WESTINGHOUSE CLASS 3

WCAP-12388

EVALUATION OF THERMAL STRATIFICATION FOR THE BYRON AND BRAIDWOOD UNITS 1 AND 2 RESIDUAL HEAT REMOVAL LINES

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SECTION 1.0

BACKGROUND AND TRANSIENT ANALYSIS

With the discovery of a crack in the Genkai Unit 1 Residual Heat Removal (RHR) suction line in June of 1988, attention has been focused on the possibility of stratification occurring in the RHR suction lines. This incident led to the issuance of NRC Bulletin 88-08, Supplement 3: "Thermal Stresses in Piping Connected to Reactor Coolant Systems," on April 11, 1989. This report addresses this issue for the Byron and Braidwood Units 1 and 2 RHR suction lines.

The assessment begins with a detailed description of the Genkai phenomenon, and a comparison of the Genkai, and Byron and Braidwood RHR suction line configurations. This comparison is very important, because it will support conclusions on the likelihood of such a transient occurring at the Byron and Braidwood Units.

A review is then provided of the overall approach used to assure that the structural integrity of the Byron and Braidwood RHR suction lines will not be compromised within conservatively determined inspection intervals, should stratification occur. Detailed thermal, stress, fatigue, and fatigue crack growth analyses have been performed to assess the effects of potential stratification.

1.1 Description of the Genkai Phenomenon

Around 9 a.m. on June 6, 1988, there was an increase in the water flow into the drain sump in the reactor containment vessel of Kyushu Electric Power Company's Genkai Nuclear Power Plant Unit 1 (PWR, 599 MWe), then operating at rated output, and a pool of water was seen on the floor. Manual operation for shutdown of the reactor was therefore started at 1:15 p.m. on the same day, and the reactor was brought to complete shutdown by 5:20 p.m.

The fluid which leaked was the primary coolant, containing radioactivity. The water flow to the drain sump, which normally is approximately one liter per hour, rose to about fifty liters per hour as of 11 a.m. on June 6. Although the amount of leakage was below Kyushu Electric's safety regulation level, the power company shut down the reactor as a precaution to investigate the source of the leakage. The amount of coolant that leaked out ultimately reached about 1,100 liters, but there was no outside radioactivity. The leakage occurred in the RHR and SI lines attached to loop A. The plant started initial commercial operation in October 1975.

Results of the inspection conducted by Kyushu Electric Power Company showed that the point of leakage was in the unisolable section of the branch line from the main primary coolant piping as shown schematically in figure 1-1. It was confirmed that the coolant leaked from a pinhole with a diameter of about one millimeter, near the welded section (elbow to straight horizontal pipe) of the stainless pipe (SS 316TP), which has an outer diameter of 8.6 inches and thickness of 0.81 inches.

The cause of cracking was determined to be high cycle thermal fatigue resulting from valve leakage. The section of the pipe was replaced and the plant was returned to power.

The cyclic loading which caused the cracking is believed to have occurred in the following way:

The isolation valve developed a packing leak, which allowed hot water from the main loop to flow down the vertical leg, and through the valve. The actual leakage flow was small, and stratified at the top of the horizontal pipe, since it was hotter than the bulk water in the horizontal section of the pipe between the elbow and isolation valve. The hot water reached the valve, warming it, and when the valve reached about 385°F the leakage flow stopped. Once the stratified flow was cut off, the valve temperature again cooled down and the leak recurred. As the stratified hot water reached the valve again the cycle repeated. This led to a severe fatigue cycling which initiated and propagated the crack. This scenario was simulated in laboratory tests.

1.2 Comparison of Genkai and the Byron and Braidwood Units

Although there are similarities between the Genkai and the Byron and Braidwood RHR suction lines, there are differences which support the conclusion that a Genkai-type transient is unlikely to occur at Byron and Braidwood. (A comparison is provided in table 1-1).

The study of the Genkai cracking incident showed that without leakage the hot water from the main loop was unable to reach the bottom of the vertical pipe because turbulence was limited to about five feet from the main loop junction. For Byron and Braidwood, the hot water is expected to reach the bottom of the vertical pipe, because the pipe is larger in diameter (12 vs. 8 inches) and the vertical distance is much shorter (4 vs. 9 feet). The isolation valves in the Byron and Braidwood RHR lines are about 4 feet and 9 feet away from the vertical leg for loop 1 and loop 3, respectively, as compared to 2-3 feet at Genkai. The schematic layouts for RHR lines at Byron and Braidwood are shown in figures 1-2 through 1-9.

When a pipe (such as the RHR suction line) is connected to a larger diameter pipe (in this case the hot leg) with high velocity turbulent flow, the turbulence will penetrate into the smaller pipe. The distance of penetration depends on the flow velocity (Reynolds number) in the larger pipe, the relative pipe inside diameters and the relative angle between the pipes. A number of experiments have been performed at Westinghouse and Mitsubishi Heavy Industries to obtain this information, and the results are summarized in figure 1-10.

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[ ].[a,c,e] Even though stratification and cycling are unlikely at Byron and Braidwood, an assessment was carried out to quantify and evaluate the effects of postulated stratification on pipe integrity.

1.3 Development of Postulated Transient

The development of a stratification transient for RHR suction lines began with the temperature profile applicable to the Genkai plant, as obtained experimentally by Mitsubishi Heavy Industries. The transient at Genkai was due to intermittent valve leakage, which provided a path for hot water to be drawn into the RHR line from the main loop. At the bottom of the vertical pipe, a stratified flow was established, with hot water filling the top 10 percent of the horizontal piping.

To establish a stratified flow transient for the Byron and Braidwood Units, a simplified, yet conservative, representation of the Genkai temperature profile was assumed to exist in the horizontal portion of each line. The same portion of the pipe as at Genkai was assumed to be filled with leakage flow at Byron and Braidwood. The water from the loop connection to the horizontal piping was assumed to be at hot leg temperature due to loop flow turbulence, since this distance is about six pipe diameters. The water was assumed to stratify in the horizontal piping. The water in the bottom of the pipe was stagnant, and was assumed to cool by a conduction-limited mechanism. The stratified flow at the top of the pipe does not cool as quickly because of its flow, as shown in figure 1-11. This creates a rather large temperature difference between the top and bottom of the pipe, which is maximized at about four feet from the start of stratification. As the flow continues, it gradually loses heat to the stagnant bulk fluid, and the top to bottom of pipe temperature difference diminishes. The development of this temperature profile is provided in detail in Appendix A.

TABLE 1-1

COMPARISON OF GENKAI, AND BYRON AND BRAIDWOOD

	GENKAI	BYRON AND BRAIDWOOD* LOOP 1	LOOP 3
Line Size	8 inch	12 inch	12 inch
Vertical Drop From RCS	9 feet	4 feet	4 feet
Distance to Isolation Valve From Vertical Drop	2-3 feet	4 feet	9 feet
Total Length of Pipe, RCS to First Isolation Valve	14-15 feet	8 feet	13 feet

*All pipe lengths are approximate since this is a compilation of eight lines for the Byron and Braidwood Units; however, the lengths are correct to about one foot.

WELD FAILURE LOCATION – GENKAI UNIT 1

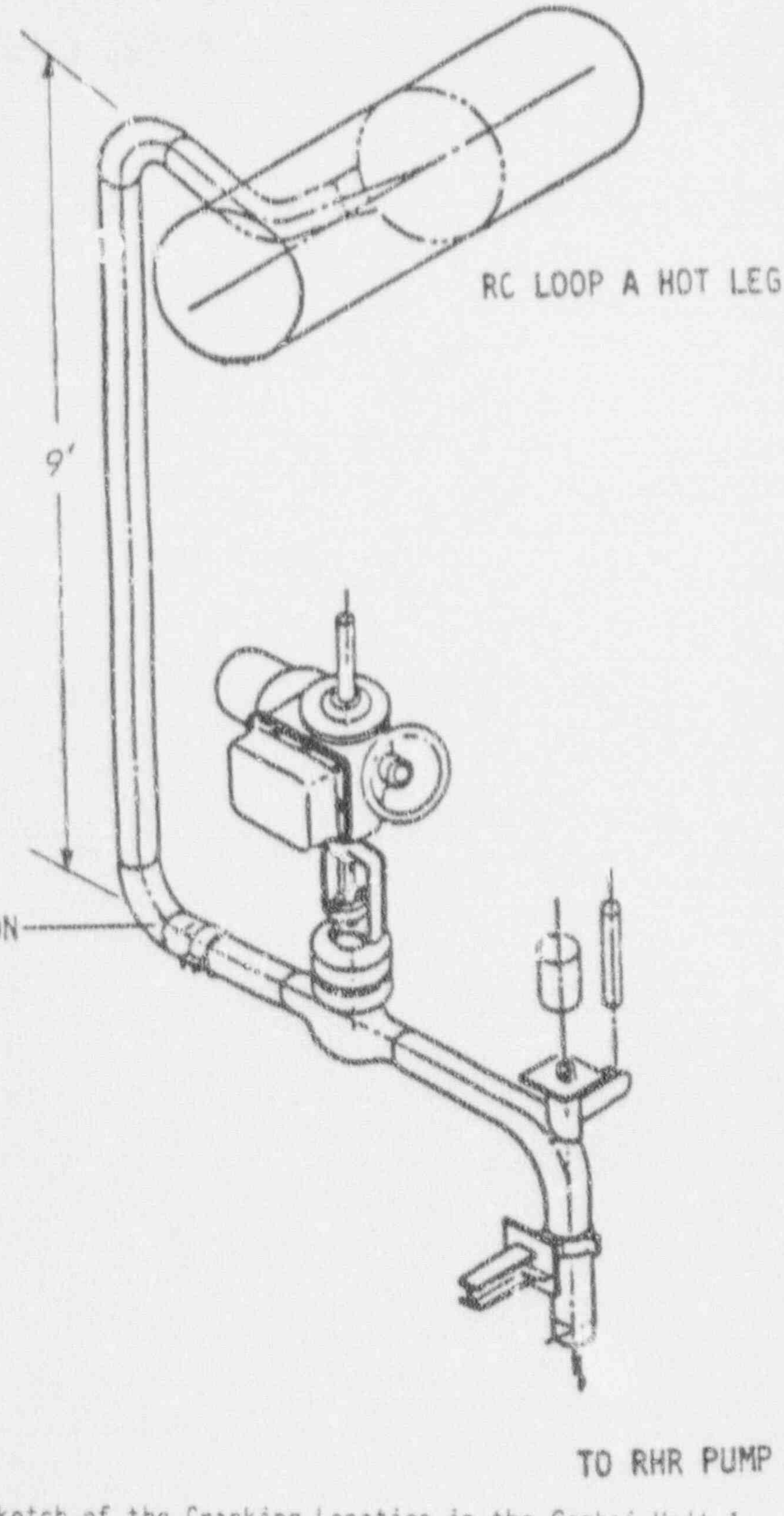

Figure 1-1. Sketch of the Cracking Location in the Genkai Unit 1 RHR Suction Line

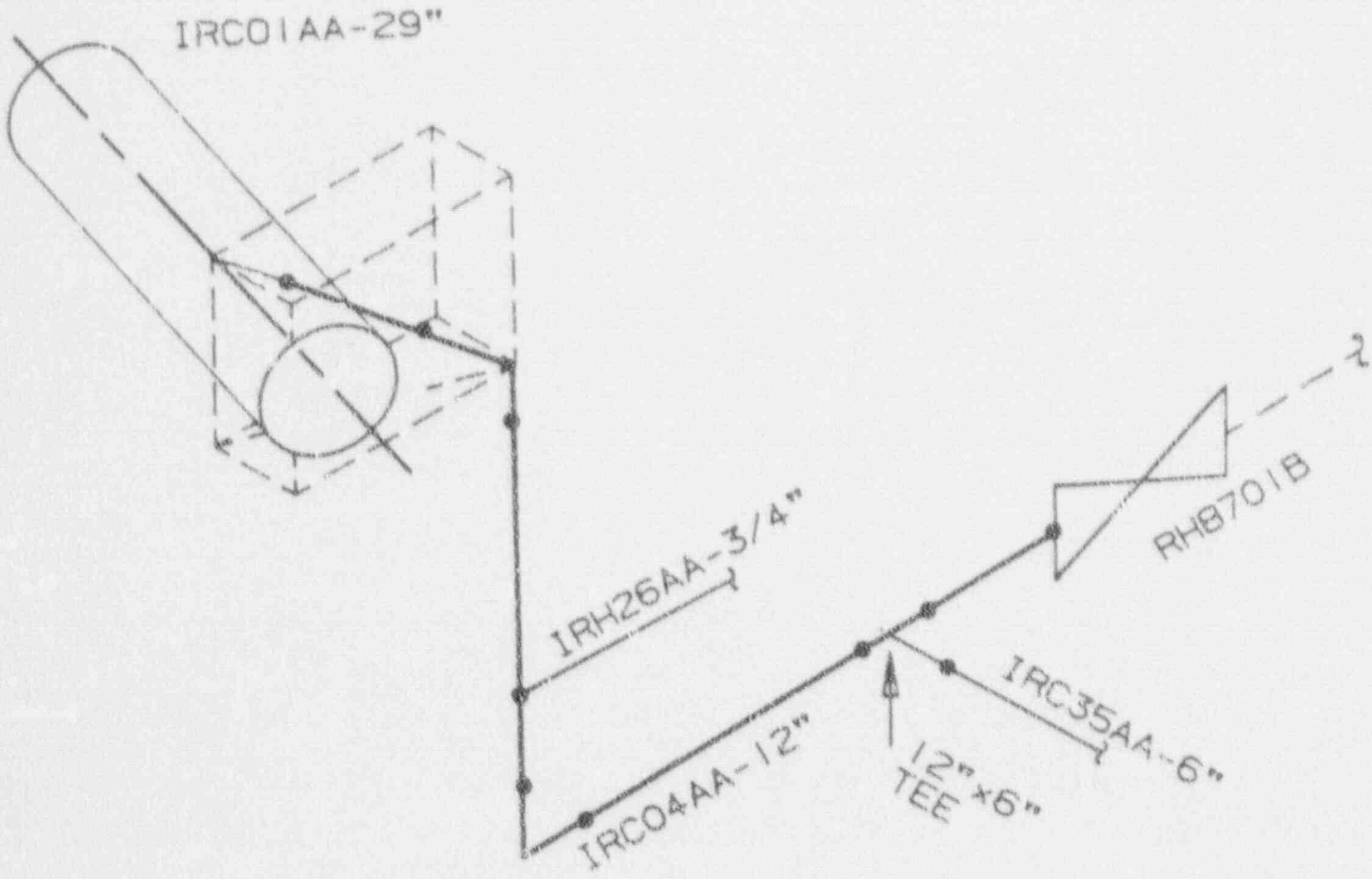

Figure 1-2. Byron Unit 1, Loop 1 RHR Line

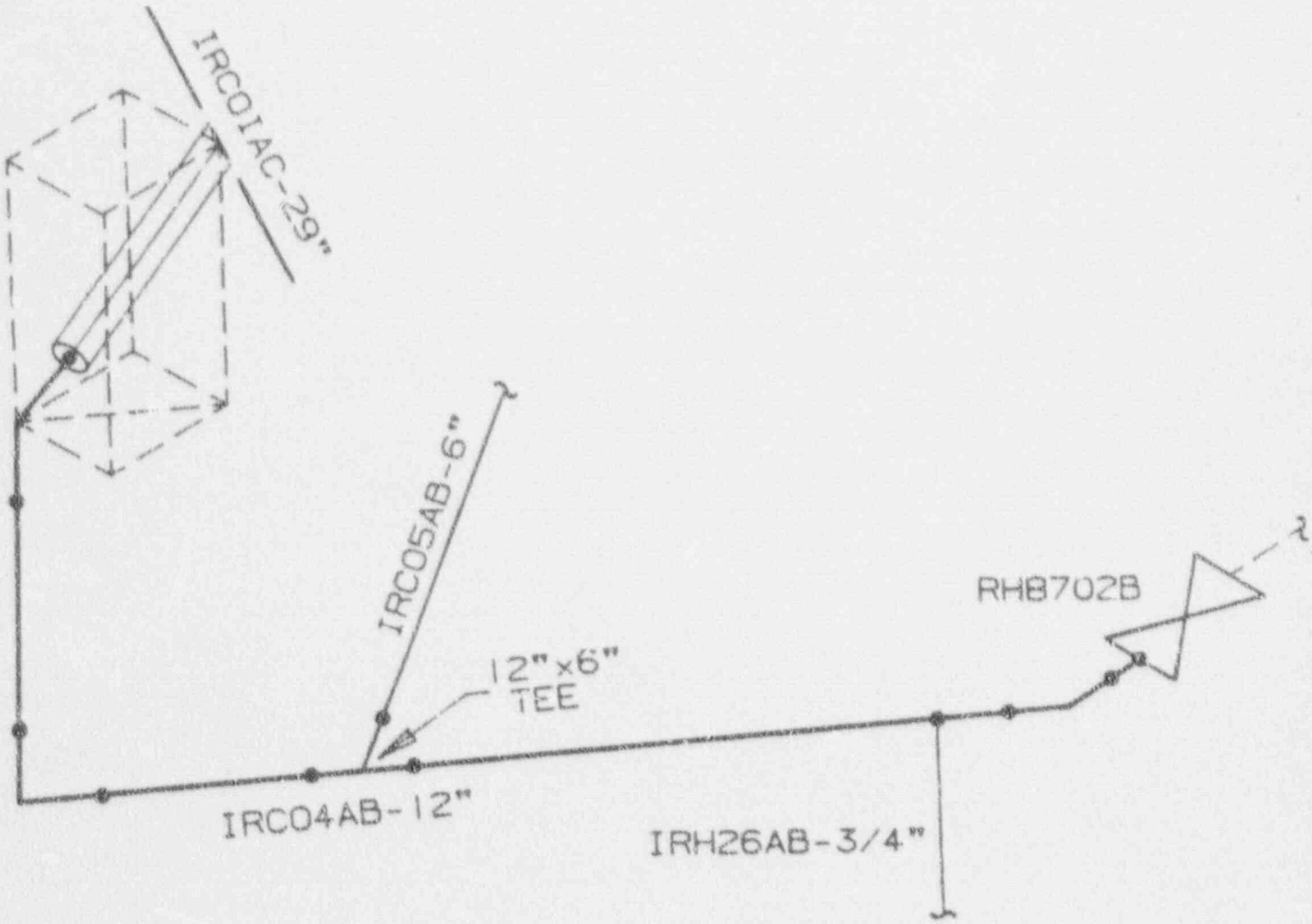

Figure 1-3. Byron Unit 1, Loop 3 RHR Line

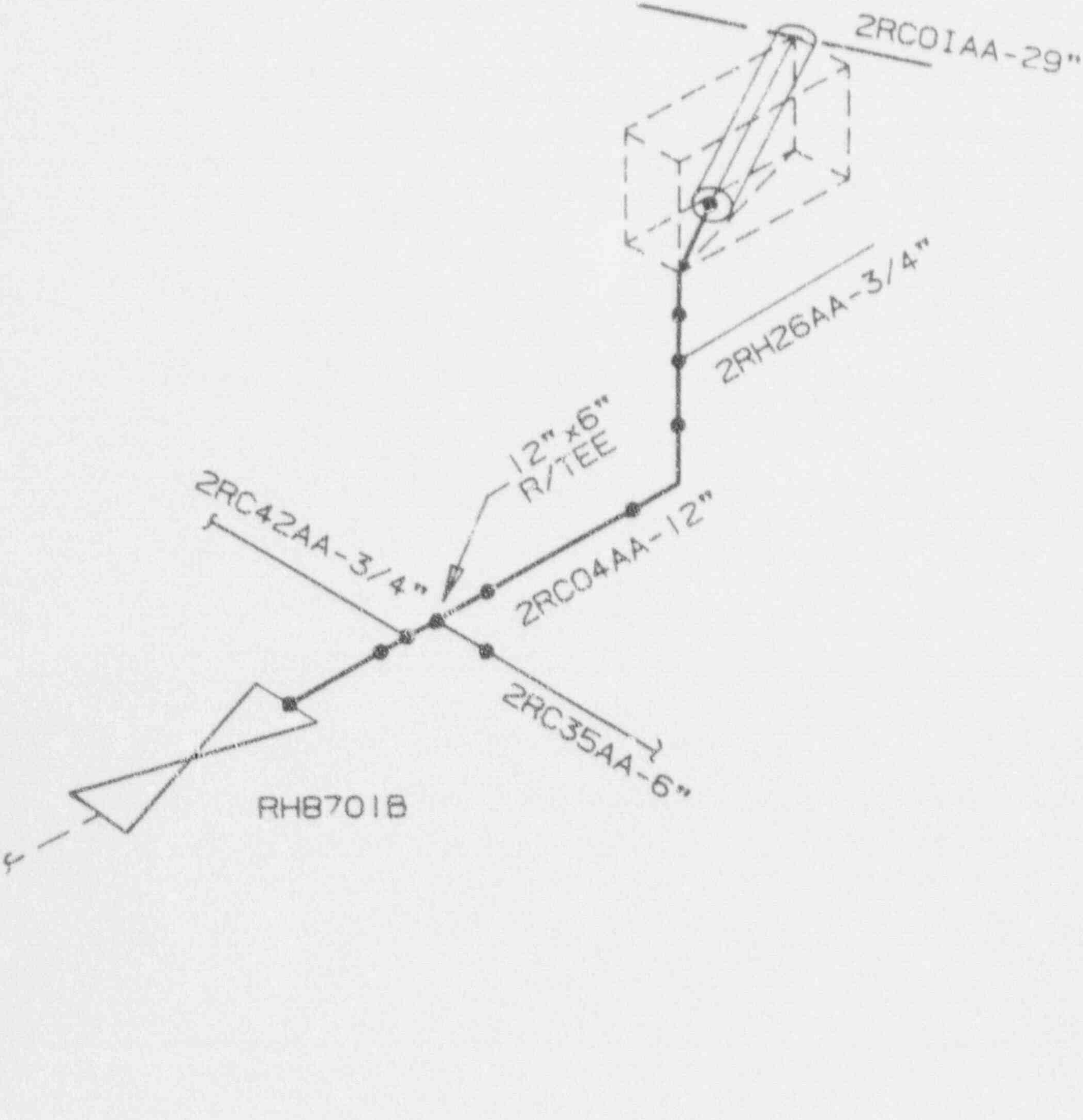

Figure 1-4. Byron Unit 2, Loop 1 RHR Line

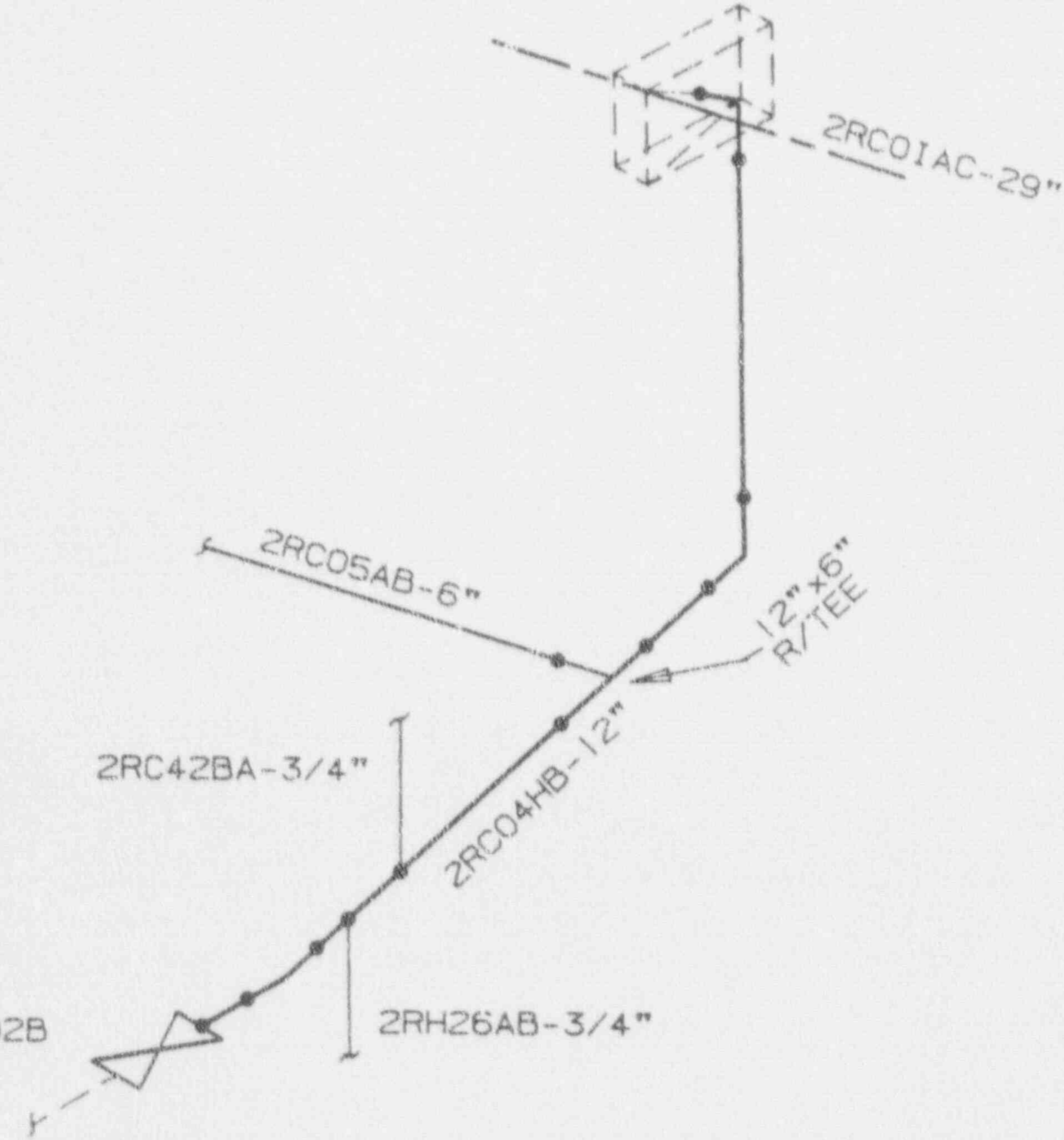

Figure 1-5. Byron Unit 2, Loop 3 RHR Line

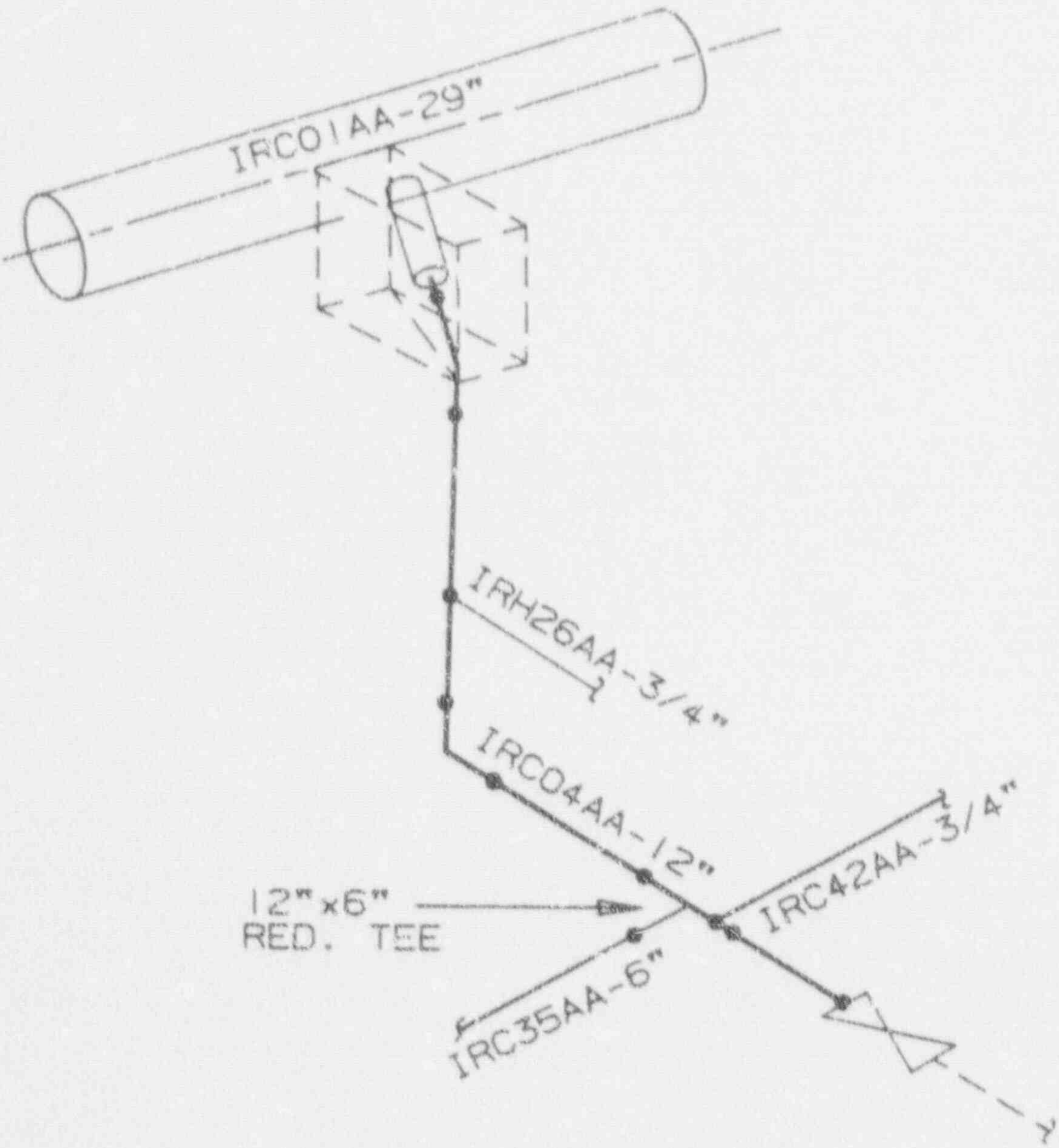

Figure 1-6. Braidwood Unit 1, Loop 1 RHR Line

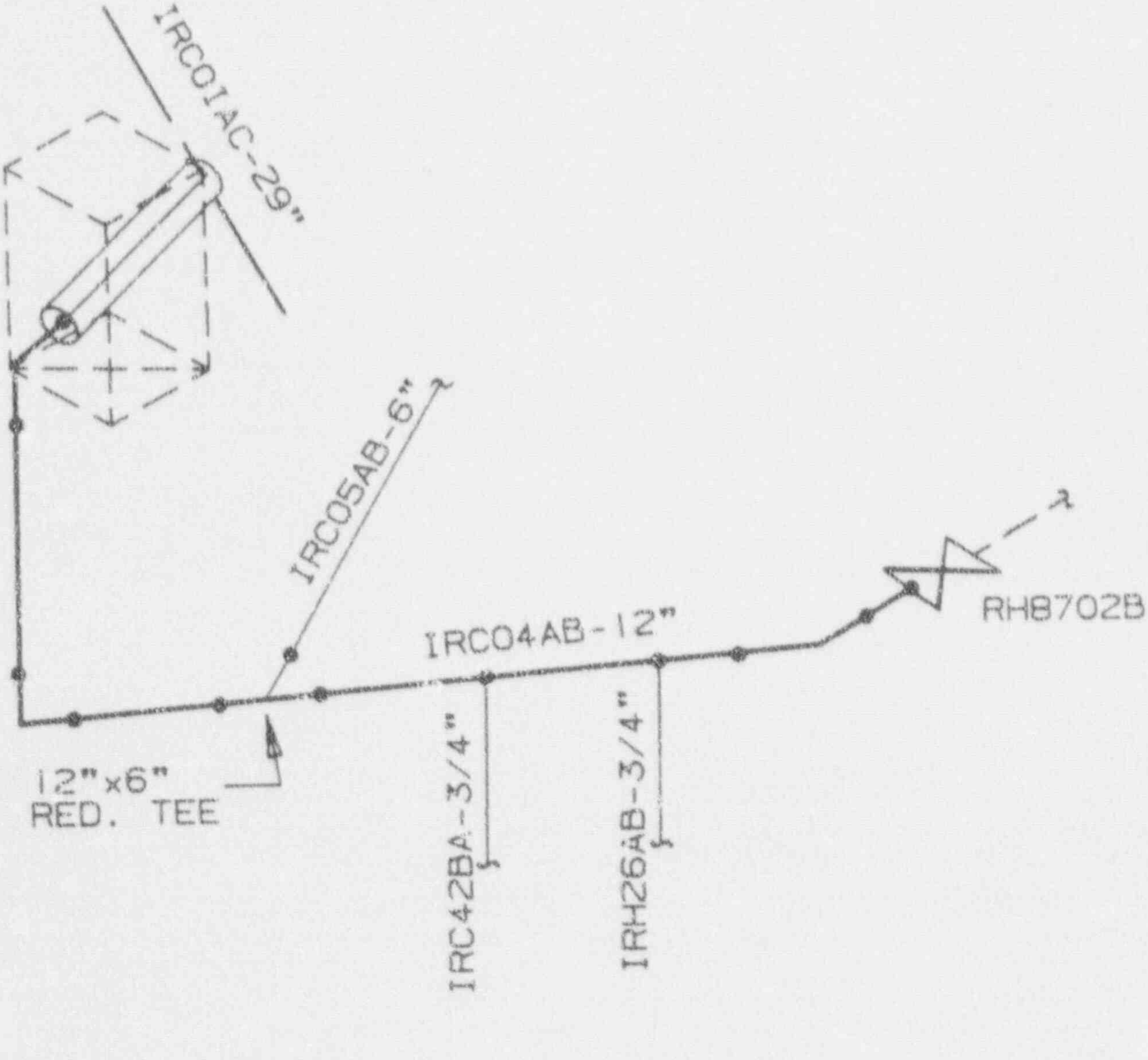

Figure 1-7. Braidwood Unit 1, Loop 3 RHR Line

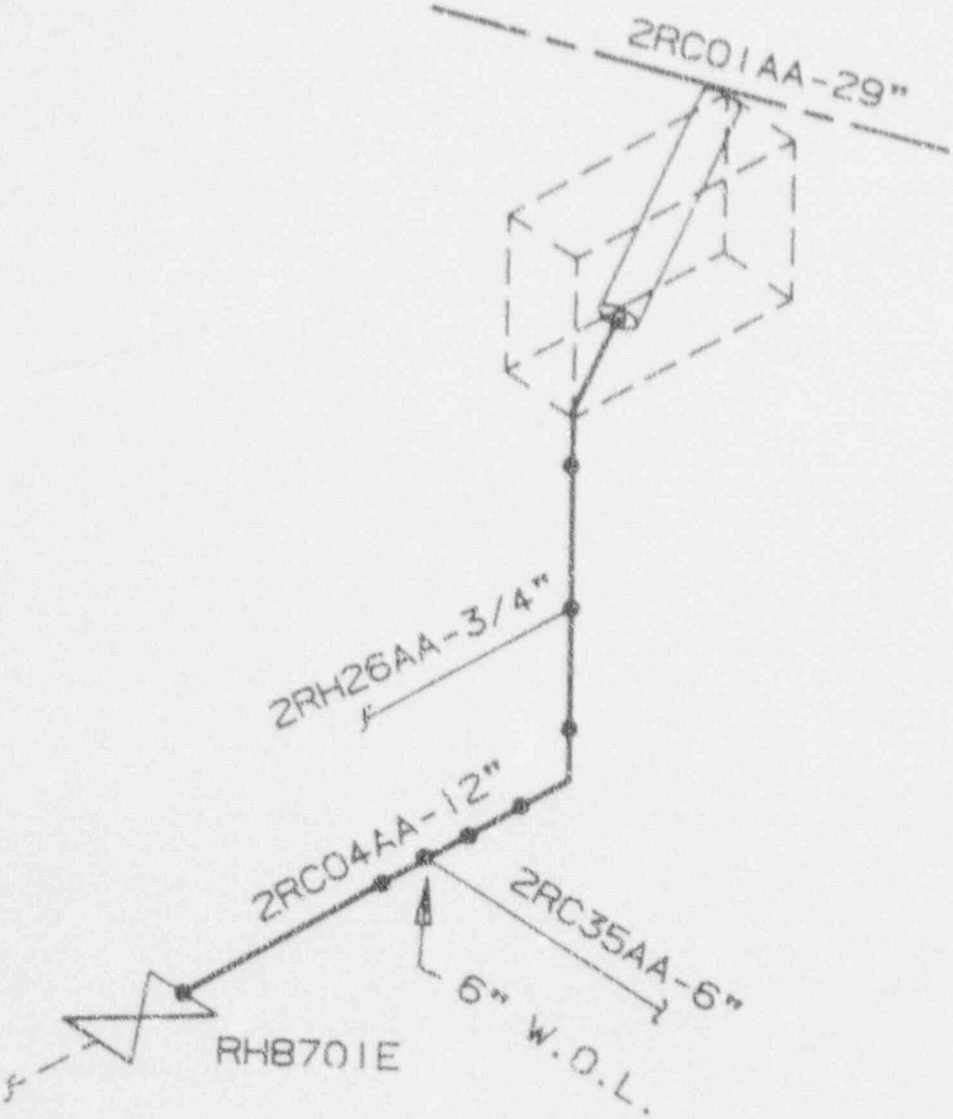

Figure 1-8. Braidwood Unit 2, Loop 1 RHR Line

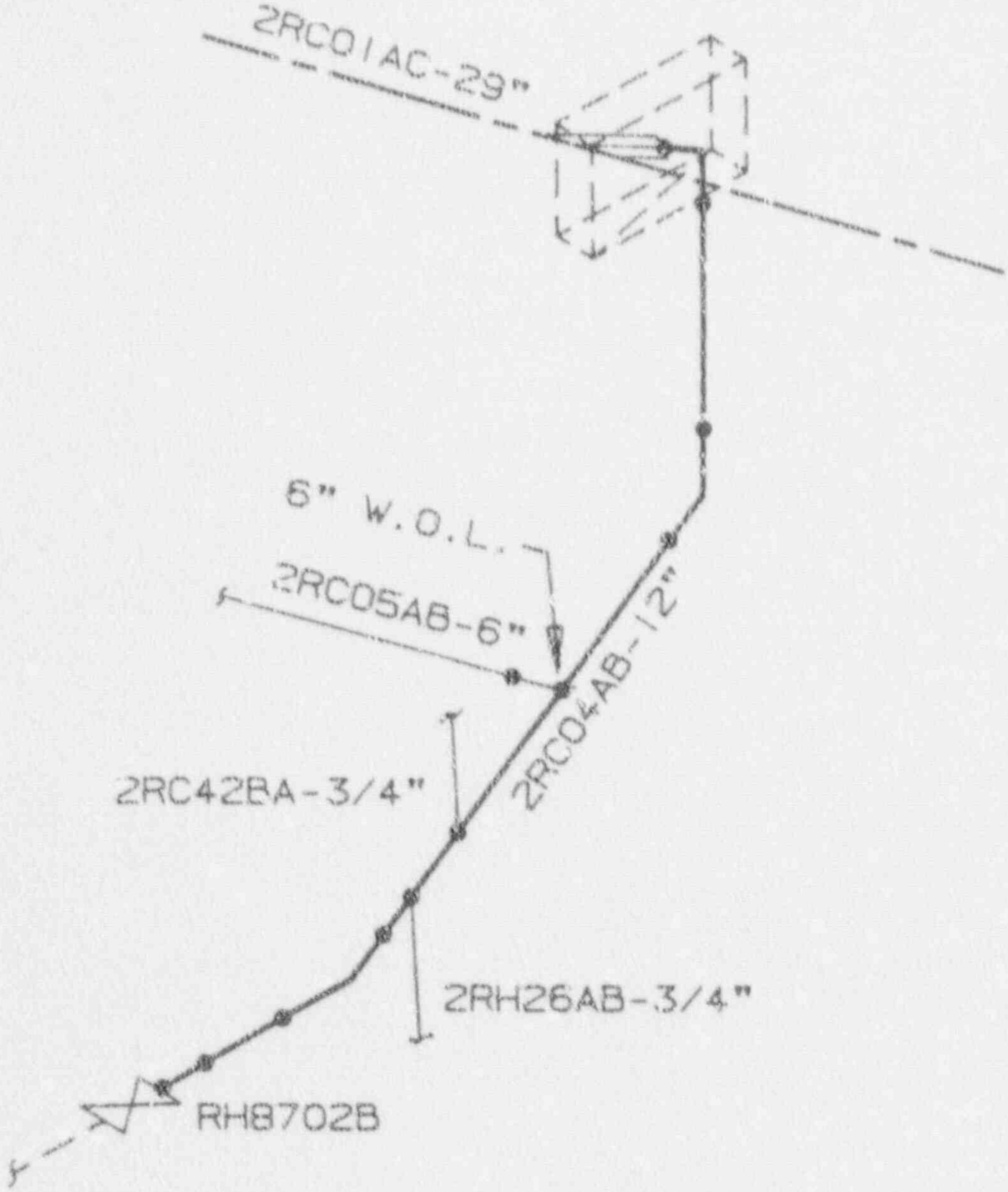

Figure 1-9. Braidwood Unit 2, Loop 3 RHR Line

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Figure 1-10. Experimental Results of Turbulent Penetration in a Pipe Connected to a High Flow Larger Diameter Pipe

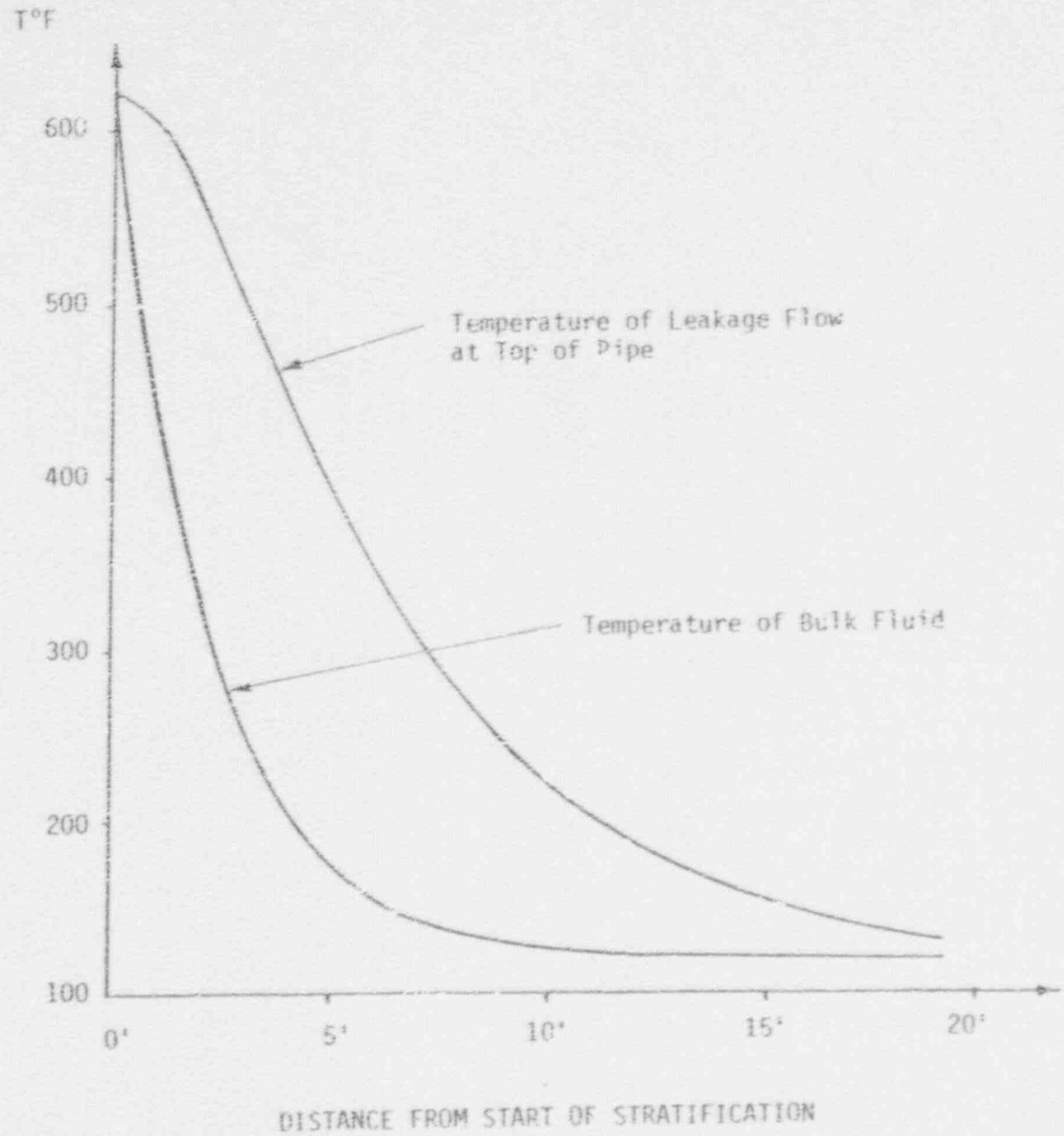

Figure 1-11. Temperature of Stratified Flow - Byron Unit 1, Loop 3, 12 inch RHR Line

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SECTION 2.0
STRESS ANALYSES

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Section 2.1 Addresses the structural effect of stratification

Section 2.2 Addresses the local stress effects of stratification

2.1 Piping System Structural Analysis

2.1.1 Introduction

The thermal stratification computer analysis of the piping system to determine loads in the piping is referred to as the piping system structural analysis. These loads are used as input to the fatigue evaluation. The thermal stratification condition consists of both axial and top-to-bottom variations in the pipe metal temperature, as described in section 1.0. The model consists of straight pipe and elbow elements for the ANSYS computer code (ref. 4). [

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These studies verified the suitability of the ANSYS computer code for the thermal stratification analysis. [

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2.1.2 Discussion

The piping layouts are very similar for all loop 1, and for all loop 3 RHR lines at the Byron and Braidwood Units (see figures 1-2 through 1-9). The loop 3 layout has about five additional feet of horizontal piping and an additional elbow near the isolation valve, which the loop 1 layout does not have. Per the discussion of turbulent penetration in section 1.2, stratification is more likely to occur in the loop 3 configuration than in the loop 1 configuration. Also, the longer length of horizontal piping will result in larger structural stresses due to potential stratification.

The piping layout for the RHR suction line analyzed (Byron Unit 1, Loop 3) is shown in figure 2-1. [

]^{a,c,e} The analyses for this line will also be conservatively applicable to the other Byron and Braidwood RHR lines. The piping analysis model consists of straight pipe and elbows. These elements provide the capability to load the piping with a top-to-bottom temperature gradient. Spring-damper elements were used at rigid support locations.

Two thermal expansion loadings were applied to the ANSYS structural model in order to determine the effects of cyclic valve leakage on pipe loading.

The first case assumed no valve leakage, therefore no top-to-bottom temperature gradient. The axial temperature gradient along the line was determined by heat transfer analysis (Appendix A) and is shown in figure 1-11 (bottom curve). The line was assumed to be at the RCS temperature between the hot leg connection and the horizontal piping due to loop turbulence.

The second analysis case assumed [

]^{a,c,e} The axial temperature distribution of this leakage was also determined by heat transfer analysis (Appendix A) and is shown in figure 1-11 (top curve). The axial temperature distribution of the remaining stagnant water was assumed to be the same as the distribution of the no-leakage case (figure 1-11, bottom curve). Therefore, a top-to-bottom temperature gradient was input for this case as a step change at the leakage flow/stagnant water interface (figure 2-5).

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2.2 Local Stress Due to Non-Linear Thermal Gradient

2.2.1 Explanation of Local Stress

Figure 2-3 shows the local axial stress components in a beam with a sharply nonlinear metal temperature gradient. Local axial stresses develop due to the restraint of axial expansion or contraction. This restraint is provided by the material in the adjacent beam cross section. For a linear top-to-bottom temperature gradient, the local axial stress would not exist. [

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2.2.2 Superposition of Local and Structural Stresses

For the purpose of this discussion, the stress resulting from the structural analysis (section 2.1) will be referred to as "structural stress." [

]^{a,c,e} Local and structural stresses may be superimposed to obtain the total stress. This is true because linear elastic analyses are performed and the two stresses are independent of one another.

Figure 2-4 presents the results of a test case that was performed to demonstrate the validity of superposition. As shown in the figure, the superposition of local and structural stress is valid. [ ]^{a,c,e}

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2.2.3 Finite Element Model of Pipe for Local Stress

The pipe finite element model is shown in figure 2-5, along with thermal boundary conditions. The entire cross section was used for modeling and analysis. [

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2.3 Stress Results

The temperature and stress results for the WECAN finite element model are presented in the plots in figures 2-6, 2-7 and 2-8. [

]^{a,c,e} The high temperature region is very localized at the top of the pipe, as expected, and the pipe wall temperature quickly drops to the stagnant water temperature of about 270°F, for the majority of the circumference. The axial stresses from this stratified flow are shown in figure 2-7, and it can be seen that the highest stress is near the hot-cold water interface, and is a positive 17.3 ksi. Compressive stresses are found at both the top and bottom of the pipe. The stress intensity (figure, 2-8) was highest at the top of the pipe, at a value of 24.2 ksi.

These stresses were combined with the structural stresses discussed in section 2.1 to obtain the total stresses from the postulated stratification event. This combined stress is then used in the fatigue and fatigue crack growth analyses of sections 3 and 4.

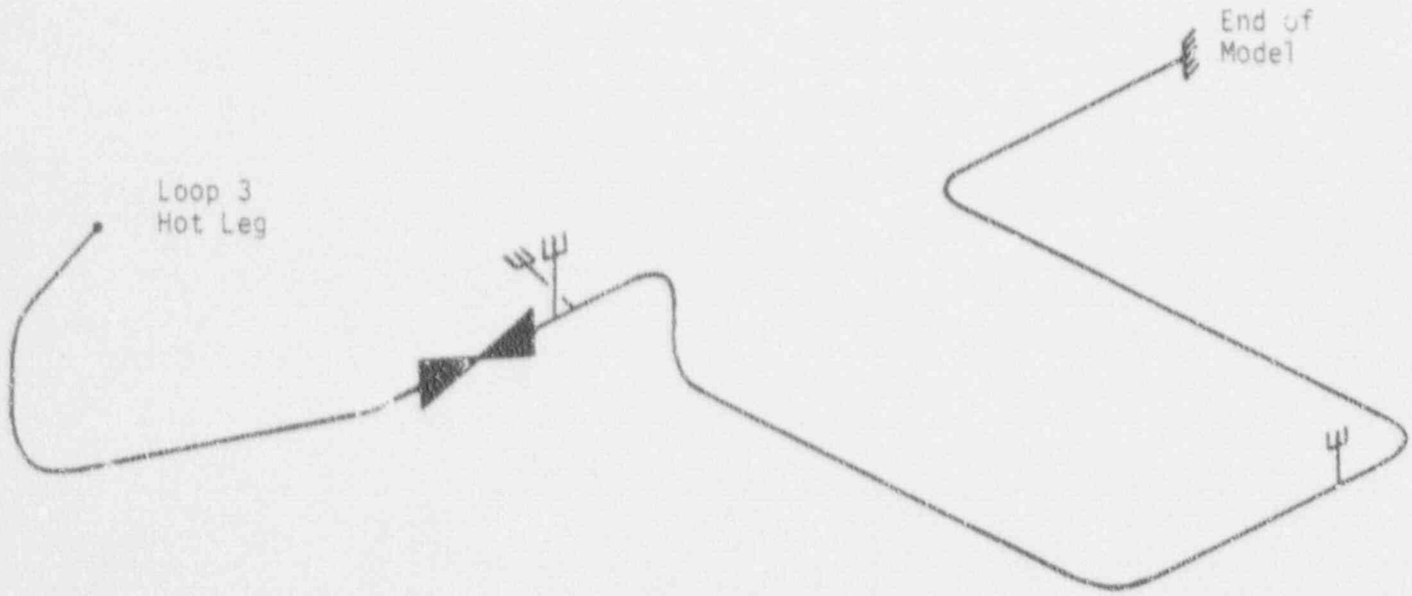

Figure 2-1. Structural Model of the Byron Unit 1, Loop 3, RHR Line

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Figure 2-2. [ ]^{a,c,e} Profile

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Figure 2-3. Local Stress in Piping Due to Thermal Stratification

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Figure 2-4. Test Case for Superposition of Local and Structural Stresses

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Figure 2-5. Piping Local Stress Model and Thermal Boundary Conditions

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Figure 2-6. RHR Line Temperature Distribution for a Temperature Difference of 213°F

Note: Original Plot in Color.

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Figure 2-7. RHR Line Local Axial Stress Distribution for a Temperature Difference of 213°F
Note: Original Plot in Color

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Figure 2-8. RHR Line Local Stress Intensity Distribution for a Temperature Difference of 213°F

Note: Original Plot in Color

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SECTION 3.0
ASME SECTION III FATIGUE USAGE FACTOR EVALUATION

3.1 Code and Criteria

Fatigue usage factors for the RHR suction line were evaluated based on the requirements of the ASME B & PV Code, Section III, Subsection NB-3600 (ref. 7), for piping components. The fatigue evaluation required for level A and B service limits in NB-3653 is summarized in table 3-1. ASME III fatigue usage factors were calculated assuming that the maximum moment stress range and the maximum stratification ΔT can coincide at any location in the horizontal piping.

3.2 Previous Design Methods

Previous evaluations of RHR suction line piping fatigue used the NB-3653 techniques but with thermal transients defined by Westinghouse design specifications, assuming the fluid flows to sweep the RHR line piping with an axisymmetric temperature loading on the pipe inside wall, and that no stratified flow due to valve leakage occurred.

3.3 Analysis for Thermal Stratification

Using the thermal transient to account for thermal stratification as described in section 1.0, the stresses in the piping components were established (section 2) and new fatigue usage factors were calculated.

Stresses in the pipe wall due to thermal stratification loading were obtained from the WECAN 2-D analysis of a 12 inch, schedule 140 pipe. [

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Two stress ranges were considered in the fatigue analysis. [

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Peak stresses, including the total surface stress from all loadings - pressure, moment, stratification - were calculated for the transient. [

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The fatigue evaluation includes:

1) Calculating the S_n and S_p ranges, K_e, and S_{alt} for the stratified/no load and stratified/unstratified load stress ranges.

2) For each value of S_{alt}, use the design fatigue curve to determine the maximum number of cycles which would be allowable if this type of cycle were the only one acting. These values, N_1, N_2...N_n, were determined from Code figures I-9.2.1 and I-9.2.2, for austenitic stainless steels.

3) For the stratified/no load case, calculate the contribution to the usage factor based on 200 design cycles.

4) For the stratified/unstratified load case, calculate the time required for crack initiation (usage factor = 1.0) based on the assumed cyclic period.

3.4 <u>Fatigue Usage Results</u>

A stress analysis was completed for the stratified flow condition, including local thermal stresses and structural piping stresses resulting from the postulated stratification. Deadweight stresses were constant, so they were not included since they would not contribute to the alternating stress. The transients analyzed alternated from stratified flow to an unstratified stagnant condition, and from stratified flow to no load condition. For stratified flow, the two curves of figure 1-11 were used, while the unstratified stagnant condition only the bottom curve was used for the bulk temperature. The criteria used are shown in table 3-1. The fatigue results are shown in table 3-2 for the critical locations.

For stresses cycling between the stratified and no load cases, the contribution to the cumulative usage factor is negligible (0.02), since only 200 cycles will occur over the design life of the plant. For the stratified/unstratified case, a usage factor of 1.0 would be obtained within the plant design life assuming continuous cycling at the governing location, and a short cyclic period (e.g. five minutes). This assumes that the full range of thermal and moment stresses occurs over the five minute period, which is conservative since the heat transfer over five minutes will not render the pipe completely unstratified. Because ASME fatigue usage factor requirements could potentially be exceeded, fatigue crack growth analysis (section 4) will be used to determine inservice inspection frequency.

In addition to the usage factor determination, a check was made for ASME Section III equation 12. The maximum equation 12 stress for the stratified/no load and stratified/unstratified ranges is 30.5 ksi, which is well within the equation 12 limit of 3 S_m (or 50 ksi).

TABLE 3-1

CODE/CRITERIA

- o ASME B&PV Code, Sec. III
  - NB3600
  - NB3200

- o Level A/B Service Limits
  - Primary Plus Secondary Stress Intensity $\leq$ 3Sm (Eq. 10)
  - Simplified Elastic-Plastic Analysis (when Eq. 10 > 3 S_m)
    - Expansion Stress, $S_e \leq$ 3Sm (Eq. 12) - Global Analysis
    - Primary Plus Secondary Excluding Thermal Bending < 3Sm (Eq. 13)
    - Elastic-Plastic Penalty Factor $1.0 \leq K_e \leq 3.333$
  - Peak Stress (Eq. 11)/Cumulative Usage Factor (U_{cum})
    - $S_{alt} = K_e S_p/2$ (Eq. 14)
    - Design Fatigue Curve
    - $U_{cum} \leq 1.0$

TABLE 3-2

FATIGUE RESULTS - BYRON UNIT 1, LOOP 3 RHR

Stratified/No Load Case (200 design cycles):

COMPONENT	ALTERNATING STRESS (ksi)	INCREMENTAL USAGE FACTOR
Long Radius Elbow	35.4	.001
Valve Weld	46.7	.005
Elbow Weld	41.2	.002
Tee	65.5	.020

Stratified/Unstratified Case:

COMPONENT	ALTERNATING STRESS (ksi)	ALLOWABLE CYCLES
Long Radius Elbow	22.5	2×10^6
Valve Weld	31.8	3×10^5
Elbow Weld	29.2	6×10^5
Tee	20.2	5×10^6

SECTION 4.0
FATIGUE CRACK GROWTH EVALUATION

Per the previous section, it was shown that should valve leakage and stratification occur in the RHR piping, without a mechanism to induce continuous cycling during power operation, 200 cycles would occur over the life of the unit, and cracks would not initiate. However, should a mechanism exist to induce cycling, crack initiation could occur. This section deals with the time required for crack propagation, and consequently, the determination of inservice inspection frequency.

4.1 Method Description

The ASME Section XI method is based on stress analysis results and material crack growth laws. The stress intensity factor (K_I) required for the fatigue crack growth calculations is obtained from the K_I expression given in reference 2 for an aspect ratio (2a/l) of 1:6. The fatigue crack growth law for stainless steel in a pressurized water environment was obtained from reference 3. The crack growth per cycle da/dN is

$$da/dN = (C)(F)(S)(E)\ \Delta K^{3.30}$$

where:

- $C = 2.42 \times 10^{-20}$
- $F =$ frequency factor ($F = 1.0$ for temperatures below 600°F)
- $S =$ minimum K to maximum K ratio correction ($S = 1.0$ for $R = 0$; $S = 1 + 1.8R$ for $0 < R < 0.8$; and $S = -43.35 + 57.97R$ for $R > 0.8$)
- $E =$ environmental factor. $E = 2.0$ (conservative recommendation from ASME Section XI task group for PWR environment)
- $\Delta K =$ range of stress intensity factor, psi $\sqrt{in}$

The stress intensity range input to the fatigue crack growth analysis is a function of the assumed cyclic period. For short cyclic periods, the stress intensity range is smaller, but the number of cycles is higher than for long cyclic periods. The reason for this is that the piping requires time to cool since it is well insulated. Stresses were obtained from transient thermal and stress analyses of a 2-D WECAN finite element model.

4.2 Fatigue Crack Growth Results

For the fatigue crack growth calculation, a number of cases were analyzed corresponding to various assumed cyclic periods. Table 4.1 summarizes the assumed periods, stress ranges, and periods of time required for the initially assumed flaws to propagate to 60 percent of the wall depth. Based on these calculations, the minimum time required for the flaw size to reach 60 percent of the wall thickness is about four years.

TABLE 4.1

FATIGUE CRACK GROWTH RESULTS SUMMARY AT GOVERNING LOCATION(1)

PERIOD (Minutes)	STRESS RANGE (ksi) MAXIMUM INSIDE	OUTSIDE	MINIMUM INSIDE	OUTSIDE	PROPAGATION TIME(2) (Years)
10	28.1	29.5	20.3	21.2	9.5
40	28.1	29.5	11.5	11.7	4.1
60	28.1	29.5	9.4	9.5	4.6

NOTES:

(1) Initial flaw size (a/t) of 15% conservatively selected.

(2) Assuming propagation to 60% of wall depth.

SECTION 5
SUMMARY AND CONCLUSIONS

A detailed evaluation of the residual heat removal lines for the Byron and Braidwood Units 1 and 2 has been completed in response to concerns raised by a pipe crack incident which occurred at Genkai Unit 1 in Japan. Although geometrical differences exist between the Byron and Braidwood Units and the Genkai Unit, which would make such a cracking incident very unlikely at the former units, the stratification transient was postulated for completeness.

After a detailed structural and finite element stress analysis was completed for the system, an ASME section III fatigue analysis showed that crack initiation is possible should continuous cycling occur during power operation.

Fatigue crack growth analysis was then performed to determine the time required for a 60 percent through wall crack to occur based on the postulated transient stratification loading, using a range of assumed cyclic periods from 10 to 60 minutes. Results of this analysis indicate that a minimum of four years of operation is required for an initial flaw of 15 percent wall thickness to grow to 60 percent wall thickness. Therefore, inservice inspection frequency should be every other refueling outage, or about three years of operation.

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2. McGowan, J. J. and Raymund, M. "Stress Intensity Factor Solutions for Internal Longitudinal Semi-Elliptical Surface Flaws in a Cylinder Under Arbitrary Loadings," Fracture Mechanics, ASTM STP 677, 1979, pp. 365-380.

3. James, L. A. and Jones, D. P., "Predictive Capabilities in Environmentally Assisting Cracking," Special Publications, PVP-Vol. 99, ASME, Nov. 1985.

4. Program ANSYS, revision 4.2B, Swanson Analysis Systems, Inc., Houston, Pennsylvania.

5. Program WECAN, version date 9/3/02A, cycle 22, 4/11/89, Westinghouse Proprietary.

6. Program FCG, cycle 3, 8/2/89, Westinghouse Proprietary.

7. ASME Boiler and Pressure Vessel Code, Section III, Division 1, 1977 Edition, through Summer, 1979 Addendum (1989 Edition, Appendix I used for high cycle fatigue curve).

APPENDIX A
THERMAL STRATIFICATION ANALYSIS

It is of interest to estimate maximum temperature differences between stratified layers of fluid in horizontal piping layouts for the purpose of studying the propensity of a given configuration for developing high stresses at the inner radii of the pipes.

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Propensity for Thermal Striping

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