

Westinghouse Non-Proprietary Class 3

WCAP-16019-NP
Revision 0

February 2003

Technical Justification for Eliminating 10" Accumulator Lines Rupture as the Structural Design Basis for Callaway Nuclear Power Plant



WCAP-16019-NP Revision 0

Technical Justification for Eliminating 10" Accumulator Lines Rupture as the Structural Design Basis for Callaway Nuclear Power Plant

**D. C. Bhowmick
C. K. Ng**

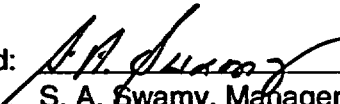
February 2003

Verified:


J. F. Petsche

Structural Mechanics Technology

Approved:


S. A. Swamy, Manager

Structural Mechanics Technology

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

© 2003 Westinghouse Electric Company LLC
All Rights Reserved

TABLE OF CONTENTS

| | |
|--|-----|
| LIST OF TABLES..... | v |
| LIST OF FIGURES | vii |
| 1 INTRODUCTION | 1-1 |
| 1.1 Background | 1-1 |
| 1.2 Scope and Objective | 1-1 |
| 1.3 References..... | 1-2 |
| 2 OPERATION AND STABILITY OF THE ACCUMULATOR LINES..... | 2-1 |
| 2.1 Stress Corrosion Cracking..... | 2-1 |
| 2.2 Water Hammer..... | 2-2 |
| 2.3 Low Cycle and High Cycle Fatigue | 2-2 |
| 2.4 Other Possible Degradation During Service of The Accumulator Lines | 2-3 |
| 3 MATERIAL CHARACTERIZATION..... | 3-1 |
| 3.1 Pipe Materials And Weld Process..... | 3-1 |
| 3.2 Material Properties | 3-1 |
| 3.3 References..... | 3-1 |
| 4 LOADS FOR FRACTURE MECHANICS ANALYSIS | 4-1 |
| 4.1 Nature Of The Loads..... | 4-1 |
| 4.2 Loads for Crack Stability Analysis..... | 4-2 |
| 4.3 Loads for Leak Rate Evaluation..... | 4-2 |
| 4.4 Summary Of Loads And Geometry For The 10" Accumulator Lines | 4-2 |
| 4.5 Governing Locations For The Accumulator Lines | 4-3 |
| 5 FRACTURE MECHANICS EVALUATION | 5-1 |

| | | |
|-------|--|-----|
| 5.1 | Global Failure Mechanism | 5-1 |
| 5.2 | Leak Rate Predictions | 5-2 |
| 5.2.1 | General Considerations | 5-2 |
| 5.2.2 | Calculation Method | 5-2 |
| 5.2.3 | Leak Rate Calculations..... | 5-3 |
| 5.3 | Stability Evaluation | 5-4 |
| 5.4 | References..... | 5-4 |
| 6 | ASSESSMENT OF FATIGUE CRACK GROWTH | 6-1 |
| 6.1 | Introduction | 6-1 |
| 6.2 | Critical Location for Fatigue Crack Growth Analysis..... | 6-1 |
| 6.3 | Design Transients..... | 6-1 |
| 6.4 | Stress Analysis | 6-1 |
| 6.5 | OBE Loads..... | 6-2 |
| 6.6 | Total Stress For Fatigue Crack Growth..... | 6-2 |
| 6.7 | Fatigue Crack Growth Analysis..... | 6-3 |
| 6.7.1 | Analysis Procedure | 6-3 |
| 6.8 | Results | 6-4 |
| 6.9 | References..... | 6-4 |
| 7 | ASSESSMENT OF MARGINS | 7-1 |
| 8 | CONCLUSIONS..... | 8-1 |
| | APPENDIX A - LIMIT MOMENT..... | A-1 |

LIST OF TABLES

| | |
|--|------|
| Table 3-1: Room Temperature Material Properties for the 10" Accumulator Lines | 3-2 |
| Table 3-2 : Representative Tensile Properties for the 10" Accumulator Lines at Operating Temperatures | 3-3 |
| Table 3-3 : Modulus of Elasticity (E) for the 10" Accumulator Lines | 3-3 |
| Table 4-1 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 1 | 4-4 |
| Table 4-2a : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 1 (Case A: 70°F)..... | 4-5 |
| Table 4-2b : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 1 (Case B: 48°F) | 4-6 |
| Table 4-3a : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 1 (Case A: 70°F)..... | 4-7 |
| Table 4-3b : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 1 (Case B: 48°F) | 4-8 |
| Table 4-4 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 2 | 4-9 |
| Table 4-5a : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 2 (Case A: 70°F)..... | 4-11 |
| Table 4-5b : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 2 (Case B: 48°F) | 4-12 |
| Table 4-6a : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 2 (Case A: 70°F)..... | 4-13 |
| Table 4-6b : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 2 (Case B: 48°F) | 4-14 |
| Table 4-7 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 3 | 4-15 |
| Table 4-8a : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 3 (Case A: 70°F)..... | 4-16 |

| | |
|---|------|
| Table 4-8b : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 3 (Case B: 48°F) | 4-17 |
| Table 4-9a : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 3 (Case A: 70°F)..... | 4-18 |
| Table 4-9b : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 3 (Case B: 48°F) | 4-19 |
| Table 4-10 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 4 | 4-20 |
| Table 4-11a :Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 4 (Case A: 70°F)..... | 4-21 |
| Table 4-11b :Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 4 (Case B: 48°F) | 4-22 |
| Table 4-12a :Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 4 (Case A: 70°F)..... | 4-23 |
| Table 4-12b :Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 4 (Case B: 48°F) | 4-24 |
| Table 5-1 : Leakage Flaw Sizes | 5-5 |
| Table 5-2 : Summary of Critical Flaw Sizes | 5-5 |
| Table 6-1 : Design Transients Considered for Fatigue Crack Growth Evaluation..... | 6-5 |
| Table 6-2 : Accumulator Lines Fatigue Crack Growth Results..... | 6-5 |
| Table 7-1 : Leakage Flaw Sizes, Critical Flaw Sizes and Margins | 7-2 |
| Table 7-2 : LBB Conservatism..... | 7-2 |

LIST OF FIGURES

| | | |
|------------|---|------|
| Figure 3-1 | Callaway Nuclear Power Plant 10" Accumulator Line Loop 1 Layout..... | 3-4 |
| Figure 3-2 | Callaway Nuclear Power Plant 10" Accumulator Line Loop 2 Layout..... | 3-5 |
| Figure 3-3 | Callaway Nuclear Power Plant 10" Accumulator Line Loop 3 Layout..... | 3-6 |
| Figure 3-4 | Callaway Nuclear Power Plant 10" Accumulator Line Loop 4 Layout..... | 3-7 |
| Figure 4-1 | Governing Weld Locations for 10" Accumulator Line Loop 2 | 4-25 |
| Figure 4-2 | Governing Weld Location for 10" Accumulator Line Loop 3 | 4-26 |
| Figure 5-1 | Fully Plastic Stress Distribution..... | 5-6 |
| Figure 5-2 | Analytical Predications of Critical Flow Rates of Steam-Water Mixtures | 5-7 |
| Figure 5-3 | [] ^{a,c,e} Pressure Ratio as a Function of L/D | 5-8 |
| Figure 5-4 | Idealized Pressure Drop Profile through a Postulated Crack | 5-9 |
| Figure 5-5 | Loads acting on the Model at the Governing Locations | 5-10 |
| Figure 5-6 | Critical Flaw Size Prediction for Node 3020 | 5-11 |
| Figure 5-7 | Critical Flaw Size Prediction for Node 3120 | 5-12 |
| Figure 5-8 | Critical Flaw Size Prediction for Node 3295 | 5-13 |
| Figure 6-1 | Schematic of Accumulator Line at RCL Cold Leg Nozzle Weld Location | 6-6 |
| Figure 6-2 | Reference Crack Growth Curves for Stainless Steel in Air Environment | 6-7 |
| Figure A-1 | Pipe with A Through-Wall Crack in Bending..... | A-2 |

1 INTRODUCTION

1.1 BACKGROUND

The current structural design basis for the 10" Accumulator lines requires postulating non-mechanistic circumferential and longitudinal pipe breaks. This results in additional plant hardware (e.g. pipe whip restraints and jet shields) which would mitigate the dynamic consequences of the pipe breaks. It is therefore highly desirable to be realistic in the postulation of pipe breaks for the 10" Accumulator lines. Presented in this report are the descriptions of a mechanistic pipe break evaluation method and the analytical results that can be used for establishing that a circumferential type of break will not occur within the Accumulator lines. The evaluations consider that circumferentially oriented flaws cover longitudinal cases.

1.2 SCOPE AND OBJECTIVE

The purpose of this investigation is to demonstrate Leak-Before-Break (LBB) of the 10" Accumulator lines. The scope of this work covers the 10" Accumulator lines from the reactor coolant loop nozzle connection to the HV-8808 isolation valves. Schematic drawings of the piping systems are shown in Section 3. The recommendations and criteria proposed in SRP 3.6.3 (Reference 1-2) are used in this evaluation. The criteria and the resulting steps of the evaluation procedure can be briefly summarized as follows:

1. Calculate the applied loads. Identify the location(s) at which the highest faulted stress occurs.
2. Identify the materials and the material properties.
3. Postulate a surface flaw at the governing location. Determine fatigue crack growth. Show that a through-wall crack will not result.
4. Postulate a through-wall flaw at the governing location(s). The size of the flaw should be large enough so that the leakage is assured of detection with margin using the installed leak detection equipment when the pipe is subjected to normal operating loads. Demonstrate that there is a margin of 10 between the calculated leak rate and the leak detection capability.
5. Using maximum faulted loads in the stability analysis, demonstrate that there is a margin of 2 between the leakage size flaw and the critical size flaw.
6. Review the operating history to ascertain that operating experience has indicated no particular susceptibility to failure from the effects of corrosion, water hammer or low and high cycle fatigue.
7. For the materials types used in the Plant, provide representative material properties.

The leak rate is calculated for the normal operating condition. The leak rate prediction model used in this evaluation is an [

]a,c,e. The crack opening area required for calculating the leak rates is obtained by subjecting the postulated through-wall flaw to normal operating loads (Reference 1-3). Surface roughness is accounted for in determining the leak rate through the postulated flaw.

It should be noted that the terms "flaw" and "crack" have the same meaning and are used interchangeably. "Governing location" and "critical location" are also used interchangeably throughout the report.

1.3 REFERENCES

- 1-1 WCAP-7211, Revision 4, "Energy Systems Business Unit Policy and Procedures for Management, Classification, and Release of Information," January 2001.
- 1-2 Standard Review Plan; public comments solicited; 3.6.3 Leak-Before-Break Evaluation Procedures; Federal Register/Vol. 52, No. 167/Friday, August 28, 1987/Notices, pp. 32626-32633.
- 1-3 NUREG/CR-3464, 1983, "The Application of Fracture Proof Design Methods Using Tearing Instability Theory to Nuclear Piping Postulating Circumferential Through Wall Cracks."

2 OPERATION AND STABILITY OF THE ACCUMULATOR LINES

2.1 STRESS CORROSION CRACKING

The Westinghouse Reactor Coolant System (RCS) Class 1 lines have an operating history that demonstrates the inherent operating stability characteristics of the design. This includes a low susceptibility to cracking failure from the effects of corrosion (e.g., intergranular stress corrosion cracking, IGSCC). This operating history totals over 1100 reactor-years, including 5 plants each having over 30 years of operation, 4 plants each with over 25 years of operation, 12 plants each with over 20 years of operation and 8 plants each with over 15 years of operation.

For stress corrosion cracking (SCC) to occur in piping, the following three conditions must exist simultaneously: high tensile stresses, susceptible material, and a corrosive environment. Since some residual stresses and some degree of material susceptibility exist in any stainless steel piping, the potential for stress corrosion is minimized by properly selecting a material immune to SCC as well as preventing the occurrence of a corrosive environment. The material specifications consider compatibility with the system's operating environment (both internal and external) as well as other material in the system, applicable ASME Code rules, fracture toughness, welding, fabrication, and processing.

The elements of a water environment known to increase the susceptibility of austenitic stainless steel to stress corrosion are: oxygen, fluorides, chlorides, hydroxides, hydrogen peroxide, and reduced forms of sulfur (e.g., sulfides, sulfites, and thionates). Strict pipe cleaning standards prior to operation and careful control of water chemistry during plant operation are used to prevent the occurrence of a corrosive environment. Prior to being put into service, the piping is cleaned internally and externally. During flushes and preoperational testing, water chemistry is controlled in accordance with written specifications. Requirements on chlorides, fluorides, conductivity, and pH are included in the acceptance criteria for the piping.

During plant operation, the reactor coolant water chemistry is monitored and maintained within very specific limits. Contaminant concentrations are kept below the thresholds known to be conducive to stress corrosion cracking with the major water chemistry control standards being included in the plant operating procedures as a condition for plant operation. For example, during normal power operation, oxygen concentration in the RCS Class 1 lines is expected to be in the parts per billion (ppb) range by controlling charging flow chemistry and maintaining hydrogen in the reactor coolant at specified concentrations. Halogen concentrations are also stringently controlled by maintaining concentrations of chlorides and fluorides within the specified limits. This is assured by controlling charging flow chemistry. Thus during plant operation, the likelihood of stress corrosion cracking is minimized.

Wall thinning by erosion and erosion-corrosion effects will not occur in the Accumulator lines due to the low velocity and the material, austenitic stainless steel, is highly resistant to these degradation mechanisms. Therefore, wall thinning is not a significant concern in the portion of the system being addressed in this evaluation.

As a result of the recent issue of Primary Water Stress Corrosion Cracking (PWSCC) occurring in V. C. Summer reactor vessel hot leg nozzle, the Alloy 82/182 weld is being currently investigated under the EPRI Materials Reliability Project (MRP) Program. It should be noted that the susceptible material under investigation is not found in the 10" Accumulator lines at the Callaway Nuclear Power Plant.

2.2 WATER HAMMER

Overall, there is a low potential for water hammer in the RCS and connecting accumulator lines since they are designed and operated to preclude the voiding condition in normally filled lines. The RCS and connecting accumulator lines including piping and components are designed for normal, upset, emergency, and faulted condition transients. The design requirements are conservative relative to both the number of transients and their severity. Relief valve actuation and the associated hydraulic transients following valve opening are considered in the system design. Other valve and pump actuations are relatively slow transients with no significant effect on the system dynamic loads. To ensure dynamic system stability, reactor coolant parameters are stringently controlled. Temperature during normal operation is maintained within a narrow range by the control rod positions; pressure is also controlled within a narrow range for steady-state conditions by the pressurizer heaters and the pressurizer spray. The flow characteristics of the system remain constant during a fuel cycle because the only governing parameters, namely system resistance and the reactor coolant pump characteristics are controlled in the design process. Additionally, Westinghouse has instrumented typical reactor coolant systems to verify the flow and vibration characteristics of the system and the connecting auxiliary lines. Preoperational testing and operating experience has verified the Westinghouse approach. The operating transients of the RCS primary piping and connected accumulator lines are such that no significant water hammer can occur.

2.3 LOW CYCLE AND HIGH CYCLE FATIGUE

An assessment of the low cycle fatigue loading is discussed in Section 6 as part of this study in the form of a fatigue crack growth analysis.

Pump vibrations during operation would result in high cycle fatigue loads in the piping system. During operation, an alarm signals the exceedance of the RC pump shaft vibration limits. Field measurements have been made on the reactor coolant loop piping in a number of plants during hot functional testing. Stresses in the elbow below the RC pump have been found to be very small, between 2 and 3 ksi at the highest. Field measurements on typical PWR plants indicate vibration amplitudes less than 1 ksi. When translated to the connecting Accumulator lines, these stresses would be even lower, well below the fatigue endurance limit for the Accumulator line material and would result in an applied stress intensity factor below the threshold for fatigue crack growth.

2.4 OTHER POSSIBLE DEGRADATION DURING SERVICE OF THE ACCUMULATOR LINES

The 10" Accumulator lines and associated fittings for the Callaway Nuclear Power Plant are forged product forms, which are not susceptible to toughness degradation due to thermal aging.

The maximum normal operating temperature of the 10" Accumulator lines is about 558°F. This is well below the temperature which would cause any creep damage in stainless steel piping.

3 MATERIAL CHARACTERIZATION

3.1 PIPE MATERIALS AND WELD PROCESS

The material types of the 10" Accumulator lines for the Callaway Nuclear Power Plant are SA376-TP304, SA312-TP304, SA358 TP304 and SA403 TP304. They are wrought product of the types used for the piping of several PWR plants. The 10" Accumulator lines do not include any cast pipes or cast fittings. The welding processes used are Gas Tungsten Arc Weld (GTAW) and Shielded Metal Arc Weld (SMAW) combination or GTAW. Figures 3-1 to 3-4 show the schematic layouts of the 10" Accumulator lines Loops 1, 2, 3 and 4 and also identify the weld locations by node points.

In the following sections the tensile properties of the materials are presented for use in the Leak-Before-Break analyses.

3.2 MATERIAL PROPERTIES

The room temperature mechanical properties of the Callaway Nuclear Power Plant 10" Accumulator lines material were obtained from the Certified Materials Test Reports (CMTRs) and are given in Table 3-1. The material properties at temperatures (70°F and 558°F) are required for the leak rate and stability analyses. The minimum and average tensile properties at the temperatures of interest stated above were calculated by using the ratio of the ASME Code Section II (Reference 3-1) properties and those tabulated in Table 3-1. Table 3-2 shows the representative minimum and average tensile properties at various operating temperatures. The modulus of elasticity values were established at various temperatures from the ASME Code Section II (see Table 3-3). In the Leak-Before-Break evaluation, the representative minimum yield and minimum ultimate strengths at operating temperature were used for the flaw stability evaluations and the representative average yield strength properties were used for the leak rate predictions. These properties are summarized in Table 3-2.

3.3 REFERENCES

- 3-1 ASME Boiler and Pressure Vessel Code Section II, Part D – Material Properties, 2001 Edition, July 1, 2001, ASME Boiler and Pressure Vessel Committee, Subcommittee on Materials.

Table 3-1: Room Temperature Material Properties for the 10" Accumulator Lines

| Heat No. (S/N)* | Material | Yield Strength (psi) | Ultimate Strength (psi) |
|-----------------|-------------|----------------------|-------------------------|
| 5-789 (396) | SA312 TP304 | 43900 | 85000 |
| ERP8 (439) | SA403 WP304 | 37845 | 83960 |
| ERLE (441) | SA403 WP304 | 37195 | 80880 |
| 5-744 (396) | SA312 TP304 | 44800 | 87700 |
| ERP8 (427) | SA403 WP304 | 37845 | 83960 |
| U4KY-H2 (371) | SA403 WP304 | 39000 | 90500 |
| 25223 (315) | SA358 TP304 | 37600 | 86900 |
| 24942 (315) | SA358 TP304 | 39600 | 85600 |
| 61107 (162) | SA358 TP304 | 48000 | 90000 |
| 45060 (99) | SA403 WP304 | 38500 | 84500 |
| F61056 (199) | SA312 TP304 | 43200 | 89800 |
| 64034 (162) | SA358 TP304 | 38400 | 85600 |
| 42276 (7) | SA403 TP304 | 41600 | 91500 |
| 44838 (243) | SA403 WP304 | 37400 | 88200 |
| U4KY-H2 (264) | SA403 WP304 | 39000 | 90500 |
| 5-751 (396) | SA312 TP304 | 46200 | 85600 |
| ERPA (592) | SA403 WP304 | 40600 | 85460 |
| 44429 (83) | SA403 WP304 | 35500 | 84500 |
| 43481 (417) | SA358 TP304 | 37400 | 88200 |
| 47741(278) | SA403 WP304 | 41400 | 90800 |
| 43778 (95) | SA403 WP304 | 44800 | 85200 |
| 3083-6-2 (559) | SA312 TP304 | 42600 | 82100 |
| 24955 (488) | SA358 TP304 | 39200 | 85700 |
| 45061 (209) | SA358 TP304 | 37000 | 84000 |
| 45059 (160) | SA403 WP304 | 37000 | 84000 |
| 43481(243) | SA403 TP304 | 37400 | 88200 |
| 41960 (7) | SA403 WP304 | 33200 | 80600 |
| ERDK (121) | SA403 WP304 | 36800 | 84380 |

*S/N : Serial Number

Table 3-2 : Representative Tensile Properties for the 10" Accumulator Lines at Operating Temperatures

| Material | Temperature (°F) | Minimum Yield (psi) | Average Yield (psi) | Minimum Ultimate (psi) |
|--|-------------------------|----------------------------|----------------------------|-------------------------------|
| SA376/SA358/SA312 TP304 or SA403 WP304 | 558 | 20827 | 24936 | 68134 |
| SA376/SA358/SA312 TP304 or SA403 WP304 | 70 | 33200 | 39749 | 80600 |

Table 3-3 : Modulus of Elasticity (E) for the 10" Accumulator Lines

| Material | Temperature (°F) | E (10⁶ psi) |
|--|-------------------------|-------------------------------|
| SA376/SA358/SA312 TP304 or SA403 WP304 | 558 | 25.510 |
| SA376/SA358/SA312 TP304 or SA403 WP304 | 70 | 28.300 |

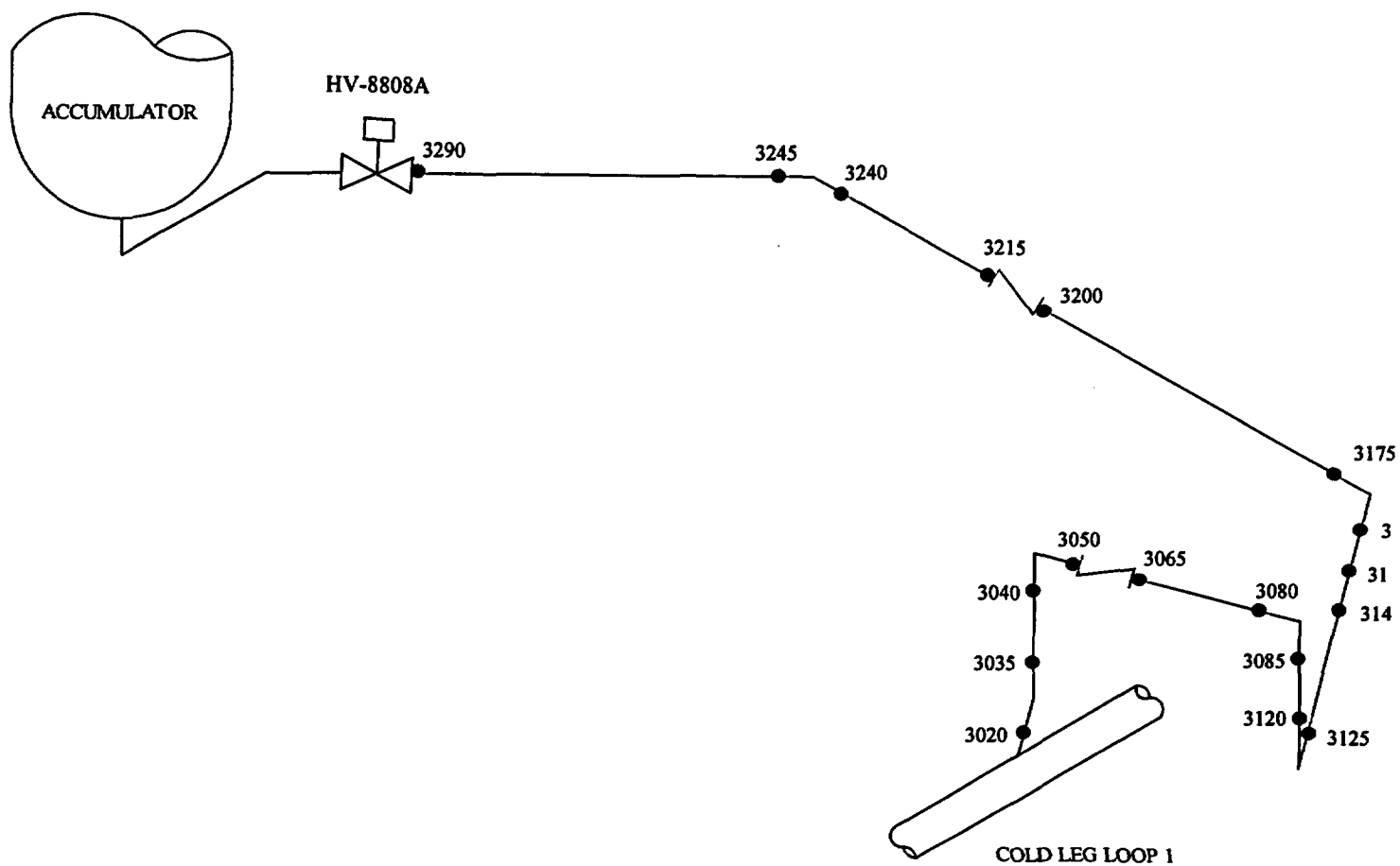


Figure 3-1 Callaway Nuclear Power Plant 10" Accumulator Line Loop 1 Layout

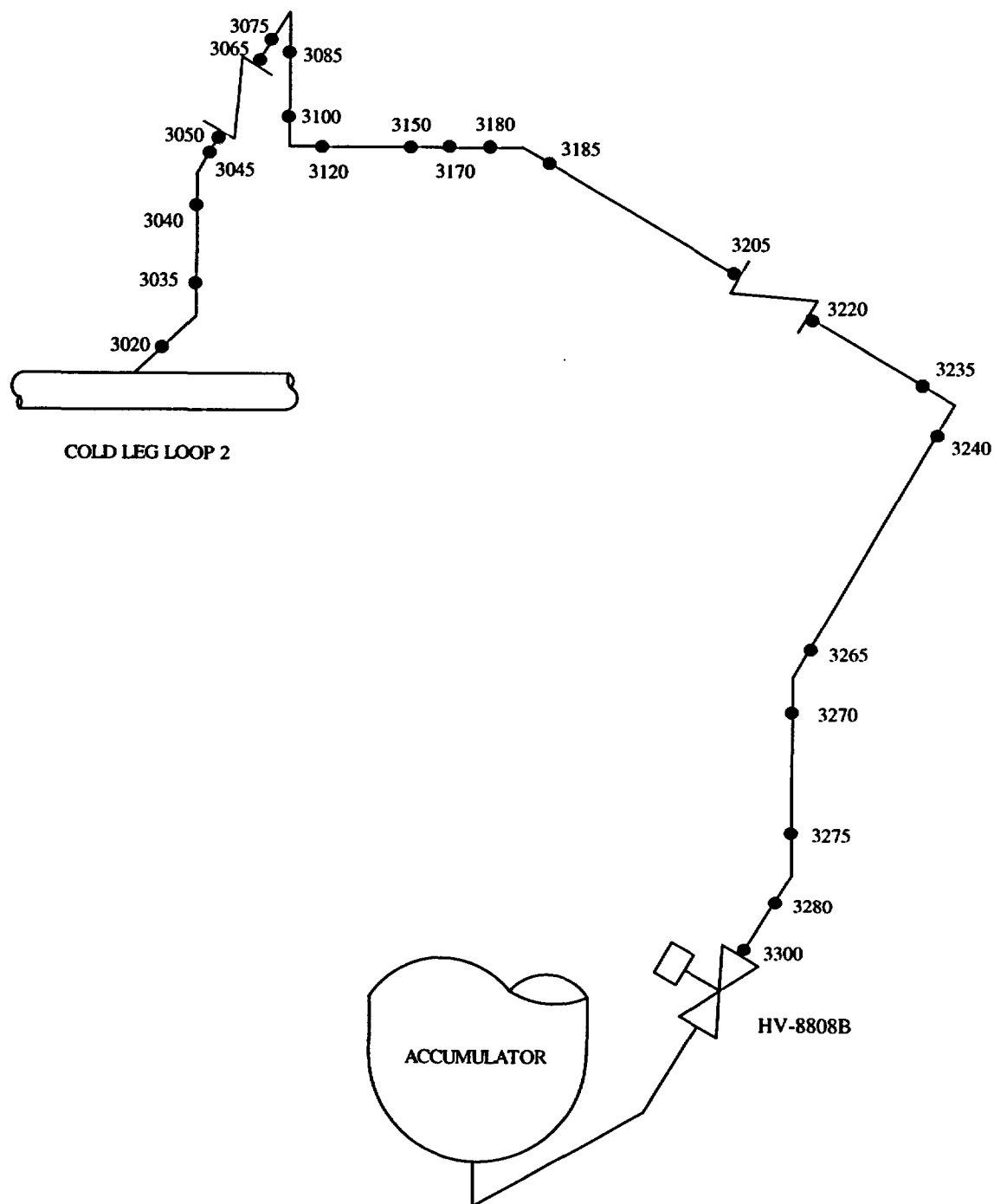


Figure 3-2 Callaway Nuclear Power Plant 10" Accumulator Line Loop 2 Layout

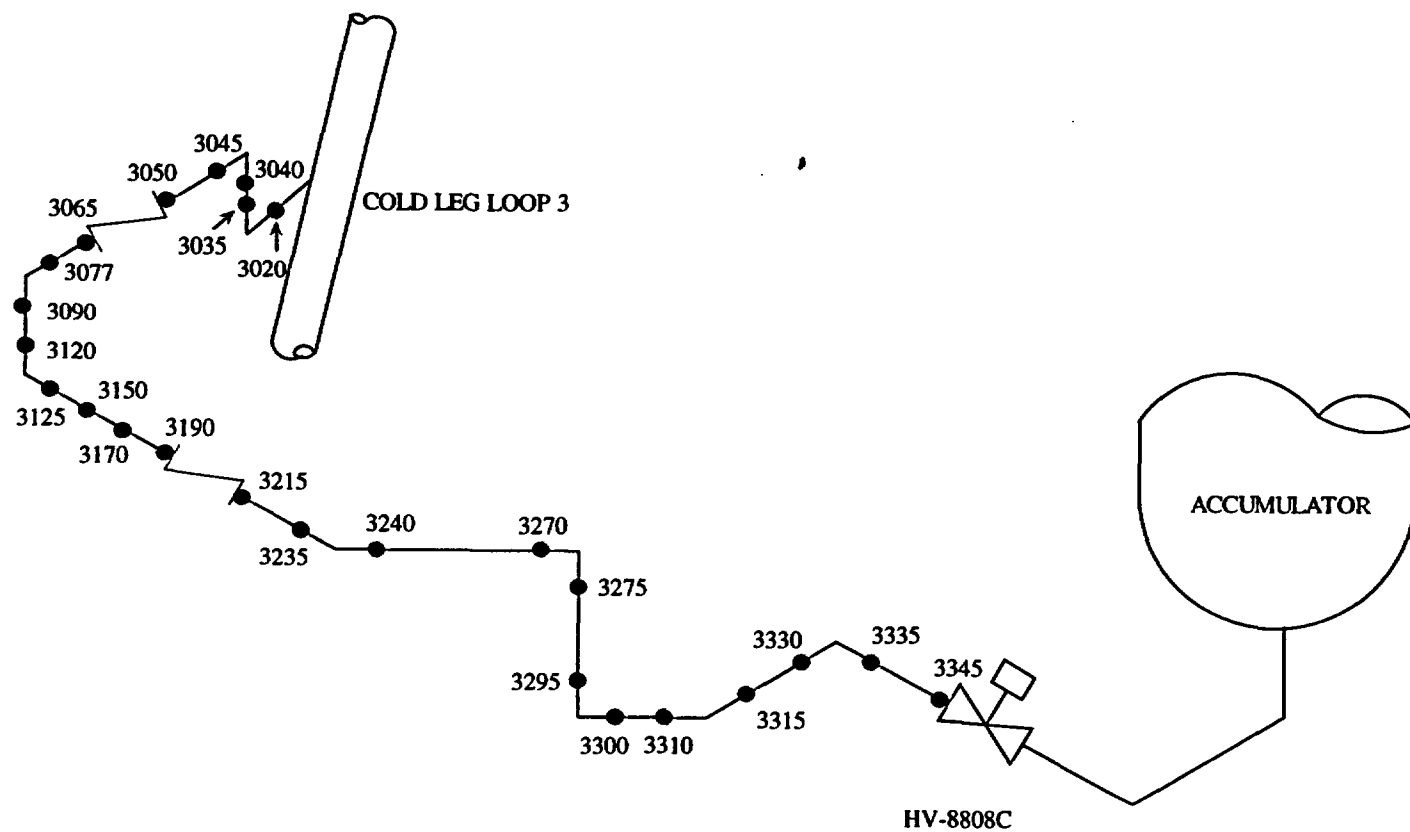


Figure 3-3 Callaway Nuclear Power Plant 10" Accumulator Line Loop 3 Layout

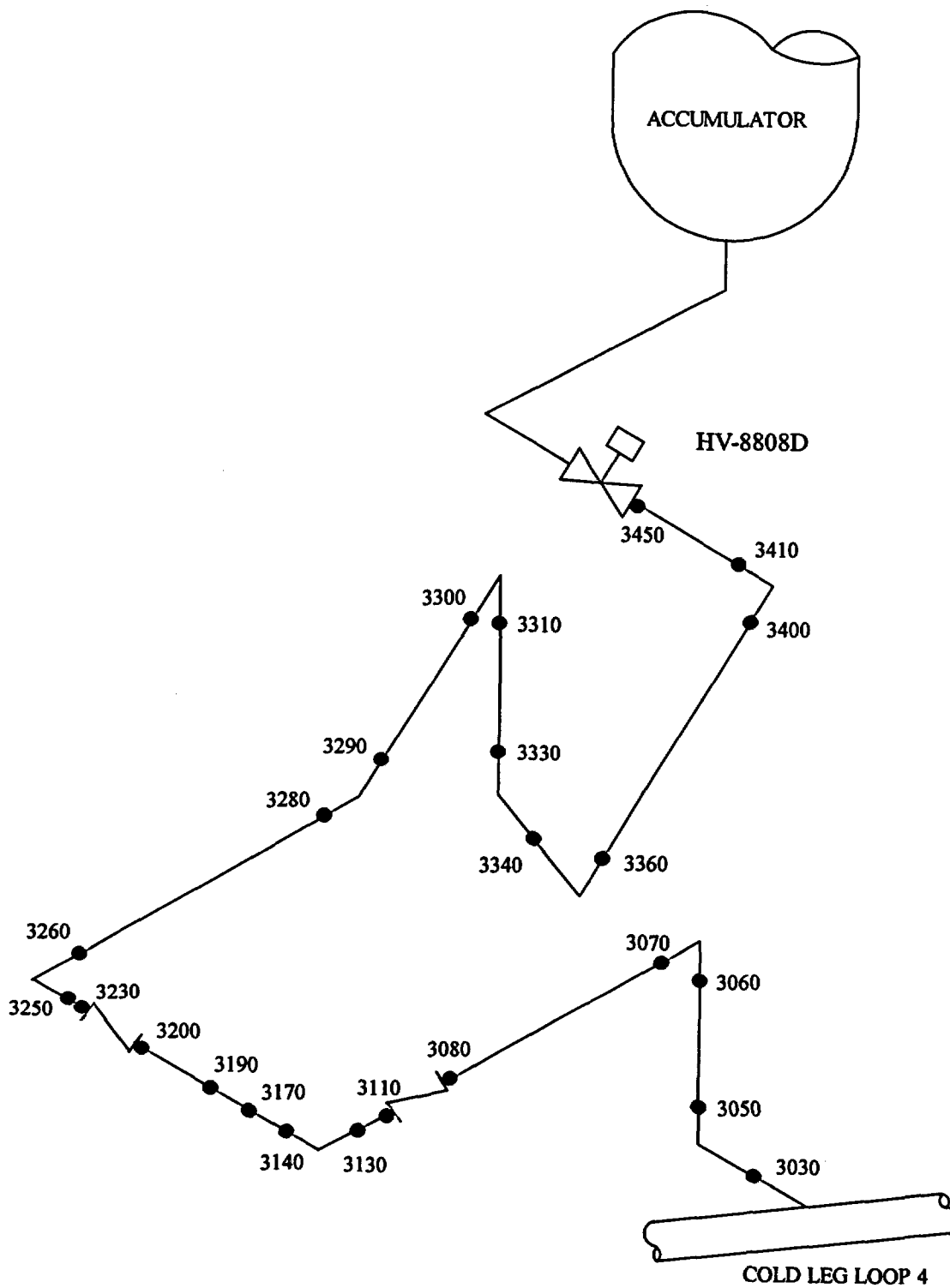


Figure 3-4 Callaway Nuclear Power Plant 10" Accumulator Line Loop 4 Layout

4 LOADS FOR FRACTURE MECHANICS ANALYSIS

4.1 NATURE OF THE LOADS

Figures 3-1 to 3-4 show the schematic layouts of the 10" Accumulator lines Loops 1, 2, 3 and 4 and also identify the weld locations by node points. The stresses due to axial loads and moments were calculated by the following equation:

$$\sigma = \frac{F}{A} + \frac{M}{Z} \quad (4-1)$$

where,

| | | |
|----------|---|----------------------------|
| σ | = | Stress |
| F | = | Axial Load |
| M | = | Moment |
| A | = | Metal Cross-Sectional Area |
| Z | = | Section Modulus |

The moment for the desired loading combinations were calculated by the following equation:

$$M = \sqrt{M_x^2 + M_y^2 + M_z^2} \quad (4-2)$$

where,

| | | |
|-------|---|-------------------------------|
| M | = | Moment For Required Loading |
| M_x | = | Torsional Moment |
| M_y | = | Y Component of Bending Moment |
| M_z | = | Z Component of Bending Moment |

The axial load and moments for crack stability analysis and leak rate predictions are computed by the methods to be explained in Sections 4.2 and 4.3.

4.2 LOADS FOR CRACK STABILITY ANALYSIS

In accordance with Standard Review Plan 3.6.3 the absolute sum of loading components can be applied which results in higher magnitude of combined loads. If crack stability is demonstrated using these loads, the LBB margin on loads can be reduced from $\sqrt{2}$ to 1.0. The faulted loads for the crack stability analysis were calculated by the absolute sum method as follows:

$$F = |F_{DW}| + |F_{TH}| + |F_P| + |F_{SSE}| \quad (4-3)$$

$$M_X = |M_{XDW}| + |M_{XTH}| + |M_{XSSE}| \quad (4-4)$$

$$M_Y = |M_{YDW}| + |M_{YTH}| + |M_{YSSE}| \quad (4-5)$$

$$M_Z = |M_{ZDW}| + |M_{ZTH}| + |M_{ZSSE}| \quad (4-6)$$

where

DW = Deadweight

TH = Normal Thermal Expansion Load

P = Load Due To Internal Pressure

SSE = Safe Shutdown Earthquake Loading Including Seismic Anchor Motion

4.3 LOADS FOR LEAK RATE EVALUATION

The normal operating loads for the leak rate predictions were calculated by the algebraic sum method as follows:

$$F = F_{DW} + F_{TH} + F_P \quad (4-7)$$

$$M_X = M_{XDW} + M_{XTH} \quad (4-8)$$

$$M_Y = M_{YDW} + M_{YTH} \quad (4-9)$$

$$M_Z = M_{ZDW} + M_{ZTH} \quad (4-10)$$

The parameters and subscripts are the same as those explained in Sections 4.1 and 4.2.

4.4 SUMMARY OF LOADS AND GEOMETRY FOR THE 10" ACCUMULATOR LINES

The load combinations were evaluated at the various weld locations. Normal loads were determined using the algebraic sum method whereas the faulted loads were combined using the absolute sum method. The normal operating loadings for the 10" Accumulator lines are

Pressure (P), Deadweight (DW) and Normal Operating Thermal Expansion (TH) loads. The faulted loadings consist of Normal Operating loads plus Safe Shutdown Earthquake (SSE) loads including the Seismic Anchor Motion. The effects of two normal operating temperature scenarios (Case A: 70°F and Case B: 48°F) for the portion of the piping between the isolation valves HV-8808 and the accumulator tanks are considered in the LBB evaluation.

Tables 4-1, 4-4, 4-7 and 4-10 show the piping geometry and normal operating condition for the 10" Accumulator lines Loops 1, 2, 3 and 4 respectively at the weld locations. The minimum pipe wall thickness at the weld counterbore is used in the analysis. The normal loads and stresses for the 10" Accumulator lines Loops 1, 2, 3 and 4 at the weld locations are tabulated in Tables 4-2, 4-5, 4-8 and 4-11 respectively, while Tables 4-3, 4-6, 4-9 and 4-12 are for the faulted loads and stresses.

4.5 GOVERNING LOCATIONS FOR THE ACCUMULATOR LINES

The welds at the 10" Accumulator lines for the Callaway Nuclear Power Plant are fabricated using the GTAW and SMAW combination or GTAW. The governing locations were established on the basis of the pipe schedules, material type, operating temperature, operating pressure, and the highest faulted stresses at the welds. All the Accumulator lines for the Callaway Nuclear Power Plant were investigated and the governing locations were identified and found to be located in Loops 2 and 3. These governing locations enveloped the 10" Accumulator lines loops 1, 2, 3 and 4 for the Callaway Nuclear Power Plant in the Leak-Before-Break analyses. Figures 4-1 and 4-2 show the schematic layout of Accumulator lines Loops 2 and 3 for the Callaway Nuclear Power Plant and also identify the governing weld locations.

The governing weld locations enveloping 10" Accumulator lines Loops 1, 2, 3 and 4 are found to be located in Loops 2 and 3 and are shown below:

Node 3020 (Accumulator Loop 2)

Node 3120 (Accumulator Loop 2)

Node 3295 (Accumulator Loop 3)

Table 4-1 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 1

| Weld Location Node | Material Type | Outer Diameter (in) | Minimum Wall Thickness (in) | Normal Operating | |
|--------------------|----------------------------------|---------------------|-----------------------------|------------------|------------------|
| | | | | Pressure (psig) | Temperature (°F) |
| 3020 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3035 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3040 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3045 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3050 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3065 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3080 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3085 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3120 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3125 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3140 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3160 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3170 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3175 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3200 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3215 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3240 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3245 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3290 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |

Table 4-2a : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 1 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 135569 | 428875 | 4890 | 6794 | 11684 |
| 3035 | 139602 | 452190 | 5035 | 7163 | 12199 |
| 3040 | 139682 | 476672 | 5038 | 7551 | 12589 |
| 3045 | 144010 | 457585 | 5194 | 7249 | 12443 |
| 3050 | 144010 | 420456 | 5194 | 6660 | 11855 |
| 3065 | 144010 | 365628 | 5194 | 5792 | 10986 |
| 3080 | 144010 | 372476 | 5194 | 5900 | 11095 |
| 3085 | 146085 | 318952 | 5269 | 5052 | 10322 |
| 3120 | 144769 | 404706 | 5222 | 6411 | 11633 |
| 3125 | 136646 | 512165 | 4929 | 8113 | 13042 |
| 3140 | 136646 | 241046 | 4929 | 3818 | 8747 |
| 3160 | 143777 | 437760 | 5186 | 6934 | 12121 |
| 3170 | 143777 | 183789 | 5186 | 2911 | 8097 |
| 3175 | 145378 | 158004 | 5244 | 2503 | 7747 |
| 3200 | 145411 | 116594 | 5245 | 1847 | 7092 |
| 3215 | 45494 | 53795 | 1641 | 852 | 2493 |
| 3240 | 45527 | 63335 | 1642 | 1003 | 2645 |
| 3245 | 46302 | 73682 | 1670 | 1167 | 2837 |
| 3290 | 42932 | 92867 | 1549 | 1471 | 3020 |

Table 4-2b : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 1 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 135590 | 426215 | 4891 | 6752 | 11642 |
| 3035 | 139600 | 449585 | 5035 | 7122 | 12157 |
| 3040 | 139680 | 474033 | 5038 | 7509 | 12547 |
| 3045 | 143988 | 455106 | 5194 | 7209 | 12403 |
| 3050 | 143988 | 418145 | 5194 | 6624 | 11817 |
| 3065 | 143988 | 363949 | 5194 | 5765 | 10959 |
| 3080 | 143988 | 370896 | 5194 | 5875 | 11069 |
| 3085 | 146087 | 318129 | 5269 | 5039 | 10309 |
| 3120 | 144771 | 403926 | 5222 | 6399 | 11620 |
| 3125 | 136678 | 510733 | 4930 | 8090 | 13020 |
| 3140 | 136678 | 239255 | 4930 | 3790 | 8720 |
| 3160 | 143899 | 438829 | 5190 | 6951 | 12142 |
| 3170 | 143899 | 179683 | 5190 | 2846 | 8037 |
| 3175 | 145539 | 152737 | 5250 | 2419 | 7669 |
| 3200 | 145573 | 112550 | 5251 | 1783 | 7034 |
| 3215 | 45656 | 50952 | 1647 | 807 | 2454 |
| 3240 | 45689 | 67256 | 1648 | 1065 | 2713 |
| 3245 | 46408 | 76921 | 1674 | 1218 | 2892 |
| 3290 | 44167 | 80885 | 1593 | 1281 | 2874 |

Table 4-3a : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 1 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 154100 | 561781 | 5558 | 8899 | 14458 |
| 3035 | 150151 | 550347 | 5416 | 8718 | 14134 |
| 3040 | 150095 | 564475 | 5414 | 8942 | 14356 |
| 3045 | 148512 | 535092 | 5357 | 8476 | 13833 |
| 3050 | 148344 | 495706 | 5351 | 7852 | 13203 |
| 3065 | 146994 | 426654 | 5302 | 6759 | 12061 |
| 3080 | 146945 | 443200 | 5300 | 7021 | 12321 |
| 3085 | 151104 | 399270 | 5450 | 6325 | 11775 |
| 3120 | 153162 | 500729 | 5525 | 7932 | 13457 |
| 3125 | 151994 | 629038 | 5482 | 9964 | 15447 |
| 3140 | 152216 | 359467 | 5490 | 5694 | 11185 |
| 3160 | 146449 | 531704 | 5282 | 8423 | 13705 |
| 3170 | 146399 | 292397 | 5281 | 4632 | 9912 |
| 3175 | 147294 | 266790 | 5313 | 4226 | 9539 |
| 3200 | 147236 | 203688 | 5311 | 3227 | 8537 |
| 3215 | 47514 | 134359 | 1714 | 2128 | 3842 |
| 3240 | 47791 | 154985 | 1724 | 2455 | 4179 |
| 3245 | 48276 | 156900 | 1741 | 2485 | 4227 |
| 3290 | 48263 | 186629 | 1741 | 2956 | 4697 |

Table 4-3b : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 1 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 154079 | 559025 | 5558 | 8855 | 14413 |
| 3035 | 150153 | 547863 | 5416 | 8679 | 14095 |
| 3040 | 150097 | 561761 | 5414 | 8899 | 14313 |
| 3045 | 148534 | 532769 | 5358 | 8439 | 13797 |
| 3050 | 148366 | 493590 | 5352 | 7819 | 13170 |
| 3065 | 147016 | 425056 | 5303 | 6733 | 12036 |
| 3080 | 146967 | 441695 | 5301 | 6997 | 12298 |
| 3085 | 151106 | 398526 | 5450 | 6313 | 11763 |
| 3120 | 153164 | 499890 | 5525 | 7919 | 13443 |
| 3125 | 151962 | 627795 | 5481 | 9945 | 15426 |
| 3140 | 152184 | 357891 | 5489 | 5669 | 11159 |
| 3160 | 146327 | 532758 | 5278 | 8439 | 13717 |
| 3170 | 146277 | 288274 | 5276 | 4566 | 9843 |
| 3175 | 147455 | 261460 | 5319 | 4142 | 9460 |
| 3200 | 147398 | 199560 | 5317 | 3161 | 8478 |
| 3215 | 47676 | 131553 | 1720 | 2084 | 3804 |
| 3240 | 47953 | 158138 | 1730 | 2505 | 4235 |
| 3245 | 48382 | 160144 | 1745 | 2537 | 4282 |
| 3290 | 47166 | 175010 | 1701 | 2772 | 4474 |

Table 4-4 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 2

| Weld Location Node | Material Type | Outer Diameter (in) | Minimum Wall Thickness (in) | Normal Operating | |
|--------------------|--|---------------------|-----------------------------|------------------|------------------|
| | | | | Pressure (psig) | Temperature (°F) |
| 3020 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3035 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3040 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3045 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3050 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3065 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3075 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3085 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3100 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3120 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3150 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3170 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3180 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3185 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3205 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3220 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3235 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3240 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |

Table 4-4 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 2

| Weld Location Node | Material Type | Outer Diameter (in) | Minimum Wall Thickness (in) | Normal Operating | |
|--------------------|--|---------------------|-----------------------------|------------------|------------------|
| | | | | Pressure (psig) | Temperature (°F) |
| 3265 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3270 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3275 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3280 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3300 | SA376/SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |

Table 4-5a : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 2 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 135921 | 457121 | 4903 | 7241 | 12144 |
| 3035 | 140738 | 489594 | 5076 | 7756 | 12832 |
| 3040 | 140817 | 517471 | 5079 | 8197 | 13276 |
| 3045 | 143286 | 503550 | 5168 | 7977 | 13145 |
| 3050 | 143286 | 463535 | 5168 | 7343 | 12511 |
| 3065 | 143286 | 393868 | 5168 | 6239 | 11408 |
| 3075 | 143286 | 397994 | 5168 | 6305 | 11473 |
| 3085 | 144950 | 327660 | 5228 | 5190 | 10419 |
| 3100 | 143954 | 447673 | 5192 | 7092 | 12284 |
| 3120 | 136012 | 552719 | 4906 | 8756 | 13662 |
| 3150 | 136012 | 142016 | 4906 | 2250 | 7156 |
| 3170 | 143735 | 304783 | 5185 | 4828 | 10013 |
| 3180 | 143735 | 131024 | 5185 | 2076 | 7260 |
| 3185 | 144670 | 132956 | 5218 | 2106 | 7324 |
| 3205 | 144764 | 80918 | 5222 | 1282 | 6503 |
| 3220 | 44847 | 38689 | 1618 | 613 | 2231 |
| 3235 | 44961 | 12451 | 1622 | 197 | 1819 |
| 3240 | 45454 | 18369 | 1640 | 291 | 1931 |
| 3265 | 45454 | 76657 | 1640 | 1214 | 2854 |
| 3270 | 43271 | 56155 | 1561 | 890 | 2450 |
| 3275 | 42315 | 77640 | 1526 | 1230 | 2756 |
| 3280 | 45454 | 122442 | 1640 | 1940 | 3579 |
| 3300 | 45454 | 88435 | 1640 | 1401 | 3040 |

Table 4-5b : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 2 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 135905 | 455720 | 4902 | 7219 | 12121 |
| 3035 | 140728 | 488417 | 5076 | 7737 | 12813 |
| 3040 | 140807 | 516466 | 5079 | 8181 | 13260 |
| 3045 | 143275 | 503066 | 5168 | 7969 | 13137 |
| 3050 | 143275 | 463193 | 5168 | 7337 | 12505 |
| 3065 | 143275 | 394618 | 5168 | 6251 | 11419 |
| 3075 | 143275 | 399012 | 5168 | 6321 | 11489 |
| 3085 | 144960 | 329472 | 5229 | 5219 | 10448 |
| 3100 | 143964 | 449375 | 5193 | 7118 | 12311 |
| 3120 | 136000 | 554473 | 4906 | 8783 | 13689 |
| 3150 | 136000 | 144348 | 4906 | 2287 | 7192 |
| 3170 | 143767 | 308671 | 5186 | 4890 | 10075 |
| 3180 | 143767 | 131206 | 5186 | 2078 | 7264 |
| 3185 | 144751 | 130836 | 5221 | 2073 | 7294 |
| 3205 | 144847 | 77069 | 5225 | 1221 | 6446 |
| 3220 | 44930 | 35367 | 1621 | 613 | 2231 |
| 3235 | 45047 | 13152 | 1625 | 208 | 1833 |
| 3240 | 45541 | 19247 | 1643 | 305 | 1948 |
| 3265 | 45541 | 78778 | 1643 | 1248 | 2891 |
| 3270 | 43304 | 55575 | 1562 | 880 | 2442 |
| 3275 | 42348 | 77463 | 1528 | 1227 | 2755 |
| 3280 | 45541 | 123668 | 1643 | 1959 | 3602 |
| 3300 | 45541 | 88544 | 1643 | 1403 | 3045 |

Table 4-6a : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 2 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 155514 | 682504 | 5609 | 10811 | 16421 |
| 3035 | 149777 | 674575 | 5403 | 10686 | 16088 |
| 3040 | 149714 | 679570 | 5400 | 10765 | 16165 |
| 3045 | 148133 | 636724 | 5343 | 10086 | 15429 |
| 3050 | 148036 | 596112 | 5340 | 9443 | 14783 |
| 3065 | 147651 | 530372 | 5326 | 8402 | 13727 |
| 3075 | 147659 | 542645 | 5326 | 8596 | 13922 |
| 3085 | 149787 | 478419 | 5403 | 7579 | 12981 |
| 3100 | 150929 | 604084 | 5444 | 9569 | 15013 |
| 3120 | 155118 | 779295 | 5595 | 12345 | 17940 |
| 3150 | 154825 | 316493 | 5585 | 5014 | 10598 |
| 3170 | 148357 | 421113 | 5351 | 6671 | 12022 |
| 3180 | 148266 | 343333 | 5348 | 5439 | 10787 |
| 3185 | 149597 | 371173 | 5396 | 5880 | 11276 |
| 3205 | 149382 | 366060 | 5388 | 5799 | 11187 |
| 3220 | 48383 | 349067 | 1745 | 5530 | 7275 |
| 3235 | 48355 | 298075 | 1744 | 4722 | 6466 |
| 3240 | 47576 | 293722 | 1716 | 4653 | 6369 |
| 3265 | 49189 | 412327 | 1774 | 6532 | 8306 |
| 3270 | 47878 | 373345 | 1727 | 5914 | 7641 |
| 3275 | 48796 | 264504 | 1760 | 4190 | 5950 |
| 3280 | 50133 | 340956 | 1808 | 5401 | 7209 |
| 3300 | 50257 | 277652 | 1813 | 4398 | 6211 |

Table 4-6b : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 2 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 155530 | 681213 | 5610 | 10791 | 16401 |
| 3035 | 149787 | 673505 | 5403 | 10669 | 16072 |
| 3040 | 149724 | 678635 | 5401 | 10750 | 16151 |
| 3045 | 148144 | 636226 | 5344 | 10078 | 15422 |
| 3050 | 148047 | 595730 | 5340 | 9437 | 14777 |
| 3065 | 147662 | 531270 | 5326 | 8416 | 13742 |
| 3075 | 147670 | 543738 | 5327 | 8613 | 13940 |
| 3085 | 149797 | 480561 | 5403 | 7612 | 13016 |
| 3100 | 150939 | 605883 | 5444 | 9598 | 15042 |
| 3120 | 155130 | 781229 | 5596 | 12375 | 17971 |
| 3150 | 154837 | 318330 | 5585 | 5043 | 10628 |
| 3170 | 148325 | 424703 | 5350 | 6728 | 12078 |
| 3180 | 148234 | 343293 | 5347 | 5438 | 10785 |
| 3185 | 149678 | 369295 | 5399 | 5850 | 11249 |
| 3205 | 149465 | 362300 | 5391 | 5739 | 11130 |
| 3220 | 48466 | 344053 | 1748 | 5450 | 7198 |
| 3235 | 48441 | 302899 | 1747 | 4798 | 6545 |
| 3240 | 47663 | 296151 | 1719 | 4691 | 6411 |
| 3265 | 49276 | 414028 | 1777 | 6559 | 8336 |
| 3270 | 47911 | 374634 | 1728 | 5935 | 7663 |
| 3275 | 48829 | 264082 | 1761 | 4183 | 5945 |
| 3280 | 50220 | 341662 | 1811 | 5412 | 7224 |
| 3300 | 50344 | 277370 | 1816 | 4394 | 6210 |

Table 4-7 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 3

| Weld Location Node | Material Type | Outer Diameter (in) | Minimum Wall Thickness (in) | Normal Operating | |
|--------------------|----------------------------------|---------------------|-----------------------------|------------------|------------------|
| | | | | Pressure (psig) | Temperature (°F) |
| 3020 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3035 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3040 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3045 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3050 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3065 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3077 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3090 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3120 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3125 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3150 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3170 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3190 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3215 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3235 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3240 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3270 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3275 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3295 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3300 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3310 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3315 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3330 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3335 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3345 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |

Table 4-8a : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 3 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 138044 | 500776 | 4979 | 7933 | 12912 |
| 3035 | 144561 | 478496 | 5214 | 7580 | 12794 |
| 3040 | 144640 | 473619 | 5217 | 7503 | 12720 |
| 3045 | 137711 | 402925 | 4967 | 6383 | 11350 |
| 3050 | 137711 | 232099 | 4967 | 3677 | 8644 |
| 3065 | 137711 | 392808 | 4967 | 6222 | 11190 |
| 3077 | 137711 | 528543 | 4967 | 8373 | 13340 |
| 3090 | 140117 | 572772 | 5054 | 9073 | 14127 |
| 3120 | 139123 | 555303 | 5018 | 8796 | 13815 |
| 3125 | 148315 | 516518 | 5350 | 8182 | 13532 |
| 3150 | 148315 | 490085 | 5350 | 7763 | 13113 |
| 3170 | 148291 | 329945 | 5349 | 5227 | 10575 |
| 3190 | 148300 | 233326 | 5349 | 3696 | 9045 |
| 3215 | 48383 | 128699 | 1745 | 2039 | 3784 |
| 3235 | 51886 | 338696 | 1872 | 5365 | 7237 |
| 3240 | 53502 | 356284 | 1930 | 5644 | 7574 |
| 3270 | 53502 | 338044 | 1930 | 5355 | 7285 |
| 3275 | 52427 | 323487 | 1891 | 5124 | 7015 |
| 3295 | 51647 | 357000 | 1863 | 5655 | 7518 |
| 3300 | 53502 | 386620 | 1930 | 6124 | 8054 |
| 3310 | 53502 | 308964 | 1930 | 4894 | 6824 |
| 3315 | 50535 | 234591 | 1823 | 3716 | 5539 |
| 3330 | 50535 | 210144 | 1823 | 3329 | 5152 |
| 3335 | 44259 | 103312 | 1596 | 1637 | 3233 |
| 3345 | 44259 | 74449 | 1596 | 1179 | 2776 |

Table 4-8b : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 3 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 138043 | 500624 | 4979 | 7930 | 12910 |
| 3035 | 144553 | 478405 | 5214 | 7578 | 12792 |
| 3040 | 144632 | 473552 | 5217 | 7501 | 12718 |
| 3045 | 137719 | 402883 | 4968 | 6382 | 11350 |
| 3050 | 137719 | 231490 | 4968 | 3667 | 8635 |
| 3065 | 137719 | 392016 | 4968 | 6210 | 11177 |
| 3077 | 137719 | 527639 | 4968 | 8358 | 13326 |
| 3090 | 140125 | 571933 | 5054 | 9060 | 14114 |
| 3120 | 139131 | 555047 | 5018 | 8792 | 13811 |
| 3125 | 148323 | 516501 | 5350 | 8182 | 13532 |
| 3150 | 148323 | 490120 | 5350 | 7764 | 13114 |
| 3170 | 148296 | 330085 | 5349 | 5229 | 10578 |
| 3190 | 148305 | 233780 | 5349 | 3703 | 9053 |
| 3215 | 48388 | 129634 | 1745 | 2054 | 3799 |
| 3235 | 51899 | 337874 | 1872 | 5352 | 7224 |
| 3240 | 53505 | 355411 | 1930 | 5630 | 7560 |
| 3270 | 53505 | 338396 | 1930 | 5360 | 7290 |
| 3275 | 52409 | 323401 | 1890 | 5123 | 7013 |
| 3295 | 51629 | 356319 | 1862 | 5644 | 7507 |
| 3300 | 53505 | 386318 | 1930 | 6120 | 8050 |
| 3310 | 53505 | 308777 | 1930 | 4891 | 6821 |
| 3315 | 50499 | 236197 | 1822 | 3742 | 5563 |
| 3330 | 50499 | 216364 | 1822 | 3427 | 5249 |
| 3335 | 44491 | 107001 | 1605 | 1695 | 3300 |
| 3345 | 44491 | 72831 | 1605 | 1154 | 2759 |

Table 4-9a : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 3 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 152011 | 689048 | 5483 | 10915 | 16398 |
| 3035 | 148507 | 603444 | 5357 | 9559 | 14916 |
| 3040 | 148404 | 576812 | 5353 | 9137 | 14490 |
| 3045 | 152648 | 471370 | 5506 | 7467 | 12973 |
| 3050 | 151928 | 430425 | 5480 | 6818 | 12298 |
| 3065 | 150978 | 568765 | 5446 | 9010 | 14456 |
| 3077 | 150934 | 619565 | 5444 | 9814 | 15259 |
| 3090 | 149412 | 620550 | 5389 | 9830 | 15219 |
| 3120 | 150556 | 605417 | 5431 | 9590 | 15021 |
| 3125 | 154154 | 556474 | 5560 | 8815 | 14375 |
| 3150 | 154176 | 532586 | 5561 | 8437 | 13998 |
| 3170 | 154225 | 400158 | 5563 | 6339 | 11902 |
| 3190 | 154249 | 296064 | 5564 | 4690 | 10254 |
| 3215 | 54544 | 202083 | 1967 | 3201 | 5169 |
| 3235 | 53279 | 397271 | 1922 | 6293 | 8215 |
| 3240 | 54293 | 413091 | 1958 | 6544 | 8502 |
| 3270 | 54481 | 396246 | 1965 | 6277 | 8242 |
| 3275 | 55068 | 394666 | 1986 | 6252 | 8238 |
| 3295 | 54094 | 497330 | 1951 | 7878 | 9829 |
| 3300 | 54953 | 487298 | 1982 | 7719 | 9701 |
| 3310 | 55003 | 418735 | 1984 | 6633 | 8617 |
| 3315 | 52470 | 367349 | 1893 | 5819 | 7712 |
| 3330 | 52523 | 306748 | 1895 | 4859 | 6754 |
| 3335 | 47376 | 228691 | 1709 | 3623 | 5332 |
| 3345 | 47275 | 243639 | 1705 | 3859 | 5565 |

Table 4-9b : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 3 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3020 | 152012 | 688883 | 5483 | 10912 | 16396 |
| 3035 | 148499 | 603296 | 5356 | 9557 | 14913 |
| 3040 | 148396 | 576718 | 5353 | 9136 | 14488 |
| 3045 | 152640 | 471324 | 5506 | 7466 | 12972 |
| 3050 | 151920 | 429820 | 5480 | 6809 | 12289 |
| 3065 | 150970 | 567968 | 5446 | 8997 | 14443 |
| 3077 | 150926 | 618650 | 5444 | 9800 | 15244 |
| 3090 | 149404 | 619684 | 5389 | 9816 | 15205 |
| 3120 | 150548 | 605128 | 5430 | 9586 | 15016 |
| 3125 | 154162 | 556463 | 5561 | 8815 | 14375 |
| 3150 | 154184 | 532625 | 5561 | 8437 | 13999 |
| 3170 | 154230 | 400243 | 5563 | 6340 | 11903 |
| 3190 | 154254 | 296319 | 5564 | 4694 | 10258 |
| 3215 | 54549 | 202101 | 1968 | 3201 | 5169 |
| 3235 | 53292 | 396447 | 1922 | 6280 | 8202 |
| 3240 | 54296 | 412357 | 1958 | 6532 | 8491 |
| 3270 | 54484 | 396504 | 1965 | 6281 | 8246 |
| 3275 | 55050 | 394566 | 1986 | 6250 | 8236 |
| 3295 | 54076 | 496316 | 1951 | 7862 | 9813 |
| 3300 | 54956 | 485647 | 1982 | 7693 | 9675 |
| 3310 | 55006 | 416684 | 1984 | 6601 | 8585 |
| 3315 | 52434 | 368446 | 1891 | 5836 | 7728 |
| 3330 | 52487 | 311920 | 1893 | 4941 | 6834 |
| 3335 | 47608 | 224299 | 1717 | 3553 | 5270 |
| 3345 | 47507 | 236261 | 1714 | 3743 | 5456 |

Table 4-10 : Summary of Callaway Nuclear Power Plant Piping Geometry and Normal Operating Condition for 10" Accumulator Line Loop 4

| Weld Location Node | Material Type | Outer Diameter (in) | Minimum Wall Thickness (in) | Normal Operating | |
|--------------------|----------------------------------|---------------------|-----------------------------|------------------|------------------|
| | | | | Pressure (psig) | Temperature (°F) |
| 3030 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3050 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3060 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3070 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3080 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 558 |
| 3110 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3130 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3140 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3170 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3190 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3200 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 2285 | 70 |
| 3230 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3250 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3260 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3280 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3290 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3300 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3310 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3330 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3340 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3360 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3400 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3410 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |
| 3450 | SA358/SA312 TP304 or SA403 WP304 | 10.750 | 0.896 | 700 | 70 |

Table 4-11a : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 4 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3030 | 137555 | 233713 | 4962 | 3702 | 8664 |
| 3050 | 141865 | 190923 | 5117 | 3024 | 8141 |
| 3060 | 141945 | 190758 | 5120 | 3022 | 8142 |
| 3070 | 135913 | 243581 | 4902 | 3859 | 8761 |
| 3080 | 135913 | 352384 | 4902 | 5582 | 10484 |
| 3110 | 135913 | 398865 | 4902 | 6318 | 11221 |
| 3130 | 135913 | 411503 | 4902 | 6519 | 11421 |
| 3140 | 142490 | 313707 | 5140 | 4969 | 10109 |
| 3170 | 142490 | 72191 | 5140 | 1144 | 6283 |
| 3190 | 145574 | 215910 | 5251 | 3420 | 8671 |
| 3200 | 145574 | 187986 | 5251 | 2978 | 8229 |
| 3230 | 45657 | 92736 | 1647 | 1469 | 3116 |
| 3250 | 45657 | 110803 | 1647 | 1755 | 3402 |
| 3260 | 49055 | 194923 | 1769 | 3088 | 4857 |
| 3280 | 49055 | 131755 | 1769 | 2087 | 3857 |
| 3290 | 48693 | 148654 | 1756 | 2355 | 4111 |
| 3300 | 48693 | 298476 | 1756 | 4728 | 6484 |
| 3310 | 48713 | 300320 | 1757 | 4757 | 6514 |
| 3330 | 47822 | 194359 | 1725 | 3079 | 4804 |
| 3340 | 48349 | 215916 | 1744 | 3420 | 5164 |
| 3360 | 48693 | 202913 | 1756 | 3214 | 4971 |
| 3400 | 40926 | 344303 | 1476 | 5454 | 6930 |
| 3410 | 44353 | 288289 | 1600 | 4567 | 6167 |
| 3450 | 44353 | 101359 | 1600 | 1606 | 3205 |

Table 4-11b : Summary of Callaway Nuclear Power Plant Normal Loads and Stresses for 10" Accumulator Line Loop 4 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3030 | 137548 | 233598 | 4961 | 3700 | 8662 |
| 3050 | 141865 | 190693 | 5117 | 3021 | 8138 |
| 3060 | 141945 | 190486 | 5120 | 3017 | 8137 |
| 3070 | 135906 | 243457 | 4902 | 3857 | 8759 |
| 3080 | 135906 | 352948 | 4902 | 5591 | 10493 |
| 3110 | 135906 | 399657 | 4902 | 6331 | 11233 |
| 3130 | 135906 | 412356 | 4902 | 6532 | 11434 |
| 3140 | 142483 | 314568 | 5139 | 4983 | 10122 |
| 3170 | 142483 | 72727 | 5139 | 1152 | 6291 |
| 3190 | 145567 | 216329 | 5251 | 3427 | 8677 |
| 3200 | 145567 | 188330 | 5251 | 2983 | 8234 |
| 3230 | 45650 | 92831 | 1647 | 1471 | 3117 |
| 3250 | 45650 | 110949 | 1647 | 1758 | 3404 |
| 3260 | 49062 | 195252 | 1770 | 3093 | 4863 |
| 3280 | 49062 | 132392 | 1770 | 2097 | 3867 |
| 3290 | 48694 | 149263 | 1756 | 2364 | 4121 |
| 3300 | 48694 | 299183 | 1756 | 4739 | 6496 |
| 3310 | 48719 | 301146 | 1757 | 4770 | 6528 |
| 3330 | 47828 | 195320 | 1725 | 3094 | 4819 |
| 3340 | 48360 | 216715 | 1744 | 3433 | 5177 |
| 3360 | 48694 | 203709 | 1756 | 3227 | 4983 |
| 3400 | 40819 | 342010 | 1472 | 5418 | 6890 |
| 3410 | 44535 | 281806 | 1606 | 4464 | 6070 |
| 3450 | 44535 | 121082 | 1606 | 1918 | 3524 |

Table 4-12a : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 4 (Case A: 70°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3030 | 153191 | 399047 | 5526 | 6321 | 11847 |
| 3050 | 147270 | 284358 | 5312 | 4504 | 9817 |
| 3060 | 147174 | 268941 | 5309 | 4260 | 9569 |
| 3070 | 156367 | 316425 | 5640 | 5012 | 10653 |
| 3080 | 155760 | 465984 | 5618 | 7382 | 13000 |
| 3110 | 154977 | 533440 | 5590 | 8450 | 14040 |
| 3130 | 154965 | 542948 | 5590 | 8601 | 14190 |
| 3140 | 149176 | 418049 | 5381 | 6622 | 12003 |
| 3170 | 148902 | 217947 | 5371 | 3452 | 8823 |
| 3190 | 147963 | 355128 | 5337 | 5626 | 10963 |
| 3200 | 147927 | 304034 | 5336 | 4816 | 10152 |
| 3230 | 47407 | 192438 | 1710 | 3048 | 4758 |
| 3250 | 47302 | 205145 | 1706 | 3250 | 4956 |
| 3260 | 49584 | 281010 | 1789 | 4451 | 6240 |
| 3280 | 49758 | 202161 | 1795 | 3202 | 4997 |
| 3290 | 49801 | 224149 | 1796 | 3551 | 5347 |
| 3300 | 49811 | 417677 | 1797 | 6616 | 8413 |
| 3310 | 50814 | 418794 | 1833 | 6634 | 8467 |
| 3330 | 51657 | 307971 | 1863 | 4879 | 6742 |
| 3340 | 51858 | 327125 | 1871 | 5182 | 7052 |
| 3360 | 50442 | 286211 | 1819 | 4534 | 6353 |
| 3400 | 49285 | 481617 | 1778 | 7629 | 9407 |
| 3410 | 46590 | 407948 | 1681 | 6462 | 8143 |
| 3450 | 46420 | 205039 | 1674 | 3248 | 4922 |

Table 4-12b : Summary of Callaway Nuclear Power Plant Faulted Loads and Stresses for 10" Accumulator Line Loop 4 (Case B: 48°F)

| Weld Location Node | Axial Force (lbs) | Moment (in-lbs) | Axial Stress (psi) | Moment Stress (psi) | Total Stress (psi) |
|---------------------------|--------------------------|------------------------|---------------------------|----------------------------|---------------------------|
| 3030 | 153198 | 398961 | 5526 | 6320 | 11846 |
| 3050 | 147270 | 284168 | 5312 | 4501 | 9814 |
| 3060 | 147174 | 268670 | 5309 | 4256 | 9565 |
| 3070 | 156374 | 316305 | 5640 | 5011 | 10651 |
| 3080 | 155767 | 466544 | 5619 | 7390 | 13009 |
| 3110 | 154984 | 534237 | 5590 | 8463 | 14053 |
| 3130 | 154972 | 543804 | 5590 | 8614 | 14204 |
| 3140 | 149183 | 418898 | 5381 | 6636 | 12017 |
| 3170 | 148909 | 218347 | 5371 | 3459 | 8830 |
| 3190 | 147956 | 355546 | 5337 | 5632 | 10969 |
| 3200 | 147920 | 304292 | 5336 | 4820 | 10156 |
| 3230 | 47400 | 192704 | 1710 | 3053 | 4762 |
| 3250 | 47295 | 205214 | 1706 | 3251 | 4957 |
| 3260 | 49591 | 281348 | 1789 | 4457 | 6246 |
| 3280 | 49765 | 202668 | 1795 | 3210 | 5005 |
| 3290 | 49802 | 224814 | 1796 | 3561 | 5358 |
| 3300 | 49812 | 418435 | 1797 | 6628 | 8425 |
| 3310 | 50820 | 419659 | 1833 | 6648 | 8481 |
| 3330 | 51663 | 308854 | 1864 | 4892 | 6756 |
| 3340 | 51869 | 327742 | 1871 | 5192 | 7063 |
| 3360 | 50443 | 286771 | 1820 | 4543 | 6362 |
| 3400 | 49392 | 479391 | 1782 | 7594 | 9376 |
| 3410 | 46772 | 401713 | 1687 | 6363 | 8051 |
| 3450 | 46602 | 220517 | 1681 | 3493 | 5174 |

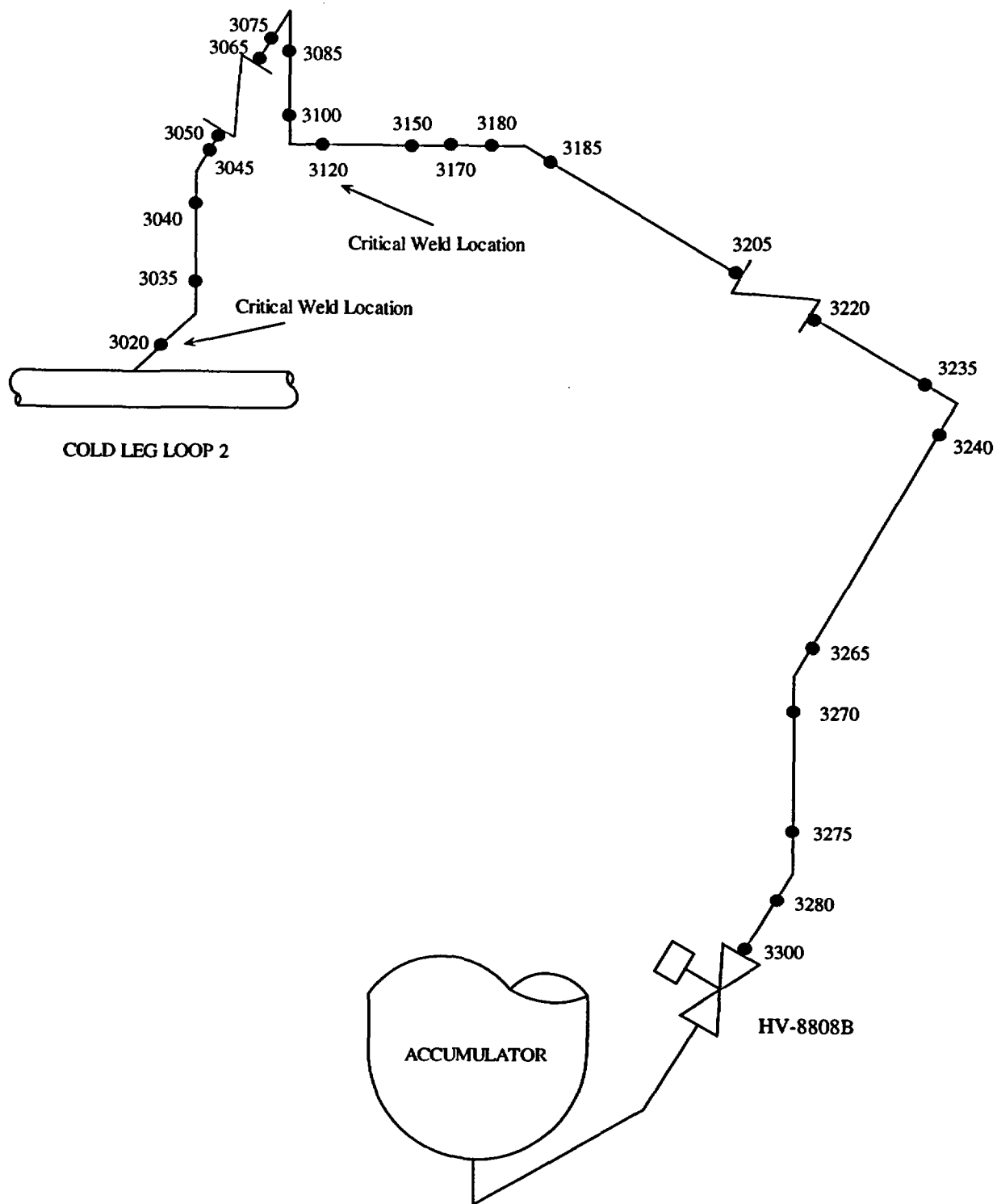


Figure 4-1 Governing Weld Locations for 10" Accumulator Line Loop 2

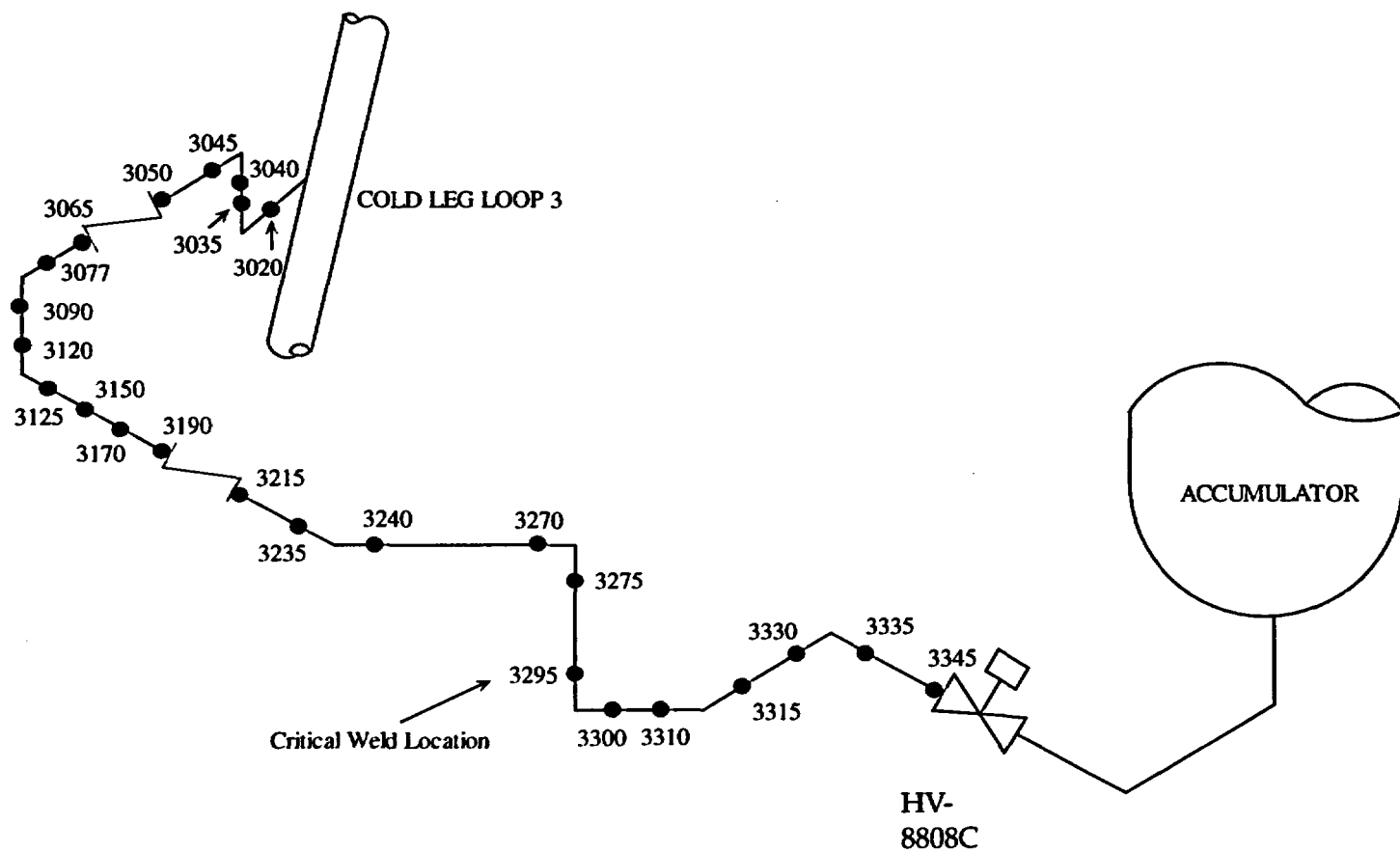


Figure 4-2 Governing Weld Location for 10" Accumulator Line Loop 3

5 FRACTURE MECHANICS EVALUATION

5.1 GLOBAL FAILURE MECHANISM

Determination of the conditions which lead to failure in stainless steel should be done with plastic fracture methodology because of the large amount of deformation accompanying fracture. One method for predicting the failure of ductile material is the []^{a,c,e} method based on traditional plastic limit load concepts, but accounting for []^{a,c,e} and taking into account the presence of a flaw. The flawed component is predicted to fail when the remaining net section reaches a stress level at which a plastic hinge is formed. The stress level at which this occurs is termed as the flow stress. []

[]^{a,c,e} This methodology has been shown to be applicable to ductile piping through a large number of experiments and is used here to predict the critical flaw size in the Accumulator lines. The failure criterion has been obtained by requiring equilibrium of the section containing the flaw (Figure 5-1) when loads are applied. The detailed development is provided in Appendix A for a through-wall circumferential flaw in a pipe section with internal pressure, axial force, and imposed bending moments. The limit moment for such a pipe is given by:

$$[]^{\text{a,c,e}} \quad (5-1)$$

where:

[]

$$]^{\text{a,c,e}} \quad (5-2)$$

The analytical model described above accurately accounts for the internal pressure as well as imposed axial force as they affect the limit moment. Good agreement was found between the analytical predictions and the experimental results (Reference 5-1). The Flaw stability evaluations, using this analytical model, are presented in Section 5.3.

5.2 LEAK RATE PREDICTIONS

Fracture mechanics analysis shows that postulated through-wall cracks in the 10" Accumulator lines would remain stable and would not cause a gross failure of this component. However, if such a through-wall crack did exist, it would be desirable to detect the leakage such that the Plant could be brought to a safe shutdown condition. The purpose of this section is to discuss the method, which will be used to predict the flow through such a postulated crack and present the leak rate calculation results for through-wall circumferential cracks.

5.2.1 General Considerations

The flow of hot pressurized water through an opening to a lower backpressure (causing choking) is taken into account. For long channels where the ratio of the channel length, L , to hydraulic diameter, D_H , (L/D_H) is greater than $[]^{a,c,e}$, both $[]^{a,c,e}$ must be considered. In this situation the flow can be described as being single-phase through the channel until the local pressure equals the saturation pressure of the fluid. At this point, the flow begins to flash and choking occurs. Pressure losses due to momentum changes will dominate for $[]^{a,c,e}$. However, for large L/D_H values, the friction pressure drop will become important and must be considered along with the momentum losses due to flashing.

5.2.2 Calculation Method

In using the $[]^{a,c,e}$

$$]^{a,c,e}.$$

The flow rate through a crack was calculated in the following manner. Figure 5-2 from Reference 5-2 was used to estimate the critical pressure, P_c , for the primary loop enthalpy condition and an assumed flow. Once P_c was found for a given mass flow, the $[]^{a,c,e}$

$]^{a,c,e}$ was found from Figure 5-3 taken from Reference 5-2. For all cases considered, since $[]^{a,c,e}$ Therefore, this method will yield the two-phase pressure drop due to momentum effects ($\Delta P_{2\phi}$) as illustrated in Figure 5-4. Now using the assumed flow rate, G , the frictional pressure drop can be calculated using

$$\Delta P_f = []^{a,c,e} \quad (5-3)$$

where the friction factor f was determined using the []^{a,c,e} The crack relative roughness, ϵ , was obtained from fatigue crack data on stainless steel samples. The relative roughness value used in these calculations was []^{a,c,e} RMS.

The frictional pressure drop using Equation 5-3 was then calculated for the assumed flow and added to the []^{a,c,e} to obtain the total pressure drop from the system under consideration to the atmosphere. Thus,

$$\text{Absolute Pressure} - 14.7 = []^{\text{a,c,e}} \quad (5-4)$$

for a given assumed flow G . If the right-hand side of Equation 5-4 does not agree with the pressure difference between the piping under consideration and the atmosphere, then the procedure is repeated until Equation 5-4 is satisfied to within an acceptable tolerance and this results in the flow value through the crack.

For the locations at the lower temperatures, the leak rate is calculated by using the simple orifice type flow formula given by []

$$(5-5)$$

$$]^{\text{a,c,e}}$$

5.2.3 Leak Rate Calculations

Leak rate calculations were performed as a function of postulated through-wall crack length for the governing locations previously identified. The crack opening area was estimated using the method of Reference 5-4 and the leak rates were calculated using the calculation methods described above. The leak rates were calculated using the normal operating loads at the governing locations identified in Section 4. Average yield strength properties from Table 3-2 were used in the leak rate calculations. The crack lengths yielding a leak rate of 10 gpm (10 times the leak detection capability of 1.0 gpm) for the governing weld locations in the 10" Accumulator lines at the Callaway Nuclear Power Plant are shown in Table 5-1.

The Callaway Nuclear Power Plant has an RCS pressure boundary leak detection system which is consistent with the guidelines of Regulatory Guide 1.45 for detecting leakage of 1 gpm in one hour.

5.3 STABILITY EVALUATION

A typical segment of the pipe under maximum loads of axial force F and moment M is schematically illustrated in Figure 5-5. In order to calculate the critical flaw size, plots of the limit moment versus crack length are generated as shown in Figures 5-6 to 5-8. The critical flaw size corresponds to the intersection of this curve and the maximum load line. The critical flaw size is calculated using the lower bound base metal tensile properties tabulated in Table 3-2.

The welds at the governing locations are GTAW/SMAW combination or GTAW. Therefore, in order to envelop all the weld process types, the "Z" factor correction for SMAW was conservatively applied (Reference 5-5) as follows:

$$Z = 1.15 [1 + 0.013 (OD - 4)] \quad (\text{for SMAW}) \quad (5-6)$$

where OD is the outer diameter in inches. Substituting $OD = 10.75$ inches, the Z factor was calculated for the 10" Accumulator lines to be 1.25 for SMAW. The "Z" correction factor for GTAW is 1.0. The applied loads were conservatively increased by the Z factors for SMAW and the plots of limit load versus crack length were generated as shown in Figures 5-6 to 5-8 for the critical locations. Table 5-2 shows the summary of critical flaw sizes.

5.4 REFERENCES

- 5-1 Kanninen, M. F. et al., "Mechanical Fracture Predictions for Sensitized Stainless Steel Piping with Circumferential Cracks" EPRI NP-192, September 1976.
- 5-2 [

]a,c,e
- 5-3 Crane, D.P., "Handbook of Hydraulic Resistance Coefficient."
- 5-4 Tada, H., "The Effects of Shell Corrections on Stress Intensity Factors and the Crack Opening Area of Circumferential and a Longitudinal Through-Crack in a Pipe," Section II-1, NUREG/CR-3464, September 1983.
- 5-5 Standard Review Plan; Public Comment Solicited; 3.6.3 Leak-Before-Break Evaluation Procedures; Federal Register/Vol. 52, No. 167/Friday, August 28, 1987/Notices, pp. 32626-32633.

Table 5-1 : Leakage Flaw Sizes

| Node Point | Temperature (°F) | Crack Length (in.) (for 10 gpm leakage) |
|-------------------|-----------------------------|--|
| 3020 | 558 | 3.87 |
| 3120 | 70 | 3.70 |
| 3295 | 70 | 6.20 |

Table 5-2 : Summary of Critical Flaw Sizes

| Node Point | Temperature (°F) | Critical Flaw Size (in) |
|-------------------|-----------------------------|------------------------------------|
| 3020 | 558 | 11.39 |
| 3120 | 70 | 12.54 |
| 3295 | 70 | 16.36 |

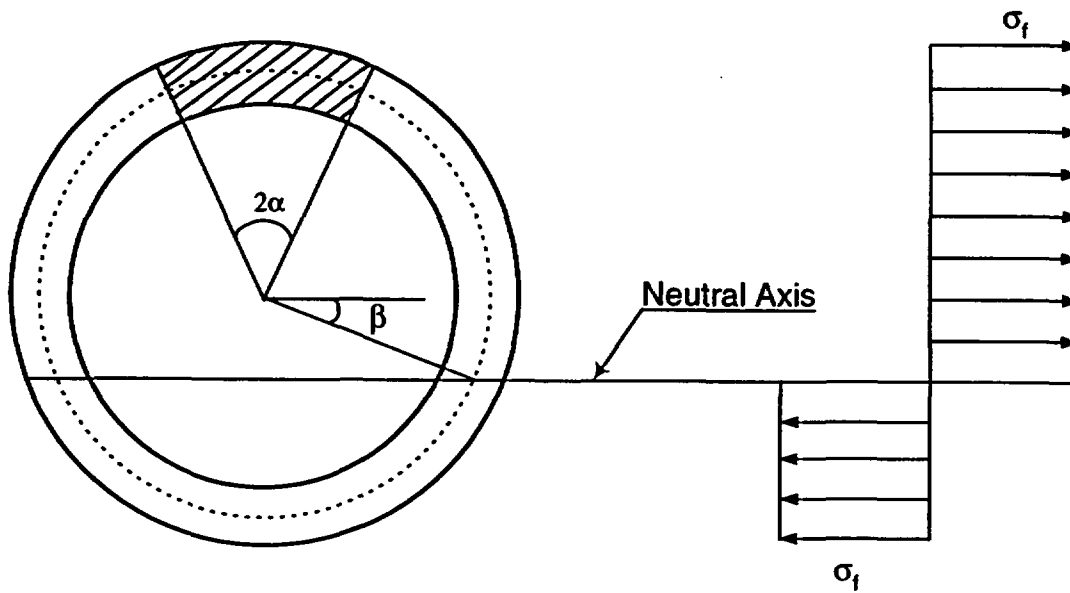


Figure 5-1 Fully Plastic Stress Distribution

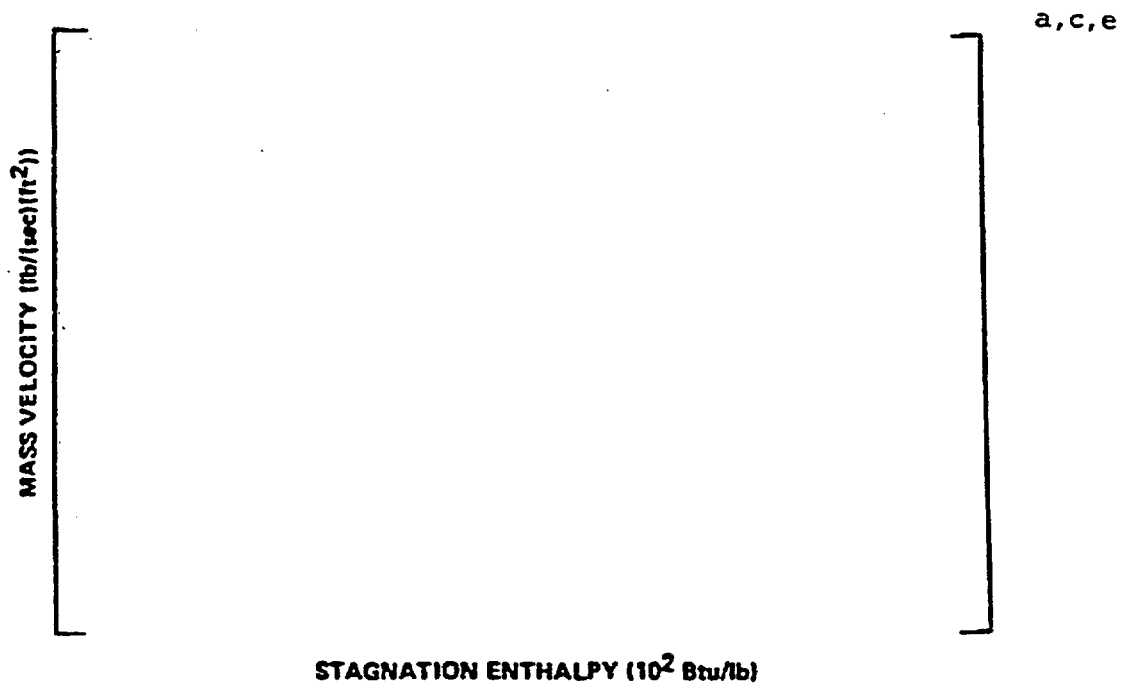


Figure 5-2 Analytical Predications of Critical Flow Rates of Steam-Water Mixtures

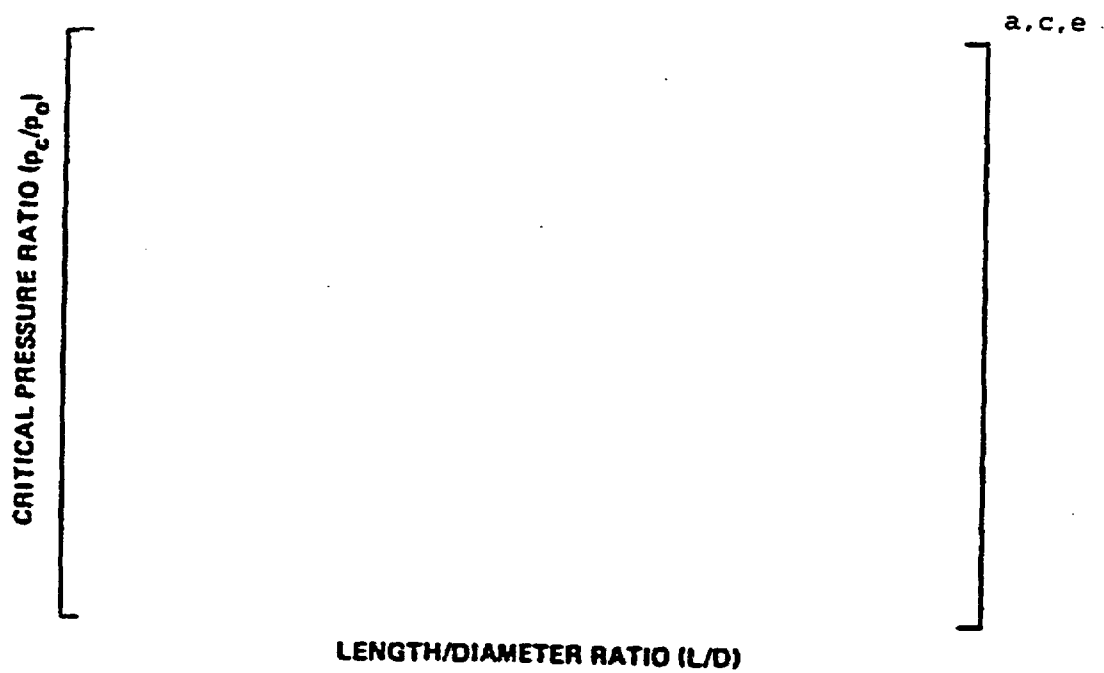


Figure 5-3 [

]a, c, e Pressure Ratio as a Function of L/D

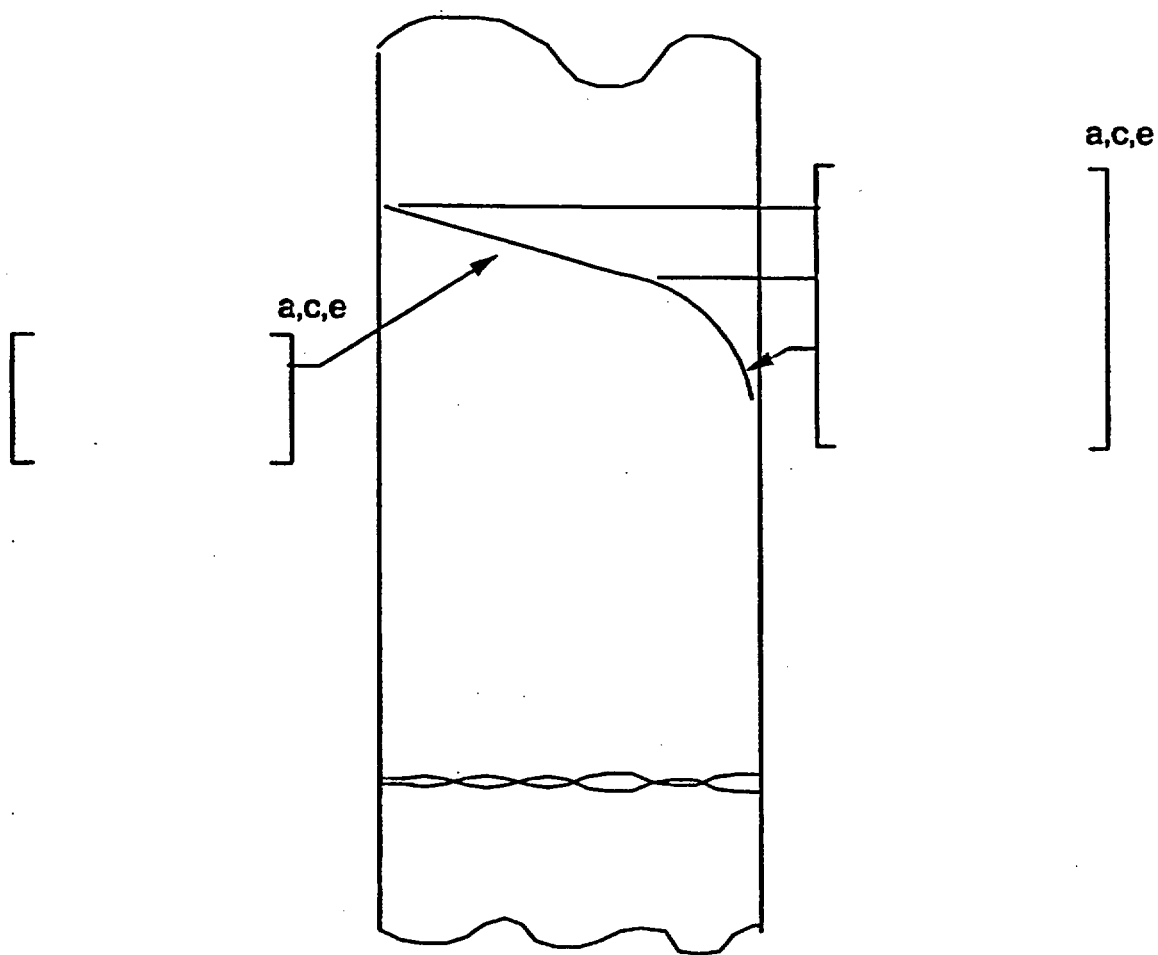


Figure 5-4 Idealized Pressure Drop Profile through a Postulated Crack

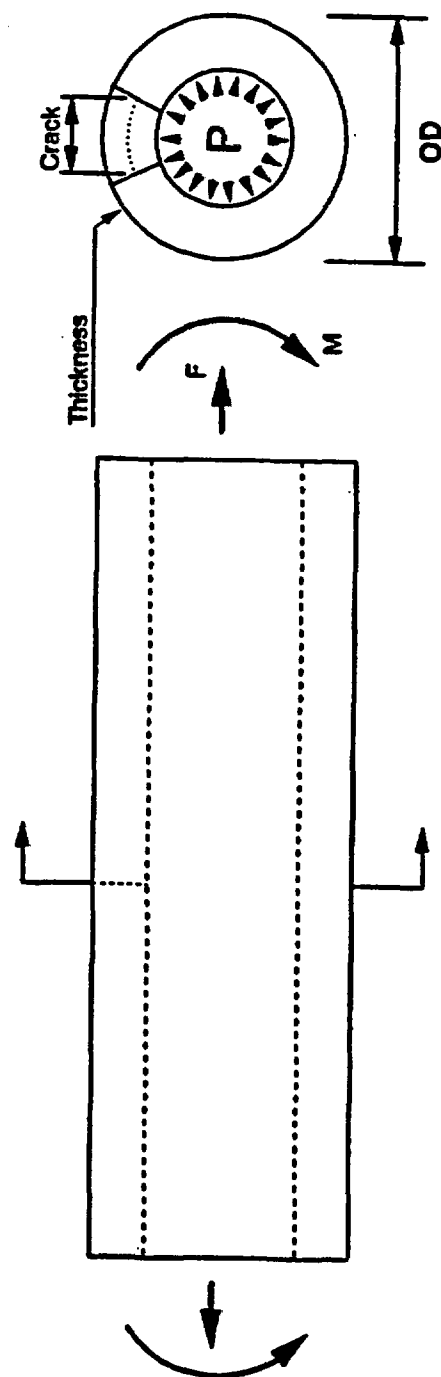


Figure 5-5 Loads acting on the Model at the Governing Locations



OD = 10.75 in $\sigma_y = 20.827$ ksi F = 155.514 kips
t = 0.896 in $\sigma_u = 68.134$ ksi M = 682.504 in-kips
SA376/SA358/SA312 TP304 or SA403 WP304 with SMAW weld

Figure 5-6 Critical Flaw Size Prediction for Node 3020



OD = 10.75 in $\sigma_y = 33.200$ ksi F = 155.130 kips
t = 0.896 in $\sigma_u = 80.600$ ksi M = 781.229 in-kips
SA376/SA358/SA312 TP304 or SA403 WP304 with SMAW weld

Figure 5-7 Critical Flaw Size Prediction for Node 3120



OD = 10.75 in

$\sigma_y = 33.200$ ksi

F = 54.094 kips

t = 0.896 in

$\sigma_u = 80.600$ ksi

M = 497.330 in-kips

SA376/SA358/SA312 TP304 or SA403 WP304 with SMAW weld

Figure 5-8 Critical Flaw Size Prediction for Node 3295

6 ASSESSMENT OF FATIGUE CRACK GROWTH

6.1 INTRODUCTION

The fatigue crack growth of the Callaway Nuclear Power Plant Accumulator lines was determined by comparison with a generic fatigue crack growth analysis of a similar piping system. The details of the generic fatigue crack growth analysis are presented below. By comparing all parameters critical to the fatigue crack growth analysis between Callaway and the generic analysis, it was concluded that the generic analysis would adequately cover the fatigue crack growth of the Callaway Nuclear Power Plant Accumulator lines.

Due to similarities in Westinghouse PWR designs, it was possible to perform a representative fatigue crack growth calculation which would be applicable to the Callaway Nuclear Power Plant. A comparison was made of the number of cycles, material, geometry, and types of discontinuities.

6.2 CRITICAL LOCATION FOR FATIGUE CRACK GROWTH ANALYSIS

The weld location at the RCL cold leg nozzle to accumulator pipe was determined to be the most critical location for the fatigue crack growth evaluation. The nozzle configuration and weld location are shown in Figure 6-1. The geometry of the accumulator pipe was identical between the Callaway Nuclear Power Plant and the generic model (10" Schedule 140). Both analyses used austenitic stainless steel at the critical location.

6.3 DESIGN TRANSIENTS

The transient conditions selected for this evaluation are based on conservative estimates of the magnitude and the frequency of the temperature fluctuations documented in various operating plant reports. These are representative of the conditions which are considered to occur during plant operation. The normal operating and upset thermal transients, in accordance with the design specification and the applicable system design criteria document, were considered for this evaluation. Out of these, 15 transients were used in the fatigue crack growth analysis and are listed in Table 6-1. There are some differences between the generic transients used in the fatigue crack growth evaluation and the Callaway Nuclear Power Plant transients but these differences will have insignificant impact on the fatigue crack growth results.

6.4 STRESS ANALYSIS

A thermal transient stress analysis was performed for a typical plant similar to the Callaway Nuclear Power Plant to obtain the through-wall stress profiles for use in the fatigue crack growth analysis. The generic Accumulator line design transients described in Section 6.3 were used.

A simplified analysis method was used to develop conservative maximum and minimum linear through wall stress distributions due to minor thermal transients. In this method, a 1-D computer program was used to perform the thermal analysis to determine the through wall temperature gradients as a function of time. The inside surface stress was calculated by using an equation, which is similar to the transient portion of ASME Section III NB 3600, Equation (11). The effect of discontinuity was included in the analysis by performing a separate 1-D thermal analysis for the pipe and nozzle. The maximum and minimum inside surface stresses were then obtained by searching the inside surface stress values calculated for each time step of the transient solution. The outside surface stresses corresponding to the maximum and minimum inside surface stresses were then calculated by a similar method. The maximum and minimum linear through wall stress distribution for each thermal transient was obtained by joining the corresponding inside and outside surface stresses by a straight line. These two stress profiles are called the maximum and minimum through wall stress distributions respectively, for convenience.

The above methodology was used for minor thermal transients. For severe thermal transients, 1-D axisymmetric finite element model of the accumulator piping was used to determine the nonlinear stress distributions. The effects of discontinuity at the critical location was included by increasing the magnitude of 1-D nonlinear through wall stress by 20 percent at the inside one third thickness of the pipe wall.

The stresses due to the generic pressure and the generic moment loading were superimposed on the through wall cyclical stresses to obtain the total maximum and minimum stress profile for each transient.

6.5 OBE LOADS

The stresses due to OBE loads were neglected in the fatigue crack growth analysis since these loads are not expected to contribute significantly to crack growth due to the small number of cycles.

6.6 TOTAL STRESS FOR FATIGUE CRACK GROWTH

The total through wall stress at a section was obtained by superimposing the generic pressure stress and the generic moment stresses on the thermal transient stresses. Thus, the total stress for fatigue crack growth at any point is given by the following equation:

$$\begin{array}{ccccccc} \text{Total Stress} & & & & \text{Stress due to} & & \text{Stress due to} \\ \text{For Fatigue} & & & & \text{Internal} & & \text{Moment (DW} \\ \text{Crack} & = & & + & \text{Pressure} & & \text{+ Thermal} \\ \text{Growth} & & & & & & \text{Expansion)} \\ & & & & & + & \text{Thermal} \\ & & & & & & \text{Transient Stress} \end{array}$$

6.7 FATIGUE CRACK GROWTH ANALYSIS

The fatigue crack growth analysis was performed to determine the effect of the design thermal transients. The analysis was performed for the critical cross section identified in Figure 6-1. A range of crack depths was postulated, and each was subjected to the thermal transients in Table 6-1, which included pressure and moment loads.

6.7.1 Analysis Procedure

The fatigue crack growth analyses presented herein were conducted in the same manner as suggested by Section XI, Appendix A of the ASME Boiler and Pressure Vessel Code (Reference 6-1). The analysis procedure involves assuming an initial flaw exists at some point and predicting the growth of that flaw due to an imposed series of fluctuating stresses. The growth of a crack per loading cycle is dependent on the range of applied stress intensity factor ΔK_I , by the following:

$$\frac{da}{dN} = C_o \Delta K_I^n \quad (6-1)$$

where " C_o " and the exponent " n " are material properties, and ΔK_I is defined as ($\Delta K_I = K_{\max} - K_{\min}$). For inert environments these material properties are constants, but for some water environments they are dependent on the level of mean stress present during the cycle. This can be accounted for by adjusting the value of " C_o " by a function of the ratio of minimum to maximum stress for any given transient. Fatigue crack growth properties of stainless steel in a pressurized water environment have been used in the analysis.

The input required for a fatigue crack growth analysis is basically the information necessary to calculate the parameter ΔK_I , which depends on crack size and structure geometry and the range of applied stresses in the area where the crack exists. Once ΔK_I is calculated, the growth due to that particular cycle can be calculated by Equation (6-1). This increment of growth is then added to the original crack size, the ΔK_I adjusted, and the analysis proceeds to the next transient. The procedure is continued in this manner until all the transients have been analyzed.

The reference crack growth law used for the stainless steel accumulator pipe system was taken from that developed by the Metal Properties Council - Pressure Vessel Research Committee Task Force In Crack Propagation Technology. The reference curve has the equation:

$$[\quad] \quad (6-2)$$

$$]^{a,c,e}$$

This equation appears in Appendix C of ASME Section XI for air environments and its basis is provided in Reference 6-2, and shown in Figure 6-2. For water environments, an environmental factor of $]^{a,c,e}$ was used, based on the crack growth tests in PWR environments reported in Reference 6-3.

6.8 RESULTS

Fatigue crack growth analyses were carried out at the critical cross section. Analysis was completed for a range of postulated flaw sizes oriented circumferentially, and the results are presented in Table 6-2. The postulated flaws are assumed to have an aspect ratio of six to one. Even for the largest postulated flaw of 0.30 inch, which is about 33 percent of the wall thickness, the result projects that flaw growth through the wall will not occur during the 40 year design life of the plant. Therefore fatigue crack growth should not be a concern for the Callaway Nuclear Power Plant Accumulator lines.

6.9 REFERENCES

- 6-1 ASME Boiler and Pressure Vessel Code Section XI, 2001 Edition, "Rules for Inservice Inspection of Nuclear Power Plant Components"
- 6-2 James, L. A., and Jones, D. P., "Fatigue Crack Growth Correlations for Austenitic Stainless Steel in Air," in Predictive Capabilities in Environmentally Assisted Cracking," ASME publication PVP-99, Dec. 1985..
- 6-3 Bamford, W. H., "Fatigue Crack Growth of Stainless Steel Piping in a Pressurized Water Reactor Environment," Trans ASME, Journal of Pressure Vessel Technology, Feb. 1979. Engineering Development Labs Report HEDL-TME-76-43, May 1976.

Table 6-1 : Design Transients Considered for Fatigue Crack Growth Evaluation

| Trans. No. | Description | No. of Occurrences |
|------------|--|--------------------|
| 1 | Unit Loading | 13200 |
| 2 | Unit Unloading | 13200 |
| 3 | Step Load Increase | 2,000 |
| 4 | Step Load Decrease | 2,000 |
| 5 | Feedwater Cycling | 2,000 |
| 6 | Reactor Trip with Cooldown No Safety Injection | 160 |
| 7 | Inadvertent RCS Depressurization | 20 |
| 8 | Control Rod Drop | 80 |
| 9 | Turbine Roll Test | 20 |
| 10 | Accumulator Actuation, Accident Operation | 21 |
| 11 | Accumulator Actuation, Inadvertent During Cooldown | 4 |
| 12 | High Head Safety Injection | 110 |
| 13 | Steady-State and Random Fluctuations | 3.2×10^6 |
| 14 | RHR Operations During Plant Cooldown | 200 |
| 15 | RHR Operations During Refueling | 80 |

Table 6-2 : Accumulator Lines Fatigue Crack Growth Results

| Initial | Crack Depth (in) After | | | |
|---------|------------------------|--|--|--|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

a,c,e

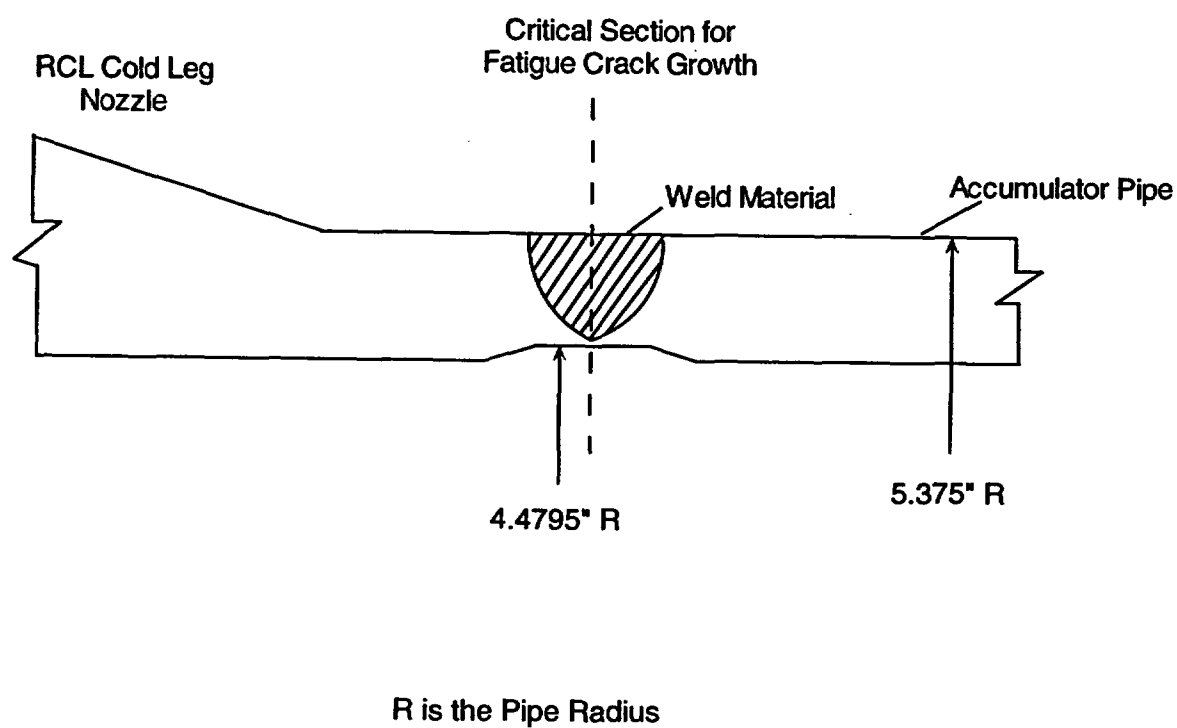


Figure 6-1 Schematic of Accumulator Line at RCL Cold Leg Nozzle Weld Location

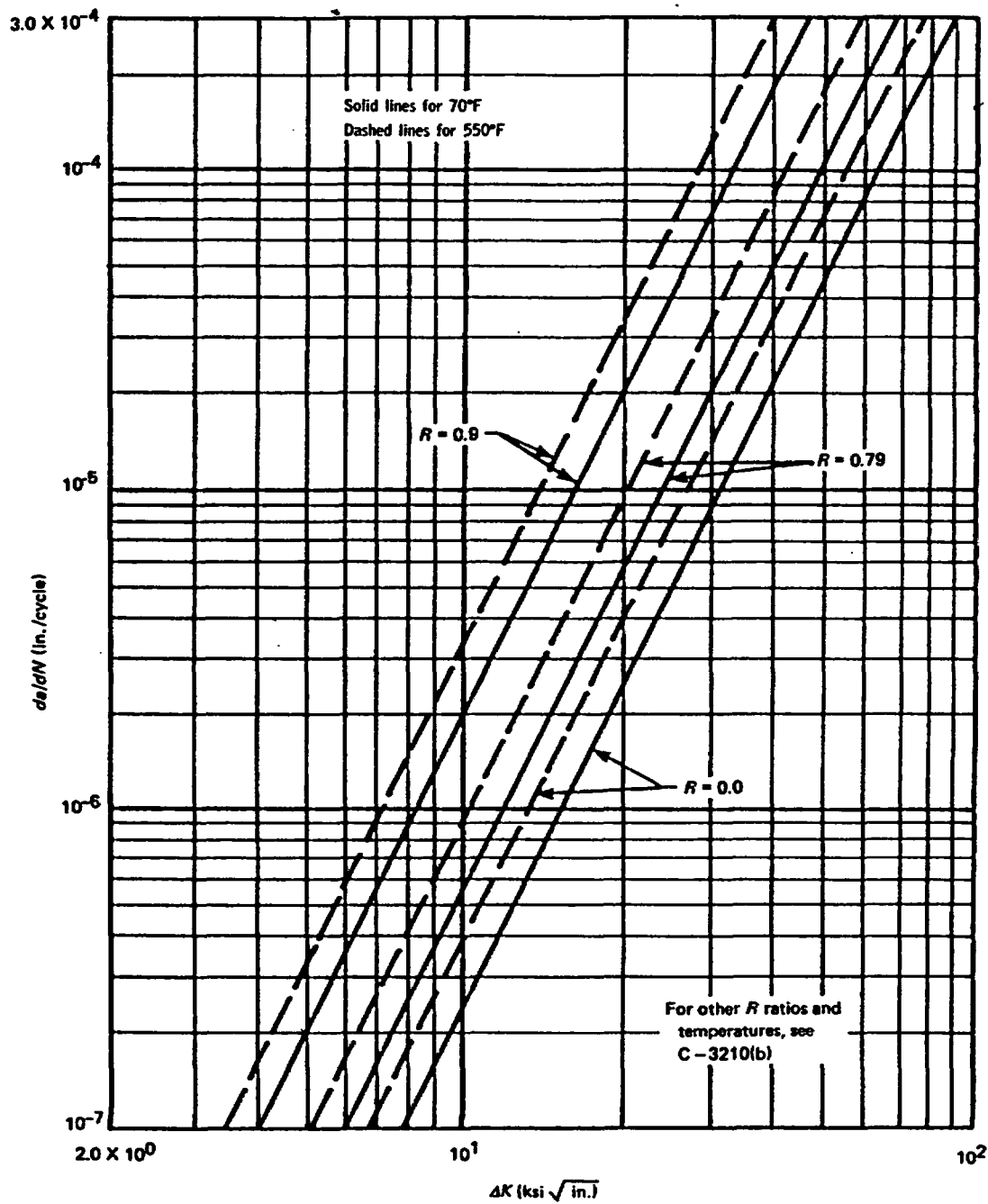


Figure 6-2 Reference Crack Growth Curves for Stainless Steel in Air Environment

7 ASSESSMENT OF MARGINS

In the preceding sections, the leak rates calculations, fracture mechanics analysis and fatigue crack growth assessment were performed. The results of the leak rates of Section 5.2 and the corresponding stability results of Section 5.3 are used in performing the assessment of margins. Margins are shown in Table 7-1.

In summary, at all the critical locations relative to:

1. Flaw Size - Using faulted loads obtained by the absolute sum method, a margin of 2 or more exists between the critical flaw and the flaw having a leak rate of 10 gpm (the leakage flaw).
2. Leak Rate - A margin of 10 exists between the calculated leak rate from the leakage flaw and the leak detection capability of 1 gpm.
3. Loads - At the critical locations the leakage flaw was shown to be stable using the faulted loads obtained by the absolute sum method (i.e., a flaw twice the leakage flaw size is shown to be stable; hence the leakage flaw size is stable). Therefore a margin on loads of 1.0 (see Section 4.2 for explanation) using the absolute summation of faulted load combinations is satisfied.

All the LBB recommended margins are satisfied.

In this evaluation, the Leak-Before-Break methodology is applied conservatively. The conservatism used in the evaluation is summarized in Table 7-2.

| Table 7-1 : Leakage Flow Sizes, Critical Flaw Sizes and Margins | | | |
|--|--------------------------------|-------------------------------|---------------|
| Node | Critical Flaw Size (in) | Leakage Flaw Size (in) | Margin |
| 3020 | 11.39 | 3.87 | 2.94 |
| 3120 | 12.54 | 3.70 | 3.39 |
| 3295 | 16.36 | 6.20 | 2.64 |

| Table 7-2 : LBB Conservatism |
|--|
| Factor of 10 on Leak Rate |
| Factor of approximately 2 on Flaw Size for All Locations |
| Algebraic Sum of Loads for Leakage |
| Absolute Sum of Loads for Stability |
| Average Material Properties for Leakage |
| Minimum Material Properties for Stability |

8 CONCLUSIONS

This report justifies the elimination of 10" Accumulator line breaks as the structural design basis for the Callaway Nuclear Power Plant as follows:

- a. Stress corrosion cracking is precluded by use of fracture resistant materials in the piping system and controls on reactor coolant chemistry, temperature, pressure, and flow during normal operation.
- b. Water hammer should not occur in the RCS piping (primary loop and the attached class 1 auxiliary lines) because of system design, testing, and operational considerations.
- c. The effects of low and high cycle fatigue on the integrity of the Accumulator lines were evaluated and shown acceptable.
- d. Ample margin exists between the leak rate of small stable flaws and the capability of the Callaway Nuclear Power Plant reactor coolant system pressure boundary leakage detection system.
- e. Ample margin exists between the small stable flaw sizes of item (d) and the critical flaw size.

The postulated reference flaw will be stable because of the ample margins in items (d) and (e) and will leak at a detectable rate which will assure a safe plant shutdown.

Based on the above, it is concluded that 10" Accumulator line breaks should not be considered in the structural design basis of the Callaway Nuclear Power Plant.

APPENDIX A - LIMIT MOMENT

[

]a,c,e

ace

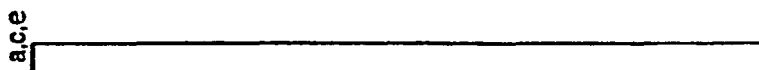


Figure A-1 Pipe with A Through-Wall Crack in Bending