Westinghouse Energy Systems

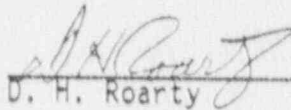Westinghouse Class 3

Structural Evaluation of the
Farley Units 1 and 2 Pressurizer
Surge Lines, Considering the Effects of
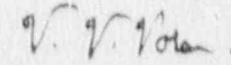Thermal Stratification

January 1991

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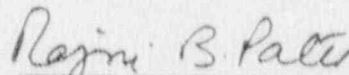
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EXECUTIVE SUMMARY

Thermal stratification has been identified as a concern which can affect the structural integrity of piping systems in nuclear plants since 1979, when a leak was discovered in a PWR feedwater line. In the pressurizer surge line, stratification can result from the difference in densities between the hot leg water and generally hotter pressurizer water. Stratification with large temperature differences can produce very high stresses, and this can lead to integrity concerns. Study of the surge line behavior has concluded that the largest temperature differences occur during certain modes of plant heatup and cooldown.

This report has been prepared to demonstrate compliance with the requirements of NRC Bulletin 88-11 for Farley Units 1 and 2. Prior to the issuance of the bulletin, the Westinghouse Owners Group had a program in place to investigate the issue, and recommend actions by member utilities. That program provided the technical basis for the plant specific transient development reported here for the Farley units.

This transient development utilized a number of sources, including plant operating procedures, surge line monitoring data, and historical records for each unit. This transient information was used as input to a structural and stress analysis of the surge line for both units. A review and comparison of the piping and support configurations for the units led to the conclusion that the surge lines are nearly identical, and thus one analysis could be done to apply to both units, for the stratification transient development and structural analysis.

The existing configurations for both Farley units have been analyzed by this WCAP. The results of the analysis indicate contact between the pipe and the whip restraints on both units. Even with this contact, the analysis has determined that Unit 1 pipe stress is within code allowables. With respect to the Unit 2 pipe whip restraint gaps, it is Alabama Power Company's intent to develop a Leak-Before-Break analysis for the surge line (separate from this effort) to justify removal of the pipe whip restraints on the pressurizer

surge line. The results of that analysis will be submitted to the NRC for approval at a later date. If necessary, Alabama Power Company will also modify the spring cans on both units to ensure sufficient travel allowance.

This analysis work also demonstrates that the requirements of NRC Bulletin 88-11 and code requirements are satisfied, assuming that proper whip restraint gaps are established and sufficient travel allowances in the spring cans are assured. The analysis results are summarized in the table which follows.

SUMMARY OF RESULTS, AND STATUS OF 88-11 QUALIFICATION

	FARLEY 1	FARLEY 2
Operating History		
Date of commercial operation	12-1-77	7-30-81
Years of water-solid heatups	0	0
Years of steam-bubble heatups	13	9
System delta T limit	320°F	320°F
Number of exceedances	0	2

Code Information

Code used for analysis	ASME Section III, 1986 Edition	

Maximum Stress and Usage Factor Results

Equation 12 stress/allowable (ksi)	40.4/51.4	40.4/51.4
Fatigue usage/allowable	0.7/1.0	0.7/1.0

Pressurizer Surge Nozzle Results

Equation 12 stress/allowable (ksi)	45.6/80.1	45.6/80.1
Fatigue usage/allowable	0.2/1.0	0.2/1.0

Support Modifications Required	Ensure sufficient travel allowance in all spring cans if whip restraint gaps are opened. (See Table 4-1)	Ensure sufficient travel allowance in all spring cans and sufficient gaps in all pipe whip restraints (See Table 4-1)
Remaining Actions by Utility	Support modifications identified above	Support and restraint modifications identified above.

Status of 88-11 Requirements

All analysis requirements met after actions above are completed.

SECTION 1.0
BACKGROUND AND INTRODUCTION

Farley Units 1 and 2 are three loop pressurized water reactors, designed to be as nearly identical as practical, in both hardware and operation. This report has been developed to provide the technical basis and results of a plant-specific structural evaluation for the effects of thermal stratification of the pressurizer surge lines for each of these units.

The operation of a pressurized water reactor requires the primary coolant loop to be water solid, and this is accomplished through a pressurizer vessel, connected to the loop by the pressurizer surge line. The Farley three loop arrangement is shown in Figure 1-1.

The pressurizer vessel contains steam and water at saturated conditions with the steam-water interface level typically between 25 and 60% of the volume depending on the plant operating conditions. From the time the steam bubble is initially drawn during the heatup operation to hot standby conditions, the level is maintained at approximately 25%. During power ascension, the level is increased to approximately 60%. The steam bubble provides a pressure cushion effect in the event of sudden changes in RCS mass inventory. Spray operation reduces system pressure by condensing some of the steam. Electric heaters, at the bottom of the pressurizer, may be energized to generate additional steam and increase RCS pressure.

As illustrated in figure 1-1, the bottom of the pressurizer vessel is connected to the hot leg of one of the coolant loops by the surge line, a 14 inch schedule 160 stainless steel pipe, a portion of which is almost horizontal, but slightly pitched down toward the hot leg.

1.1 Background

During the period from 1982 to 1988, a number of utilities reported unexpected movement of the pressurizer surge line, as evidenced by crushed insulation, gap closures in the pipe whip restraints, and in some cases unusual snubber movement. Investigation of this problem revealed that the movement was caused by thermal stratification in the surge line.

Thermal stratification had not been considered in the original design of any pressurizer surge line, and was known to have been the cause of service-induced cracking in feedwater line piping, first discovered in 1979. Further instances of service-induced cracking from thermal stratification surfaced in 1988, with a crack in a safety injection line, and a separate occurrence with a crack in a residual heat removal line. Each of the above incidents resulted in at least one through-wall crack, which was detected through leakage, and led to a plant shutdown. Although no through wall cracks were found in surge lines, inservice inspections of one plant in the U.S. and another in Switzerland mistakenly claimed to have found sizeable cracks in the pressurizer surge line. Although both these findings were subsequently disproved, the previous history of stratified flow in other lines led the USNRC to issue Bulletin 88-11 in December of 1988. A copy of this bulletin is included as Appendix B.

The bulletin requested utilities to establish and implement a program to confirm the integrity of the pressurizer surge line. The program required both visual inspection of the surge line and demonstration that the design requirements of the surge line are satisfied, including the consideration of stratification effects.

Prior to the issuance of NRC Bulletin 88-11, the Westinghouse Owners Group had implemented a program to address the issue of surge line stratification. A bounding evaluation was performed and presented to the NRC in April of 1989. This evaluation compared all the WOG plants to those for which a detailed plant specific analysis had been performed. Since this evaluation was unable to demonstrate the full design life for all plants, a generic justification for continued operation was developed for use by each of the WOG plants, the basis of which was documented in references 1 and 2.

The Westinghouse Owners Group implemented a program for generic detailed analysis in June of 1989, and this program involved individual detailed analyses of groups of plants. This approach permitted a more realistic approach than could be obtained from a single bounding analysis for all plants, and the results were published in June of 1990 [3].

The followup to the Westinghouse Owners Group Program is a demonstration of the applicability of reference [3] to each individual unit, and the performance of evaluations which could not be performed on a generic basis. The goal of this report is to accomplish these followup actions, and to therefore complete the requirements of the NRC Bulletin 88-11 for Farley Units 1 and 2.

1.2 Description of Surge Line Thermal Stratification

It will be useful to describe the phenomenon of stratification, before dealing with its effects. Thermal stratification in the pressurizer surge line is the direct result of the difference in densities between the pressurizer water and the generally cooler RCS hot leg water. The lighter pressurizer water tends to float on the cooler heavier hot leg water. The potential for stratification is increased as the difference in temperature between the pressurizer and the hot leg increases and as the insurge or outsurge flow rates decrease.

At power, when the difference in temperature between the pressurizer and hot leg is relatively small, the extent and effects of stratification have been observed to be small. However, during certain modes of plant heatup and cooldown, this difference in system temperature could be as large as 320°F, in which case the effects of stratification are significant, and must be accounted for.

Thermal stratification in the surge line causes two effects:

o   Bending of the pipe is different than that predicted in the original design.

o   Potentially reduced fatigue life of the piping due to the higher stress resulting from stratification and thermal oscillations (striping).

1.3 Scope of Work

The primary purpose of this work was to develop transients applicable to the
Farley units which include the effects of stratification and to evaluate these
effects on the structural integrity of the surge lines. This work will
therefore complete the demonstration of compliance with the requirements of
NRC Bulletin 88-11.

The transients were developed following the same general approach originally
established for the Westinghouse Owners Group. Conservatism inherent in the
original approach were refined through the use of monitoring results, plant
operating procedures and operator interviews, and historical data on plant
operation.

The resulting transients were used to perform an analysis of the surgeline,
wherein the existing support configuration was modeled, and surge line
displacements, stresses and support loadings were determined. This analysis
and its results are discussed in Section 3 and 4.

The stresses were used to perform a fatigue analysis for the surge line, and
the methodology and results of this work are discussed in Section 5. The
summary and conclusions of this work are summarized in Section 6.
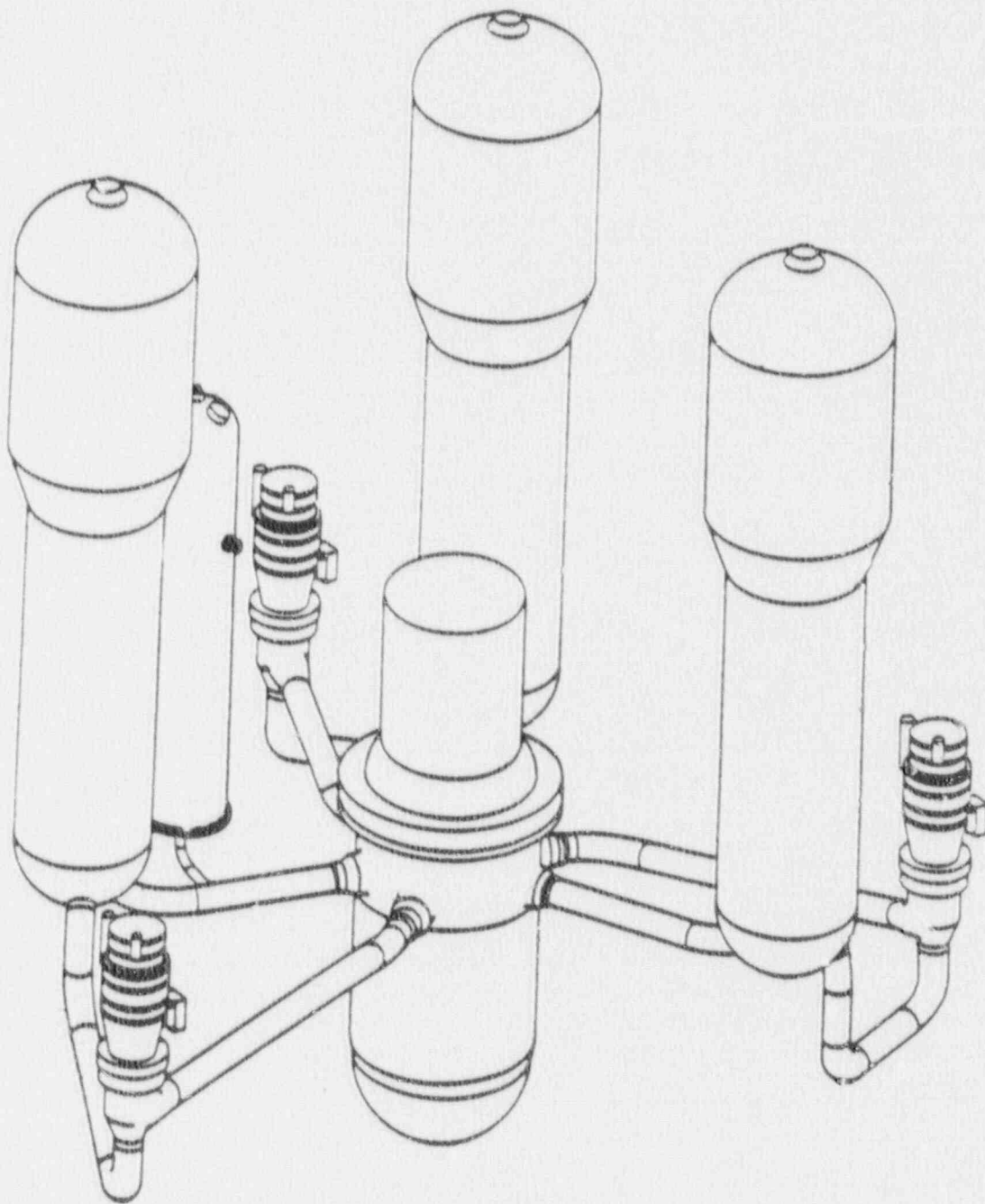
Figure 1-1. Schematic of Farley Units 1 and 2 Loop Layout

SECTION 2.0
SURGE LINE TRANSIENT AND TEMPERATURE PROFILE DEVELOPMENT

2.1 General Approach

The transients for the pressurizer surge line were developed from a number of sources, including the most recent systems standard design transients. The heatup and cooldown transients, which involve the majority of the severe stratification occurrences, were developed from review of operating procedures, operator interviews, monitoring data and historical records for each unit. The total number of heatup and cooldown events specified remains unchanged at 200 each, but a number of sub-events have been defined to reflect stratification effects, as described in more detail later.

The normal and upset transients, except for heatup and cooldown, for the Farley Units 1 and 2 surge lines are provided in Table 2-1. For each of the transients the surge line fluid temperature was modified from the original design assumption of uniform temperature to a stratified distribution, according to the predicted temperature differentials between the pressurizer and hot leg, as listed in the table. The transients have been characterized as either insurge/outsurges (I/O in the table) or fluctuations (F). Insurge/outsurge transients are generally more severe, because they result in the greatest temperature change in the top or bottom of the pipe. Typical temperature profiles for insurges and outsurges are shown in Figure 2-1.

Transients identified as fluctuations (F) typically involve low surge flow rates and smaller temperature differences between the pressurizer and hot leg, so the resulting stratification stresses are much lower. This type of cycle is important to include in the analysis, but is generally not the major contributor to fatigue usage.

The development of transients which are applicable to Farley Units 1 and 2 was based on the work already accomplished under programs completed for the

Westinghouse Owners Group [1,2,3]*. In this work all the Westinghouse plants were grouped based on the similarity of their response to stratification. The three most important factors influencing the effects of stratification were found to be the structural layout, support configuration, and plant operation.

The transient development for the Farley units took advantage of the similarity in the surge line layouts, as well as the similarity of the plants' operating procedures. Thus one set of transients was deemed applicable to both units.

The transients developed here, and used in the structural analysis, have taken advantage of the monitoring data collected on several Westinghouse plants, as well as operator interviews and historical operation data for the Farley units. Each of these will be discussed in the sections to follow.

2.2 System Design Information

The thermal design transients for a typical Reactor Coolant System, including the pressurizer surge line, are defined in Westinghouse Systems Standard Design Criteria 1.3, Revision 1.

The design transients for the surge line consist of two major categories:

(a) Heatup and Cooldown transients

(b) Normal and Upset operation transients (by definition, the emergency and faulted transients are not considered in the ASME Section III fatigue life assessment of components).

---

*Numbers in brackets refer to references listed in Section 7.

In the evaluation of surge line stratification, the typical FSAR chapter 3.9 definition of normal and upset design events and the number of occurrences of the design events remains unchanged.

The total number of current heatup-cooldown cycles (200) remains unchanged. However, sub-events and the associated number of occurrences ("Label", "Type" and "Cycle" columns of tables 2-2a and 2-2b) have been defined to reflect stratification effects, as described later.

2.3 Development of Normal and Upset Transients

Transients in the surge line were characterized as either insurges or outsurges (I/O) or fluctuations (F). Insurges and outsurges are the more severe transients and result in the greatest change in temperature in the top or bottom of the pipe. An insurge may cool the entire pipe cross section significantly, to very close to the temperature of the RCS hot leg. Conversely, an outsurge can sweep the line and heat the pipe to close to the temperature of the pressurizer. The typical behavior of insurge and outsurge thermal transients is shown in figure 2-1.

Fluctuations, as opposed to the insurge-outsurge transients, are caused by relatively insignificant surges and result in variations in the hot-cold interface level. These variations in the interface level do not change the overall global displacement of the pipe and hence are analyzed as changes in local stress only.

The redefinition of the thermal fluid conditions experienced by the surge line during normal and upset transients was necessary to reflect the indirectly observed fluid temperature distributions. These redefined thermal fluid conditions were developed based on the existing design transient system parameters assumed to exist at the time of the postulated transient and the knowledge gained from the monitoring programs. The redefined thermal fluid conditions conservatively account for the thermal stratification phenomena.

To determine the normal and upset pipe top-to-bottom temperature difference,
"ΔT_{strat}" (table 2-1), the following conservatism was introduced. [-----
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[---

--]^{a,c,e}

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

2.4 Monitoring Results and Operator Interviews

2.4.1 Monitoring

Monitoring was performed on Farley Unit 2, using temporary sensors on the
surge line piping, as shown in figure 2-2. This data, along with monitoring
information collected as part of the Westinghouse Owners Group generic
detailed analysis[3] was utilized in this analysis.

The pressurizer surge line monitoring programs utilized externally mounted
temperature sensors (resistance temperature detectors or thermocouples). The
temperature sensors were attached to the outside surface of the pipe at
various circumferential and axial locations. In all cases these temperature
sensors were securely clamped to the piping outer wall using clamps, taking
care to properly insulate the area against heat loss due to thermal convection
or radiation.

The Farley Unit 2 temperature sensor configuration at a given pipe location consists of five sensors mounted as shown in figure 2-2. Temperature sensor configurations were mounted at various axial locations. The multiple axial locations give a good picture of how the top to bottom temperature distribution may vary along the longitudinal axis of the pipe. In addition, the pressurizer surge line monitoring program utilized displacement sensors (lanyards) mounted at four axial locations to detect vertical and horizontal movements, as shown in igure 2-2. Typically, data were collected at [---------]^{a,c,e} intervals or less, during periods of high system delta T.

Existing plant instrumentation was used to record various system parameters. These system parameters were useful in correlating plant conditions with stratification in the surge line. A list of typical plant parameters monitored is given below.

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Data from the temporary sensors was stored on magnetic floppy disks and converted to hard copy time history plots with the use of common spreadsheet software. Data from existing plant instrumentation was obtained from the utility plant computer.

2.4.2 Operational Practices

An operations interview was conducted at the Farley plant on October 6, 1989. The two Farley units operate with similar if not identical operating

procedures, so the discussion that follows is applicable to both Farley Units
1 and 2. Since the maximum temperature difference between the pressurizer and
the reactor coolant loop occurs during the plant heatup and cooldown,
operations during these events were the main topic of the interview. Figure
2-3 describes the heatup process, and figure 2-4 is the corresponding plot for
the cooldown process.

In both heatup and cooldown, the plant has an administrative limit of 320°F on
temperature difference between pressurizer and reactor coolant system.

2.5 Historical Operation

In the analysis, all heatups and cooldowns were assumed to reach the maximum
system delta T values discussed in the previous section. A review of
historical records from each of the two units (operator logs, surveillance
test reports, etc.) was performed. From this review, two pieces of
information were extracted; a characteristic maximum system delta T
distribution for these units, and the number of maximum delta T exceedences.
The number of heatups and cooldowns experienced to date and their associated
system delta temperature values are listed in Table 2-3. This data is
presented graphically in Figure 2-5.

The historical operation data for both units are listed below. Due to the
fact that both units operate similarly, the effective average of the two units
as percentages of total occurrences is shown graphically in Figure 2-6. This
average was considered in the transient development process.

	Unit 1		Unit 2	
System (ΔT) Range (°F)	Number of Heatups & Cooldowns	Percent of Occurrences	Number of Heatups & Cooldowns	Percent of Occurrences
[------	--	--	--	--
-------	--	--	--	--
-------	--	--	--	--
-------	--	--	--	--
------	--	--	--	---]a,c,e

The above table was used to ensure that the transients analyzed for Farley
Units 1 and 2 encompassed the prior operating history of both units.

2.6 Development of Heatup and Cooldown Transients

The heatup and cooldown transients used in the analysis were developed from a
number of sources, as discussed in the overall approach. The transients were
built upon the extensive work done for the Westinghouse Owners Group [1,2,3],
coupled with plant specific considerations for Farley Units 1 and 2.

The transients were developed based on monitoring data, historical operation
and operator interviews conducted at a large number of plants, including
Farley. For each monitoring location, the top-to-bottom differential
temperature (pipe delta T) vs. time was recorded, along with the temperatures
of the pressurizer and hot leg during the same time period. The difference
between the pressurizer and hot leg temperature was termed the system delta
T.

From the pipe and system delta T information collected in the WOG effort,
individual plants' monitoring data were reduced to categorize stratification
cycles (changes in relatively steady-state stratified conditions) using the
rainflow cycle counting method. This method considers delta T range as
opposed to absolute values.

[---

---]a,c,e

The resulting distributions (for I/O transients) were cycles in each RSS range above 0.3, for each mode (5,4,3 and 2). A separate distribution was determined for each plant at the reactor coolant loop nozzle and a chosen critical pipe location. Next, a representative RSS distribution was determined by multiplying the average number of occurrences in each RSS range by two. Therefore, there is margin of 100% on the average number of cycles per heatup in each mode of operation.

2.6.1 Piping Transients

Transients, which are represented by delta T pipe with a corresponding number of cycles were developed by combining the delta T system and cycle distributions. For mode 5, delta T system is represented by a historical system distribution developed from a number of WOG plants (generic distribution). Using data from a number of plants is beneficial as the resulting transients are more representative of a complete spectrum of operation than might be obtained from only a few heatups and cooldowns.

For modes 4, 3 and 2, the delta T system was defined by one maximum value for each mode. The values were based on the maximum system delta T obtained from the monitored plants for each mode of operation. An analysis was conducted to determine the average number of cycles per cooldown relative to the average number of cycles per heatup. [---
----

---]^{a,c,e} The transients for all modes were then enveloped in ranges of ΔT_{pipe}, i.e., all cycles from transients within each ΔT_{pipe} range were added and assigned to the pre-defined ranges. These cycles were then applied in the fatigue analysis with the maximum ΔT_{pipe} for each range. The values used are as follows:

For Cycles Within Pipe Delta T Range   Pipe Delta T

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        [----------                    ---
        ----------                     ---
        ----------                     ---
        ----------                     ---
        ----------                     ---
        ----------                     ---
        ----------                     ---.]a,c,e
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This grouping was done to simplify the fatigue analysis. The actual number of cycles used for the analysis for each sub-event in heatup and cooldown is shown in Table 2-2.

2.6.2 Hot Leg Nozzle Transients

Because of main coolant pipe flow effects the stratification transients loadings at the reactor coolant hot leg nozzle are different. These transients have been applied to the main body of the nozzle as well as the pipe to nozzle girth butt weld.

Plant monitoring included sensors located near the nozzle to surge line pipe weld. Based on the monitoring, a set of transients were developed for the nozzle region to reflect conditions when stratification could occur in the nozzle, Table 2-2b. The primary factor affecting these transients was the flow in the main coolant pipe. Significant stratification was noted only when the reactor coolant pump was not operating in the loop with the surge line. Transients were then developed using a conservative number of "pump trips."

The fatigue analysis of the nozzle was then performed using the "nozzle transients" of Table 2-2b and the pipe transients of Table 2-2a. The analysis included both the stratification loadings from the nozzle transients, and the pressure and bending loads from the piping transients.

2.6.3 Summary

The final result of this complex process is a table of transients
corresponding to the sub events of the heatup and cooldown process. A
mathematical description of the process is given in Appendix C. [--------------
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The critical location is the location with the highest combination of pipe
delta T and number of stratification cycles.

The total transients for heatup and cooldown are identified as HC1 thru HC9
for the pipe, and HC1 thru HC8 for the nozzle as shown in tables 2-2(a) and
2-2(b) respectively. Transients HC7 thru HC9 for the pipe and HC7 and HC8 for
the nozzle represent transients which occur during later stages of the heatup.

As indicated in Section 2.5, based on a review of the Farley operating
records, there were two events in which the system delta T exceeded the
transient basis upper limit of [---

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

2.7 Axial Stratification Profile Development

In addition to transients, a profile of the [---------------------------------
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Two types of profile were generated to envelope the stratified temperature
distributions observed and predicted to occur in the line. These two profiles
are based on the [

]a,c,e

The second case [

]a,c,e

]a,c,e

These three configurations are illustrated in Figure 2-9. The Farley units
fall under the category of [--

--]^{a,c,e}

Review and study of the monitoring data for all the plants revealed a
consistent pattern of development of delta T as a function of distance from
the hot leg intersection. This pattern was consistent throughout the
heat-up/cooldown process, for a given plant geometry. This pattern was used
along with plant operating practices to provide a realistic yet somewhat
conservative portrayal of the pipe delta T along the surge line.

The combination of the hot/cold interface and pipe delta T as functions of
distance along the surge line forms a profile for each individual plant
analyzed. Since Farley Units 1 and 2 have similar surge line configurations,
the profile applies to both units.

2.8 <u>Striping Transients</u>

The transients developed for the evaluation of thermal striping are shown in
table 2-4.

[--

--]^{a,c,e}

Striping transients use the labels HST and CST denoting striping transients (ST). Table 2-4 contains a summary of the HST1 to HST8 and CST1 to CST7 thermal striping transients which are similar in their definition of events to the heatup and cooldown transient definition.

These striping transients were developed during plant specific surge line evaluations and are considered to be a conservative representation of striping in the surge line[3]. Section 5 contains more information on specifically how the striping loading was considered in the fatigue evaluation.

TABLE 2-1
SURGE LINE TRANSIENTS WITH STRATIFICATION
NORMAL AND UPSET TRANSIENT LIST

| | | | TEMPERATURES (°F) | | |
| | | | MAX | NOMINAL | |
LABEL	TYPE	CYCLES	ΔT_{strat}	PRZ T	RCS T
[-----------------------	-	-	-	-	-
------------------------	-	-	-	-	-
------------------------	-	-	-	-	-
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TABLE 2-1 (Cont'd.)

SURGE LINE TRANSIENTS WITH STRAT ˙ICATION
NORMAL AND UPSET TRANSIENT LIST

LABEL	TYPE	CYCLES	MAX ΔT_{Strat}	NOMINAL PRZ T	RCS T
			TEMPERATURES (°F)		

[-------------------------   -   -   -   -   -

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TABLE 2-2a

SURGE LINE PIPE TRANSIENTS WITH STRATIFICATION - FARLEY UNITS 1 AND 2

HEATUP/COOLDOWN (HC) - 200 CYCLES TOTAL

			TEMPERATURES (°F)		
			MAX	NOMINAL	
LABEL	TYPE	CYCLES	ΔT_{Strat}	PRZ T	RCS T
[--	-	-	-	-	-

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----------------]a,c,e
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TABLE 2-2b
SURGE LINE NOZZLE TRANSIENTS WITH STRATIFICATION - FARLEY UNITS 1 AND 2
HEATUP/COOLDOWN (HC) - 200 CYCLES TOTAL

			TEMPERATURES (°F)		
			MAX	NOMINAL	
LABEL	TYPE	CYCLES	ΔT_{Strat}	PRZ T	RCS T
[--	-	-	-	-	-
----	-	-	-	-	-
----	-	-	-	-	-
----	-	-	-	-	-
----	-	-	-	-	-
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	-	-	-	-	-

------------------------------.]a,c,e

TABLE 2-3 HISTORICAL COLLECTION OF HEATUPS AND COOLDOWNS
FARLEY UNITS 1 AND 2

Farley Unit 1

System ΔT Range (°F)	Number of Events Experienced to Date**		Number of Heatup & Cooldown Events Considered in 40 Year Design
	Heatups	Cooldowns	
[-------	----	----	-----
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Farley Unit 2

System ΔT Range (°F)	Number of Events Experienced to Date**		Number of Heatup & Cooldown Events Considered in 40 Year Design
	Heatups	Cooldowns	
[-------	---	----	-----
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*Two cycles per event were assumed, resulting in four cycles at ΔT > 320°F.
**Only those with a maximum System ΔT available are listed.

TABLE 2-4

SURGE LINE TRANSIENTS - STRIPING

FOR HEATUP (H) and COOLDOWN (C)

Label

[ ]a,c,e

a,c,e

Figure 2-1.   Typical Insurge-Outsurge (I/O) Temperature Profiles

a,c,e
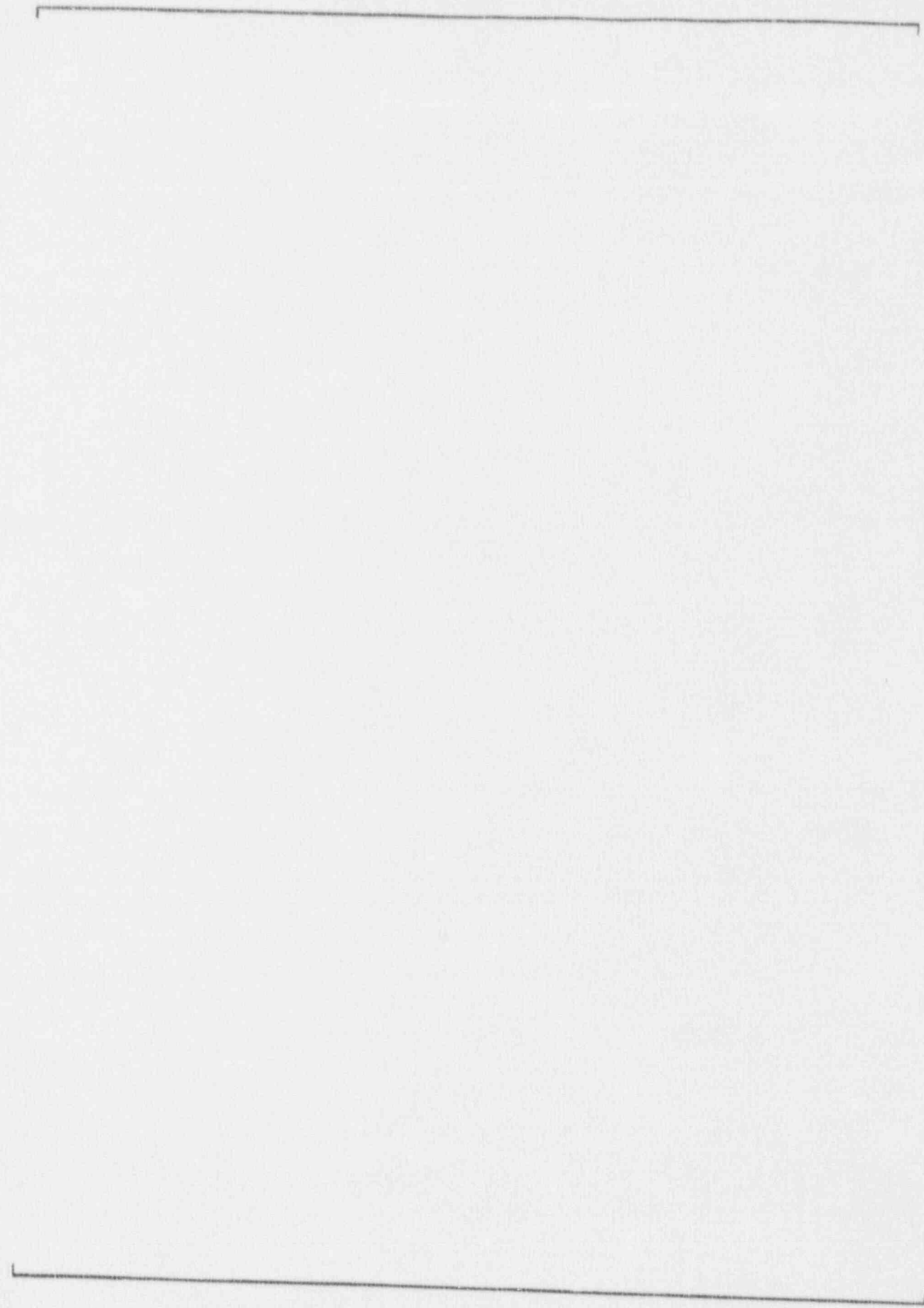
Figure 2-2. Monitoring Locations for Farley Unit 2 Surge Line

a,c,e

Figure 2-3. Heatup Curve for Farley Units 1 and 2

a,c,e

Figure 2-4. Cooldown Curve for Farley Units 1 and 2

4933c/1276890.10

a,c,e
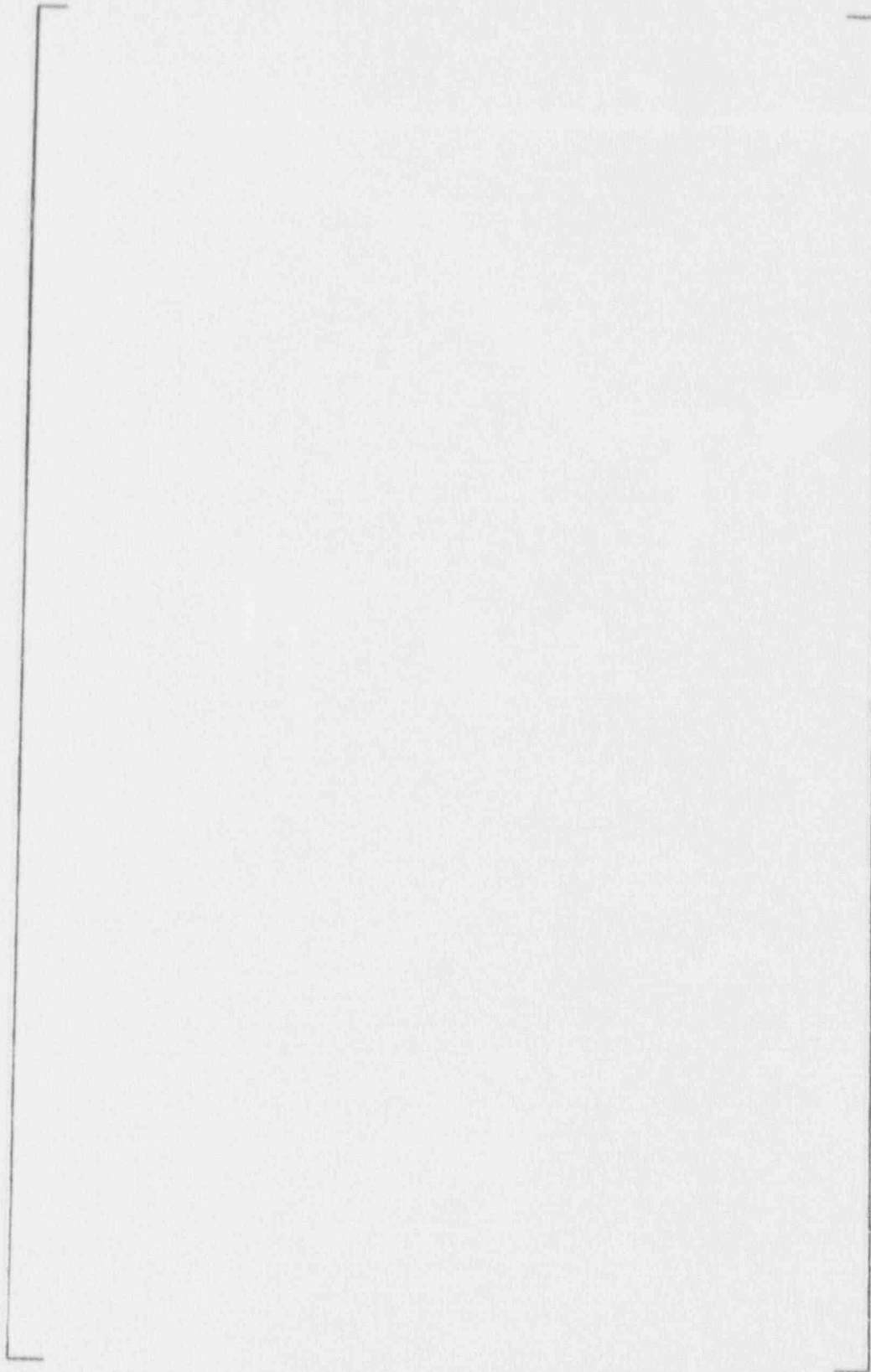
Figure 2-5.   Historical Heatups and Cooldowns for Farley Units 1 and 2
Compared with the Number of Events Used in the Analysis

a,c,e

2-25

Figure 2-6. Summary of Historical Data from the Farley Units 1 and 2,
Shown as an Effective Average for Both Units, Compared
to the Distribution Used in this Analysis

a,c,e

2-25

Figure 2-7. Example Axial Stratification Profile for Low Flow Conditions

a,c,e

Figure 2-8. Temperature Profiles for Farley Units 1 and 2

4935x/012781 10

2-27
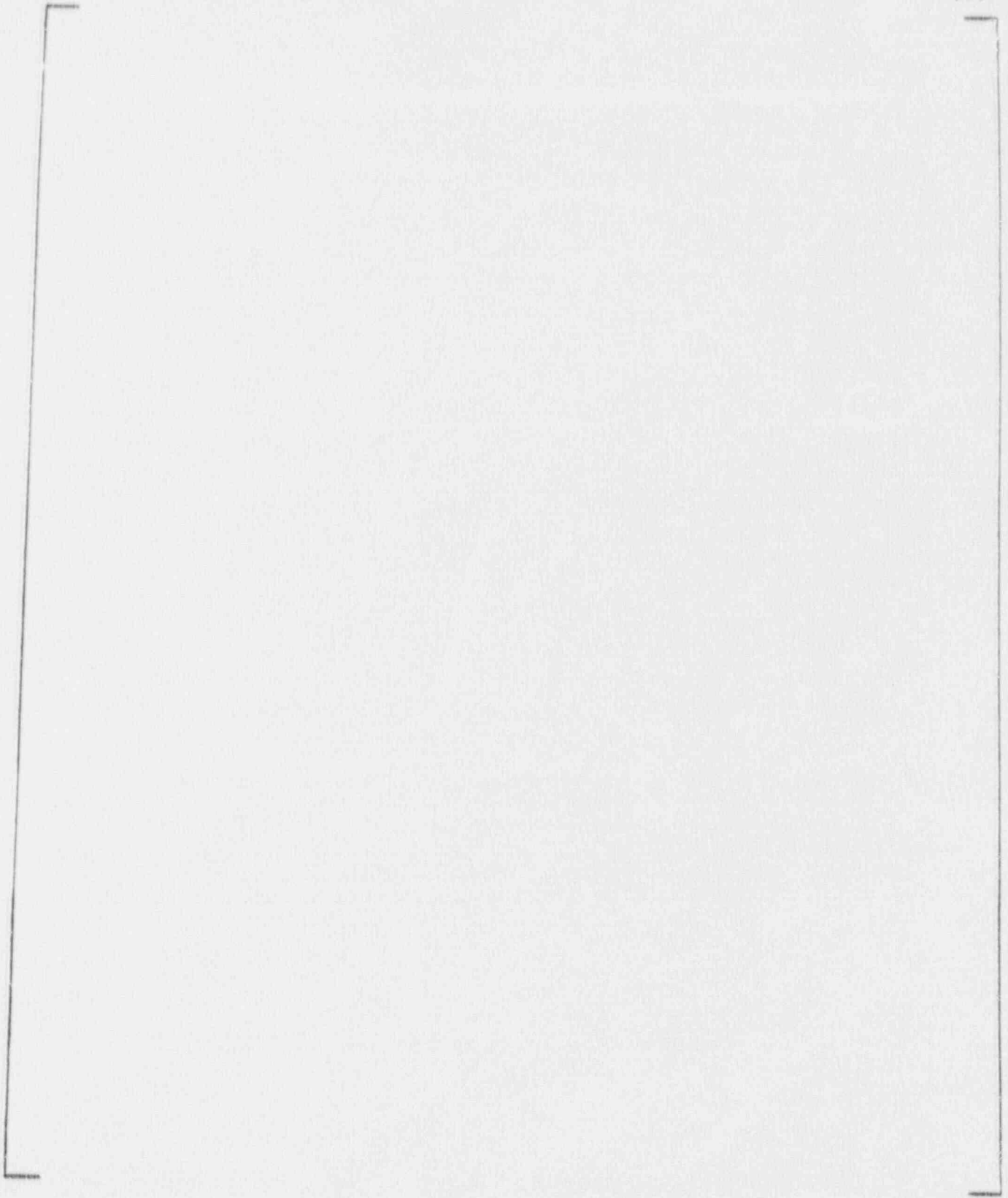
Figure 2-9. Geometry Considerations

SECTION 3.0
STRESS ANALYSES

The flow diagram (figure 3-1) describes the procedure to determine the effects
of thermal stratification on the pressurizer surge line based on transients
developed in section 2.0. [--

--------------]a,c,e

3.1 Surge Line Layouts

The Farley Units 1 & 2 surge line layouts are documented in reference [4].
The Unit 1 design is a replicate of the Unit 2 design. The layout is shown
schematically in figure 3-2. Below is a table summarizing the existing Farley
surge line support configurations.

	Support Label	
Support Type	Unit 1	Unit 2
Spring	RC-R1	2RC-R1
Snubber	RC-R7	2RC-R2
Spring	RC-R2	2RC-R3
Pipe Whip Restraint	PSR-1	PSR-1
Pipe Whip Restraint	PSR-2	PSR-2
Pipe Whip Restraint	PSR-3	PSR-3
Pipe Whip Restraint	PSR-4	PSR-4
Pipe Whip Restraint	PSR-5	PSR-5
Pipe Whip Restraint	PSR-6	PSR-6
Pipe Whip Restraint	PSR-7	PSR-7
Pipe Whip Restraint	PSR-8	PSR-8
Pipe Whip Restraint	PSR-9	PSR-9

Since snubbers and springs allow thermal growth, the Farley Units 1 & 2 surge lines have essentially similar support configurations for the thermal stratification analysis. The piping size is 14 inch schedule 160 and the pipe material is stainless steel for the surge lines in both units. Farley Unit 1 surge line pipe has SA 376-Type 316, Farley Unit 2 has SA 376-Type 304.

Experience with the analysis of thermal stratification has indicated that surge line layout has a significant effect on the resulting stratification induced global pipe bending moments. One of the important factors regarding surge line layout was found to be [--
---]a,c,e

For the existing support design the Farley Units 1 and 2 surge line design also includes nine pipe whip restraints. These pipe whip restraints have gaps ranging from 0" to 2.625" between the restraint and pipe. The actual gaps in pipe whip restraint (PWR) for both units were modeled. For the spring hangers, the actual travel allowances were also modeled in Unit 2 model. For Unit 1 design, travel allowance was assumed to be sufficient (since there was no evidence of spring cans bottoming out from walkdown information).

Based upon a review of whip restraint drawings and the visual inspection reports[4] of Farley Units 1 and 2 pressurizer surge lines, it was concluded that some of the whip restraints impeded vertical motion due to stratification. Furthermore, the spring can 2RC-3 was actually found to be bottomed out in 1988. The travel allowance of this support was increased in 1988 to accommodate the stratification displacements.

The structural evaluation addressed by this WCAP assumes that proper whip restraint gaps have been established and sufficient travel allowance in the spring cans have been assured for the future operation. With respect to the

pipe whip restraint modification to ensure proper gaps, it is Alabama Power Company's intent to develop Leak-Before-Break analysis for the surge line (separate from this effort) to justify removal of the pipe whip restraints on the pressurizer surge line. The results of that analysis will be submitted to the NRC for approval at a later data. Alabama Power Company will also modify the spring cans to ensure sufficient travel allowance for future operation.

3.2 Piping System Global Structural Analysis

The piping system was modeled by pipe, elbow, and linear and non-linear spring elements using the ANSYS computer code. The geometric and material parameters are included. [--
---   --------------------------------------

--]^{a,c,e} The stiffness of snubber supports and spring hangers are neglected in the model because they are inconsequential for the thermal condition although the potential for these members exceeding their displacement tolerance are verified, as discussed.

For the Farley surge line design, under the thermal stratification loadings, many unintended thermal constraint conditions were predicted to occur at the pipe whip restraint locations. This is mainly due to the fact that the pipe whip restraints were originally designed with the considerations of the normal thermal expansion loading only, and consequently, less than adequate gap-clearance for the higher displacements resulting from stratification existed in the pipe whip restraints. [--
----
--]^{a,c,e}

The hot-cold temperature interface along the length of a surge line [------
----
--   ------- ----]^{a,c,e}

[--- ----

--]^{a,c,e}

Each thermal profile loading defined in section 2 was broken into [--------
-----------]^{a,c,e} Table 3-1 shows the loading cases considered in the
analysis. Within each operation the [--

-- ----------
-------------------------------]^{a,c,e} Consequently, all the thermal
transient loadings defined in section 2 could be evaluated.

The pressurizer and RCL temperature listed in table 3-. reflect the
approximate system ∆T. System temperatures are used to define the boundary
displacements at both RCL and pressurizer nozzles.

In order to meet the ASME Section III Code Stress limits, global structural
models of the Farley Units 1 and 2 surge lines were developed using the
information provided by reference [4] and the ANSYS general purpose finite
element computer code. The model was constructed using [---------------------
--------------- -----]^{a,c,e} to reflect the layout of straight pipe, bends and
field welds as shown in Figure 3-2. [--

--]^{a,c,e} (see table 3-2).

For the stratified condition, [---

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

The global piping stress analyses were based on two models due to the difference in bottomed out spring and pipe whip restraint gap conditions between the two units. The first model represents the existing Unit 1 support and restraint configuration and the second model represents the existing Unit 2 support and restraint configuration. For the future support configuration, both models were assumed totally free from any thermal constraint caused by pipe whip restraint contacts and/or spring can bottomed out. The results of the ANSYS global structural analysis provided thermal expansion moments. The ASME Section III equation (12) stress intensity range was evaluated for both support configurations. For the existing support configuration, a system delta T = 337°F was evaluated for Unit 2 and delta T = 320°F for Unit 1. For the future support configuration, a system delta T = 320°F was evaluated for both units. In all cases, excluding the Unit 2 existing configuration, the maximum ASME equation (12) stress intensity range in the surge line was found to be under the code allowable of 3Sm. Maximum equation (12) and equation (13) stress intensity ranges are shown in table 3-3. From this table, it should be noted that, for Unit 1, modifications to the whip restraint gaps are not necessary, as long as sufficient travel allowances are provided in the spring cans. For Unit 2, both spring can travel allowances and whip restraint gaps require verification.

The pressurizer nozzle loads from pipe thermal stratification were also evaluated according to the requirements of the ASME code. The evaluation included the calculations of primary plus secondary stress intensities and the fatigue usage factors. The maximum stress intensity is 45.6 ksi compared to the code allowable value of 80.1 ksi, and the maximum fatigue usage factor is reported in Section 5. It was found that the Farley pressurizer nozzle met the code stress requirements.

In order to superimpose local and global stresses, several stress analyses were performed using the 3-D pipe model. [-------------------------------------
----

--]a,c,e

[--
------------------------------------]a,c,e

3.3 Local Stresses-Methodology and Results

3.3.1 Explanation of Local Stress

Figure 3-3 depicts 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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--]a,c,e

3.3.2 Finite Element Model of Pipe for Local Stress

A short description of the pipe finite element model is shown in figure 3-4.
The model with thermal boundary conditions is shown in figure 3-5. Due to
symmetry of the geometry and thermal loading, only half of the cross section
was required for modeling and analysis. [------------------------------------
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--]a,c,e

[---

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

3.3.3 Pipe Local Stress Results

Figure 3-6 shows the temperature distributions through the pipe wall [------
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---------]^{a,c,e}

3.3.4 PCL Hot Leg Nozzle Analysis

[---

---------------]^{a,c,e} A summary of stresses for unit loading is shown in
table 3-5.

3.4 Total Stress from Global and Local Analyses

[---

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[--

-----------------]a,c,e

3.5 Thermal Striping

3.5.1 Background

At the time when the feedwater line cracking problems in PWR's was first
discovered, it was postulated that thermal oscillations (striping) may
significantly contribute to the fatigue cracking problems. These oscillations
were thought to be due to either mixing of hot and cold fluid, or turbulence
in the hot-to-cold stratification layer from strong buoyancy forces during low
flow rate conditions. (See figure 3-11 which shows the thermal striping
fluctuation in a pipe). Thermal striping was verified to occur during
subsequent flow model tests[8]. Results of the flow model tests were used
to establish boundary conditions for the stratification analysis and to
provide striping oscillation data for evaluating high cycle fatigue.

Thermal striping was also examined during water model flow tests performed for
the Liquid Metal Fast Breeder Reactor (LMFBR) primary pipe loop[9]. The
stratified flow was observed to have a dynamic interface region which
oscillated in a wave pattern. These dynamic oscillations were shown to
produce significant fatigue damage (primary crack initiation). The same
interface oscillations were observed in experimental studies of thermal
striping which were performed in Japan by Mitsubishi Heavy Industries[10].
The thermal striping evaluation process was discussed in detail in reference 3.

3.5.2 Thermal Striping Stresses

Thermal striping stresses are a result of differences between the pipe inside
surface wall and the average through wall temperatures which occur with time,
due to the oscillation of the hot and cold stratified boundary. (See figure
3-12 which shows a typical temperature distribution through the pipe wall).
[---
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The peak stress range and stress intensity was calculated from a 3-D finite
element analysis. [---
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---------------------------]^{a,c,e} The methods used to determine alternating
stress intensity are defined in the ASME code. Several locations were
evaluated in order to determine the location where stress intensity was a
maximum.

Stresses were intensified by K_3 to account for the worst stress
concentration for all piping elements in the surge line. The worst piping
element was the butt weld.

[---

-- -----

--]^{a,c,e}

3.5.3 Factors Which Affect Striping Stress

The factors which affect striping are discussed briefly below:

[---
---]^{a,c,e}

[

]^{a,c,e}

[

]^{a,c,e}

[-- --

-- --

---------------------------------]a,c,e

TABLE 3-1

TEMPERATURE DATA USED IN THE ANALYSIS

Type of Operation	Max System ΔT(°F)	Analysis Cases	Pressurizer Temp (°F)	RCL Temp (°F)	T_{Top} (°F)	T_{Bot} (°F)	Pipe ΔT (°F)
[----------- ---		-	---	---	---	---	---
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		-	---	---	---	---	---
		-	---	---	---	---	---
		-	---	---	---	---	---][a,c,e]

TABLE 3-2

COMPARISON OF WESTDYN AND ANSYS PIPING THERMAL DISPLACEMENTS
AND SUPPORT LOADS FOR A TYPICAL SURGE LINE MODEL*

a,c,e

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* The existing support configuration was used in this study.

TABLE 3-3
Summary of Farley Surge Line
Thermal Stratification Stress Results

	Unit 1 Support Configuration		Unit 2 Support Configuration		
ASME Code Equation	Existing+	Future*	Existing+	Future*	Code Allowableᐃ
	(ksi)	(ksi)	(ksi)	(ksi)	(ksi)
12	48.7	40.4	55.4	40.4	51.4
13	40.0	40.0	40.0	40.0	48.6

---

* Future support configuration represents no bottoming out of spring cans
and no pipe whip restraint contact under all thermal loadings with maximum
system ᐃT = 320°F

+ Existing support configuration represents the actual spring bottom out
and/or PWR contact condition under all thermal loadings with maximum
system ᐃT = 337°F (for Unit 2) and 320°F (for Unit 1).

If the system ᐃT is maintained at 310°F for Unit 2, the Equation 12
stress will be 50.96 ksi.

ᐃ Conservative envelope of the two units.

TABLE 3-4
FARLEY SURGE LINE
MAXIMUM LOCAL AXIAL STRESSES AT [--------------------]a,c,e
(14 inch Schedule 160)

| | | Local Axial Stress (psi) | |
Location	Surface	Maximum Tensile	Maximum Compressive
[-	------	------	------------a,c,e
"	--- ----	-----	------
"	------	-----	------
"	------	------	------
"	------	-----	------
"	-------	-----	------
"	------	-----	------
"	-------	-----	------
"	------	-----	-----
"	-------	----	------]

[--]a,c,e

TABLE 3-5

SUMMARY OF PRESSURE AND BENDING INDUCED STRESSES
IN THE SURGE LINE RCL NOZZLE FOR UNIT LOAD CASES

| | | | All Stress in psi | | | |
| | | | Linearized Stress Intensity Range | | Peak Stress Intensity Range | |
Location	Diametral Location	Unit Loading Condition	Inside	Outside	Inside	Outside
						a,c,e
[---------	-----	-------	----	----	----	-----
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TABLE 3-6
STRIPING FREQUENCY AT 2 MAXIMUM LOCATIONS FROM 15 TEST RUNS

		Frequency (HZ)						Total Duration # Cycles Lgth. in Seconds
		Min	% (Duration)	Max	% (Duration)	Avg	% (Duration)	
[---------------								

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a,c,e

Figure 3-1. Schematic of Stress Analysis Procedure
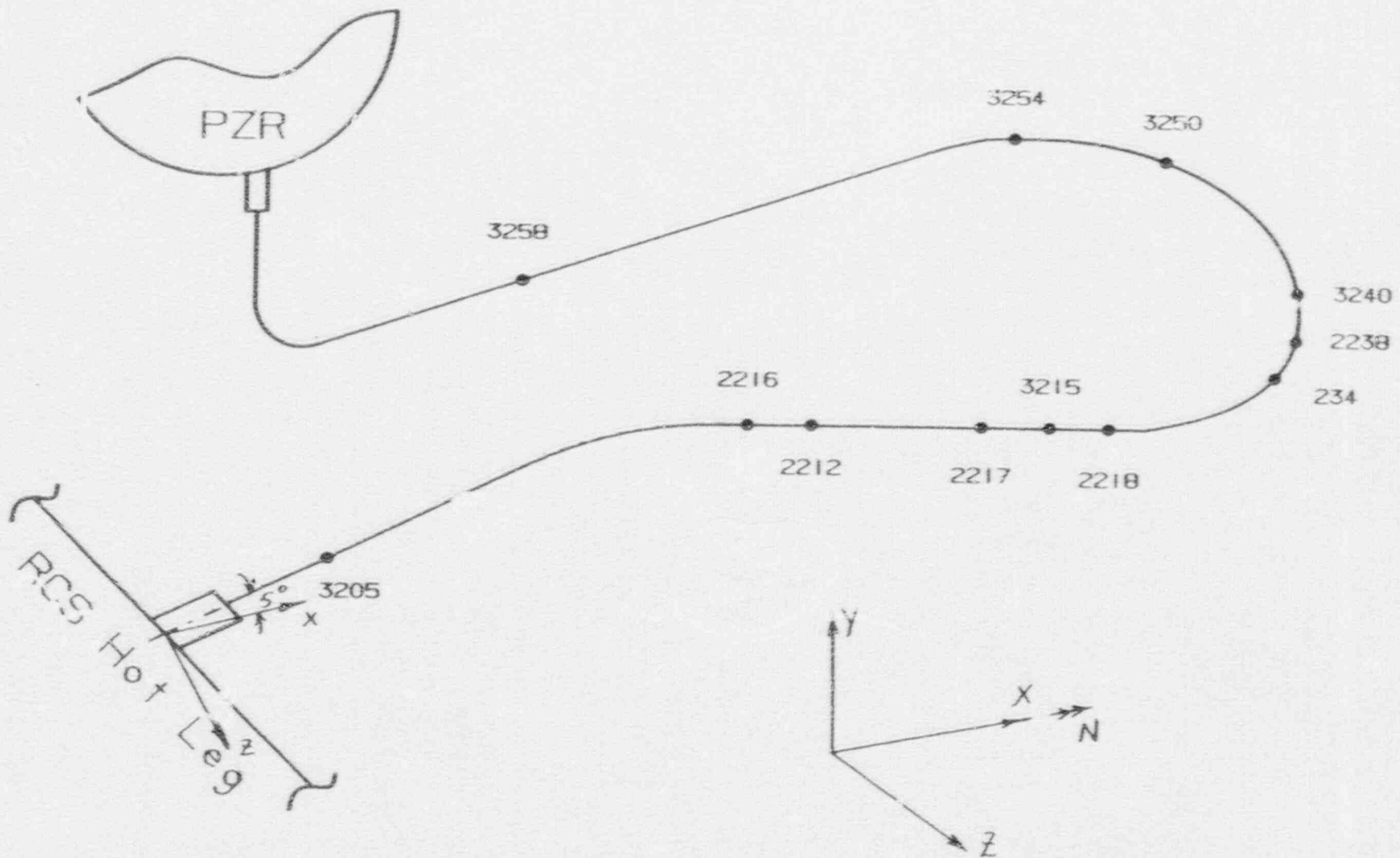
Figure 3-2. Pressurizer Surge Line Layout: Farley Units 1 & 2

a,c,e

3-20

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

4933s/011781 10

a,c,e
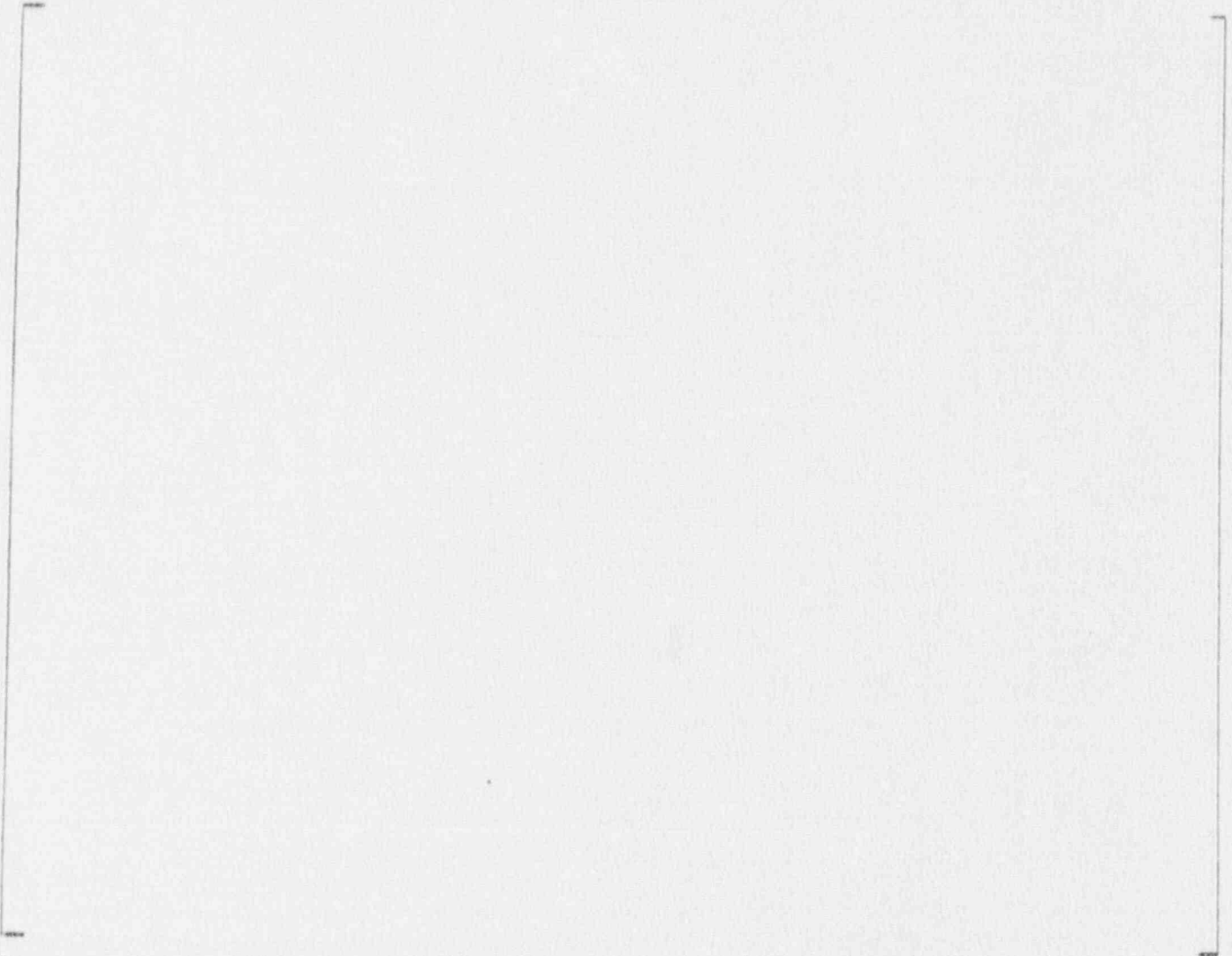
Figure 3-4. Local Stress - Finite Element Models/Loading

a,c,e
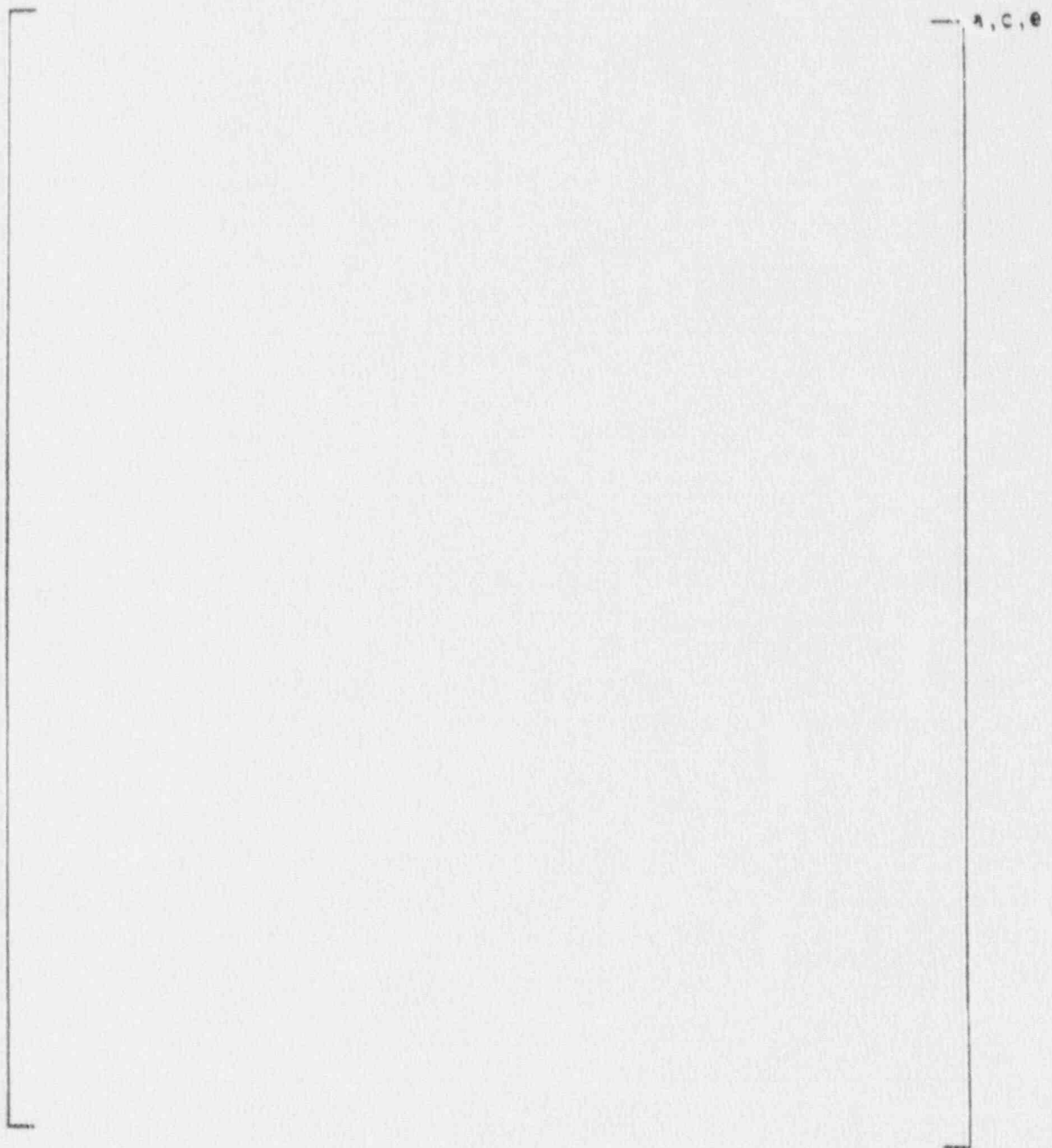
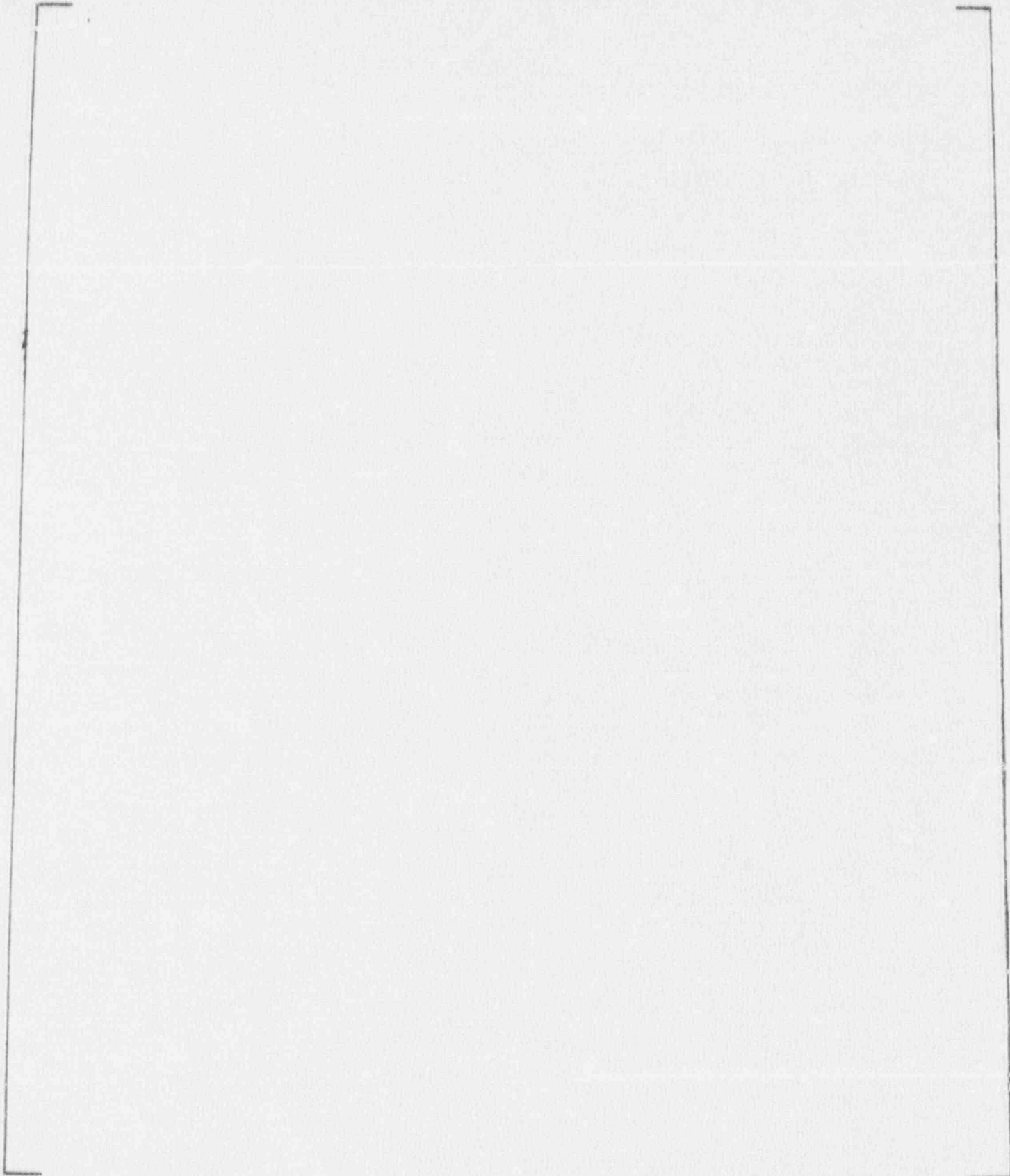Figure 3-5. Piping Local Stress Model and Thermal Boundary Conditions

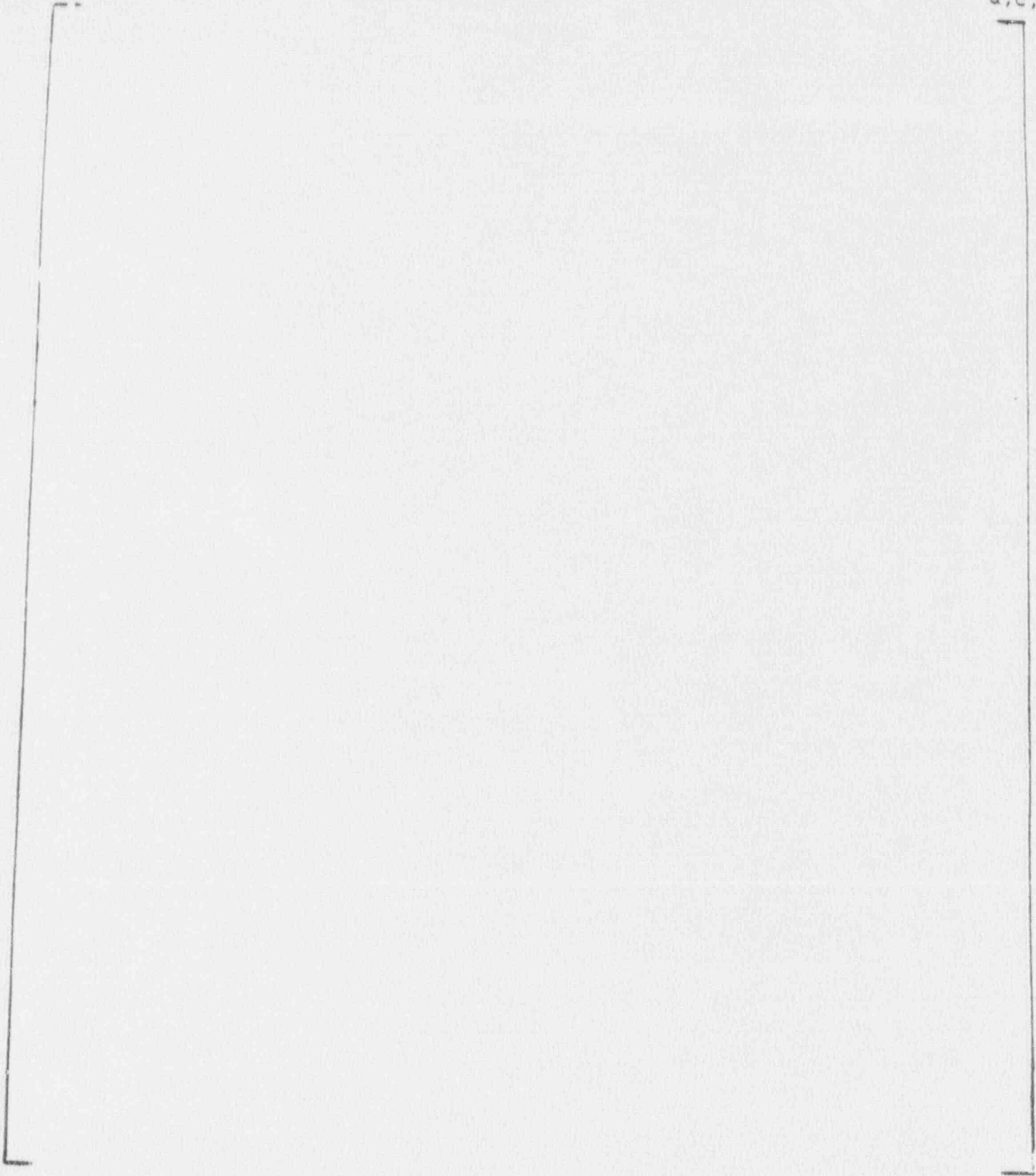Figure 3-6. Surge Line Temperature Distribution at [ ]^{a,c,e} Axial
Locations

a,c,e

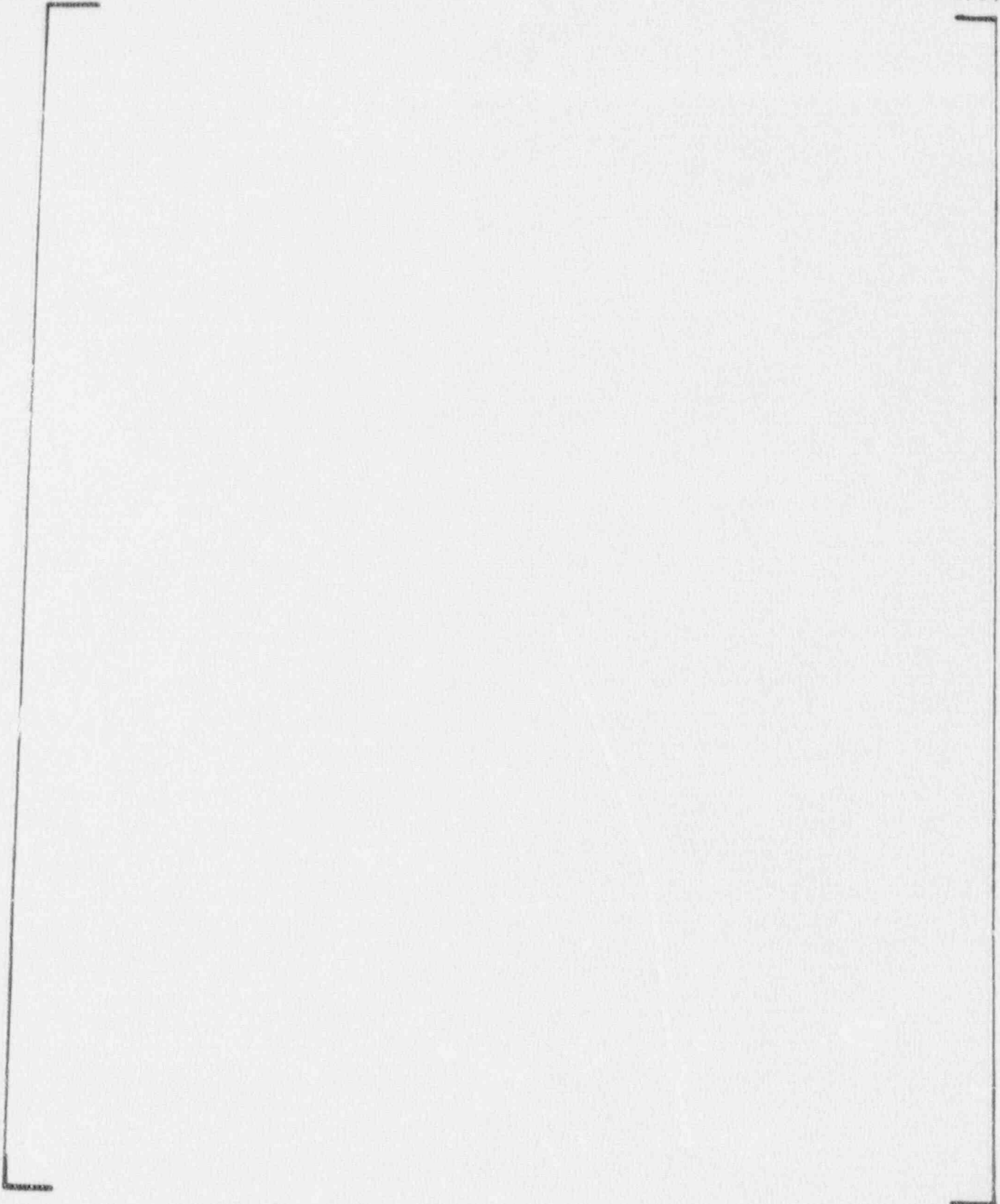Figure 3-7. Surge Line Local Axial Stress Distribution at [   ]^{a,c,e} Axial Locations

a,c,e

Figure 3-8. Surge Line Local Axial Stress on Inside Surface at
[   ]a,c,e Axial Locations

a,c,e

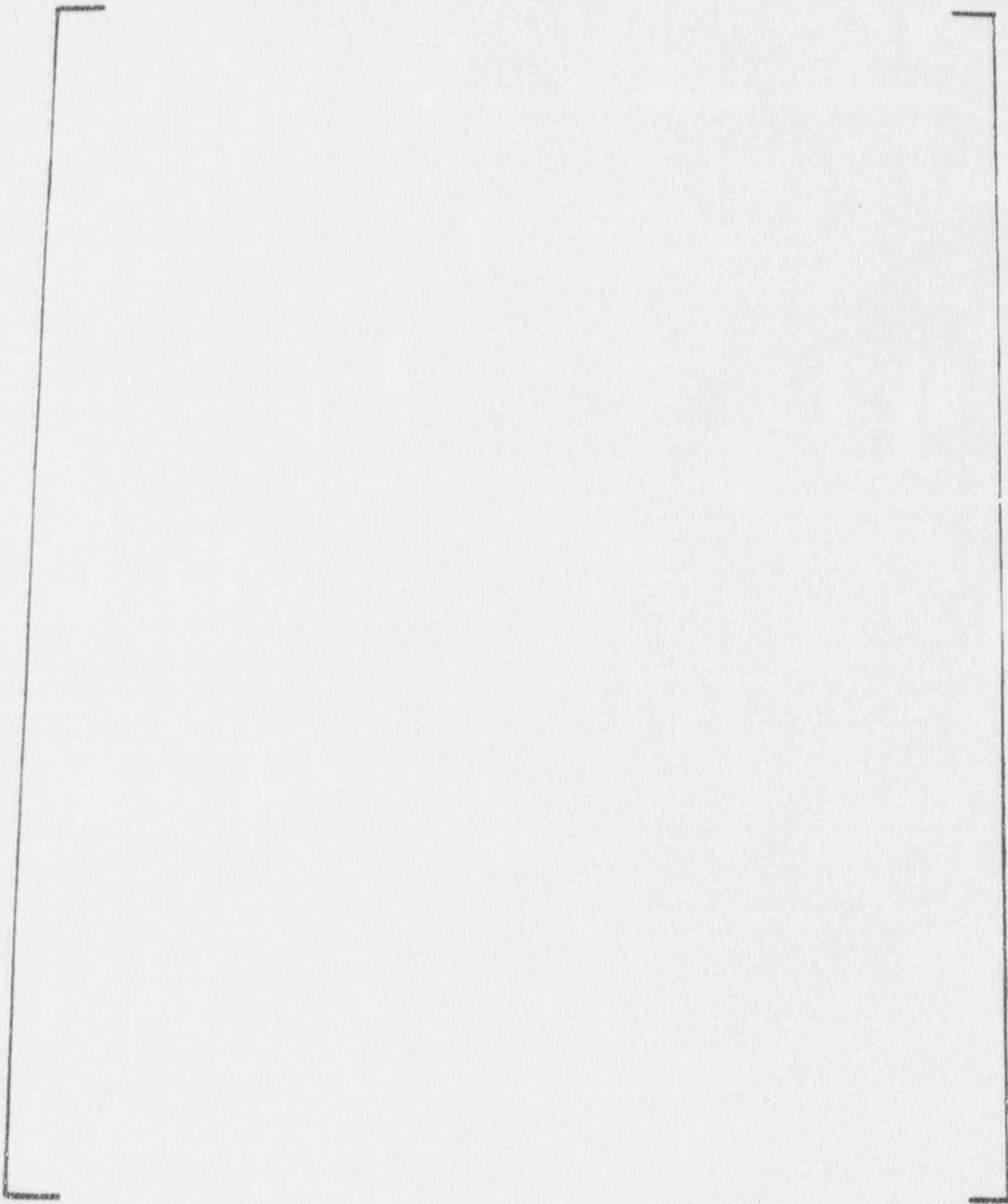Figure 3-9. Surge Line Local Axial Stress on Outside Surface at
[   ]^{a,c,e} Axial Locations

a,c,e

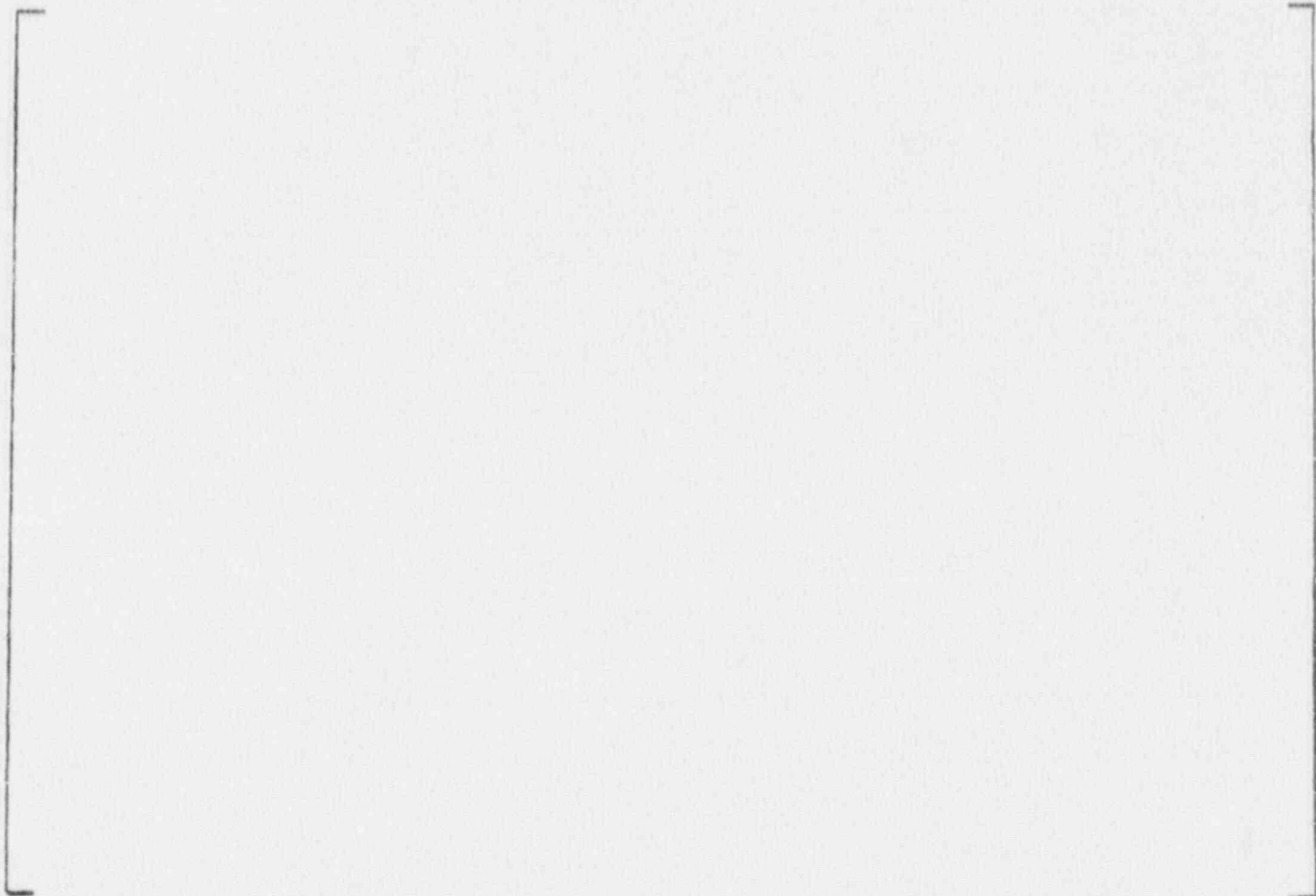Figure 3-10.   Surge Line RCL Nozzle 3-D WECAN Model: 14 Inch Schedule 160

a,c,e

Figure 3-11. Thermal Striping Fluctuation

a,c,e

Figure 3-12. Thermal Striping Temperature Distribution

SECTION 4.0
DISPLACEMENTS AND SUPPORT LOADINGS

The Farley specific support displacements along the surge lines were calculated under the thermal stratification and normal thermal loads for both existing and future support configurations. Table 4-1 shows the maximum values of the support displacements in the surge line. Nodes associated with supports and global coordinates are shown in figure 3-2.

The support displacements listed in Table 4-1 along with displacements due to other loadings should be verified for the future support configuration, to ensure that the spring hangers and snubbers have enough travel allowance. Insufficient allowance would result in an unevaluated condition for thermal stratification. For the displacements at pipe whip restraint locations, enough gaps should be also maintained between the pipe outside surface and the whip restraint surface so that the pipe will be free to move during all normal and stratified thermal conditions.

From the stress analysis in Section 3, it is not necessary to modify the Unit 1 existing spring can travel allowances or to open up the whip restraint gaps. However, in the future, if whip restraint gaps are opened, the spring cans must be modified to provide sufficient travel allowances according to the future configuration displacements listed in Table 4-1.

For Unit 2, since the spring cans have been already modified to accommodate stratification, only modification of whip restraint gaps is necessary for future operation. Such modification will be performed in conjunction with the Leak-Before-Break application.

TABLE 4-1

Farley Unit 1 Maximum Support Displacement
Under Thermal Stratification & Normal Operation Condition

Displacements (inches) at Support Locations

Support	Node	Existing Support Configuration			Future Support Configuration		
		DX	DY	DZ	DX	DY	DZ
RC-R1	2216	0.79	0.38/-0.11	+0.1/-0.42	0.79	-0.16	0.11/-0.42
RC-R7	2217	0.86	+0.33/-0.13	+0.14/-0.3	0.86	-0.37	0.14/-0.32
RC-R2	2238	1.45	-1.1	+0.31/-0.22	1.45	-3.04	0.14/-0.22

Displacement at Whip Restraint Locations

Support	Node	Existing Support Configuration			Future Support Configuration		
		DX	DY	DZ	DX	DY	DZ
2PSR-1	3258	0.26	-0.45	0.15/-0.21	0.26/-0.03	-0.53	0.04/-0.21
2PSR-2	3254	0.57	-0.65	0.09/-0.52	0.57	-1.35	-0.52
2PSR-3	3250	1.17	-1.13	0.16/-0.58	1.17	-2.66	-0.58
2PSR-4	3240	1.44	-1.16	0.291-0.3	1.44	-3.06	0.11/-0.30
2PSR-5	234	1.36	-0.79	0.34/-0.02	1.36	-2.62	0.22/-0.02
2PSR-6	2218	1.00	0.08/-0.16	0.23/-0.13	1.00	-1.01	0.19/-0.13
2PSR-7	3215	0.72	0.40/-0.09	0.05/-0.55	0.72	0.02/-0.09	0.07/-0.55
2PSR-8	2212	0.52	0.29/-0.05	-0.88	0.52	0.21/-0.05	-0.88
2PSR-9	3205	0.16	0.02/-0.004	-1.21	0.16	0.03/-0.004	-1.21

TABLE 4-1 (continued)

Farley Unit 2 Maximum Support Displacement
Under Thermal Stratification & Normal Operation Condition

Displacements (inches) at Support Locations

Support	Node	Existing Support Configuration			Future Support Configuration		
		DX	DY	DZ	DX	DY	DZ
2RC-R1	2216	0.79	0.53/-0.13	0.04/-0.42	0.79	-0.33	0.09/-0.42
2RC-R2	2217	0.86	0.48/-0.15	0.07/-0.32	0.86	-0.57	0.12/-0.32
2RC-R3	2238	1.45	-0.70	0.26/-0.22	1.45	-3.45	0.09/-0.22

Displacement at Whip Restraint Locations

Support	Node	Existing Support Configuration			Future Support Configuration		
		DX	DY	DZ	DX	DY	DZ
PSR-1	3258	0.26	-0.45	0.13/-0.22	0.26/-0.07	-0.58	0.01/-0.22
PSR-2	3254	0.56	-0.44	0.05/-0.53	0.56	-1.50	-0.53
PSR-3	3250	1.17	-0.74	0.11/-0.59	1.17	-2.98	-0.59
PSR-4	3240	1.44	0.74	0.24/-0.31	1.43	-3.47	0.06/-0.31
PSR-5	234	1.36	-0.47	0.28/-0.03	1.36	-3.03	0.17/-0.03
PSR-6	2218	1.00	0.26/-0.19	0.15/-0.13	1.00	-1.28	0.17/-0.13
PSR-7	3215	0.72	0.53/-0.11	0.01/-0.55	0.72	-0.11	0.06/-0.55
PSR-8	2212	0.52	0.39/-0.05	-0.88	0.52	0.14/-0.05	-0.88
PSR-9	3205	0.16	0.03/-0.004	-1.21	0.16	0.03/-0.004	-1.21

SECTION 5.0
ASME SECTION III FATIGUE USAGE FACTOR EVALUATION

5.1 Methodology

Surge line fatigue evaluations have typically been performed using the methods
of ASME Section III, NB-3600 for all piping components [----------------------
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of the nature of the stratification loading, as well as the magnitudes of the
stresses produced, the more detailed and accurate methods of NB-3200 were
employed using finite element analysis for all loading conditions.
Application of these methods, as well as specific interpretation of Code
stress values to evaluate fatigue results, is described in this section.

Inputs to the fatigue evaluation included the transients developed in section
2.0, and the global loadings and resulting stresses obtained using the methods
described in section 3.0. In general, the stresses due to stratification were
categorized according to the ASME Code methods and used to evaluate Code
stresses and fatigue cumulative usage factors. It should be noted that, [---
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5.1.1 Basis

The ASME Code, Section III, 1986 (Reference [6]) Edition was used to evaluate
fatigue on surge lines with stratification loading. This was based on the
requirement of NRC Bulletin 88-11 (Appendix B of this report) to use the
"latest ASME Section III requirements incorporating high cycle fatigue".

Specific requirements for class 1 fatigue evaluation of piping components are given in NB-3653. These requirements must be met for Level A and Level B type loadings according to NB-3653 and NB-3654.

According to NB-3611 and NB-3630, the methods of NB-3200 may be used in lieu of the NB-3600 methods. This approach was used to evaluate the surge line components under stratification loading. Since the NB-3650 requirements and equations correlate to those in NB-3200, the results of the fatigue evaluation are reported in terms of the NB-3650 piping stress equations. These equations and requirements are summarized in Table 5-1.

The methods used to evaluate these requirements for the surge line components are described in the following sections.

5.1.2 Fatigue Stress Equations

<u>Stress Classification</u>

The stresses in a component are classified in the ASME Code based on the nature of the stress, the loading that causes the stress, and the geometric characteristics that influence the stress. This classification determines the acceptable limits on the stress values and, in terms of NB-3653, the respective equation where the stress should be included. Table NB-3217-2 provides guidance for stress classification in piping components, which is reflected in terms of the NB-3653 equations.

The terms in Equations 10, 11, 12 and 13 include stress indices which adjust nominal stresses to account for secondary and peak effects for a given component. Equations 10, 12 and 13 calculate secondary stresses, which are obtained from nominal values using stress indices C1, C2, C3 and C3' for pressure, moment and thermal transient stresses. Equation 11 includes the K1, K2 and K3 indices in the pressure, moment and thermal transient stress terms in order to represent peak stresses caused by local concentration, such as notches and weld effects. The NB-3653 equations use simplified formulas to

determine nominal stress based on straight pipe dimensions. [---------
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---]^{a,c,e}

For the RCL nozzles, three dimensional (3-D) finite element analysis was used
as described in Section 3.0. [---

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

Classification of local stress due to thermal stratification was addressed
with respect to the thermal transient stress terms in the NB-3653 equations.
Equation 10 includes a Ta-Tb term, classified as "Q" stress in NB-3200, which
represents stress due to differential thermal expansion at gross structural
discontinuities. [--------------- -------------------------------------
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---]^{a,c,e} The impact of this on the
selection of components for evaluation is discussed in Section 5.1.3.

Stress Combinations

The stresses in a given component due to pressure, moment and local thermal
stratification loadings were calculated using the finite element models
described in Section 3.0. [--

-----------------]^{a,c,e} This was done for specific components as follows:

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

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--]^{a,c,e}

From the stress profiles created, the stresses for Equations 10 and 11 could
be determined for any point in the section. Experience with the geometries
and loading showed that certain points in the finite element models
consistently produced the worst case fatigue stresses and resulting usage
factors, in each stratified axial location. [--------------------------------
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--]^{a,c,e}

Equation 12 Stress

Code Equation 12 stress represents the maximum range of stress due to thermal expansion moments as described in Section 3.2. This used an enveloping approach, identifying the highest stressed location in the model. By evaluating the worst locations in this manner, the remaining locations were inherently addressed.

Equation 13 Stress

Equation 13 stress, presented in Section 3.2, is due to pressure, design mechanical loads and differential thermal expansion at structural discontinuities. Based on the transient set defined for stratification, the design pressures were not significantly different from previous design transients. Design mechanical loads are defined by the design specification for surge lines built to the ASME Code.

The "Ta-Tb" term of Equation 13 is only applicable at structural discontinuities. [--
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---]^{a,c,e}

Thermal Stress Ratchet

The requirements of NB-3222.5 are a function of the thermal transient stress and pressure stress in a component, and are independent of the global moment loading. As such, these requirements were evaluated for controlling components using applicable stresses due to pressure and stratification transients.

Allowable Stresses

Allowable stress, Sm, was determined based on note 3 of Figure NB-3222-1. For secondary stress due to a temperature transient or thermal expansion loads ("restraint of free end deflection"), the value of Sm was taken as the average of the Sm values at the highest and lowest temperatures of the metal during the transient. The metal temperatures were determined from the transient definition. When part of the secondary stress was due to mechanical load, the value of Sm was taken at the highest metal temperature during the transient.

5.1.3 Selection of Components for Evaluation

Based on the results of the global analyses and the considerations for controlling stresses in Section 5.1.2, [-- --- --]^{a,c,e} The method to evaluate usage factors using stresses determined according to Section 3.0 is described below.

5.2 Fatigue Usage Factors

Cumulative usage factors were calculated for the controlling components using the methods described in NB-3222.4(e), based on NB-3653.5. Application of these methods is summarized below.

Transient Loadcases and Combinations

From the transients described in Section 2.0, specific loadcases were developed for the usage evaluation. [-- --- --- --- --]^{a,c,e}
Each loadcase was assigned the number of cycles of the associated transient as defined in Section 2.0. These were input to the usage factor evaluation, along with the stress data as described above.

Usage factors were calculated at controlling locations in the component as follows:

1) Equation 10, Ke, Equation 11 and resulting Equation 14 (alternating stress - Salt) are calculated as described above for every possible combination of the loadsets.

2) For each value of Salt, the design fatigue curve was used to determine the maximum number of cycles which would be allowed if this type of cycle were the only one acting. These values, N_1, $N_2 \ldots N_n$, were determined from Code Figures I-9.2.1 and I-9.2.2, curve C, for austenitic stainless steels.

3) Using the actual cycles of each transient loadset, n_1, $n_2, \ldots n_n$, calculate the usage factors U_1, $U_2 \ldots U_n$ from $U_i = n_i/N_i$. This is done for all possible combinations. Cycles are used up for each combination in the order of decreasing Salt. When N_i is greater than 10^{11} cycles, the value of U_i is taken as zero.

[---

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-------------------]a,c,e

4) The cumulative usage factor, Ucum, was calculated as Ucum = U_1 + U_2 + ... + U_n. To this was added the usage factor due to thermal striping, as described below, to obtain total Ucum. The Code allowable value is 1.0.

5.3 Fatigue Due to Thermal Striping

The usage factors calculated using the methods of Section 5.2 do not include the effects of thermal striping. [--
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Thermal striping stresses are a result of differences between the pipe inside surface wall and the average through wall temperatures which occur with time, due to the oscillation of the hot and cold stratified boundary. This type of stress is defined as a thermal discontinuity peak stress for ASME fatigue analysis. The peak stress is then used in the calculation of the ASME fatigue usage factor.

[---

-------]^{a,c,e} The methods used to determine alternating stress intensity are defined in the ASME code. Several locations were evaluated in order to determine the location where stress intensity was a maximum.

Thermal striping transients are shown at a ΔT level and number of cycles. The striping ΔT for each cycle of every transient is assumed to attenuate and follow the slope of the curve shown on figure 5-2. Figure 5-2 is conservatively represented by a series of 5 degree temperature steps. Each step lasts [--]^{a,c,e} seconds. Fluctuations are then calculated at each temperature step. Since a constant frequency of [------]^{a,c,e} is used in all of the usage factor calculations, the total fluctuations per step is constant and becomes:

[---]^{a,c,e}

Each striping transient is a group of steps with [----]^{a,c,e} fluctuations per step. For each transient, the steps begin at the maximum ΔT and decreases by [--]^{a,c,e} steps down to the endurance limit of ΔT equal to [-----]^{a,c,e} The cycles for all transients which have a temperature step at the same level were added together. This became the total cycles at a step. The total cycles were multiplied by [----]^{a,c,e} to obtain total fluctuations. This results in total fluctuations at each step. This calculation is performed for each step plateau from [------------------------------------]^{a,c,e} to obtain total fluctuations. Allowable fluctuations and ultimately a usage factor at each plateau is calculated from the stress which exists at the ΔT for each step. The total striping usage factor is the sum of all usage factors from each plateau.

The usage factor due to striping, alone, was calculated to be a maximum of [-----]^{a,c,e} This is reflected in the results to be discussed below.

5.4 Fatigue Usage Results

NRC Bulletin 88-11 [7] requires fatigue analysis be performed in accordance with the latest ASME III requirements incorporating high cycle fatigue and thermal stratification transients. ASME fatigue usage factors have been calculated considering the phenomenon of thermal stratification and thermal striping at various locations in the surge line. Total stresses included

[---
-----------------------------------]^{a,c,e} The total stresses for all
transients in the bounding set were used to form combinations to calculate
alternating stresses and resulting fatigue damage in the manner defined by the
Code. Of this total stress, the stresses in the 14 inch schedule 160 pipe due
to [---
--]^{a,c,e}

The maximum usage factor on Farley surge lines occurred at [-------------------
---]^{a,c,e}
For the [---
-----]^{a,c,e} the maximum cumulative usage factor of 0.7 was calculated.

It is also concluded that the Farley pressurizer surge nozzles will meet the
code stress allowables under the cyclic loading from pipe thermal
stratification, and meet the fatigue usage requirements of ASME Section III,
with a cumulative usage factor equal to 0.2.

TABLE 5-1
CODE/CRITERIA

o   ASME B&PV Code, Sec. III, 1986 Edition
    - NB3600
    - NB3200

o   Level A/B Service Limits
    -   Primary Plus Secondary Stress Intensity $\leq$ 3Sm (Eq. 10)

    -   Simplified Elastic-Plastic Analysis

        -   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 5-2
SUMMARY OF ASME FATIGUE REQUIREMENTS

Parameter	Description	Allowable (if applicable)
Equation 10	Primary plus secondary stress intensity; if exceeded, simplified elastic-plastic analysis may be performed	< 3Sm
K_e	Elastic-plastic penalty factor; required for simplified elastic-plastic analysis when Eq. 10 is exceeded; applied to alternating stress intensity	
Equation 12	Expansion stress; required for simplified elastic-plastic analysis when Eq. 10 is exceeded	< 3Sm
Equation 13	Primary plus secondary stress intensity excluding thermal bending stress; required for simplified elastic-plastic analysis when Eq. 10 is exceeded	< 3Sm
Thermal Stress Ratchet	Limit on radial thermal gradient stress to prevent cyclic distortion; required for use of Eq. 13	
Equation 11	Peak stress intensity - Input to Eq. 14	
Equation 14	Alternating stress intensity - Input to Ucum	
Ucum	Cumulative usage factor (fatigue damage)	< 1.0

a,c,e
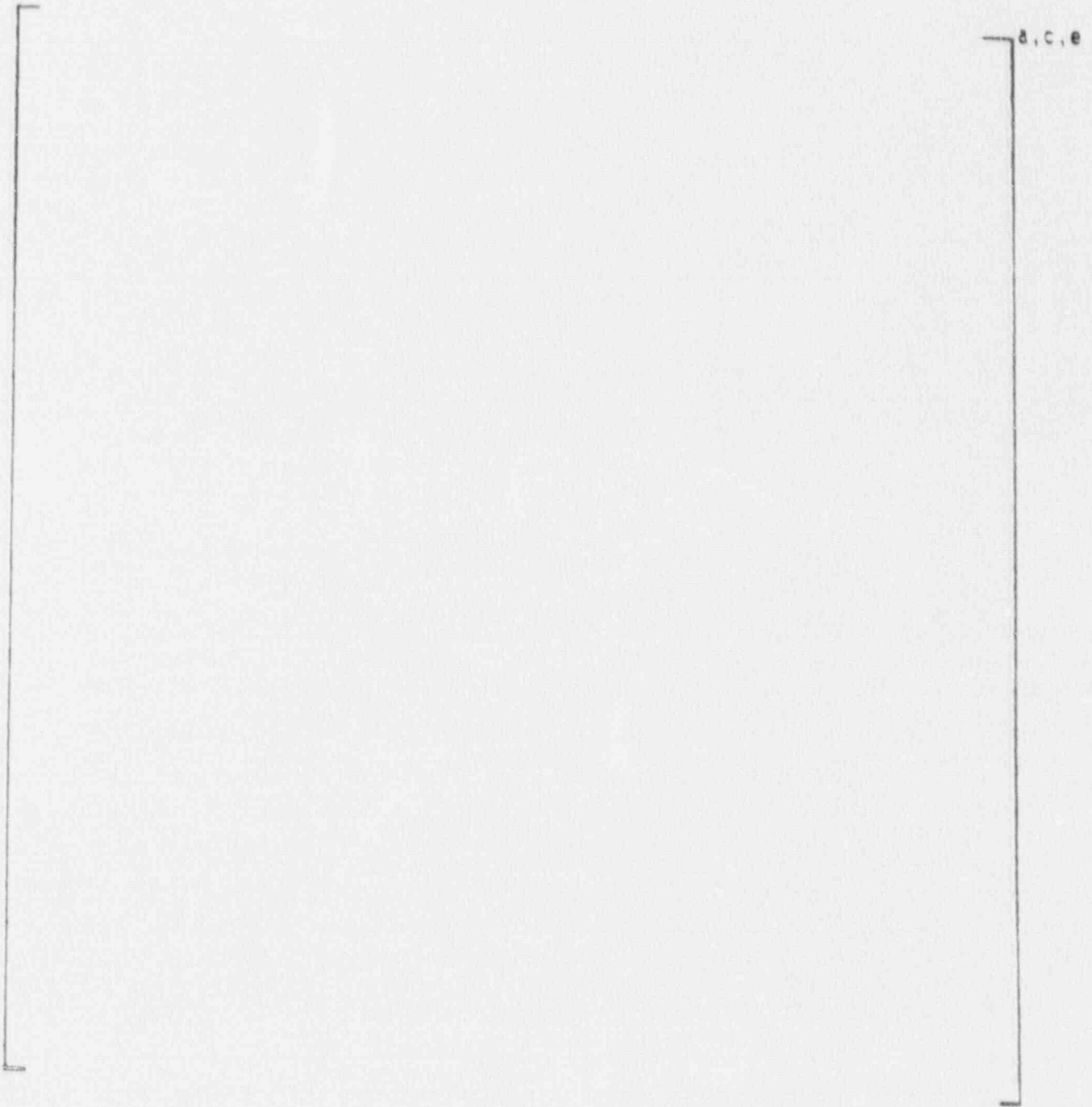
Figure 5-1. Striping Finite Element Model

a,c,e

Figure 5-2.   Attenuation of Thermal Striping Potential by Molecular
Conduction (Interface Wave Height of One Inch)

SECTION 6.0
SUMMARY AND CONCLUSIONS

The subject of pressurizer surge line integrity has been under intense investigation since 1988. The NRC issued Bulletin 88-11 in December of 1988, but the Westinghouse Owners Group had put a program in place earlier that year, and this allowed all members to make a timely response to the bulletin.

The Owners Group programs were completed in June of 1990, and have been followed by a series of plant specific evaluations. This report has documented the results of the plant specific evaluation for the Farley Nuclear Units.

Following the general approach used in developing the surge line stratification transients for the WOG, a set of transients and stratification profile were developed specifically for Farley. A study was made of the historical operating experience at the Farley units, and this information, as well as plant operating procedures and monitoring results, was used in development of the transients and profiles.

From the stress analysis in Section 3 and fatigue evaluation in Section 5, it is not necessary to modify the Unit 1 existing spring can travel allowances or to open up the whip restraint gaps. However, in the future, if whip restraint gaps are opened, the spring cans must be modified to provide sufficient travel allowances according to the future configuration displacements listed in Table 4-1.

For Unit 2, since the spring cans have been already modified to accommodate stratification, only modification of whip restraint gaps is necessary for future operation. Such modification will be performed in conjunction with the Leak-Before-Break application.

The results of this plant specific analysis demonstrated acceptance to the requirements of the ASME Code Section III, including both stress limits and fatigue usage, for the full licensed life of the units. This report demonstrates that the Farley plants have now completely satisfied the requirements of NRC Bulletin 88-11.

SECTION 7.0
REFERENCES

1. Coslow, B. J., et al.. "Westinghouse Owners Group Bounding Evaluation for Pressurizer Surge Line Thermal Stratification" Westinghouse Electric Corp. WCAP-12278, (proprietary class 2) and WCAP-12278 (non-proprietary), June 1989.

2. Coslow, B. J., et al., Westinghouse Owners Group Pressurizer Surge Line Thermal Stratification Program MUHP-1090 Summary Report," Westinghouse Electric Corp. WCAP-12508 (proprietary class 2) and WCAP 12509 (non-proprietary), March 1990.

3. Coslow, B. J., et al., "Westinghouse Owners Group Pressurizer Surge Line Thermal Stratification Generic Detailed Analysis Program MUHP-1091 Summary Report," Westinghouse Electric Corp. WCAP-12639 (proprietary class 2) and WCAP-12640 (non-proprietary), June 1990.

4. Alabama Power Co. Letter NDS-90-2043, 10/18/90 from J. E. Garlington.

5. Farley Units 1 and 2 Surge Line Piping Analysis, Westinghouse Central File ALA-145-15B and APR-145-153.

6. ASME B&PV Code Section III, Subsection NB, 1986 Edition.

7. "Pressurizer Surge Line Thermal Stratification," USNRC Bulletin 88-11, December 20, 1988.

8. "Investigation of Feedwater Line Cracking in Pressurized Water Reactor Plants," WCAP-9693, Volume 1, June 1990 (Westinghouse Proprietary Class 2).

9. Woodward, W. S., "Fatigue of LMFBR Piping due to Flow Stratification," ASME Paper 83-PVP-59, 1983.

10. Fujimoto, T., et al., "Experimental Study of Striping at the Interface of Thermal Stratification" in _Thermal Hydraulics in Nuclear Technology_, K. H. Sun, et al., (ed.) ASME, 1981, pp. 73 ff.

11. Holman, J. P., _Heat Transfer_, McGraw Hill Book Co., 1963.

12. Yang, C. Y., "Transfer Function Method of Thermal Stress Analysis: Technical Basis," Westinghouse Electric WCAP 12315, Westinghouse Proprietary, May 1990.

APPENDIX A
LIST OF COMPUTER PROGRAMS

This appendix lists and summarizes the computer codes used in the pressurizer surge line thermal stratification analysis. The codes are:

1. WECAN
2. STRFAT2
3. ANSYS
4. FATRK/CMS

A.1 WECAN

A.1.1 Description

WECAN is a Westinghouse-developed, general purpose finite element program. It contains universally accepted two-dimensional and three-dimensional isoparametric elements that can be used in many different types of finite element analyses. Quadrilateral and triangular structural elements are used for plane strain, plane stress, and axisymmetric analyses. Brick and wedge structural elements are used for three-dimensional analyses. Companion heat conduction elements are used for steady state heat conduction analyses and transient heat conduction analyses.

A.1.2 Feature Used

The temperatures obtained from a static heat conduction analysis, or at a specific time in a transient heat conduction analysis, can be automatically input to a static structural analysis where the heat conduction elements are replaced by corresponding structural elements. Pressure and external loads can also be include in the WECAN structural analysis. Such coupled thermal-stress analyses are a standard application used extensively on an industry wide basis.

A.1.3 Program Verification

Both the WECAN program and input for the WECAN verification problems, currently numbering over four hundred, are maintained under configuration control. Verification problems include coupled thermal-stress analyses for the quadrilateral, triangular, brick, and wedge isoparametric elements. These problems are an integral part of the WECAN quality assurance procedures. When a change is made to WECAN, as part of the reverification process, the configured inputs for the coupled thermal-stress verification problems are used to reverify WECAN for coupled thermal-stress analyses.

A.2 STRFAT2

A.2.1 Description

STRFAT2 is a program which computes the alternating peak stress on the inside surface of a flat plate and the usage factor due to striping on the surface. The program is applicable to be used for striping on the inside surface of a pipe if the program assumptions are considered to apply for the particular pipe being evaluated.

For striping the fluid temperature is a sinusoidal variation with numerous cycles.

The frequency, convection film coefficient, and pipe material properties are input.

The program computes maximum alternating stress based on the maximum difference between inside surface skin temperature and the average through wall temperature.

A.2.2 Feature Used

The program is used to calculate striping usage factor based on a ratio of actual cycles of stress for a specified length of time divided by allowable cycles of stress at maximum the alternating stress level. Design fatigue curves for several materials are contained into the program. However, the user has the option to input any other fatigue design curve, by designating that the fatigue curve is to be user defined.

A.2.3 Program Verification

STRFAT2 is verified to Westinghouse procedures by independent review of the stress equations and calculations.

A.3 ANSYS

A.3.1 Description

ANSYS is a public domain, general purpose finite element code.

A.3.2 Feature Used

The ANSYS elements used for the analysis of stratification effects in the surge and RHR lines are STIF 20 (straight pipe), STIF 60 (elbow and bends) and STIF14 (spring-damper for supports).

A.3.3 Program Verification

As described in section 2.1, the application of ANSYS for stratification has been independently verified by comparison to WESTDYN (Westinghouse piping] analysis code) and WECAN (finite element code). The results from ANSYS are also verified against closed form solutions for simple beam configurations.

A.4 FATRK/CMS

A.4.1 Description

FATRK/CMS[19] is a Westinghouse developed computer code for fatigue tracking (FATRK) as used in the Cycle Monitoring System (CMS) for structural components of nuclear power plants. The transfer function method is used for transient thermal stress calculations. The bending stresses (due to global stratification effects, ordinary thermal expansion and seismic) and the pressure stresses are also included. The fatigue usage factors are evaluated in accordance with the guidelines given in the ASME Boiler and Pressure Vessel Code, Section III, Subsections NB-3200 and NB-3600. The principal stress directions are allowed to vary and the worst bending stress combinations are considered to obtain the most conservative fatigue results.

The code can be used both as a regular analysis program or an on-line monitoring device.

A.4.2 Feature Used

FATRK/CMS is used as an analysis program for the present application. The input data which include the weight functions for thermal stresses, the unit bending stress, the unit pressure stress, the bending moment vs. stratification temperatures, etc. are prepared for all locations and geometric conditions. These data, as stored in the independent files, can be appropriately retrieved for required analyses. The transient data files contain the time history of temperature, pressure, number of occurrence, and additional condition necessary for data flowing. The program prints out the total usage factors, and the transients pairing information which determine the stress range magnitudes and number of cycles. The detailed stress data may also be printed.

A.4.3 Program Verification

FATRK/CMS is verified according to Westinghouse procedures with several levels of independent calculations as described below = (1) transfer function method of thermal stresses as compared with direct WECAN finite element analyses. (2) combined stresses as compared with hand calculations and WECEVAL analyses. (3) The fatigue usage factor results as compared with WECEVAL analyses.

APPENDIX B

USNRC BULLETIN 88-11

In December of 1988 the NRC issued this bulletin, and it has led to an extensive investigation of surge line integrity, culminating in this and other plant specific reports. The bulletin is reproduced in its entirety in the pages which follow.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
WASHINGTON, D.C. 20555

December 20, 1988

NRC BULLETIN NO. 88-11: PRESSURIZER SURGE LINE THERMAL STRATIFICATION

Addressees:

All holders of   rating licenses or construction permits for pressurized water
reactors (PWRs).

Purpose:

The purpose of this bulletin is to (1) request that addressees establish and
implement a program to confirm pressurizer surge line integrity in view of the
occurrence of thermal stratification and (2) require addressees to inform the
staff of the actions taken to resolve this issue.

Description of Circumstances:

The licensee for the Trojan plant has observed unexpected movement of the
pressurizer surge line during inspections performed at each refueling outage
since 1982, when monitoring of the line movements began. During the last
refueling outage, the licensee found that in addition to unexpected gap clo-
sures in the pipe whip restraints, the piping actually contacted two re-
straints. Although the licensee had repeatedly adjusted shims and gap sizes
based on analysis of various postulated conditions, the problem had not been
resolved. The most recent investigation by the licensee confirmed that the
movement of piping was caused by thermal stratification in the line. This
phenomenon was not considered in the original piping design. On October 7,
1988, the staff issued Information Notice 88-80, "Unexpected Piping Movement
Attributed to Thermal Stratification," regarding the Trojan experience and
indicated that further generic communication may be forthcoming. The licensee
for Beaver Valley 2 has also noticed unusual snubber movement and significantly
larger-than-expected surge line displacement during power ascension.

The concerns raised by the above observations are similar to those described in
NRC Bulletins 79-13 (Revision 2, dated October 16, 1979), "Cracking in
Feedwater System Piping" and 88-08 (dated June 22, 1988), "Thermal Stresses in
Piping Connected to Reactor Coolant Systems."

8812150118

Discussion:

Unexpected piping movements are highly undesirable because of potential high piping stress that may exceed design limits for fatigue and stresses. The problem can be more acute when the piping expansion is restricted, such as through contact with pipe whip restraints. Plastic deformation can result, which can lead to high local stresses, low cycle fatigue and functional impairment of the line. Analysis performed by the Trojan licensee indicated that thermal stratification occurs in the pressurizer surge line during heatup, cooldown, and steady-state operations of the plant.

During a typical plant heatup, water in the pressurizer is heated to about 440°F; a steam bubble is then formed in the pressurizer. Although the exact phenomenon is not thoroughly understood, as the hot water flows (at a very low flowrate) from the pressurizer through the surge line to the hot-leg piping, the hot water rides on a layer of cooler water, causing the upper part of the pipe to be heated to a higher temperature than the lower part (see Figure 1). The differential temperature could be as high as 300°F, based on expected conditions during typical plant operations. Under this condition, differential thermal expansion of the pipe metal can cause the pipe to deflect significantly.

For the specific configuration of the pressurizer surge line in the Trojan plant, the line deflected downward and when the surge line contacted two pipe whip restraints, it underwent plastic deformation, resulting in permanent deformation of the pipe.

The Trojan event demonstrates that thermal stratification in the pressurizer surge line causes unexpected piping movement and potential plastic deformation. The licensing basis according to 10 CFR 50.55a for all PWRs requires that the licensee meet the American Society of Mechanical Engineers Boiler and Pressure Vessel Code Sections III and XI and to reconcile the pipe stresses and fatigue evaluation when any significant differences are observed between measured data and the analytical results for the hypothesized conditions. Staff evaluation indicates that the thermal stratification phenomenon could occur in all PWR surge lines and may invalidate the analyses supporting the integrity of the surge line. The staff's concerns include unexpected bending and thermal striping (rapid oscillation of the thermal boundary interface along the piping inside surface) as they affect the overall integrity of the surge line for its design life (e.g., the increase of fatigue).

Actions Requested:

Addressees are requested to take the following actions:

1. For all licensees of operating PWRs:

    a. Licensees are requested to conduct a visual inspection (ASME, Section XI, VT-3) of the pressurizer surge line at the first available cold shutdown after receipt of this bulletin which exceeds seven days.

This inspection should determine any gross discernable distress or structural damage in the entire pressurizer surge line, including piping, pipe supports, pipe whip restraints, and anchor bolts.

b. Within four months of receipt of this Bulletin, licensees of plants in operation over 10 years (i.e., low power license prior to January 1, 1979) are requested to demonstrate that the pressurizer surge line meets the applicable design codes* and other FSAR and regulatory commitments for the licensed life of the plant, considering the phenomenon of thermal stratification and thermal striping in the fatigue and stress evaluations. This may be accomplished by performing a plant specific or generic bounding analysis. If the latter option is selected, licensees should demonstrate applicability of the referenced generic bounding analysis. Licensees of plants in operation less than ten years (i.e., low power license after January 1, 1979), should complete the foregoing analysis within one year of receipt of this bulletin. Since any piping distress observed by addressees in performing action 1.a may affect the analysis, the licensee should verify that the bounding analysis remains valid. If the opportunity to perform the visual inspection in 1.a does not occur within the periods specified in this requested item, incorporation of the results of the visual inspection into the analysis should be performed in a supplemental analysis as appropriate.

Where the analysis shows that the surge line does not meet the requirements and licensing commitments stated above for the duration of the license, the licensee should submit a justification for continued operation or bring the plant to cold shutdown, as appropriate, and implement Items 1.c and 1.d below to develop a detailed analysis of the surge line.

c. If the analysis in 1.b does not show compliance with the requirements and licensing commitments stated therein for the duration of the operating license, the licensee is requested to obtain plant specific data on thermal stratification, thermal striping, and line deflections. The licensee may choose, for example, either to install instruments on the surge line to detect temperature distribution and thermal movements or to obtain data through collective efforts, such as from other plants with a similar surge line design. If the latter option is selected, the licensee should demonstrate similarity in geometry and operation.

d. Based on the applicable plant specific or referenced data, licensees are requested to update their stress and fatigue analyses to ensure compliance with applicable Code requirements, incorporating any observations from 1.a above. The analysis should be completed no later than two years after receipt of this bulletin. If a licensee

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*Fatigue analysis should be performed in accordance with the latest ASME Section III requirements incorporating high cycle fatigue.

is unable to show compliance with the applicable design codes and
other FSAR and regulatory commitments, the licensee is requested to
submit a justification for continued operation and a description of
the proposed corrective actions for effecting long term resolution.

2.   For all applicants for PWR Operating Licenses:

a.   Before issuance of the low power license, applicants are requested to
demonstrate that the pressurizer surge line meets the applicable
design codes and other FSAR and regulatory commitments for the
licensed life of the plant. This may be accomplished by performing a
plant-specific or generic bounding analysis. The analysis should
include consideration of thermal stratification and thermal striping
to ensure that fatigue and stresses are in compliance with applicable
code limits. The analysis and hot functional testing should verify
that piping thermal deflections result in no adverse consequences,
such as contacting the pipe whip restraints. If analysis or test
results show Code noncompliance, conduct of all actions specified
below is requested.

b.   Applicants are requested to evaluate operational alternatives or
piping modifications needed to reduce fatigue and stresses to
acceptable levels.

c.   Applicants are requested to either monitor the surge line for the
effects of thermal stratification, beginning with hot functional
testing, or obtain data through collective efforts to assess the
extent of thermal stratification, thermal striping and piping
deflections.

d.   Applicants are requested to update stress and fatigue analyses, as
necessary, to ensure Code compliance.* The analyses should be
completed no later than one year after issuance of the low power
license.

3.   Addressees are requested to generate records to document the development
and implementation of the program requested by Items 1 or 2, as well as
any subsequent corrective actions, and maintain these records in accor-
dance with 10 CFR Part 50, Appendix B and plant procedures.

Reporting Requirements:

1.   Addressees shall report to the NRC any discernable distress and damage
observed in Action 1.a along with corrective actions taken or plans and
schedules for repair before restart of the unit.

*If compliance with the applicable codes is not demonstrated for the full
duration of an operating license, the staff may impose a license condition such
that normal operation is restricted to the duration that compliance is actually
demonstrated.

2. Addressees who cannot meet the schedule described in Items 1 or 2 of Actions Requested are required to submit to the NRC within 60 days of receipt of this bulletin an alternative schedule with justification for the requested schedule.

3. Addressees shall submit a letter within 30 days after the completion of these actions which notifies the NRC that the actions requested in Items 1b, 1d or 2 of Actions Requested have been performed and that the results are available for inspection. The letter shall include the justification for continued operation, if appropriate, a description of the analytical approaches used, and a summary of the results.
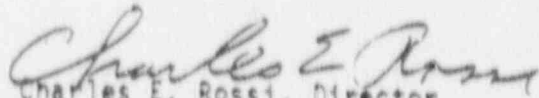
Although not requested by this bulletin, addressees are encouraged to work collectively to address the technical concerns associated with this issue, as well as to share pressurizer surge line data and operational experience. In addition, addressees are encouraged to review piping in other systems which may experience thermal stratification and thermal striping, especially in light of the previously mentioned Bulletins 79-13 and 88-08. The NRC staff intends to review operational experience giving appropriate recognition to this phenomenon, so as to determine if further generic communications are in order.

The letters required above shall be addressed to the U.S. Nuclear Regulatory Commission, ATTN: Document Control Desk, Washington, D.C. 20555, under oath or affirmation under the provisions of Section 182a, Atomic Energy Act of 1954, as amended. In addition, a copy shall be submitted to the appropriate Regional Administrator.

This request is covered by Office of Management and Budget Clearance Number 3150-0011 which expires December 31, 1989. The estimated average burden hours is approximately 3000 person-hours per licensee response, including assessment of the new requirements, searching data sources, gathering and analyzing the data, and preparing the required reports. These estimated average burden hours pertain only to these identified response-related matters and do not include the time for actual implementation of physical changes, such as test equipment installation or component modification. The estimated average radiation exposure is approximately 3.5 person-rems per licensee response.

Comments on the accuracy of this estimate and suggestions to reduce the burden may be directed to the Office of Management and Budget, Room 3208, New Executive Office Building, Washington, D.C. 20503, and to the U.S. Nuclear Regulatory Commission, Records and Reports Management Branch, Office of Administration and Resource Management, Washington, D.C. 20555.

If you have any questions about this matter, please contact one of the technical contacts listed below or the Regional Administrator of the appropriate regional office.

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(301) 492-1153

Attachments:
1. Figure 1
2. List of Recently Issued NRC Bulletins
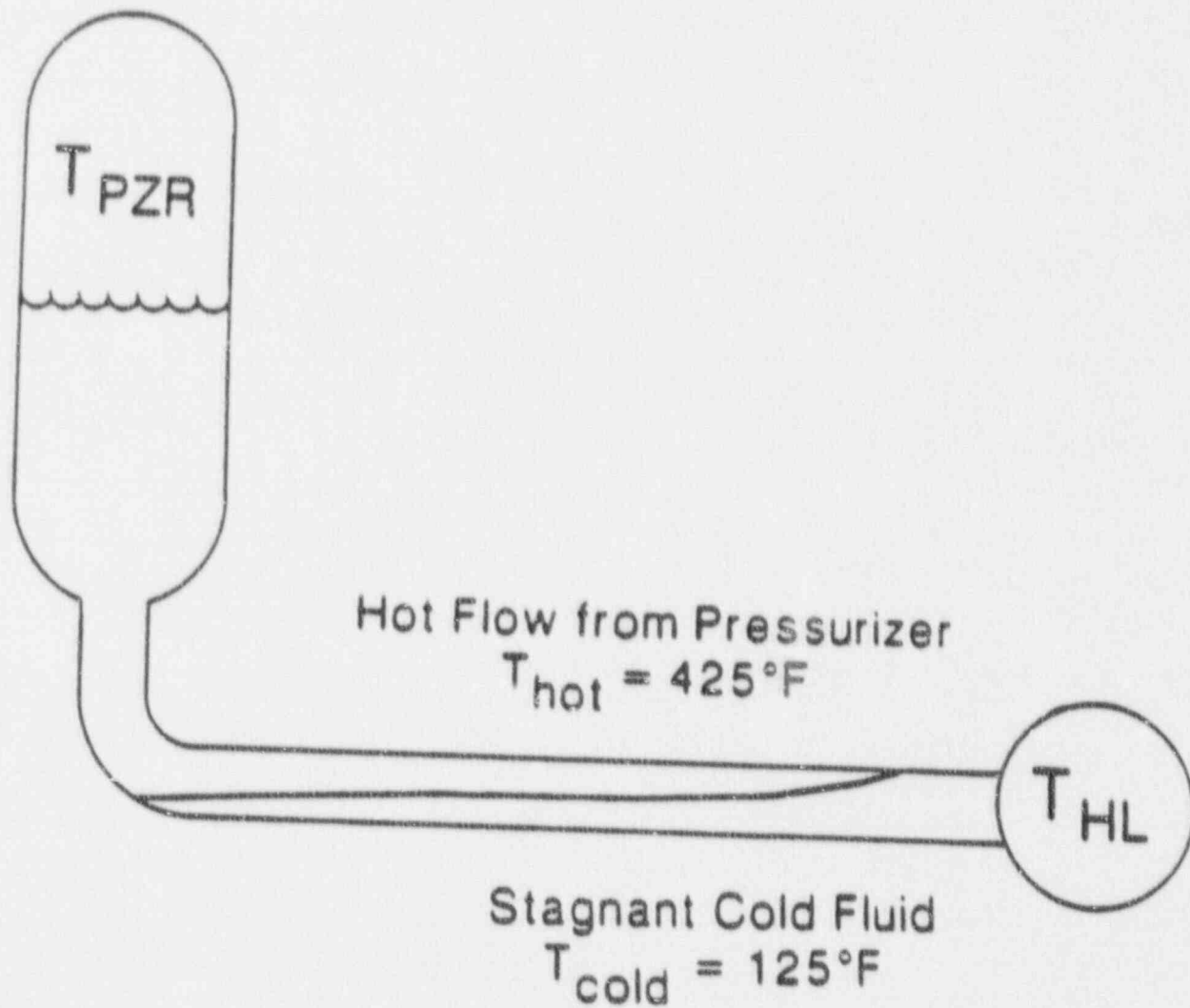
Surge Line Stratification

T_{PZR}

Hot Flow from Pressurizer
$T_{hot} = 425°F$

T_{HL}

Stagnant Cold Fluid
$T_{cold} = 125°F$

Figure 1

APPENDIX C

TRANSIENT DEVELOPMENT DETAILS

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