which have been detected in service, either through UT examination or leakage. There has generally been a comfortable margin between the size crack that was observed and that which would be predicted to cause failure under service loading conditions. Also, as discussed below, there is still considerable margin between these net section collapse limits and the actual cracks which would cause instability.

## 6.2 Tearing Modulus Analysis

Elastic-plastic fracture mechanics analyses are presented in Reference 17 which give a more accurate representation of the crack tolerance capacity of stainless steel piping than the net section collapse approach described above. Figures 6.2 and 6.3 graphically depict the results of such an analysis (Reference 17). Through-wall circumferential defects of arc-length equal to  $60^\circ$  through  $300^\circ$  were assumed at various cross sections of a typical BWR Recirculation System. Loads were applied to these sections of sufficient magnitude to produce net section limit loads, and the resulting values of tearing modulus were compared to that required to cause unstable fracture (Figure 6.2). Note that in all cases there is

substantial margin, indicating that the net section collapse limits of the previous section are not really failure limits. Figure 6.3 summarizes the results of all such analyses performed for 60° through-wall cracks in terms of margin on tearing modulus for stability. The margin in all cases is substantial.

### 6.3 Leak Versus Break Flaw Configuration

Of perhaps more significance to the leak-before-break argument is the flaw configuration depicted in Figure 6.4. This configuration addresses the concerns raised by the occurrence of part-through flaws growing, with respect to the pipe circumference, before breaking through the outside surface to cause leakage. Figure 6.4 presents typical size limitations on such flaws based on the conservative, net section collapse method of Section 6.1. Note that very large crack sizes are predicted for the stress levels of Figure 6.4. Also shown on this Figure are typical detectability limits for short through-wall flaws (which are amenable to leak detection) and long part-through flaws (which are amenable to detection by UT). The margins between the detectability limits, and the conservative, net section collapse failure limits are substantial. It is noteworthy that the likelihood of flaws developing which

are characterized by the vertical axis shown in Figure 6.4 (constant depth 360° circumferential cracks) is so remote as to be considered impossible. Material and stress asymmetries always tend to propagate one portion of the crack faster than the bulk of the crack front, which will eventually result in "leak-before-break." This observation is borne out by extensive field experience with BWR IGSCC.

#### 6.4 Axial Cracks

The recent IGSCC occurrences at Monticello and Hatch 1 were predominately short, axial cracks which grew through the wall but remained very short in the axial direction. This behavior is consistent with expectations for axial IGSCC since the presence of a sensitized weld heat-affected zone is necessary, and this heat-affected zone is limited to approximately 0.25 inch on either side of the weld. Since the major loadings in the above net section collapse analysis are bending moments on the cross section due to seismic loadings, and since these loads do not exist in the circumferential direction, the above leak-before-break arguments are even more persuasive for axially oriented cracks. There is no known mechanism for axial cracks to

lengthen before growing through-wall and leaking, and the potential rupture loading on axial cracks is less than that on circumferential cracks.

#### 6.5 Multiple Cracks

Recent analyses performed for EPRI (Reference 22) indicate that the occurrence of multiple cracks in a weld, or cracking in multiple welds in a single piping line do not invalidate the leak-before-break arguments discussed above.

#### 6.6 Crack Detection Capability

IGSCC in BWR piping is detected through two means: non-destructive examination (NDE) and leakage detection. Although neither is perfect, the two means complement one another well. This detection capability combined with the exceptional inherent toughness of stainless steel, results in essentially 100% probability that IGSCC would be detected before it significantly degraded the structural integrity of a BWR piping system.



The primary means of non-destructive examination for IGSCC in BWR piping is ultrasonics. This method has been the subject of considerable research and development in recent years, and significant improvements in its ability to detect IGSCC have been achieved. Nevertheless, recent UT experience at Brunswick 1, Monticello, Hatch 1 and 2, and elsewhere indicate that there is still considerable room for improvement, especially in the ability to distinguish cracks or crack-like indications from innocuous geometric conditions.

Figure 6.4, however, illustrates a significant aspect of UT detection capability with respect to leak-before-break. The types of cracking most likely to go undetected by UT are relatively short circumferential or axial cracks which are most amenable to detection by leakage. Conversely, as part-through cracks lengthen, and thus become more of a concern with respect to leak-before-break, they become readily detectable by UT, and are less likely to be misinterpreted as geometric conditions.

Typical leakage detection capability for BWR reactor coolant system piping is through sump level and drywell activity monitoring. These systems have sensitivities on the order of 1.0 gallon per minute (GPM) of unidentified leakage (i.e., not from known sources such as valve packing or pump seals). Plant technical specification limits typically require investigation/corrective action at 5.0 GPM unidentified leakage.

Table 6.1 provides a tabulation of typical flaw sizes to cause 5.0 GPM leakage in various size piping (Reference 15).

Also shown in this table are the critical crack lengths for through-wall cracks based on the net section collapse method of analysis discussed above. For conservatism, the leakage values are based on pressure stress only, while the critical crack lengths are based on the sum of all combined loads, including seismic. (Considering other normal operating loads in the leakage analysis would result in higher rates of leakage for a given crack size.) Note that there is considerable

margin between the crack length to produce 5.0 GPM leakage and the critical crack length, and that this margin increases with increasing pipe size.

#### 6.9 Historical Experience

The above theories regarding crack detectability have been borne out by experience. Indeed, of the approximately 400 IGSCC incidents to date in BWR piping, all have been detected by either UT or leakage, and none have even come close to violating the structural integrity of the piping (Reference 22).

NOMINAL PIPE SIZE	CRACK LENGTH FOR 5 GPM LEAK (in.)	CRITICAL CRACK LENGTH $\ell_c$ (in.)	$\ell/\ell_c$
4" SCH 80	4.50	6.54	0.688
10" SCH 80	4.86	15.95	0.305
24" SCH 80	4.97	35.79	0.139

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Table 6.1  
EFFECT OF PIPE SIZE ON THE RATIO OF THE CRACK LENGTH  
FOR 5 GPM LEAK RATE AND THE CRITICAL CRACK LENGTH  
(ASSUMED STRESS  $\sigma = S_m/2$ )

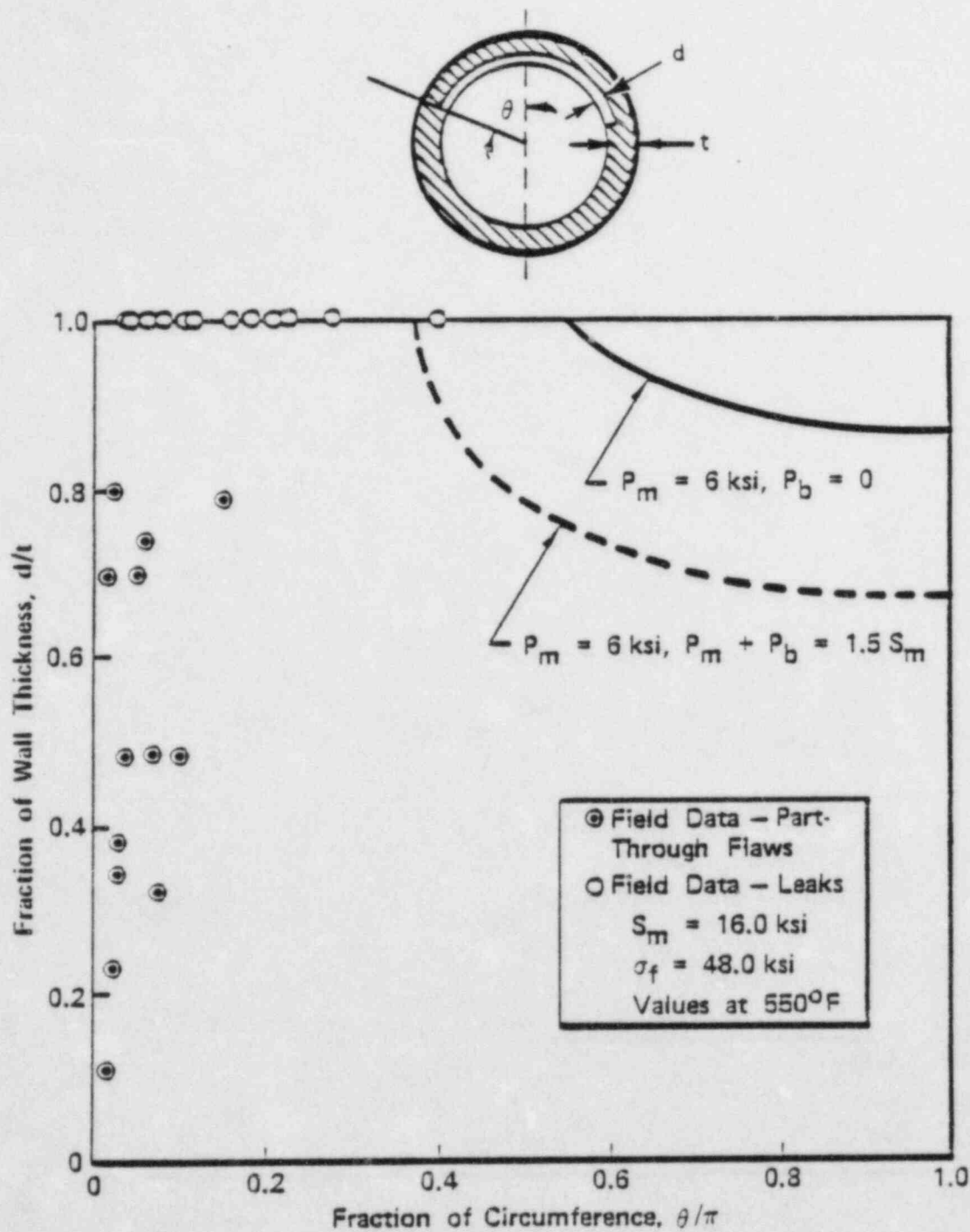
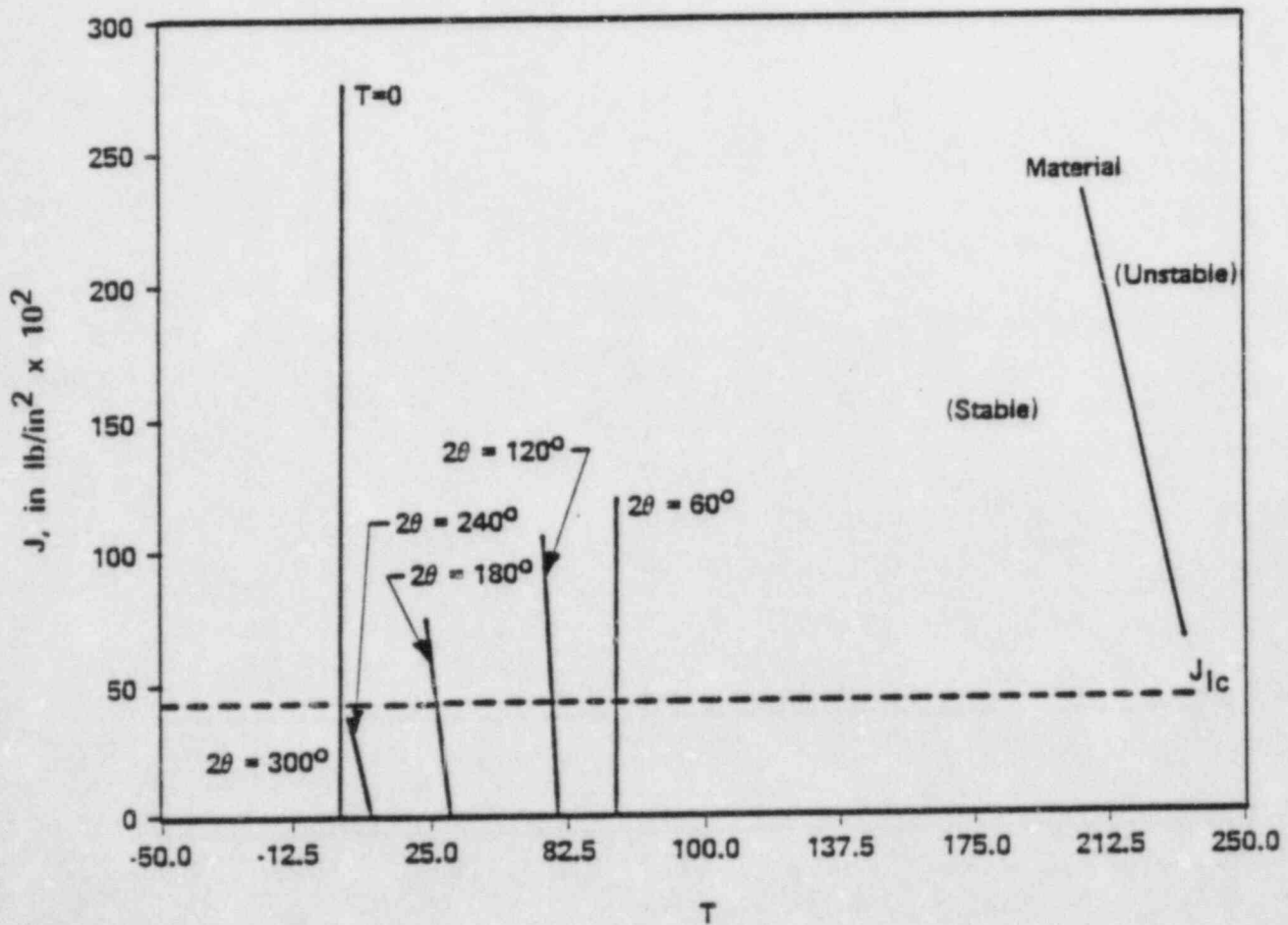
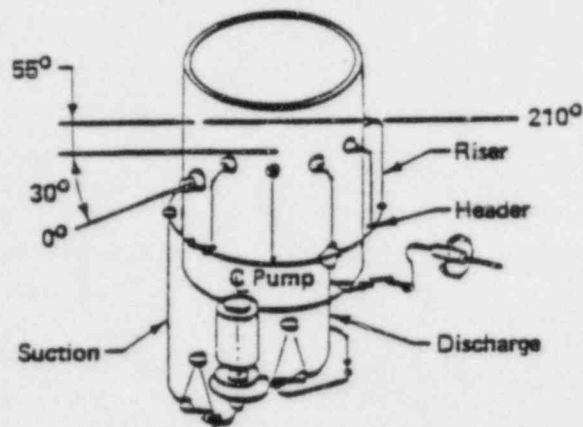


Figure 6.1  
TYPICAL RESULT OF NET SECTION COLLAPSE ANALYSIS OF  
CRACKED STAINLESS STEEL PIPE

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GPC-07-102  
Revision 1





FGPC83.03-37

Figure 6.2  
STABILITY ANALYSIS FOR BWR RECIRCULATION SYSTEM  
(STAINLESS STEEL)

NUMBER OF OBSERVATIONS

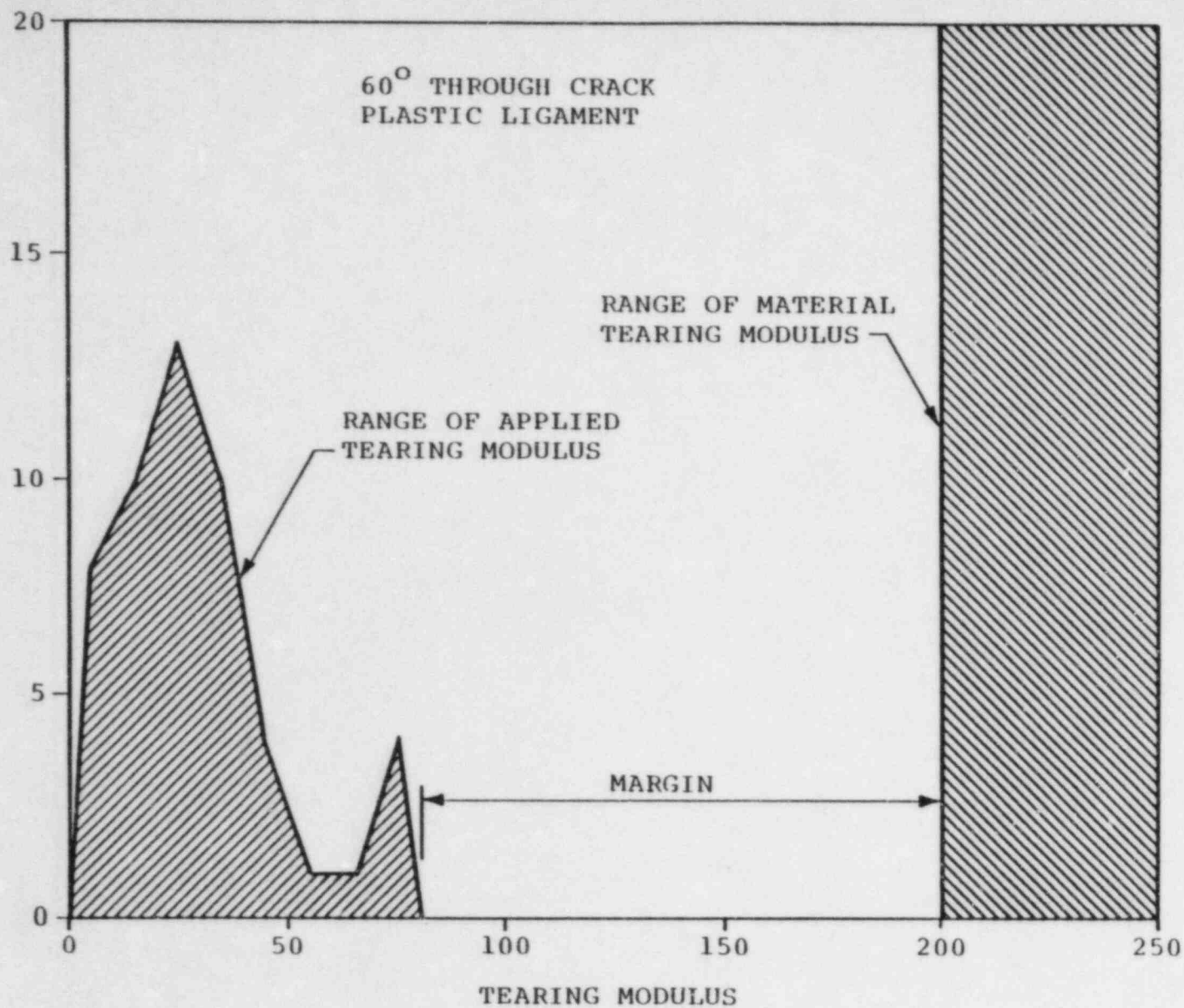
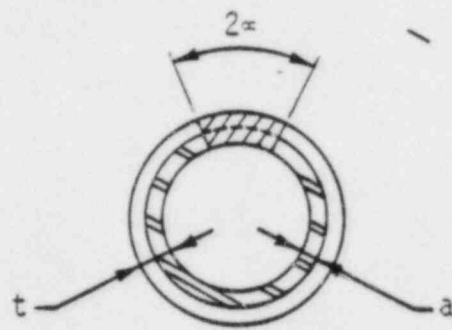


Figure 6.3  
SUMMARY OF LEAK BEFORE BREAK ASSESSMENT  
OF BWR RECIRCULATION SYSTEM

FGPC83,03-38



PIPE CROSS SECTION

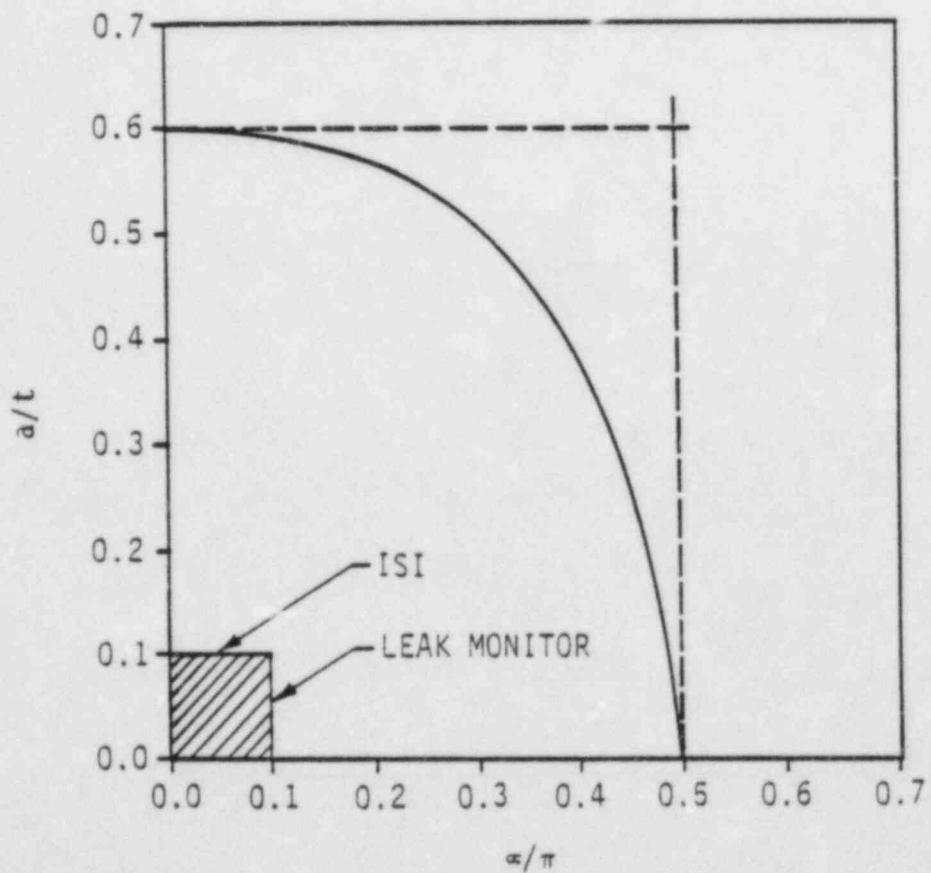


Figure 6.4  
TYPICAL PIPE CRACK FAILURE LOCUS FOR COMBINED  
THROUGH - WALL PLUS 360° PART - THROUGH CRACK

The evaluation of the repairs to the Recirculation System reported herein shows that the resulting stress levels are acceptable for all design conditions. The stress levels have been assessed from the standpoint of load capacity of the components, fatigue, and the resistance to crack growth.

Acceptance criteria for the analyses have been established in Section 3.0 of this report which demonstrate that:

1. There is no loss of design safety margin over that provided by the current Code of Construction for Class 1 piping and pressure vessels (ASME Section III).
2. During the design lifetime of each repair, the observed cracks will not grow to the point where the above safety margins would be exceeded.

Analyses have been performed and results are presented which demonstrate that the unrepaired pipe welds of the Recirculation and RHR systems and the repaired welds of

the Recirculation system satisfy the acceptance criteria by a large margin, and that:

1. The design life of each repair is at least five years.
2. The unrepaired flaws will not grow to an unacceptable size for at least the next 5 years.

Furthermore, it is concluded that recent IGSCC experienced in the Recirculation and RHR systems at Hatch 2 does not increase the probability of a design basis pipe rupture at the plant. This conclusion expressly considers the nature of the cracking which has been repaired at Hatch 2, and the likelihood that other similar cracking may have gone undetected. The conclusion is based primarily on the extremely high inherent toughness and ductility of the stainless steel piping material, the tendency of cracks in such piping to grow through-wall and leak before affecting structural load carrying capacity of the piping, and the fact that as cracks lengthen and are less likely to "leak-before-break", they become more amenable to detection by other NDE techniques such as UT and RT.



1. ASME Boiler and Pressure Vessel Code Section III, Subsection NB, 1980 Edition.
2. ASME Boiler and Pressure Vessel Code Section XI, Paragraph IWB-3640 (Proposed), "Acceptance Criteria for Austenitic Steel Piping" (Approved by Main Committee in March 1983 for incorporation into Section XI).
3. General Electric Stress Report 22A4264, Revision 0.
4. General Electric Design Specification 22A1344, Revision 3.
5. Bechtel Power Corporation letter to J. E. Charnley, dated May 20, 1983, "E. I. Hatch Nuclear Plant Unit 2, Bechtel Job 6511-034-D3063, Recirculation Line Welding Repair File: A19.3/A21.1 (DCR83-63)."
6. ASME Boiler and Pressure Vessel Code Section XI, 1980 Edition with Addenda through Winter 1981.

7. Rybicki, E. F., and McGuire, P. A., "The Effects of Induction Heating Parameters on Controlling Residual Stress in Intermediate Size Pipes," American Society of Mechanical Engineers, 81-PVP-31.
8. Bertossa, D. C., et al, "Techniques to Mitigate BWR Pipe Cracking in Existing Plants (Induction Heating Stress Improvement)", Third Semi-annual Progress Report, November 1979-May 1980; NEDC-25146-2, EPRI-RP1394-1, from General Electric to Electric Power Research Institute, May 1980.
9. NUTECH Test Specification for Confirmation Test of Mini Weld Overlay Analytical Model, GPC-07-104, Revision 2, June 1983, File Number GPC007.0104.
10. NUTECH Testing Corporation, Test Plan and Procedure for Test Confirmation of Mini Weld Overlay Analytical Model, GPC-07-103, Revision 0, May 1983, File Number GPC007.0103.
11. ANSYS Computer Program, Swanson Analysis Systems, Revision 4.

12. Schneider, P.J., "Temperature Response Charts," John Wiley and Sons, 1963.
13. NUTCRAK Computer Program, Revision 0, April 1978, File Number 08.039.0005.
14. EPRI-2423-LD, "Stress Corrosion Cracking of Type 304 Stainless Steel in High Purity Water - a Compilation of Crack Growth Rates," June 1982.
15. EPRI-NP-2472, "The Growth and Stability of Stress Corrosion Cracks in Large-Diameter BWR Piping," July 1982.
16. NUREG-0744, Volume 1 for Comment, "Resolution of the Reactor Materials Toughness Safety Issue."
17. EPRI-NP-2261, "Application of Tearing Modulus Stability Concepts to Nuclear Piping," February 1982.
18. NUTECH Internal Memo, PCR-83-003, "Weld Residual Stress for IGSCC Crack Growth Calculations," March 4, 1983

19. Buchalet, C. B. and Bamford, W. H., "ASTM 8th National Symposium on Fracture Mechanics, 1974," ASTM STP-590, 1975.
20. NUTECH Report NSP-81-105, Revision 2, "Design Report for Recirculation Safe End and Elbow Repairs, Monticello Nuclear Generating Plant," December 1982.
21. NUTECH Computer Program PISTAR, Version 2.0, User's Manual, Volume 1, TR-76-002, Revision 4, File Number 08.003.0300.
22. Presentation by EPRI and BWR Owners Group to U. S. Nuclear Regulatory Commission, "Status of BWR IGSCC Development Program," October 15, 1982.
23. Bushnell, D., "Stress, Stability, and Vibration of Complex Branched Shells of Revolution: Analysis and User's Manual for BOSOR4," Naval Ship Research and Development Center Report LMSC-0243605, 1972.



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