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DESIGN REPORT
FOR
RECIRCULATION LINE
SAFE END AND ELBOW REPAIRS
MONTICELLO
NUCLEAR GENERATING PLANT

Prepared for:
Northern States Power Company

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

Prepared by:

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

Reviewed by:

P. E. Reeves for
R. H. Smith
Project Quality Assurance Engineer

Approved by:

for P. C. Riccardella, P.E.
Senior Director

Issued by:

Norman Eng
N. Eng
Project Manager

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NAME / TITLE	INITIALS
J. E. Charnley/Principal Engineer	JEC
J.F. Copeland/Staff Consultant for P. C. Riccardella/Senior Director	JFC
S. Kulat/Consultant I	S.D.K.
H. L. Gustin/Engineer	HLG
Y. S. Wu/Consultant I	YSW

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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 States of Minnesota and California and am competent to review this document.

Certified by:

J. E. Charnley

J. E. Charnley

Professional Engineer
State of Minnesota
Registration No. 14372
State of California
Registration No. 16340

Date 17 November 1982

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1.0 INTRODUCTION

This report summarizes evaluations performed by NUTECH to assess weld overlay repairs of recirculation inlet safe end and elbow welds at Northern States Power Company's Monticello Nuclear Generating Plant. Weld overlay repairs have been applied to address leakage and additional ultrasonic and radiographic 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 required design life of each weld overlay repair is at least one fuel cycle. The amount that the actual design life exceeds one fuel cycle will be established by a combination of future analysis and testing.

Leakage was observed adjacent to three safe end to pipe welds (RREJ-3, RRFJ-3, and RRCJ-3). In addition, small crack indications have been detected adjacent to a riser to elbow weld (RRDJ-5). All four of these welds were repaired with the weld overlay design evaluated in this report.

Figure 1.1 shows the safe ends and the elbow in relation to the reactor pressure vessel (RPV) and other portions of the recirculation system.

The existing pipe material is ASTM A358, Class 1, Type 304. The existing safe end material is SA336, Grade F8. The existing elbow material is ASTM, A240, Type 304.

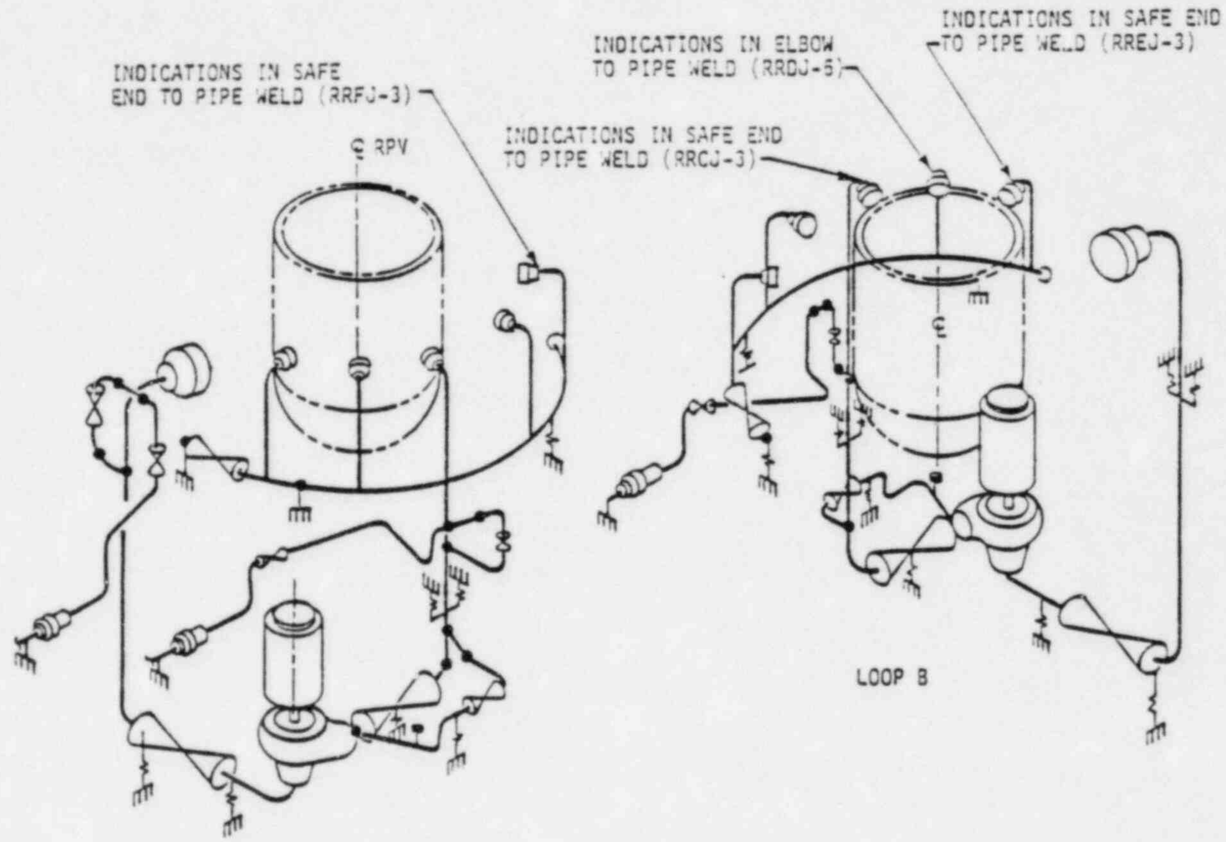

Figure 1.1

CONCEPTUAL DRAWING OF RECIRCULATION SYSTEM

2.0 REPAIR DESCRIPTION

The through wall cracks and other indications around and to both sides of the existing safe end and elbow 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 and 2.2. The weld deposited band over the through wall crack will provide wall thickness equal that required for the adjacent uncracked piping. In addition, the weld metal deposition will produce a favorable compressive residual stress pattern and the weld metal will be type 308L, which is resistant to propagation of IGSCC cracks.

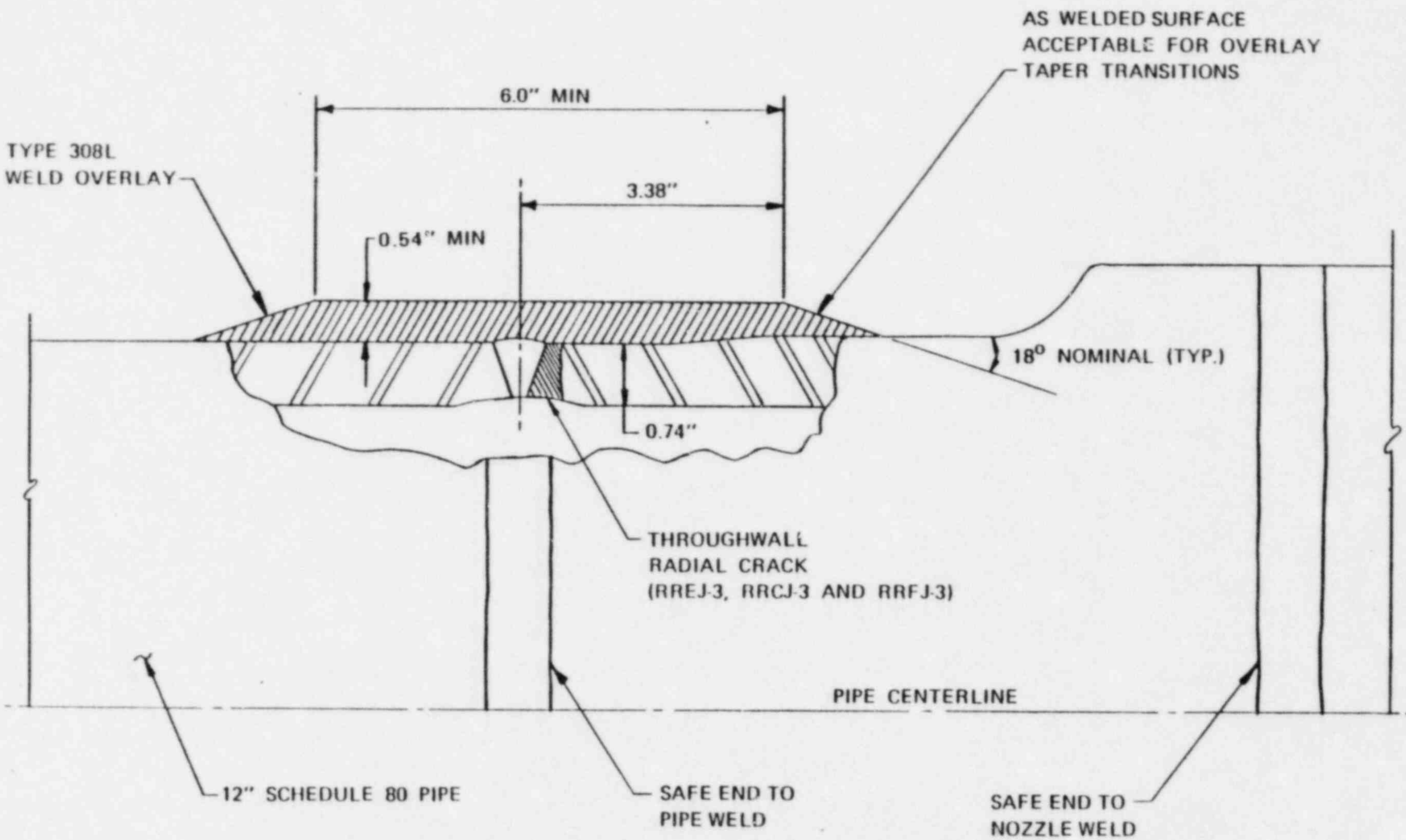

Figure 2.1
SCHEMATIC OF SAFE END TO PIPE WELD OVERLAY
(THERMAL SLEEVE OMITTED)

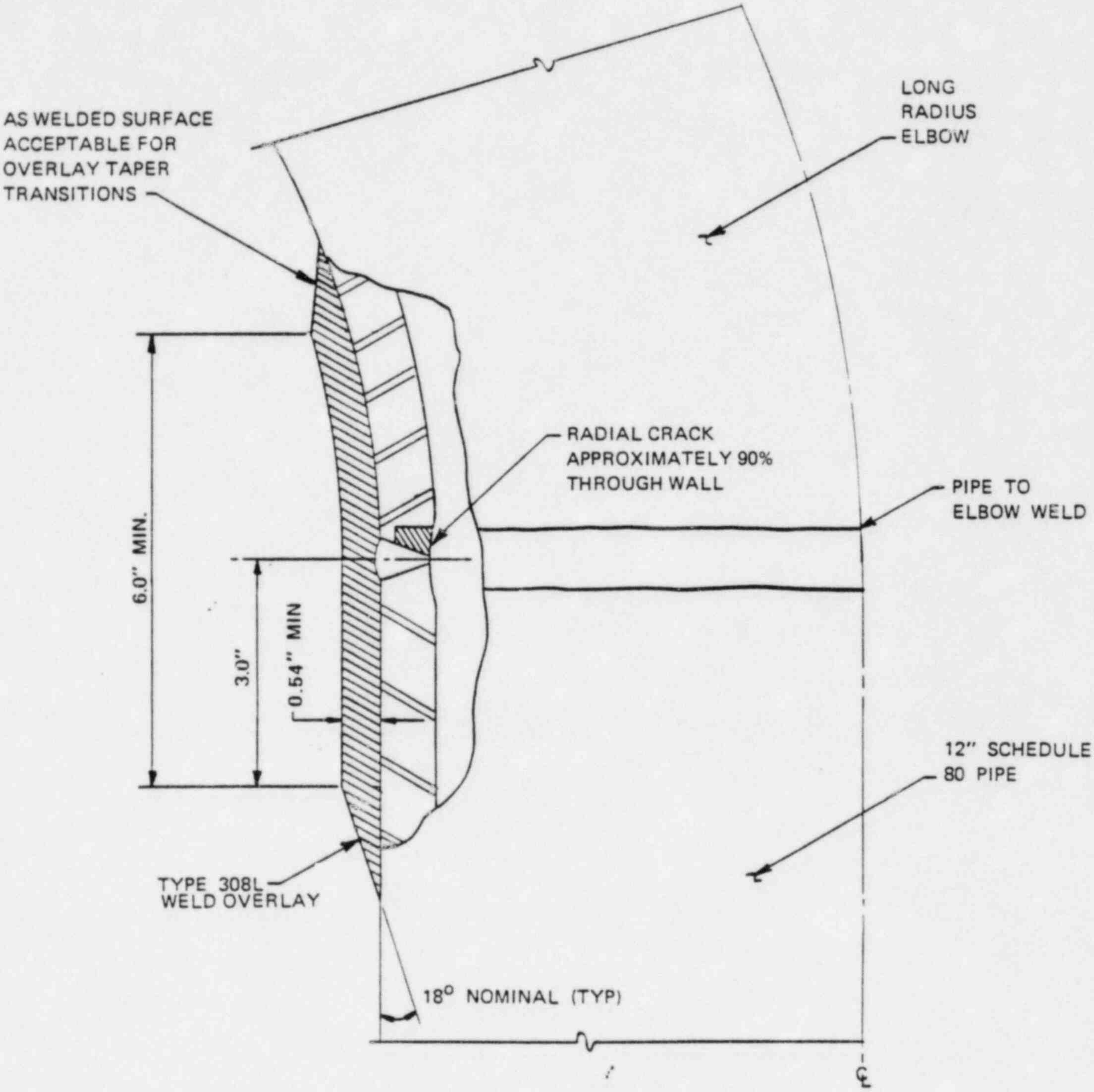

Figure 2.2
SCHEMATIC OF ELBOW TO PIPE WELD OVERLAY

3.0 EVALUATION CRITERIA

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 Strength Evaluation

Adequacy of the strength of the weld overlay repairs with respect to applied mechanical loads is demonstrated with the following criteria:

1. An ASME Boiler and Pressure Vessel Code Section III, Class 1 (Reference 1) analysis of the safe end weld overlay repairs was performed using the worst case loads for any recirculation inlet safe end. An ASME Boiler and Pressure Vessel Code, Section III, Class 1 analysis of the elbow weld overlay repair was performed using the worst case loads for any recirculation inlet elbow.

2. The ultimate load capacity of the 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.

3.2 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 include:

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, as well as a fatigue strength reduction factor of 5.0 to account for the existing crack, 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. Allowable number of cycles was determined from the stainless steel fatigue curve of Reference 1.

3.3 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 the cracked and repaired safe end and elbow welds (Reference 2).

The design life of each repair was established as the minimum of either the predicted time for the observed through wall crack to grow to the allowable crack depth or five years.

4.0 LOADS

The loads considered in the evaluation of the safe end and elbow weld overlay repairs consist of 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 described in Section 5.2.2.

4.1 Mechanical and Internal Pressure Loads

The design pressure of 1248 psi for the recirculation system was obtained from Reference 3. The dead weight and seismic loads applied to the safe end and elbow welds were obtained from the recent NUTECH analysis of the Monticello Reactor Recirculation System piping (Reference 4). The highest loads for any recirculation inlet safe end were applied to the safe end weld overlay. Thus the safe end weld overlay analysis applies to all recirculation inlet safe ends. The highest loads for any recirculation inlet elbow were applied to the elbow weld overlay. Thus, the elbow weld overlay analysis applies to all recirculation inlet elbows.

4.2 Thermal Loads

The thermal expansion loads for the highest loaded recirculation inlet safe end and elbow were also obtained from Reference 4 and applied to the weld overlay repairs.

The only transient thermal condition defined in Reference 4 that occurs at the safe ends or elbows is the normal startup and shutdown cycling. The maximum allowable heatup or cooldown rate is 100°F per hour.

An additional thermal transient was defined in the RPV Design Specification (Reference 5) to account for potential low pressure coolant injection (LPCI) into the recirculation system during a loss of coolant accident (LOCA). The thermal transient was very conservatively defined as a step change in water temperature from 546°F to 90°F at a flow velocity of 10 feet per second. One of these LPCI cycles is assumed to occur every five years (Reference 6). Also defined in Reference 6 is a thermal transient based on actual plant operation due to the initiation of shutdown cooling. The shutdown cooling transient is defined as a 50°F step change in water temperature and it occurs 10 times per year.

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5.0 EVALUATION METHODS AND RESULTS

The evaluation of the weld overlay repairs consists of a code stress analysis per Reference 1 and a fracture mechanics evaluation per Section XI (Reference 7).

5.1 Code Stress Analysis

The weld overlayed regions were assumed to be axisymmetric. That is, a through wall radial crack was conservatively assumed to be 360 degrees around the pipe and one inch long centered on the existing safe end and elbow welds. Thus the assumed crack conservatively envelopes all observed cracks in the safe end and elbow welds. In addition, all analyses were conservatively performed using a weld overlay thickness of 0.50 inch which is seven percent smaller than the actual minimum thickness of 0.54 inch. A finite element model of the cracked and weld overlayed region was developed using the ANSYS (Reference 8) computer program. Figure 5.1 shows the model. The pressure stress profile for a design pressure of 1248 psi was calculated with this model. The results are shown in Figure 5.2.

The ANSYS model was also used for the rapid thermal transients. The exterior boundary was assumed to be insulated. The temperature distribution in the weld overlay subject to the normal start up cycle defined in Section 4.2 can be readily calculated using Chart 16 of Reference 9. The maximum through wall temperature difference was determined to be less than 2°F for the normal startup cycle.

The maximum thermal stress for use in the fatigue crack growth analysis was calculated by hand using the method in Reference 10 for the normal startup transient and was calculated directly by the ANSYS model for the LPCI and shutdown cooling transients. The results are given in Table 5.1 for all three thermal transients. The through wall thermal stresses listed in Table 5.1, which were calculated without the beneficial presence of the secondary thermal sleeve, are classified as peak stresses. Thus the only ASME code limit for them is the fatigue usage factor.

The results of a code stress analysis per Reference 1 are given in Table 5.2. The allowable stress values given in Table 5.2 are based on Reference 1, Article NB 3600 limits. All results apply to the most limiting case of either the safe end or elbow weld overlay repair.

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 10 startups and shutdown cooling initiation cycles per year plus one LPCI injection every five years. The results are summarized in Table 5.2.

5.2 Fracture Mechanics Evaluation

Three types of fracture mechanics evaluations were performed. The allowable crack depth was calculated based on Reference 3. Crack growth due to both fatigue and IGSCC was calculated using the NUTECH computer program NUTCRAK (Reference 11) with material constants and methodology from References 12 and 13. Finally, the ultimate margin to failure for a crack assumed to propagate all the way around the original safe end or elbow material to the weld overlay was calculated per References 14 and 15. All analyses summarized below apply to the most limiting case of either the safe end or elbow weld overlay repair.

5.2.1 Allowable Crack Depth

The allowable depth for a 1 inch long radial crack was determined using Reference 2. The dimensions of the limiting section of the safe end repair were used. Thus, the ratio of applied primary stress to Code allowable stress (S_m) was calculated in the following manner:

$$\text{Stress Ratio} = \frac{PR/t}{Sm}$$

P	=	1248 psi (Design Pressure)
R	=	6.915 inches (Outside Radius of Overlay)
t	=	1.187 inch (Minimum Thickness of Pipe plus Overlay)
S_m	=	16,900 psi (Table 5.2)

Substitution yields:

Stress Ratio = .43

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The nondimensional crack length was calculated in the following manner:

$$\text{Nondimensional Length} = \frac{L}{(Rt)^{1/2}}$$

L = 1 inch

R = 6.915 inches

t = 1.187 inch

Substitution yields:

Nondimensional Length = .35

Thus per Table IWB-3642-1 of Reference 2, the allowable crack depth is 75 percent of the wall thickness. The allowable crack depth is then 0.89 inch.

5.2.2 Crack Growth

The existing through wall crack 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 material properties from Reference 13. The fatigue cycles considered are shown in Figure 5.3.

The steady state axial stresses in the weld overlay are significantly higher than the hoop stresses. Thus fatigue crack growth will be predominately in the radial direction. The model used to calculate fatigue crack growth conservatively assumed that the through wall crack was a circumferential crack 360° around the weld. Thus the results from this model are conservative compared to the actual case of a short axial through wall crack. The fatigue crack growth law used is given in Table 5.3.

Steady state axial stress due to pressure, dead weight, thermal expansion and weld residual stress were considered. The stress due to pressure, dead weight and thermal expansion were obtained from the ANSYS model. The weld residual stress due to the original weld, combined with the through wall crack and the weld overlay repair is difficult to estimate. It was judged that the weld residual stress due to the original weld was significantly reduced by the through wall crack and the weld overlay repair. Thus two bounding weld residual stress distributions were considered. The first distribution was zero residual stress and the second was a through wall bending stress of 36 ksi, with compression on the inside surface.

Fatigue crack growth is not a strong function of steady state stresses such as weld residual stress. Thus the fatigue crack growth for both assumed weld residual stress distributions were similar. The total radial crack growth due to fatigue for five years of operation (Figure 5.3) was determined to be approximately 0.005 inch, which is well below the allowable crack growth of 0.24 inch. The model that was used and the fatigue crack growth as a function of time are shown in Figure 5.4.

The existing crack will not grow due to IGSCC into the IGSCC resistant weld overlay. However, it could grow axially due to the average value across the thickness of the steady state hoop stresses. The average value of weld residual stress across the thickness is zero for all three residual stress distributions used in Reference 10 as well as for the two distributions described above. The hoop stress is caused only by pressure. Two IGSCC growth laws were considered based on the data compiled in Reference 12. The growth laws are given in Table 5.3. The crack was assumed to be through wall and one inch long as shown in Figure 5.5. It should be noted that the weld overlay will help

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arrest crack propagation, but the extent of this beneficial effect is not known. For this reason, the crack was conservatively modeled as a one inch long through wall crack in a 0.622 inch thick infinite plate. The plate thickness is that of the pipe without the overlay for analysis purposes.

Using this conservative model, the axial IGSCC growth of the crack for five years of operation was determined to be approximately 0.009 inch. When this small increase in crack length is added to the actual crack configuration (Figure 5.5), the crack is still well within the limits of the weld overlay. The IGSCC growth as a function of time is also shown in Figure 5.5.

5.2.3 Tearing Modulus

The largest size to which the existing crack could reasonably be expected to grow was postulated to be a 0.75 inch radius flaw. This assumes growth of the crack in the axial direction, even though such propagation is not predicted by the analysis of Section 5.2.2. After such propagation, the assumed crack would be completely surrounded by IGSCC resistant material: the weld between safe end (elbow) and pipe, the weld overlay, and the safe end (elbow). A tearing modulus evaluation was then performed for this postulated crack. The applied loads are pressure, dead weight, seismic and thermal expansion.

The evaluation was performed using the methodology of Reference 14 with material properties from Reference 15.

The postulated flaw and the results are shown in Figure 5.6. 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 combination moving up this line, and unstable fracture is predicted at the intersection of this applied loading line with the material resistance line.

Figure 5.6 shows that the predicted burst load is in excess of five times the actual loading. Thus, there is a safety factor for normal loads including OBE seismic of at least five, which is well in excess of the safety factor inherent in the ASME Code, even in the presence of this worst case assumed crack. The analogous safety factor for SSE seismic is also well in excess of that required by the ASME Code for low probability events.

5.3 Effect on Recirculation System

Installation of the weld overlay repairs will cause a small amount of radial and axial shrinkage underneath the overlay. Based on measurements of a welding mockup, the maximum radial shrinkage will be 3/16 inch and the maximum axial shrinkage will be 1/64 inch. These measured shrinkages are conservative compared to the expected actual overlay shrinkage because the weld overlay thickness of the mockup was 0.9 inch compared to the actual weld overlay thickness 0.54 inch.

The effect on the recirculation system of the maximum expected weld shrinkage was evaluated. Figure 5.7 shows the configuration of the safe end, nozzle and thermal sleeve without an overlay. The effect of the shrinkage on the low alloy steel nozzle, the thermal sleeve and the crotch of the safe end was determined by extending the ANSYS model to include these areas. The model was also extended to the centerline of the 12" riser pipe. The revised ANSYS model is shown in Figure 5.8.

The measured shrinkages from the weld mockup were imposed as boundary conditions on this model. The resulting stresses are steady state secondary stresses (similar to other weld residual stresses) and thus are not limited by the ASME Code (Reference 1). A plot of the deformed model is shown (greatly exaggerated) in Figure 5.9. The most significant results of this analysis are listed below.

1) The calculated longitudinal displacement at the centerline of the 12" riser is 0.004 inch, which induces a stress of less than 1.0 ksi at the sweepolet to manifold weld. There is no radial displacement at this location.

2) The displacements at the weld between the safe end and the low alloy nozzle are less than 0.001 inch and the induced stresses are less than 1.0 ksi.

3) The radial displacement at the crotch of the safe end is 0.005 inch and the axial displacement is less than 0.001 inch. The induced stresses are less than yield stress.

4) The maximum compressive strain underneath the weld overlay is approximately three percent which agrees with the imposed radial displacement divided by the radius ($\frac{3/16}{5.69}$ = 0.03). All the parts of the safe end and thermal sleeves (ring nut, plate spring, set screws, thermal sleeve and safe end) were fabricated from either 304 stainless steel or Inconel X-750 (References 16 and 17). Both of these materials can withstand compressive three percent steady state secondary strain without significant deleterious effect.

The threads between the safe end and the ring nut will be forced tightly together. It will be almost impossible to unthread the ring nut, however the only time when ring nut removal is required is during safe end replacement. If this becomes necessary, then the ring nut and safe end can both be removed by cutting.

5) All stresses are below yield stress at an axial distance from the centerline of the safe end to pipe weld of greater than 8.0 inches. Thus, the significant effects of the weld overlay are limited to the region within approximately four inches of the ends of the overlay.

PARAMETER	NORMAL STARTUP CYCLE (CYCLE 1)	INITIATION SHUTDOWN COOLING CYCLE (CYCLE 2)	LPCI CYCLE (CYCLE 3)
EQUIVALENT LINEAR TEMPERATURE ΔT_1	2^oF	*	*
PEAK TEMPERATURE ΔT_2	0	*	*
THROUGH WALL THERMAL STRESS σ	368 PSI	6770 PSI	61,730 PSI

* VALUES NOT EXPLICITLY DETERMINED AS TRANSIENTS WERE EVALUATED WITH ANSYS MODEL.

Table 5.1

THERMAL STRESS RESULTS

CATEGORY	EQUATION NUMBER	ACTUAL STRESS OR THICKNESS	SECTION III NB ALLOWABLE
S		NA	S_m = 16,900 PSI
REQUIRED THICKNESS	(1)	0.54"	0.50"
PRIMARY	(9)	23,170 PSI	25,350 PSI
PRIMARY + SECONDARY	(10)	39,110 PSI	50,700 PSI
PEAK CYCLE 1 CYCLE 2 CYCLE 3	(11)	* (40,678)5 (29,964)5 (84,920)5	N/A
USAGE FACTOR (40 YR)		0.60	1.0

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

Table 5.2

CODE STRESS ALLOWABLES 12" SAFE END AND ELBOW

CASE	GROWTH LAW $\frac{da}{dT}$ or $\frac{da}{dN}$
FATIGUE*	$2.84 \times 10^{-8} K^{2.57}$
IGSCC BEST ESTIMATE**	$1.843 \times 10^{-12} K^{4.615}$
IGSCC WORST CASE***	$4.116 \times 10^{-12} K^{4.615}$

* EPRI NP2423-LD JUNE 1982 8ppm O_2 DATA

** BEST ESTIMATE EPRI NP2423-LD JUNE 1982 0.2ppm O_2 DATA

*** UPPER BOUND EPRI NP2423-LD JUNE 1982 0.2ppm O_2 DATA

Table 5.3

CRACK GROWTH CASES

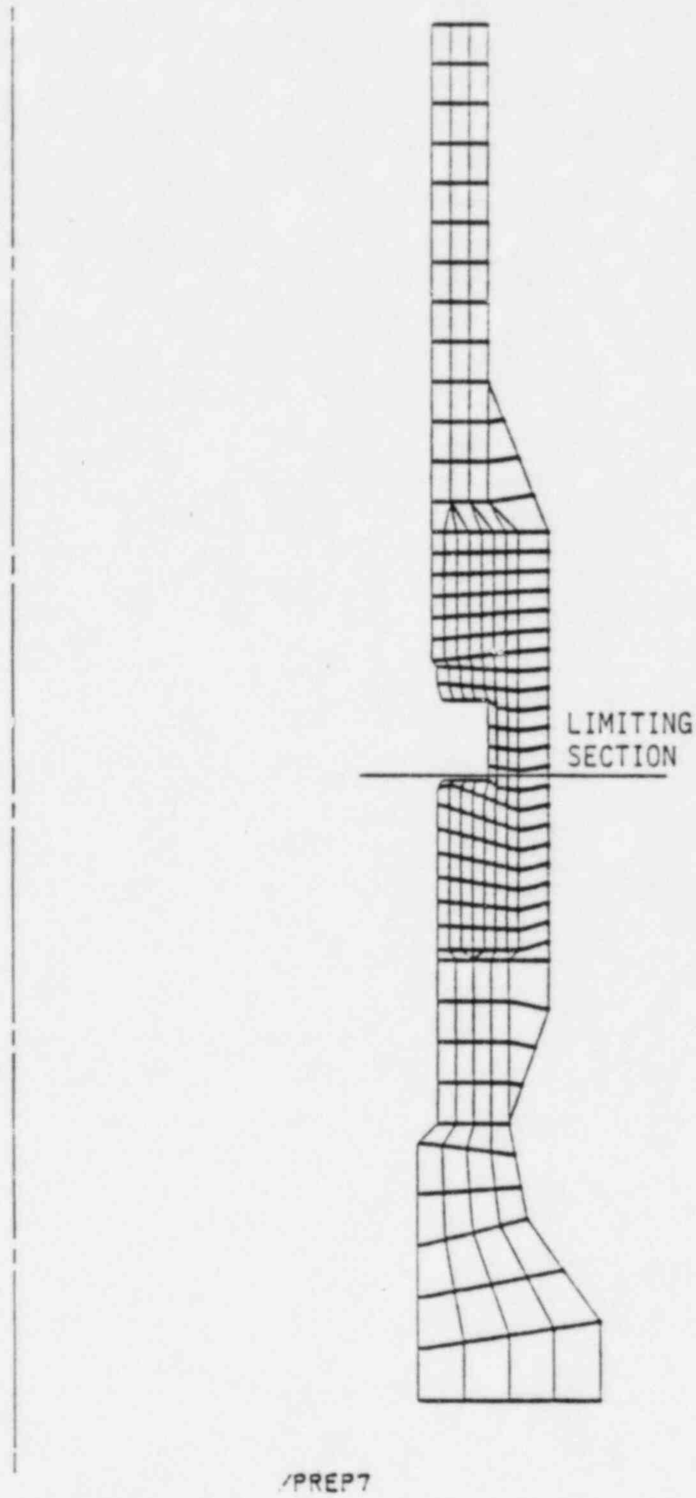

Figure 5.1
ANSYS MODEL OF 12" SAFE END AND ELBOW WELD OVERLAY

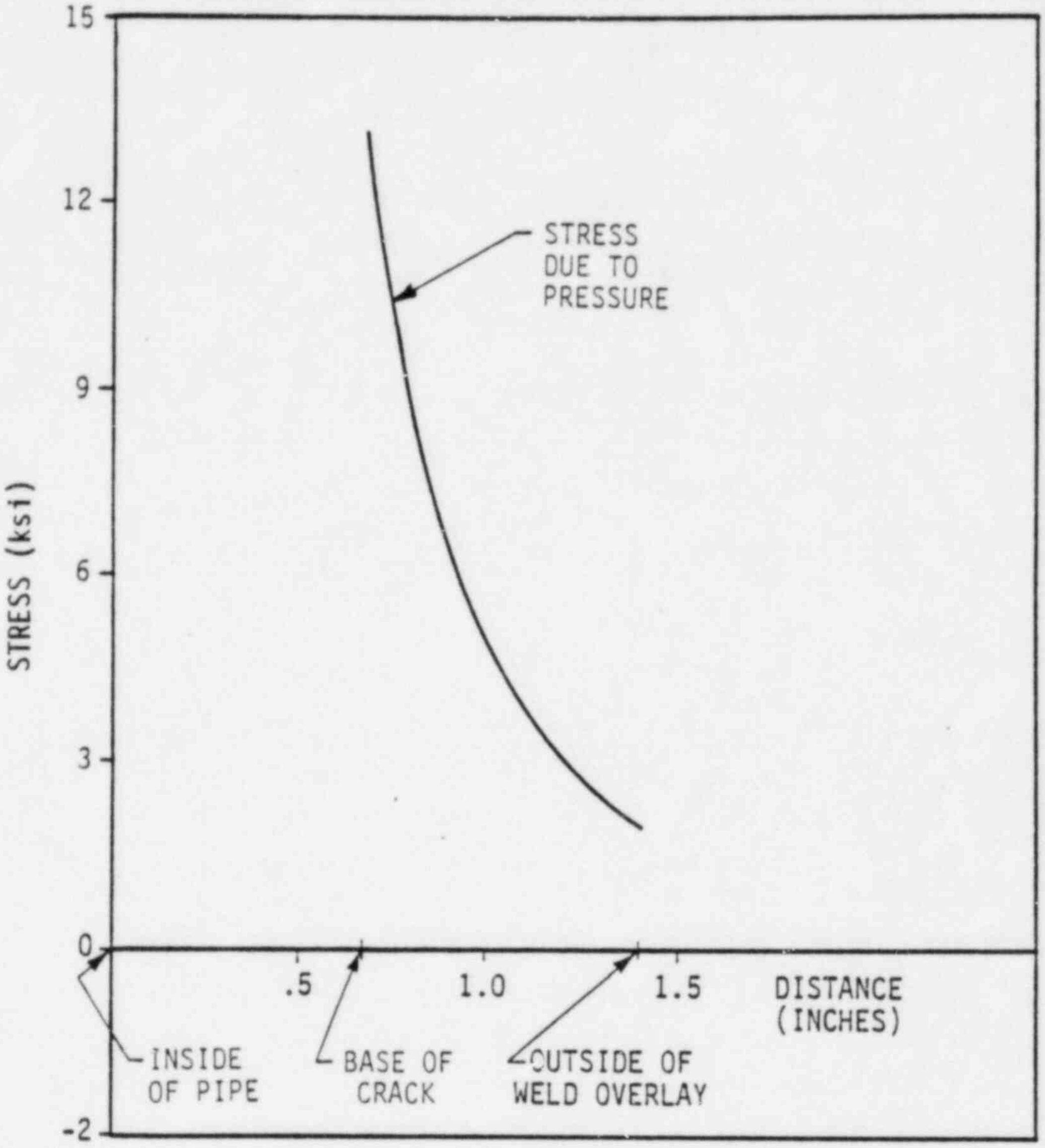

Figure 5.2

APPLIED STRESS PROFILE THROUGH LIMITING
SECTION 12" SAFE END

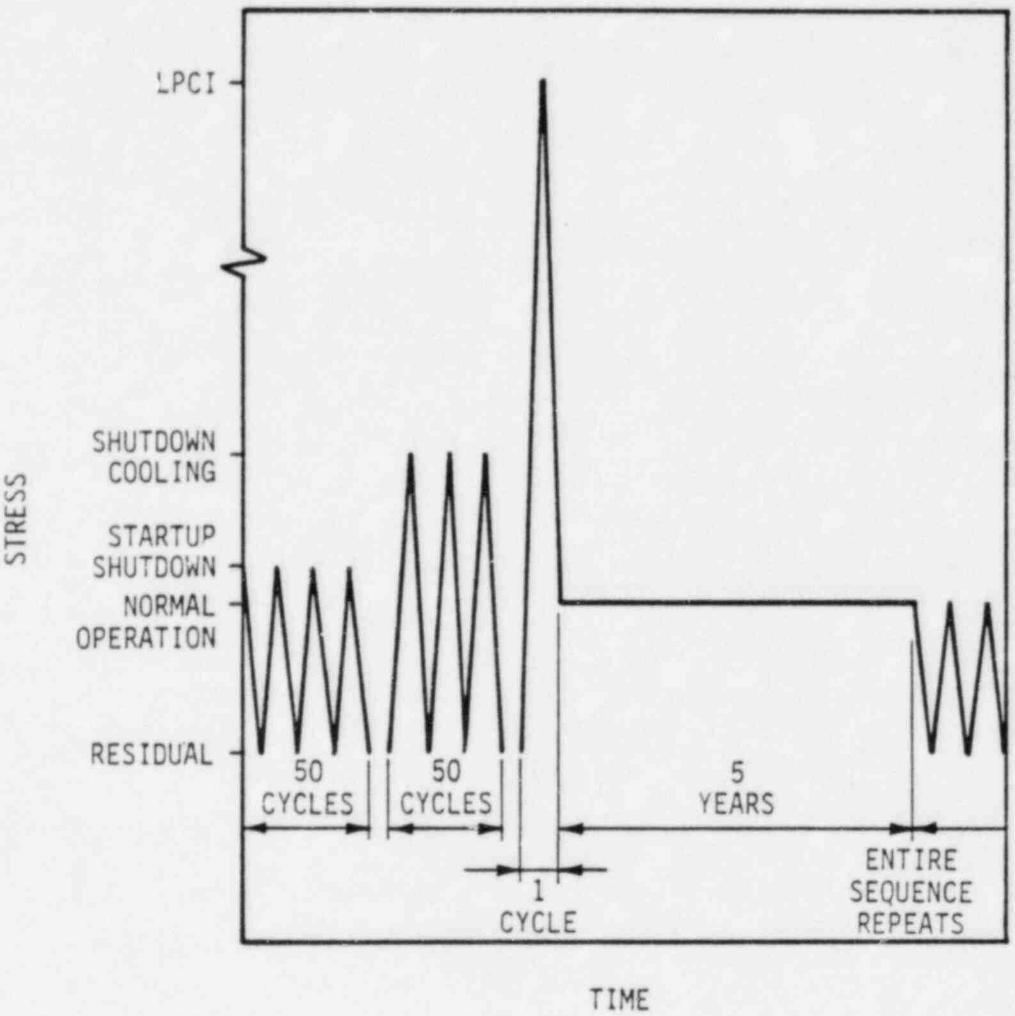

Figure 5.3
THERMAL TRANSIENTS

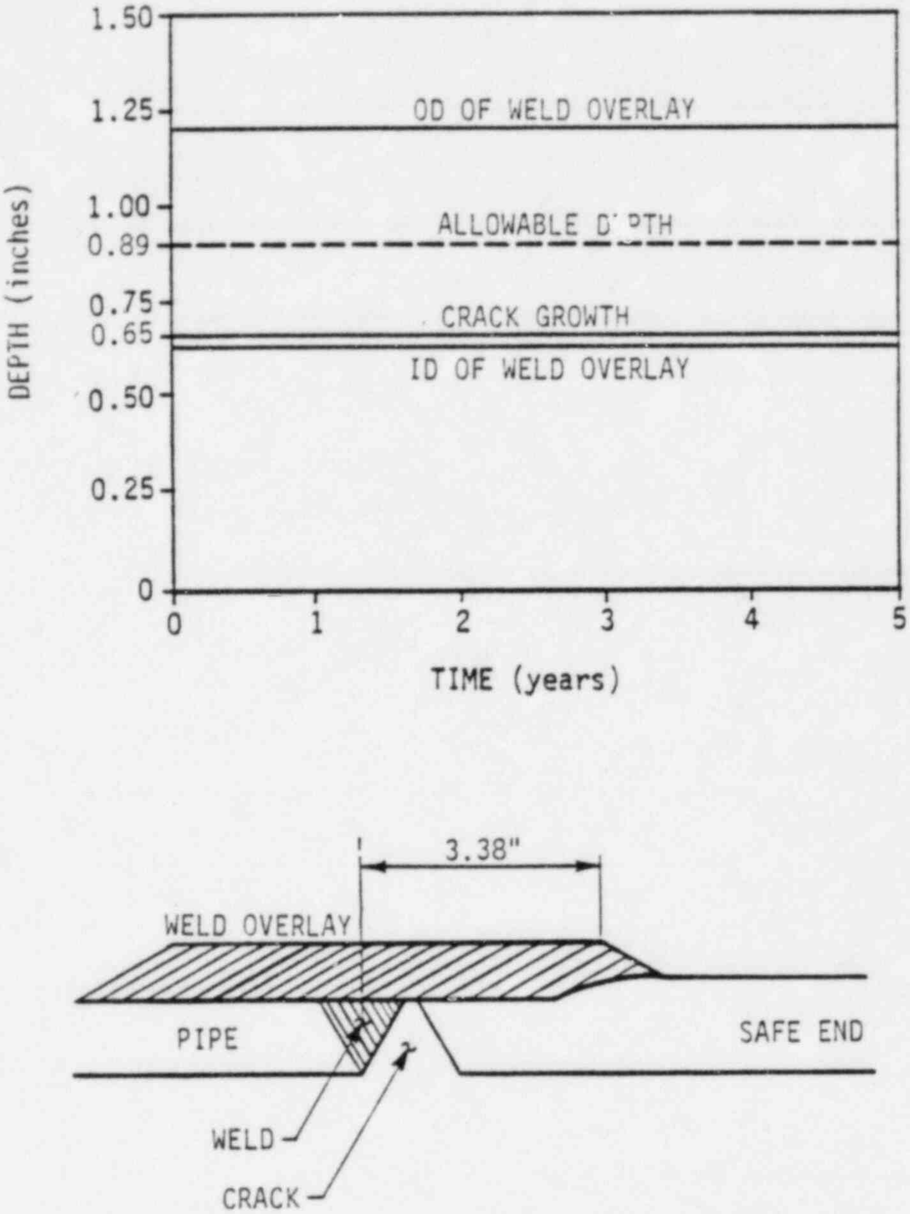

Figure 5.4

RADIAL CRACK GROWTH 12" SAFE END AND ELBOW

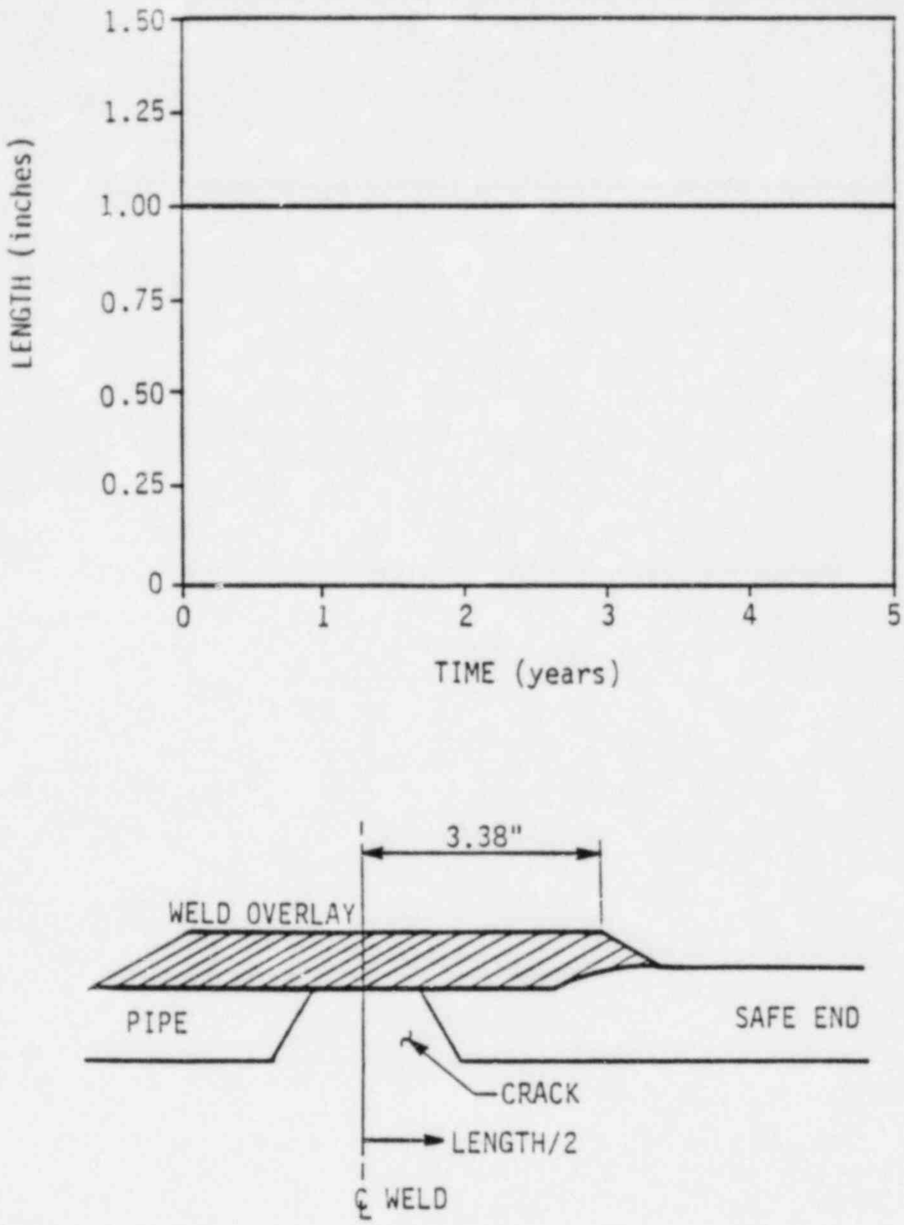

Figure 5.5
AXIAL CRACK GROWTH 12" SAFE END AND ELBOW

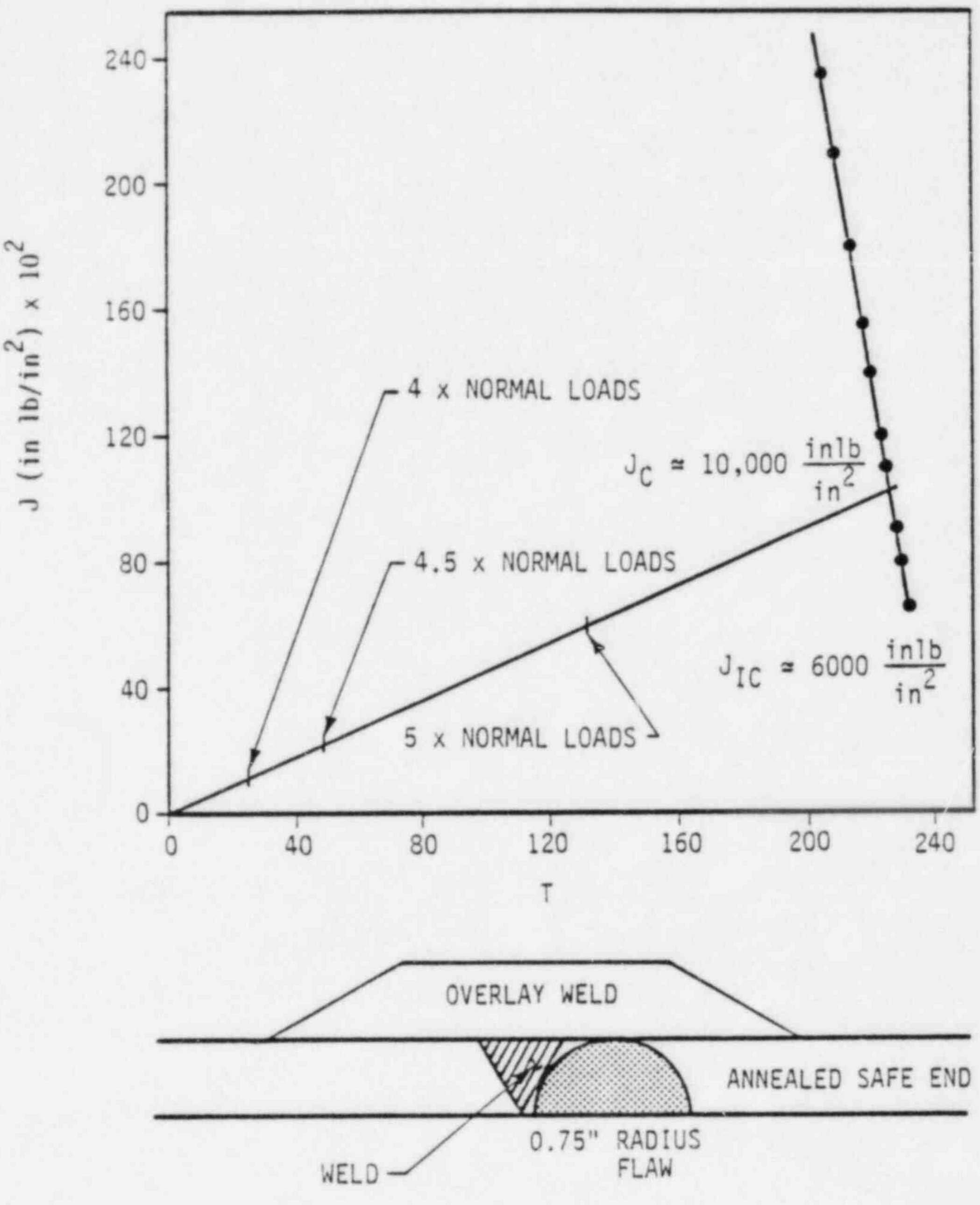

Figure 5.6

TEARING MODULUS 12" SAFE END AND ELBOW

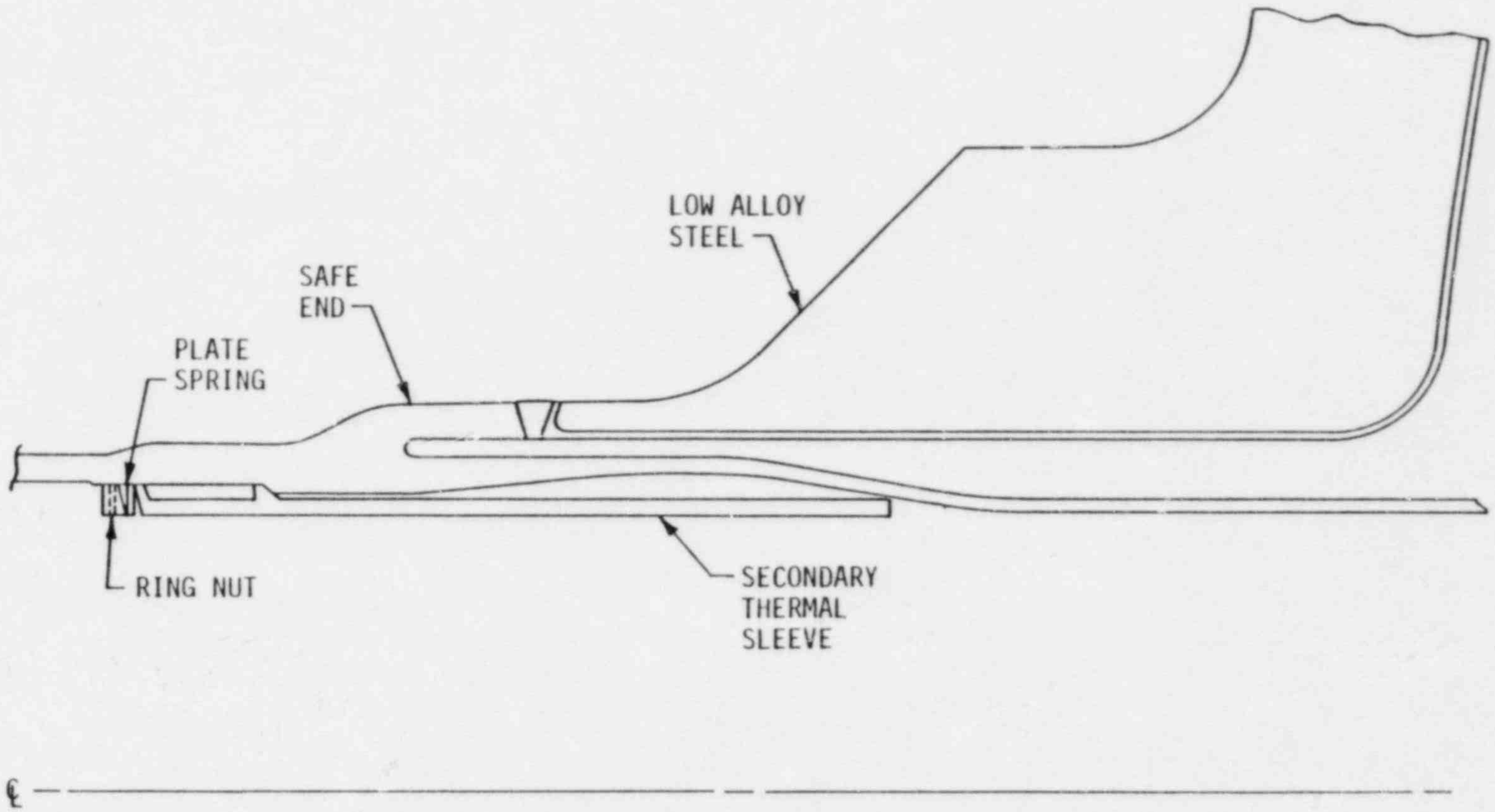

Figure 5.7
ACTUAL GEOMETRY

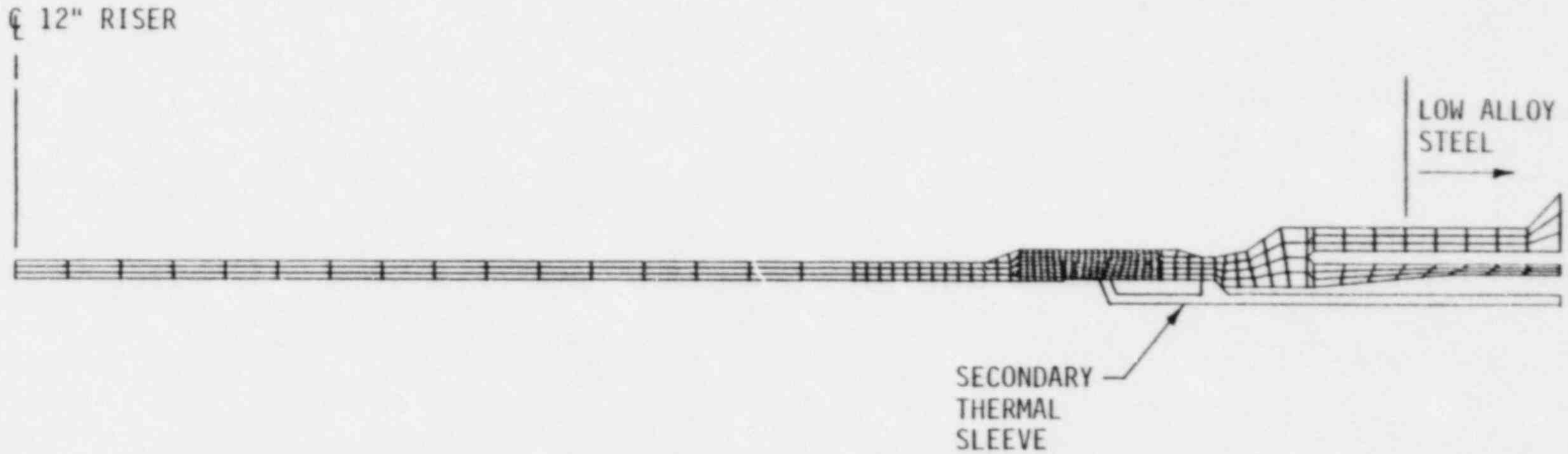

Figure 5.8

REVISED ANSYS MODEL

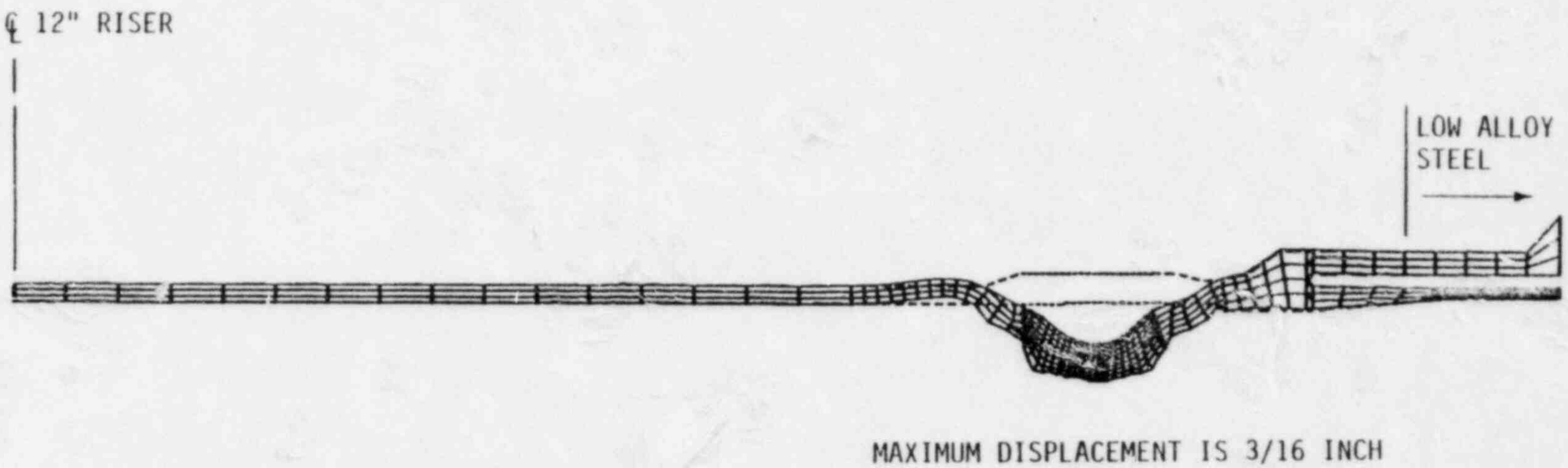

Figure 5.9
DEFORMED GEOMETRY

6.0 SUMMARY AND CONCLUSIONS

The evaluation of the repairs to the recirculation elbow and safe end 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 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 those provided by both the original Construction Code for the piping system (B31.1) or 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 repaired welds satisfy these criteria by a large margin, and that the design life of each repair is at least five years.

7.0 REFERENCES

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2. ASME Boiler and Pressure Vessel Code Section XI, Article IWB-3640 (Proposed), "Acceptance Criteria for Flaws in Austenitic Stainless Steel Piping" (Presented to Section XI Subgroup on Evaluation Standards in September 1982).

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4. "NUTECH Reanalysis of the Reactor Recirculation Piping System," Letter to S. J. Hammer from G. A. Wiederstein, GAW-82-014, File Number 30.2354.0003.

5. Purchase Specification for Monticello Reactor Pressure Vessel, General Electric Document Number 21A1112, Revision 6.

6. Telecon between NUTECH (J. E. Charnley and N. Eng) and NSP (S. J. Hammer), "Weld Overlay Repair Program Technical Issues," dated October 20, 1982, File 30.1281.0001.

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8. ANSYS Computer Program, Swanson Analysis Systems, Revision 3.

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10. NUTECH Report NSP-81-103, Revision 0, "Design Report for Recirculation Line End Cap Repair, Monticello Nuclear Generating Plant."

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