CEOG COMBUSTION ENGINEERING OWNERS GROUP

CE NPSD-1043

SUMMARY OF COMBUSTION ENGINEERING OWNERS GROUP PROGRAMS IN RESPONSE TO NRC BULLETIN 88-08

Final Report

CEOG Task 866

Prepared for the
C-E OWNERS GROUP
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ABB Combustion Engineering Nuclear Operations

ABB

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Executive Summary

NRC Bulletin 88-08 identified thermal stratification as a cause of potentially large stresses in primary pressure boundary lines connected to reactor coolant systems. Though 88-08 was mainly concerned with nonisolable sections of Class 1 lines where stratification could result from in-or out-leakage of cooler fluid, it directed that all lines be identified in which thermal stratification could result in top-to-bottom differences in wall temperature greater than 50°F. Nuclear Plant Owners were to implement a program to provide continued assurance that those pipe sections will not be subjected to stresses that could result in fatigue failure.

To address these concerns, a program was established by the Combustion Engineering Owners Group (CEOG) to identify Class 1 lines where thermal stratification could be present and, for the lines in which thermal stratification was found, to update, as necessary, related plant specific design basis documentation.

An evaluation based on a set of qualitative criteria, which included flow rate, line size, line orientation, sources thermal stratification and line stiffness, was done to identify lines susceptible to large moments due to thermal stratification. Results were reviewed based on a comparable set of quantitative criteria. While this re-evaluation confirmed the conclusions made based on the qualitative criteria for lines greater than two inches, it indicated that small lines could, depending on size and schedule and source of stratification, be subject to variations in wall temperatures greater than 50°F. However, the occurrence of significant moments due to stratification for these small lines should be evaluated based on plant specific arrangements.

Data on Class 1 lines were obtained at a number of operating plants. Lines in which wall temperatures higher than 50°F were measured included the Safety Injection (SI), Pressure Operated Relieve Valve (PORV) and Shutdown Cooling (SDC) lines. In each of these lines the cause of the thermal stratification was found to be different; natural convection in SI lines, two-phase flow in PORV lines and a combination of turbulent penetration and natural convection in SDC lines. In addition, leakage through the valve isolating the auxiliary from the main spray line was also identified as a possible source of thermal stratification.

Programs for each of these lines were established with the ultimate goal of providing design basis data to evaluate the additional stress due to thermal stratification for each of the operating plants. Each of these programs followed a similar format in which in-plant data were recorded for

each of these lines and evaluated to develop methods used to predict wall temperatures for other plants.

These predictions were then used to calculate forces and moments due to thermal stratification. The Safety Injection and Shutdown Cooling lines were separated into classes and bounding loads computed for the plants in each of the classes. However, the widely different routing and support points for the Pressure Operated Relief Valve and Auxiliary Spray lines required that loads due to thermal stratification be computed on a plant specific basis.

A procedure is discussed by which the moments due to thermal stratification can be compared or combined with the existing plant specific design basis loads to evaluate the influence of these loads on existing fatigue usage factors. Three levels of evaluation are recommended: the first, a Screening evaluation where in the magnitude of the thermal stratification moments are compared to those for the existing design basis transients; the second, an Incremental Usage Factor approach where the influence of these transients are conservatively added to the usage factor for the other design basis transients; and third, should the first and second indicate a usage factor greater than one, revisions to the Design Analysis.

NRC Bulletin 88-08 requires owners of plant licenses provide assurance that these loads will not result in fatigue failure. Section 10CFR50.55.a requires this assurance be based on an analysis based on Section III of the ASME Code. Section 10CFR50.71.e requires the FSAR to be updated should the results of this evaluation be used as part of any licensing amendment submitted to the NRC. Thus, while there is no specific directive requiring an updating of the design analysis of record for these lines, the results of the above evaluation should be documented and included with the design analysis of record.

CEOG ACTIVITIES IN RESPONSE TO 88-08

ACTION	RESPONSE	UTILITY PARTICIPANT
Action #1 Review System to Identify any section of Piping Subjected to similar conditions	Task 578: Evaluates the potential for Temperature Oscillation due to Valve Leakage from Systems connected to the RCS and Local Temperature Stratification in dead-end or valved out piping runs and identifies those systems	Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Omaha Public Power District (Ft. Calhoun)
	Task 626: Identify and Evaluate systems where outleakage from the RCS	Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (ST. Lucie 1,2) Maine Yankee Omaha Public Power District (Ft. Calhoun)
Action #2 Inspect those Pipes that may be subjected to excessive Thermal Stresses	Task 578: Suggest the need for a more accurate thermal loading definition. Recommends data collection to determine the significance and generic applicability of these loads.	Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Omaha Public Power District (Ft. Calhoun)
	Task 626: Inspection Locations are recommended in the Identified systems	Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Omaha Public Power District (Ft. Calhoun)
	Task 732: Inspection of Piping potentially affected by Thermal Stratification	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Northeast Utilities (MP2) Omaha Public Power District (Ft. Calhoun)
Action #3 Plan and Implement a Program to provide continued Assurance those pipes will not be subjected to stresses that could cause Fatigue Failure	Task 578: Suggest the need for a more accurate thermal loading definition. Recommends data collection to determine the significance and generic applicability of these loads.	Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Omaha Public Power District (Ft. Calhoun)
	Task 626: Several recommendations were made: Instrumentation and Data Collection Outleakage Flow Rate Detection	Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Omaha Public Power District (Ft. Calhoun)

CEOG ACTIVITIES IN RESPONSE TO 88-08

ACTION	RESPONSE	UTILITY PARTICIPANT
Action #3 Plan and Implement a Program to provide continued Assurance those pipes will not be subjected to stresses that could cause Fatigue Failure	Task 588: Temperature Measurements of SI, SDC and PORV piping. Evaluation of results which showed evidence of stratified flow conditions in safety injection and PORV pipings; ΔT's > 50°F threshold established.	Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee
	Task 741: Developed methodology to predict wall temperature resulting from thermal stratification due to natural convection for different safety injection lines configurations.	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Northeast Utilities (MP2) Omaha Public Power District (Ft. Calhoun)
	Task 818: Use results of Task 741 to predict wall Temperatures and moments due to thermal stratification	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee
	Task 732: Inspection of Piping potentially affected by Thermal Stratification	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Northeast Utilities (MP2) Omaha Public Power District (Ft. Calhoun)
	Task 773: Use PORV line measurements at ANO2 and BG&E to develop model to predict wall temperatures due to condensation related thermal stratification.	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Northeast Utilities (MP2)
	Task 827: Model developed in Task 773 used to determine plant specific wall temperatures and moments due to thermal stratification	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Maine Yankee Northeast Utilities (MP2)
	Task 772: Wall temperatures measured in the ANO2 shutdown cooling line used to predict moments for shutdown cooling lines in other plants. These	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2)

CEOG ACTIVITIES IN RESPONSE TO 88-08

ACTION	RESPONSE	UTILITY PARTICIPANT
Action #3 Plan and Implement a Program to provide continued Assurance those pipes will not be subjected to stresses that could cause Fatigue Failure	models used as the basis for a JCO	Maine Yankee Omaha Public Power District (Ft. Calhoun)
	Task 813: SDC wall measurements taken at ANO2 and APS were evaluated to determine the basis for the high wall temperature differences recorded in the ANO2 SDC line. Evaluation formed the basis for justifying that the temperature distributions used in Task 772 were bounding.	Arizona Public Service (Palo Verde 1,2,3) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Omaha Public Power District (Ft. Calhoun)
	Task 886: Conservative model for leakage related thermal stratification used to calculate moments at the aux spray-main spray line junction.	Arizona Public Service (Palo Verde 1,2,3) Baltimore Gas & Electric (Calvert Cliffs 1,2) Entergy Operations (ANO2, WSES3) Florida Power & Light (St. Lucie 1,2) Omaha Public Power District (Ft. Calhoun)

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1.0 INTRODUCTION

1.1 Background

NRC Bulletins 88-08 and 88-11 identified thermal stratification as a cause of potentially large stresses in primary pressure boundary lines connected to reactor coolant systems.

The CEOG had previously recognized that potentially large moments could result from the bending induced by top-to-bottom differences in line temperature due to thermal stratification of the fluid. CEOG Task 482 (Reference CEOG-1) identified conditions under which the thermal stratification could occur in the main spray lines to the pressurizer due to two phase flow. These conditions where then used with plant measurements to perform plant specific evaluations for stress and fatigue.

Bulletin 88-11 was specific to surge lines and treated thermal stratification as a new design basis transient. The CEOG effort in addressing this issue was divided into measurement and analysis programs. Based on the measurements, documented in References CEOG-2 and 3, a bounding thermal stratification loading was developed. This loading was applied to each of the plant specific lines to determine the change in Cumulative Fatigue Usage. The results, documented in References CEOG-2,3, formed the basis for the submittal of Reference CEOG-4 (Reference CEOG-5 is the non-proprietary version) to the NRC and the resulting acceptable Safety Evaluation Report issued by the NRC for CE plants.

Bulletin 88-08 was concerned with non-isolable sections of Class 1 lines where stratification could result from in-or out-leakage of cooler fluid. The events that caused Bulletin 88-08 to be issued are listed in Table 1-1. Reference 14 was a letter from the NRC addressing the issue requesting all lines be identified in which thermal stratification could result in top-to-bottom differences in wall temperature greater than 50°F.

NRC Bulletin 88-08 and its three supplements require utility action, listed in Table 1-2, related to identification of unisolable lines susceptible to stresses due to thermal stratification. Plant specific responses, at the time of the initial Bulletin, are listed in Table 1-3.

Because of the similarity in the design of these lines for CE design plants a number of generic programs were planned to provide the necessary information for updating plant specific design reports.

1.2 Physical Basis

NRC Bulletin 88-08 was initially issued in response to the discovery of cracks in the cold leg Safety Injection nozzle at the Farley plant. These cracks, between the RCS side check valve and the cold leg (Figure 1-1), were attributed to large stresses resulting from thermal stratification of the flow. In this case, the stratification was due to leakage of cold fluid past the check valve.

A flow can be thermally stratified flow with a continuous variation in density or with more of a step change in density (Figure 1-2). The former can be due to natural convection between the hot and cold ends of a pipe, whereas a leakage film or a two-phase flow can be represented as having an interface between the hot and cold fluids.

The stability of either configuration depends on the local balance of body forces and inertial forces. This ratio is termed the Richardson Number (Ri) expressed as (Reference 5),

$$\mathrm{Ri} = -g\,(\partial\rho / \partial z) \;/\; (\partial u / \partial z)^2$$

Evaluation of the Richardson number depends on the local variation of density and velocity with vertical distance.

A flow is stable if when, subjected to some disturbance, for example a pressure pulse, the motion following application of the disturbance is damped out and the original configuration is maintained. The flow is unstable if the disturbance grows, resulting in a new flow configuration.

For a Richardson number larger than one, O[1], the flow is stable, whereas for all values less than O[1] the flow is unstable, (Figure 1-3). A negative value of Ri implies a decrease of density with depth; the density of the upper fluid is larger than the lower fluid.

In the positive range, $0 < Ri < O[1]$, the flow can become dynamically unstable to certain sizes (wave lengths) of disturbances. The value of Ri at which the flow is unstable depends on the variation of density and velocity with height as well as the presence of external boundaries with viscosities being important. In general, the presence of boundaries and high viscosity tend to increase the stability of the stratified flow.

A global Richardson number can be related to the temperature and pipe size in a reactor coolant by considering a global Richardson number defined as follows. The body forces on a homogenous lower film (l) of thickness some fraction of the line diameter D, under a homogeneous upper fluid (u), can be approximated by,

$$Fb \sim (\rho u-\rho l)g\ D$$

The inertial forces between the upper and lower fluid can be approximated as,

$$Fi \sim \delta\ |Vu-Vl|^2$$

The ratio of the body force to inertial force is defined as a global Richardson Number, in this case defined as,

$$Rio= -[(\rho u- \rho l)g\ D]/[\ \rho\ |Vu-Vl|^2]$$

Based on the Boussinesq approximation between density variation and temperature Rio can be expressed as,

$$Rio = g\beta\ (Tu-Tl)D/\ |Vu-Vl|^2$$

The flow will be stable if the temperature of the upper fluid is greater than the lower; $(Tu > Tl)$, and unstable for the opposite situation, $(Tu < Tl)$.

Thus, a fluid can become thermally stratified provided the Richardson number is positive and greater than approximately one. This situation occurs in slow moving flows in which the density of the upper fluid is less than the lower fluid, transport of a heavier fluid under a lighter one, transport of a lighter fluid over a heavier one, natural convection[1], two-phase flow.

1.2.1 Leakage

Leakage can be thought of as the transport of a lighter or heavier fluid into one with a higher or lower density.

Leakage will occur in the direction of decreasing pressure. Furthermore, in-leakage is herein defined as leakage into the RCS whereas out-leakage is defined as leakage out of the RCS, Figure 1-4.

1.2.2 Transport Related Stratification

In terms of density differences a positive Richardson number can occur in transport processes in which the body forces exceed or are equal to the inertial forces. Such situations occur in the cases of two-phase flow: e.g. gas over liquid, in which thermal equilibrium does not exist, or vapor state over liquid state in which both are at saturation temperature. Such cases include natural convection[1], steam over liquid and any other transport processes in which thermal equilibrium is not present in either the unsteady and/or steady condition.

Situations in which stratification can occur in lines connected to the RCS are represented in Figure 1-5.

1.3 TASCS Program

EPRI, in response to utility needs in responding the NRC Bulletins 88-08 and 88-11, in 1988 initiated the Thermal Stratification Cycling and Striping (TASCS) program (Reference 2). The program was based on the assessment that the majority of the reported events related to thermal stratification were due to leakage, Table 1-1. The definitions used in the TASCS program of these three phenomena are:

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[1] For natural convection the body and inertial forces are in balance and the Richardson number is one.

Stratification: Hot water over cold water in a pipe. Generally there is a distinct interface. The condition is generally steady or quasi-steady[2].

Cycling: Rapid changes in fluid temperature due a change in stratification conditions; e.g. transition from stable to unstable (mixed) condition.

Striping: Fast or slow changes in wall temperature due to local variations in interface level related to interfacial waves.

The program concentrated on these mechanisms as related to leakage, Figure 1-6. Of major interest was the phenomena titled turbulent penetration in which the flow across the junction of a branch and main line results in a secondary flow, transporting both energy (temperature) and momentum into the branch line. In addition, the program investigated heating rates for leakage films. Data were also documented on the occurrence of thermal cycling in tests performed at Mitsubishi Heavy Industries (MHI) on typical non-isolable sections.

A workshop, in which the majority of the results were reported, was held in June, 1993 and the program completed with the publication of the final report in 1994.

1.4 CEOG Programs

The information and actions published in NRC Bulletin 88-08 and its three supplements are summarized in Table 1-2

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[2] Fast and slow are defined as relative to the response time of the pipe wall to a step change in temperature. This response time, defined as

$$\tau = \frac{t^2}{\alpha}$$

where t is the wall thickness and α is the thermal diffusivity. For stainless steel this varies from about 20 seconds for two inch, Schedule 160 pipe to about 300 seconds for twelve inch, Schedule 160 pipe.

In response to the initial and the subsequent bulletins, the Combustion Engineering Owners Group (CEOG) established a program to provide CEOG members with the information needed to respond.

The program was divided in the phases represented in Table 1-4.

The initial tasks were directed at identification of lines in which stratification may be expected to be present, inspection of these and other lines to determine unexpected movement and/or the presence of any damage that, as in the case of the surge line, may be attributed to thermal stratification, and finally, to describe a set of representative measurements on these lines to determine the presence and magnitude of angular variations in wall temperature.

Based on an evaluation of these results, the program undertook tasks to identify and model the cause of the stratification and apply these models to prediction of fluid and wall temperatures in the NSSS.

Based on these predictions and the routing and geometry of the lines in individual plants, these thermal stratification loads were applied to determine forces and moments.

These results were then documented for plant specific evaluations by the task participants.

1.5 Closure

The issuing of NRC Bulletin 88-08 established thermal stratification as a thermal loading condition that had, in specific instances, resulted in leakage from the primary pressure boundary. In response to the initial bulletin and subsequent supplements, the Combustion Engineering Owners Group (CEOG) initiated work on what was to prove a long term program to address locations in lines connected to the RCS where stratification could occur and to evaluate the effect of loads due to thermal stratification on design limits.

Because of the similarity in the design of these lines for CE design plants, a number of generic programs were designed to provide the necessary information for updating plant specific design reports. The following sections summarize the results of these tasks.

Table 1-1

Reported Events Related to Thermal Stratification, Cycling and Striping

PLANT EVENTS CAUSED BY TASCS

- Leakage from Safety Injection Piping at Farley & Tihange

  attributed to leakage into the RCS

- Leakage from RHR Return Piping at Genkai

  attributed to leakage outward from RCS

- Leakage from Isolation Condenser Piping at Nine Mile Point

  attributed to leakage toward recirculation system

- Steam Generator Feedwater Nozzle Safe-end Leakage in Numerous Plants

  attributed to stratified flow conditions

- Pressurizer Surge Line Support Interference at Several Plants

  attributed to stratification

Table 1-2
NRC Bulletin 88-08 and Supplements; Required Actions

NRC Bulletin 88-08	Information	Required Action
Original Issue	Failed ECCS piping due to inleakage (Farley)	1. Identify sections of piping with similar conditions 2. Inspect piping that may be subjected to excessive related thermal stresses 3. Plan and implement a program to provide continued assurance pipe stresses will not result in fatigue failure
Supplement 1	Failed ECCS Piping due to inleakge (Tihange)	None
Supplement 2	Need to enhance UT to detect cracks in SS	None
Supplement 3	Failed RHR piping due to outleakage (Japan)	None

Table 1-3

Plant Specific Responses to NRC Bulletin 88-08

Utility	Unit	Action 1 System Identified	Action 2 Inspection	Action 3 Plan Implementation
FP&L	1,2	No system can be subjected to thermal stresses	N/A	N/A
LP&L	Waterford . 3	Prz Aux Spray SI SDC	NDE of welds SI - Leakage improbable	N/A
MY	MY	Prz Main Spray Aux Spray Line	No action required - Task 482	N/A
OPPD	Ft Calhoun	Prz Surge Line Pzr Spray Line PORV SI, SDC	Plan specific report PORV - Mod. made SI, SDC - More analysis required	Temperature monitoring UT examination
SCE	2,3	Prz Aux Spray Prz Spray	Modifications/ chk valve relocation	Continue to evaluate
NU	1,2,3	Units 1 & 2 unaffected	N/A	N/A
AP&L	1	HP Injection Lines Prz Aux Spray Line	Visual Inspection/UT Replacement of aux line	Temperature Monitoring Program
	2	Prz Aux Spray HPSI Main spray header	N/A	N/A
APS	1,2,3	Prz Aux Spray Line	NDE - No indication of high thermal fatigue	Monitoring, Analysis and Modifications
BG&E	1,2	Prz Main Spray Prz Surge Line PORV SI	CEOG effort PORV/SI - Analysis required	Recognize need to identify causes for stratification
CPC	Palisades	Prz Aux Spray	UT/NDE Testing Results of inspection OK!!	No fatigue failure concern exists

Table 1-4
Phases of CEOG Programs in Response to NRC Bulletin 88-08

BULLETINS 88-08

IDENTIFICATION
of susceptible lines: Large diameter lines with identifiable sources of hot and cold temperatures

INSPECTIONS
of susceptible lines: Walkdowns looking for evidence of line motion and support contact

For each of the LINES identified with possible significant stresses due to thermal stratification

MEASUREMENTS
of wall temperatures: Outside wall temperature during heatup, operation and cooldown and simultaneous recording of related plant parameters

EVALUATION
of wall temperature measurements and relation to plant parameters

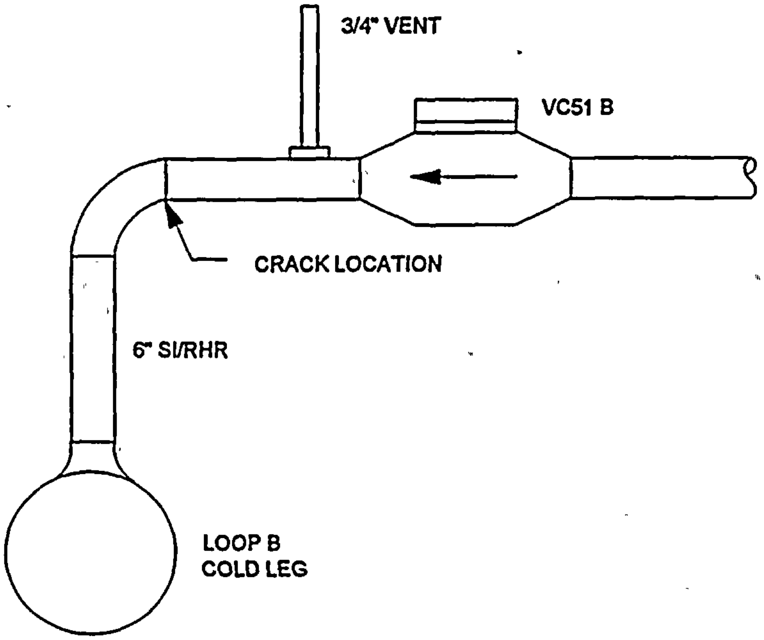
MODELS
to predict wall temperatures, based and benchmarked to plant data

MOMENTS
based on limiting conditions for transients related to plant operation

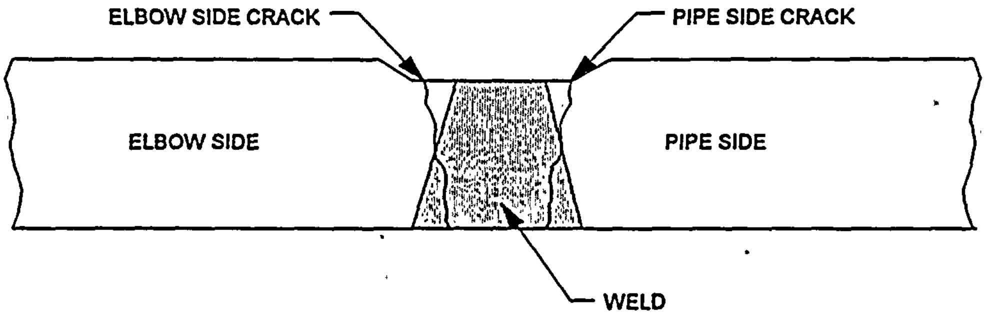
STRESS
evaluations for plant specific lines

DOCUMENTATION
changes to ASME Design Specifications and Reports

FARLEY AND TIHANGE

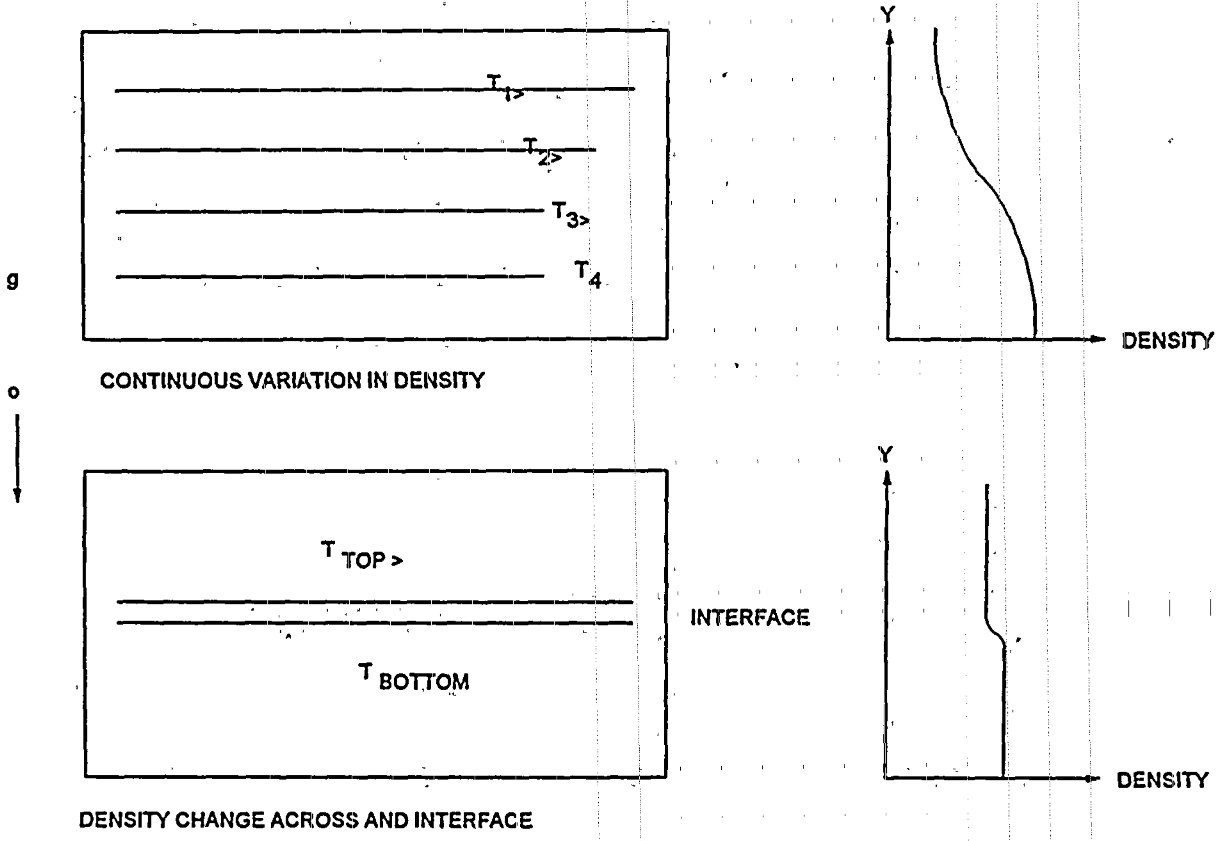


6" SI/RHR TO LOP B LINE CRACK LOCATION



- INLEAKAGE FROM HIGHER PRESSURES IN CHARGING SYSTEM
- INTERACTIONS BETWEEN COLD INLEAKAGE AND HOT RCS FLUID CAUSED THERMAL CYCLING
- FATIGUE CRACKS PROPAGATED CAUSING LOCAL LEAKAGE
- DESCRIBED IN NRC BULLET 88-08 AND ITS SUPPLEMENTS

Figure 1-1 Cracks in Farley ECCS Line Due to Leakage of Colder Fluid



CONTINUOUS VARIATION IN DENSITY

DENSITY CHANGE ACROSS AND INTERFACE

Figure 1-2 Stratified Flows

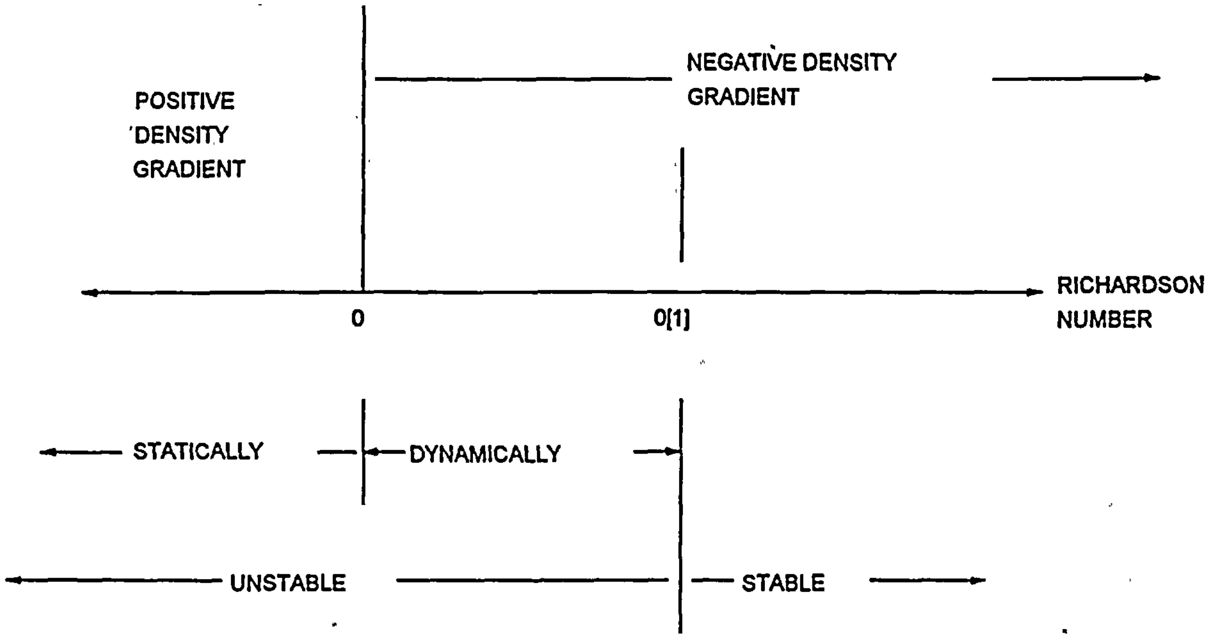


Figure 1-3 Stability Limits

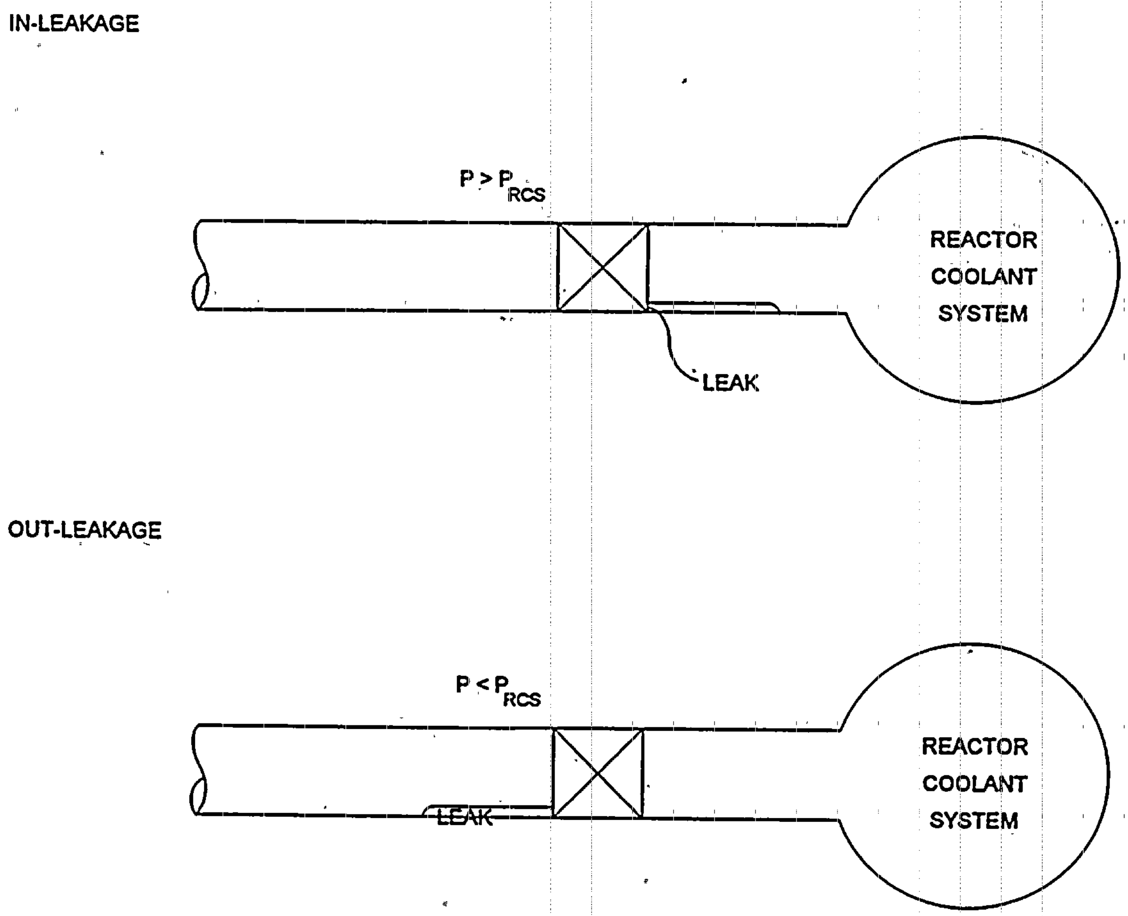


Figure 1-4 Leakage Definitions

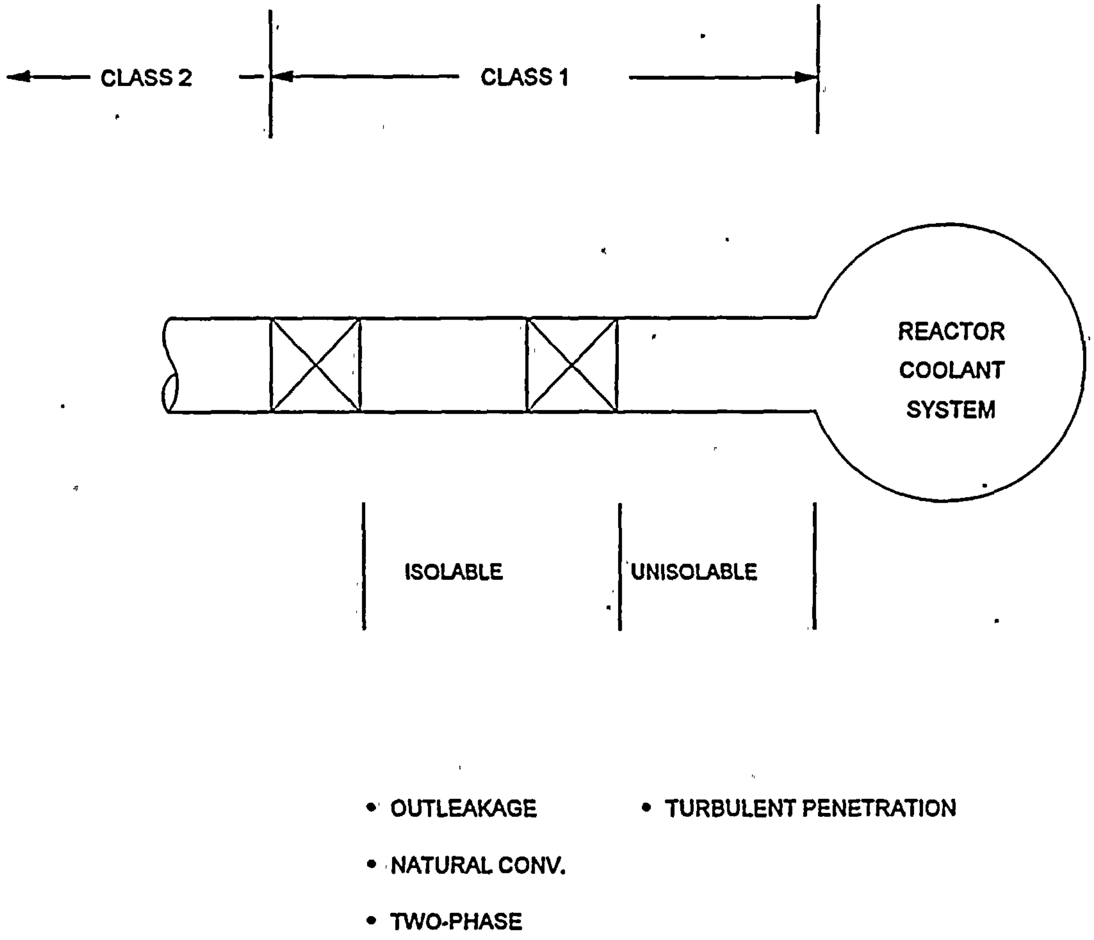
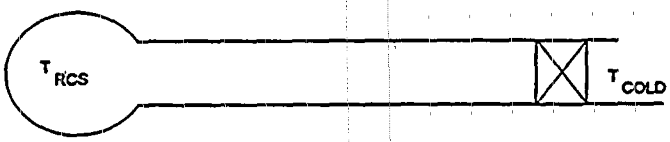


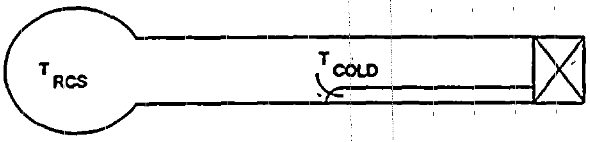
Figure 1-5 Causes of Thermal Stratification in Lines Connected to the RCS

THERMAL STRATIFICATION CONSIDERED IN TASCS PROGRAM

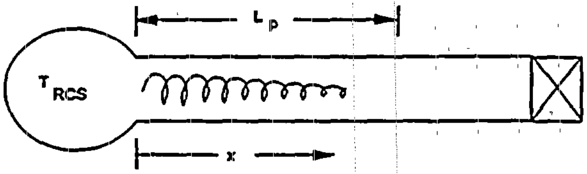
1. OPEN-CLOSED END LINE CONFIGURATION



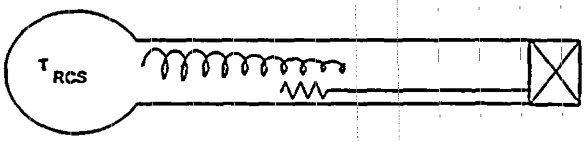
2. STRATIFICATION DUE TO LEAKAGE



3. STRATIFICATION DUE TO TURBULENT PENETRATION



4. THERMAL CYCLING



5. THERMAL STRIPING

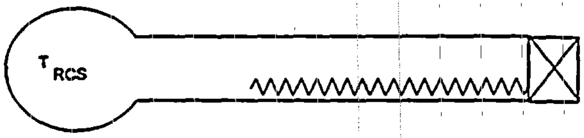


Figure 1-6 Thermal Stratification Considered in TASCS Program

2.0 IDENTIFICATION AND INSPECTION PROGRAMS

The initial tasks in this program were to identify and inspect lines susceptible to thermal stratification. This was done in two programs: the first in response to the failures attributed to the inleakage of coolant in the original issue and supplement 1 of 88-08 (Reference CEOG-6); the second in response to the supplement 3 and the failure due to out leakage (Reference CEOG-7). These tasks are listed in Table 2-1. The participants in these tasks are listed in Table 2-2. Lines connected to the Reactor Coolant System (RCS) for the participants in CEOG Task 626 are listed in Appendix A.

The lines identified as having to be evaluated in response to Bulletin 88-08 are listed in Table 2-3.

2.1 Identification

2.1.1 Qualitative Criteria

The following qualitative criteria were used in CEOG Tasks 578 and 626 to identify lines susceptible to significant stresses related to thermal stratification.

1. FLOW RATES: Based on the definition of Richardson number, high flow rates tend to destabilize the flow. Thus low flow rates would tend to promote stratification.

2. PIPE SIZE: Conduction in the circumferential direction tends to result in uniform wall temperatures. This is applicable to small diameter lines with higher ratios of thickness to diameter (high schedule).

3. LINE ORIENTATION: Vertical orientation results in fluid mixing, for the top of the line cooler than the bottom, and a stable stratification for top hotter than the bottom.

4. SOURCE OF STRATIFICATION: This includes leakage or RCS flow that has cooled to containment conditions or two-phase flow.

5. RELATIVE STIFFNESS: Large diameter, high schedule lines with a long stratified sections connected to shorter length of connecting line tend to have higher moments due to stratification.

The lines identified as being susceptible to thermal stratification, based on the application of these criteria, are listed in Table 2-4. The majority of the lines identified as not being susceptible to thermal stratification were eliminated on the basis of the source of stratification being outleakage from the RCS. Though not affecting the non-isolable portion of the line, these could, however, introduce stresses in the portion of the line down stream of the first isolation valve.

2.1.2 Quantitative Criteria

The qualitative selection criteria were used primarily for identifying lines for which measurements should be taken to confirm the presence of thermal stratification, the magnitude of the wall temperature difference and the relationship between thermal stratification and plant operating conditions. The result was identification of thermal stratification in the Safety Injection, Shutdown Cooling, PORV and Auxiliary Spray lines. Note that of these lines, only the Auxiliary spray lines was identified as subject to inleakage.

Subsequent to the completion of the CEOG programs, a set of quantitative criteria were developed that could be used to verify the selections made in the earlier CEOG tasks. These criteria are as follows:

1. <u>Stability of flow stratification:</u> The stability of the stratification can be related to the global Richardson number defined as,

$$Ri_g \approx [g\beta\Delta TD / \Delta V^2] \rangle 1$$

where:		
	β	Coefficient of thermal expansion for the fluid
	ΔT	Temperature difference of the hot and cold fluids
	D	Line diameter
	ΔV	Relative velocity between the hot and cold layers

2. <u>Wall Temperature Difference</u> : The difference in wall temperature is a function of the ability of heat to be conducted through the wall, from the hotter (lower) to the cooler (upper) fluid. This can be expressed as ,

$$N^2L \approx \sqrt{\frac{hD}{k(t/D)}} \rangle 1$$

where:

h = area average heat transfer coefficient = (hA)c+(hA)h/ (Ac+Ah)
(   )h for the hot fluid heat transfer coefficient and area
(   )c for the colder fluid heat transfer coefficient and area.
D = line inner diameter
k = wall thermal conductivity
t = wall thickness

3. Fluid Temperature : The following five sources of thermal stratification of the fluid have been identified:

1. Forced Convection (Hot over Cold fluid)
2. Natural Convection (Isolated line)
3. Two phase fluid (Condensation)
4. Turbulent Penetration (Turbulent mixing)
5. Leakage (Colder or Warmer Fluid)

The first two depend on transport of the cooler or hotter fluid. The third is based on the differences in heat transfer coefficients between the liquid and vapor phases. The fourth and fifth require that the source of fluid that intrudes into the fluid occupying the line; e.g. turbulent penetration the hotter fluid tends to flow over the, almost stationary, lower cooler fluid, while for leakage, a cooler leakage film flows under the almost stationary, upper hotter fluid.

In both cases, a source of colder fluid must be present. This normally is related to having a line be of sufficient length to result in reaching ambient (containment) temperature. This can be evaluated based on the following expression.

$$\sqrt{\frac{hD}{k(\frac{t}{D})}(\frac{L}{D})} \rangle 1$$

where, for the line :

D = diameter
t = thickness
L = length
k = thermal conductivity
h = heat transfer coefficient between the wall and ambient based on natural convection; wall insulated h=.15, uninsulated h=1.0

The severity of thermal stratification caused by leakage depends on the leak rate of cooler fluid being large enough to preclude being heated by hotter fluid. This can be estimated according to the following relationship.

$$\frac{hD^2}{mCp}\left(\frac{L}{D}\right) \langle\ 1$$

where, for the line:

D = Diameter
L= length
h = the heat transfer coefficient between the hotter fluid and the cooler leakage fluid based on forced convection,
m = leakage rate.

4. Moments: Moments due to thermal stratification will depend on the relative stiffness between the stratified section and the remainder of the line. For the line assumed to be fixed at the start of the stratified section, this can be approximated by the expression,

$$M = (EI\alpha\Delta T_W / D) f(k/K)$$

where:

α = coefficient of liner expansion of the line
ΔTw = difference in top-to-bottom wall temperatures
D = Outside diameter of the line
t = Line thickness
E = Young's modulus
I = Moment of inertia about neutral axis; $\pi/64(D^4-(D+2t)^4)$

L = Length of line over which the ΔT_w is applied

Lo = Length of line without stratification

f(k/K)= Functional ratio between stiffness (K) of the stratified section and stiffness (k) of the remainder of the line. For bending primarily in one plane, this function can be written as:

$$f(k/K) = (k\delta/K\delta + k\theta/K\theta)/\,(1+ k\delta/K\delta + k\,\theta/\,K\theta)$$

where δ is the stiffness of the lateral displacement and θ the stiffness of the angular displacement. For a uniform beam, with stratification over length L, these stiffnesses are; $K\delta = EI/2L^2$, $K\theta = EI/L$.

Application of these criteria to the lines listed in Table 2-3 resulted in the following conclusions.

A. Small Diameter Lines:

1: <u>Stability of Stratification</u>: Vertical orientation in which the hotter fluid would be at the bottom, such as safety valve lines, will result in a negative Richardson number thus no stable stratification. Vertical orientation with the hotter fluid at the top of the line, as with a number of branch lines, can result in a stable stratification in the vertical direction. However, in cases where these lines are connected to the RCS , this stable configuration can be upset by secondary flows in these lines driven by flow in the RCS. Whereas the vertical up orientation will tend to produce uniform fluid and wall temperatures, vertical down will tend to result in an axial variation in fluid and wall temperature, but little or no circumferential variations.

In a number of small lines, the Richardson number is expected to be greater than 1 due to normally low velocities: e.g. for charging/letdown lines, 2 inches in diameter, difference in fluid temperature of 100°F would require a velocity of about .7 ft/sec and a volume flow rate greater than about 7 gpm for an unstable flow, Ri <1 . For flow rates less than this, stratification would be stable, Ri > 1..

2. <u>Wall Temperature Difference</u>: The criterion for wall temperatures, $N^2L< 1$, is a function of not only line size and schedule, but of the mechanism expected to cause the stratification. Typical values of heat transfer coefficients for the

mechanisms that have been evaluated in the course of the CEOG programs are listed in Table 2-5. A plot of N^2L for Schedule 160 lines three inches and less Figure 2-1, show that lines smaller than about 1 inch should have small variations in wall temperature.

The lower value of differences in wall temperature is defined in Reference 14 as being less than 50°F. As shown in Appendix B, turbulent penetration and leakage, based on use of values from the related CEOG programs, could have differences in top-to-bottom wall temperature greater than 50 F for lines smaller than 1 inch.

3. <u>Moments:</u> Moments are related to the relative stiffness of the section with thermal stratification as compared with the remainder of the line. Small lines, due to small moments of inertia, tend to be relatively flexible. However, values of moments need to be evaluated based on specific plant routings to determine the restraint placed on the stratified section by the remainder of the line.

B. Large Diameter Lines:

1. <u>Wall Temperature Difference</u>: These large diameter, high schedule lines, with heat transfer coefficients the order of magnitude of 10 (natural convection) to 100 (forced convection) will have values of $N^2L > 1$. Thus top-to-bottom temperature differences can be significant:.

2. <u>Moments</u>: The criterion is stated in terms of moments and forces due to thermal stratification. The influence of these stresses on line fatigue needs to include the stresses due to mechanical and deadweight loads. This evaluation needs to consider on a case by case basis the validity of neglecting larger lines based on stress levels due to thermal stratification being negligible.

Though the lines listed in Table 2-6 are based on source of stratification, the above conclusions are applicable to the selected lines. Recent evidence of cracking in a drain line (Reference 15) was attributed to possible turbulent penetration and, as such, is included in the lines to be considered. This is discussed in Section 4.6.

2.2 Justification for Continued Operation (JCO)

Measurements confirmed that there were Class 1 lines in which thermal stratification could result in loads that were not considered as part of the original Design Basis for the plants. A draft JCO (Appendix C) was provided to participants in CEOG Task 732 (Reference CEOG-9) for submittal to the NRC.

2.3 Inspection

A set of visual inspections were recommended on the lines identified as being susceptible to thermal stratification. Guidelines for the inspections (Reference CEOG-10) emphasized that the inspection make note of lines that may have shifted as compared to baseline inspection, the shift due possibly to bending caused by thermal stratification. Inspections completed by plant personnel are on record for the participating plants.

2.4 Selected Lines

Five lines (References CEOG-6,7) were selected, Table 2-7, for obtaining wall temperature measurements: Auxiliary spray line and Hot Leg Injection lines were selected on the basis of possible leakage between these branch line and the intersecting line; the Main Spray, Safety Injection (SI) lines, lines connected to the Pressure Operated Relief Valves (PORVs) and the Shutdown Cooling (SDC) lines were considered based on having the potential for large differences in wall temperature caused by one of the thermal-hydraulic mechanisms listed above.

Of these lines, the main spray line had been the subject of prior efforts for CE plants (Reference CEOG-1) and was not included as part of the CEOG program to respond to Bulletin 88-08.

For the remaining lines, tasks were defined to obtain generic information that could eventually be used in preparing plant specific responses.

Table 2-1
CEOG Programs to Identify Lines Susceptible to Thermal Stratification in Response to NRC Bulletin 88-08

Action	CEOG Response (Task)
Review Systems to identify sections of piping subjected to similar (thermal stratification) conditions	Task 578: Evaluate potential for temperature oscillations due to valve leakage from systems connected to the RCS and stratification due to dead-end or valved out piping Task 626: Identify and evaluate systems with the potential for outleakage from the RCS
Inspect those pipes that may be subjected to excessive thermal stresses (due to thermal stratification)	Task 578: Evaluates potential for differences in wall temperature. Task 626: Recommends inspection locations Task 732: Inspection of potentially affected piping
Plan and implement a program to provide continued assurance.those pipes will not be subjected to stresses that could cause fatigue failure	Task 578: Recommends piping for data collection Task 626: Recommends piping for data collection and screening for stress levels Task 588: Program to measure wall temperatures in SI, SDC and PORV piping; all exceed 50°F.

Table 2-2
CEOG Participants in Identification and Inspection Tasks

Tasks	Participants	Plants
578	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO-2, WSES-3
	Florida Power & Light	St. Lucie 1,2
	Maine Yankee	Maine Yankee
	Northeast Utilities	MP2
	Omaha Public Power Dist	FCNS
588	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO-2, WSES-3
	Florida Power & Light	St. Lucie 1,2
	Maine Yankee	Maine Yankee
626	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO-2, WSES-3
	Florida Power & Light	St. Lucie 1,2
	Maine Yankee	Maine Yankee
	Omaha Public Power Dist	FCNS
732	Arizona Public Service	PVNGS 1,2,3
	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO-2, WSES-3
	Florida Power & Light	St. Lucie 1,2
	Maine Yankee	Maine Yankee
	Northeast Utilities	MP2
	Omaha Public Power Dist	FCNS

Table 2-3
Lines Connected to the RCS

System	Line	Diameter	Schedule
RCS	Surge	12	160
	SI	12	160
	HIPSI, LIPSI	6	120
	SDC	12	160
	Drain Lines	2	80
	Hot Leg Inj	3	120
RV	Waste	.75	40
	Vent	.75	40
	Level	.75	40
	Sample	.75	40
CVCS	Charging	2	160
	Letdown	2	160
PRZ	Main Spray	4	160
	Aux Spray	2	160
	PORV	3	160
	Safety	3	40

TABLE 2-4

LINES WITH POSSIBLE SIGNIFICANT STRESS LEVELS DUE TO THERMAL STRATIFICATION BASED ON QUALITATIVE SELECTION CRITERIA

SYSTEM	LINE	CRITERIA					NOTE
		1 Stability	2 Wall Temp	3 Orientation	4 Fluid Temp	5 Stresses	
RCS	Surge						1
	SI				X		2
	SDC				X		3
	Drain			X			4
	Branch						5
RV	Waste	X	X		X	X	6
	Vent	X	X		X	X	6
	Level	X	X		X	X	6
	Sampl	X	X		X	X	6
CVCS	Chrgn	X					7
	Ltdwn	X					7
PRZ	Main	X					8
	Aux						9
	PORV						10
	Safety			X			11

X= Criteria used to eliminate the noted line from either having a stable thermal stratification, significant wall temperature differences and/or significant stresses due to thermal stratification moments.

Notes:

1. Surge Line: Forced Convection related in- and out-surges
2. SI: Outleakage
3. SDC: Outleakage
4. Drain lines: Outleakage and vertical down orientation
5. SDC Branch: Hot leg injection.
6. Outleakage and low stiffness
7. CVCS: Continual flow during normal operation
8. Main spray: continual flow should prevent stratification
9. Aux spray: possible inleakage
10. PORV: two-phase
11. SV: Vertical sections and slope should promote any condensate runback

Table 2.5

Heat Transfer Coefficients and Interface Angle for Heat Transfer Mechanisms Causing Thermal Stratification

HEAT TRANSFER MECHANISM	Natural Convection	Leakage	Turbulent Penetration	Two-Phase
h_{hot}	10	10	35	200
h_{cold}	10	100	15	5
Interface Angle	90°	15°	125°	155°
h_{avg}	10	17.5	21	32
Reference	CEOG-13	CEOG-19	CEOG-17	CEOG-18

TABLE 2-6

CAUSES OF THERMAL STRATIFICATION IN LINES CONNECTED TO THE RCS BASED ON SOURCES OF STRATIFICATION

SYSTEM	LINE	CAUSES OF THERMAL STRATIFICATION					NOTES
		1.Leak	2.Forced Conv	3.Natural Conv	4.Two Phase	5.Turb Pen	
RCS	Surge		X				1
	SI	O		X			2
	SDC	O				X	3
	Drain	O				X	4
	Branch						5
RV	Waste	O					
	Gas Vent	O					
	Water Lvl	O					
	Sample	O					
CVCS	Charging	O					
	Letdown	O					
PRZ.	Main Spray	O			X		6
	Aux Spray	I					
	PORV	O			X		7
	Safety	O					8

Cause of Stratification: O= outleakage
I= inleakage
X= Flow related

Notes:
1. Surge Line: Addressed in Bulletin 88-11, CEOG Task
2. SI: Long isolated section could result in thermal stratification due to natural convection
3. SDC: Long line that could cool to ambient
4 Drain: turbulent penetration in evidence per Reference 15.
5. Hot Leg Injection: No leakage due to multiple isolation valves
6. Main Spray: Steam condensation results in water-steam stratification; CEOG Task 482
7. PORV: Possible steam condensation
8. Safety: Vertical would result in run-back of condensation

Table 2-7
Lines Identified with Possibly Significant Stresses due to Thermal Stratification

System	Line	Diameter	Schedule	Criteria
RCS	Surge Line	12	160	Forced Convection
	Safety Injection	12	160	Natural Convection
	Shutdown Cooling	12	160	Turbulent Penetration
	Hot Leg Injection	3	120	Out-Leakage
PRZ	Main Spray	4	120	Two Phase
	Auxiliary Spray	2	160	Out-Leakage
	PORV	4	120	Two Phase

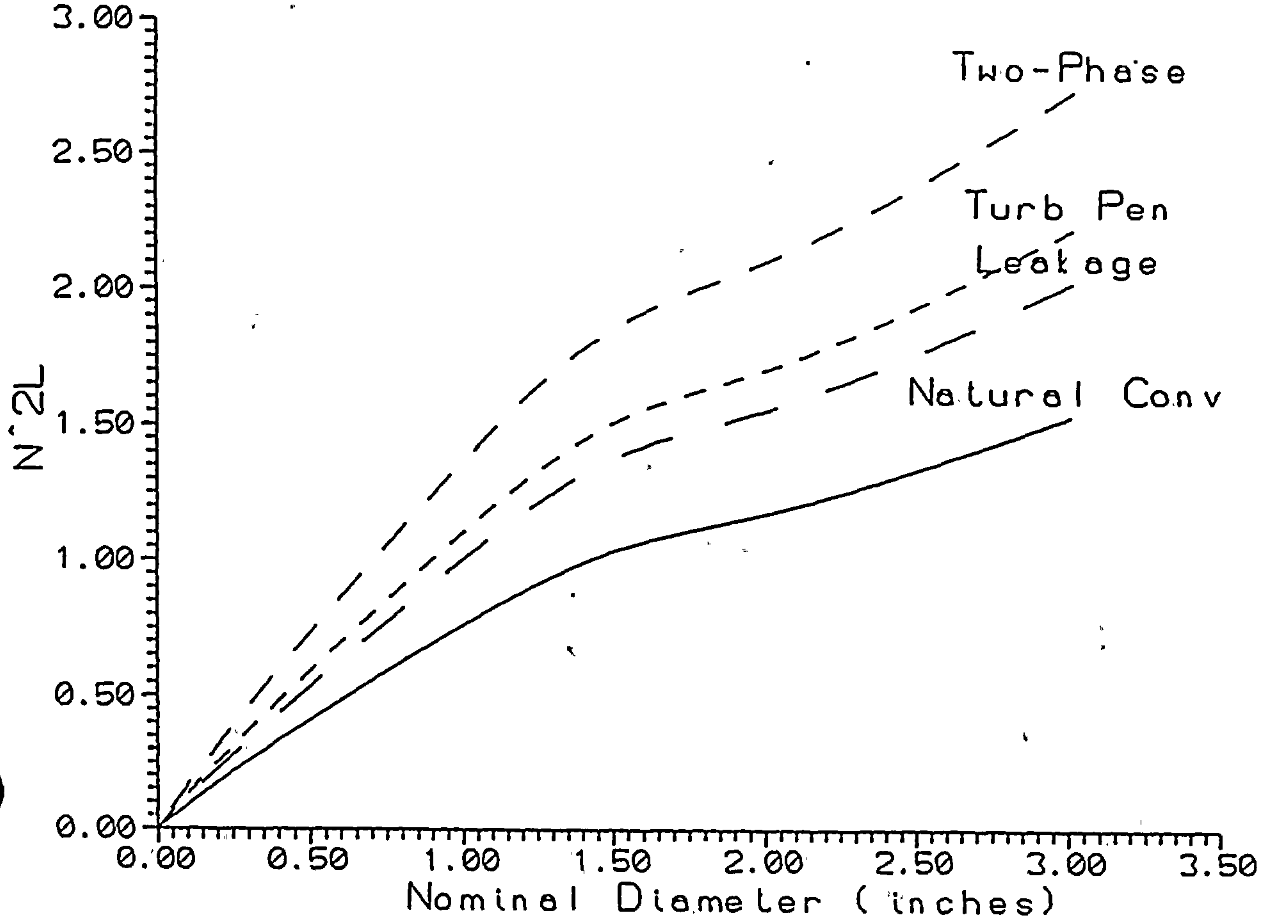


Figure 2-1 Wall Temperature Parameter for Schedule 160 Pipe

3.0 MEASUREMENT PROGRAM

3.1 Wall Temperature Measurements

Wall temperature measurements were taken on the lines listed in Table 3-1. The objective was to ascertain if the lines identified as having thermal stratification did indeed exhibit wall temperatures indicative of thermal stratification. These measurements were obtained at a two pilot plants, Calvert Cliffs Unit 2 (BG&E) and ANO-2 (Entergy Operations). Guidelines were issued for the collection of line wall temperature data (Reference CEOG-11) planned for the Measurements phase of the overall program.

Wall temperatures measurements (Reference CEOG-8) included the Safety Injection (SI), Pressure Operated Relief Valve (PORV), and Shutdown Cooling (SDC) lines. In each of these lines, the cause of the thermal stratification was found to be different: natural convection in SI lines, two-phase flow in PORV lines and a combination of turbulent penetration and natural convection in SDC lines.

Measurements on the Auxiliary Spray line were not done as part of this program but were included in the overall assessment of non-isolable lines. Measurements indicated in-leakage to be possible in certain lines. An evaluation of these lines was completed for participating CE plants (Reference CEOG-19).

Measurements on the Hot Leg Injection line were not included in a CEOG program but were evaluated based on plant specific data.

3.2 Data Related to Leakage Caused Thermal Stratification

Wall temperature measurements taken at Farley, Figure 3-1 and in the MHI tests, Figure 3-2 , both show a cyclical variation of wall temperature with time. In both cases the variations appear random, consistent with the TASCS results of the variations resulting from the interaction of turbulent penetration with a leakage film. In addition, per the TASCS results, the change in leakage film temperature due to heat transfer with the primary fluid would tend to limit these variations to locations close to the valve.

These are unlike the stratification data obtained from surge line tests, Figure 3-3 , which were attributed to the intrusion of the surge front into the line. In this case wall temperatures tended to follow, in a quasi-steady manner, changes in either pressurize (Thot end) or RCS (Tcold end) temperatures[3].

The cold fluid leakage at Farley occurred because of the arrangement of Safety Injection lines specific to this design of Westinghouse plants. In ABB-Combustion Engineering plants, the high pressure at the RCS end of the Safety Injection line compared to the remainder of the line minimizes any change for leakage of cold safety injection fluid. The primary leakage path would be of hot fluid from the RCS past the valve, which would tend to be unstable, thus mixing with the fluid in the isolated section of the line.

3.3 Measured Data

Data taken at Calvert Cliffs Unit 2 are similar to that from ANO-2. Thus, generalizations will be based on a sample of the Calvert Cliffs Unit 2 data.

3.3.1 Safety Injection (SI) Line

Measurements locations and a sample of the data taken at BG&E are shown in Figure 3-4. The data indicate a quasi-steady change in wall temperatures and top to bottom differences in wall temperature with changes in RCS temperature, with no noticeable variations in wall temperature with time. Evaluation of the data indicate that the differences in wall temperature decrease with axial distance from the isolation valve to the SIT tank isolation valve some 20-60 pipe diameters away.

The flow in the line being stationary under normal conditions, natural convection was attributed as the cause of stratification in the SI line.

3.3.2 Pressure Operated Relief Valve (PORV) Line

Typical measurements and thermocouple locations are shown in Figure 3-5. Following a period in which the conditions in the pressurizer were changed by energizing the heaters,

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[3] Cyclical variations, as might be due to striping, were superimposed on these general increases and decreases in top to bottom variations in wall temperature

the wall temperature at the top stayed about constant, the wall temperatures close to the bottom of the line decreased. Largest temperature differences were closest to the pressurizer, decreasing to close to zero some 20 diameters downstream. The temperature difference returned to almost zero sometime after the heaters were turned off. The measurements indicated a primarily quasi-steady behavior.

The flow in the line can be two-phase, comprised of saturated vapor and saturated to sub-cooled condensate, thus causing the observed thermal stratification.

3.3.3 Shutdown Cooling (SDC) Line

Shutdown Cooling line thermocouple locations and representative data[4] are shown in Figure 3-6. Data show minor top to bottom variation in wall temperature until a change in hot leg conditions: e.g. change in the number of operating RCPs from two to four.

Flow in the SDC line is normally stationary. Interaction between the flow in the hot leg across the SDC nozzle results in a secondary flow in the shutdown cooling line. The "penetration" of momentum and energy of this flow will cause the fluid in the line to reach temperatures closer to those in the hot leg than at the isolation valve.

3.3.4 Pressurizer Auxiliary Spray Line

Auxiliary spray line measurements, taken at ANO-2, Figure 3-7, show a correlation of changes in wall temperature with charging flow. The wall temperatures return to an almost uniform condition with cessation of charging pump operation.

The increase in pressure on the charging pump side of the flow isolation valve appears to result in leakage across the valve into the main spray line. Thus stratification can be attributed to leakage of cooler fluid upstream of the valve into the warmer fluid downstream.

3.4 Closure

As reviewed in the TASCS program, the causes of the thermal stratification related damage documented in NRC Bulletin 88-08 and its supplements was due to leakage.

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[4] Variations in signals with time were found to be random and attributed to noise in the data acquisition system.

Evaluation of results of the CEOG measurement program indicated leakage to have a role in only one of the four lines identified as being susceptible to significant stresses due to thermal stratification. However, as in the case of the surge line and NRC Bulletin 88-11, thermal stratification was not in the original set of design basis loading conditions. Thus, in compliance with 10CFR50, all four lines were selected for further evaluation.

In addition, results of the measurement program were used as the basis for providing guidelines (Reference CEOG-9) for CEOG plants to file with the NRC a Justification for Continued Operation, documented in Appendix A.

CEOG tasks, Table 3-1, were established to evaluate, model and predict moments due to thermal stratification in the remaining lines. The tasks for each of these lines are summarized in the following sections.

Table 3-1
Lines Selected for CEOG Tasks in Response to NRC Bulletin: 88-08

Line	Task	Subject
Safety Injection	741	Wall Temperatures due to Thermal Stratification
	818	Evaluate Stresses and Fatigue in SI Lines
Shutdown Cooling	772	JCO for Shutdown Cooling Lines with Thermal Strat.
	813	Data on Thermal Stratification in SDC Lines
PORV	773	Evaluation of Thermal Stratification in PORV Lines
	827	Evaluate Stresses and Fatigue in PORV lines
Auxiliary Spray Line	886	Evaluate moments due to in-leakage thermal stratification
Hot Leg Injection Branch Line	813	Pressure measurements to determine leakage

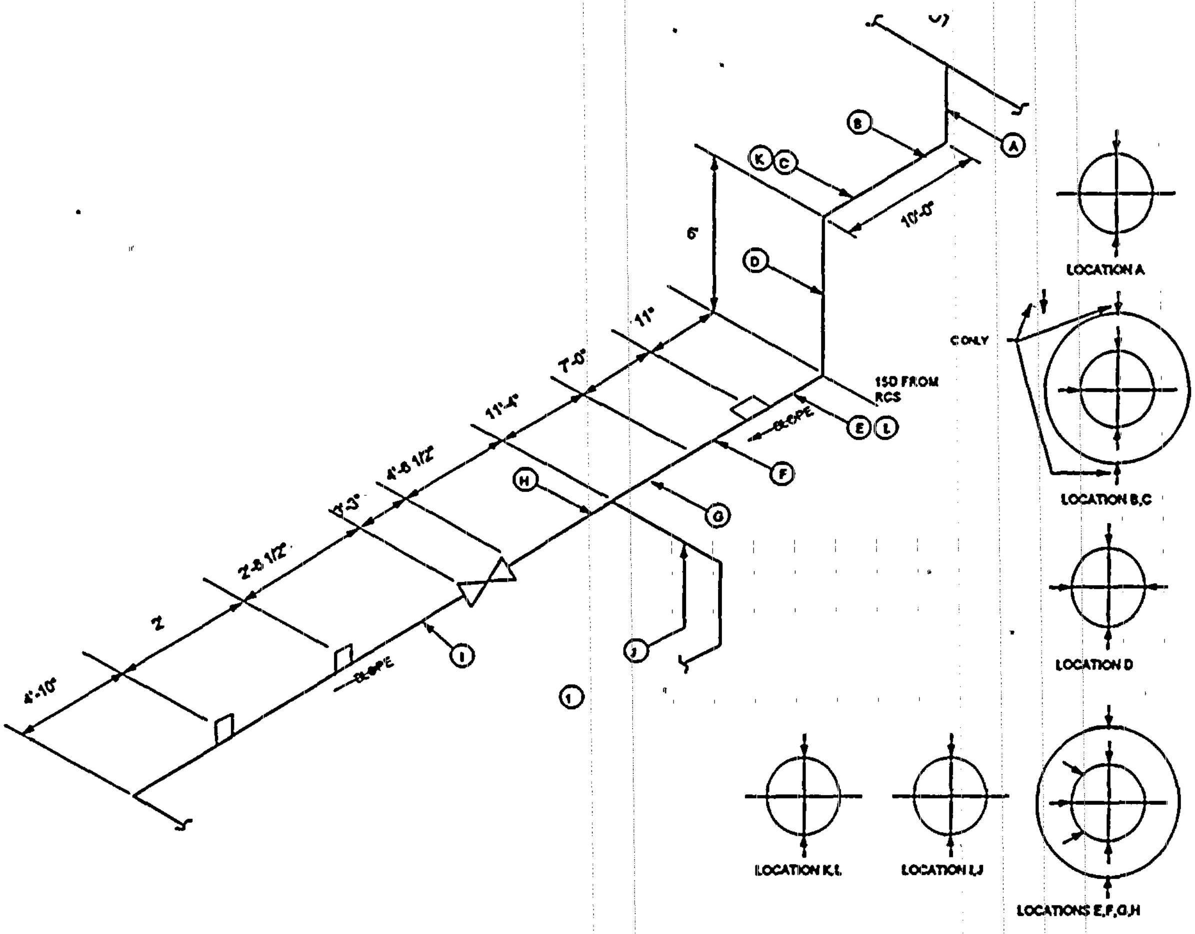


Figure 4.3-2 Instrumented Locations on Shutdown Cooling Lines - PVNGS

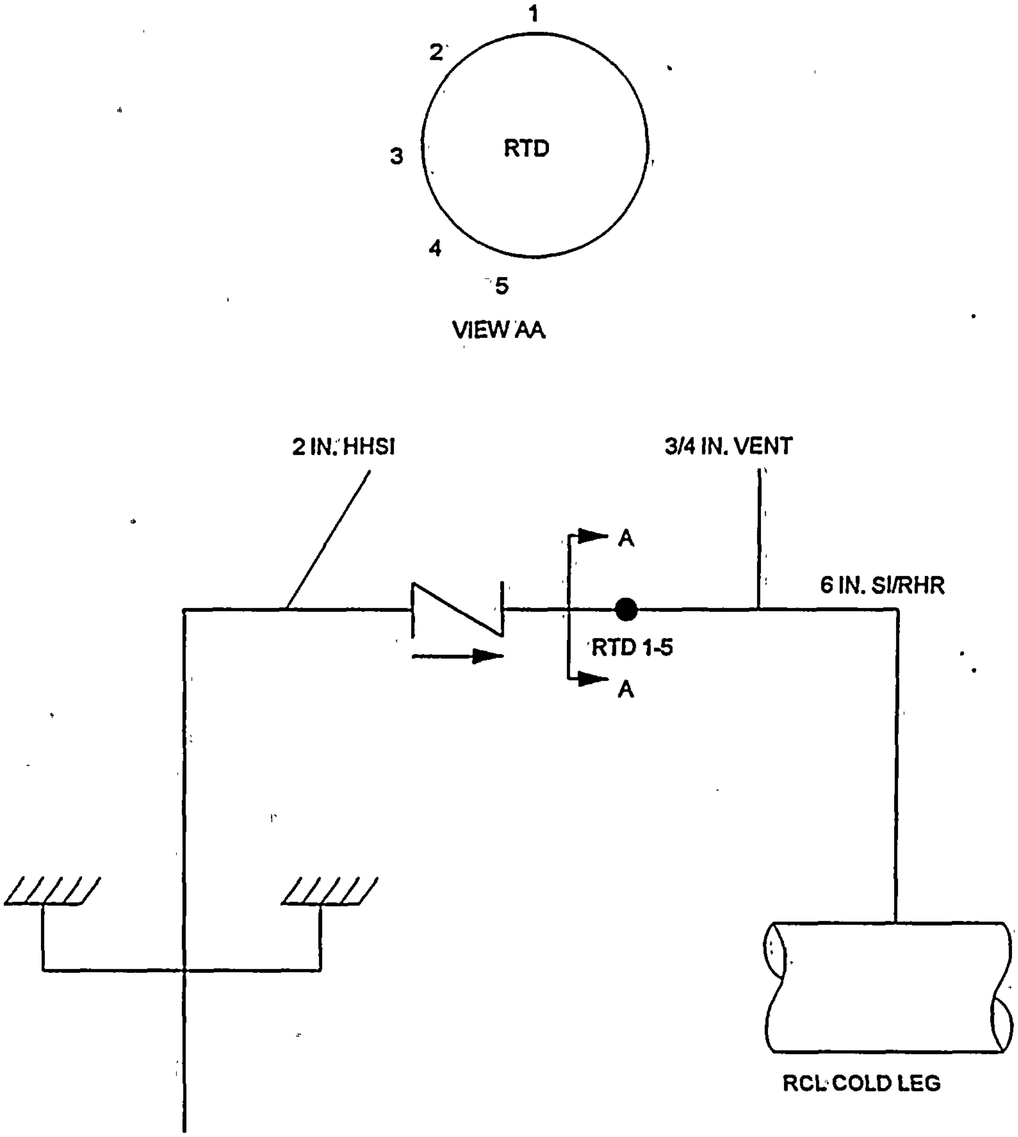


Figure 3-1 Wall Temperature Data taken at Farley-Locations

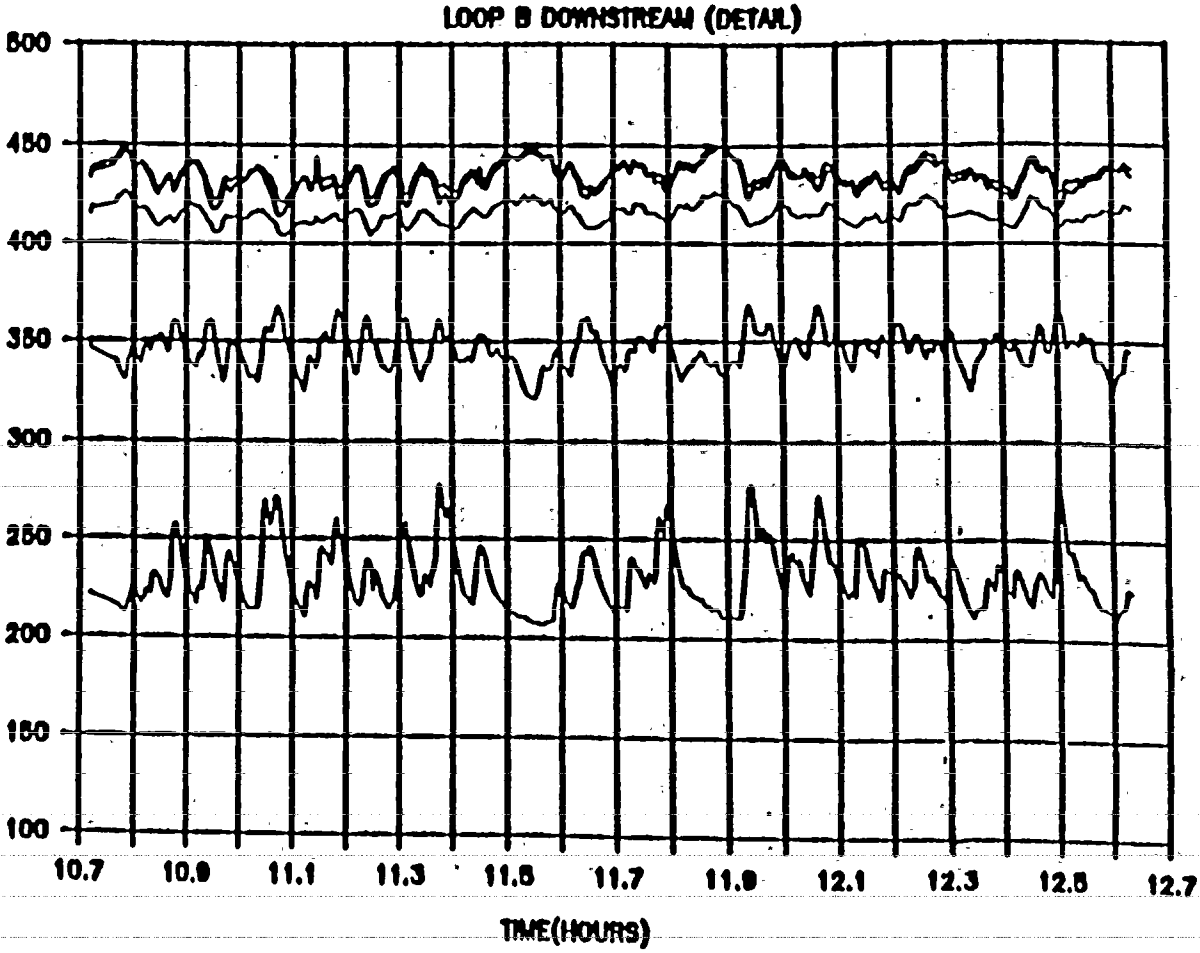


Figure 3-1 Wall Temperature Data taken at Farley-Data

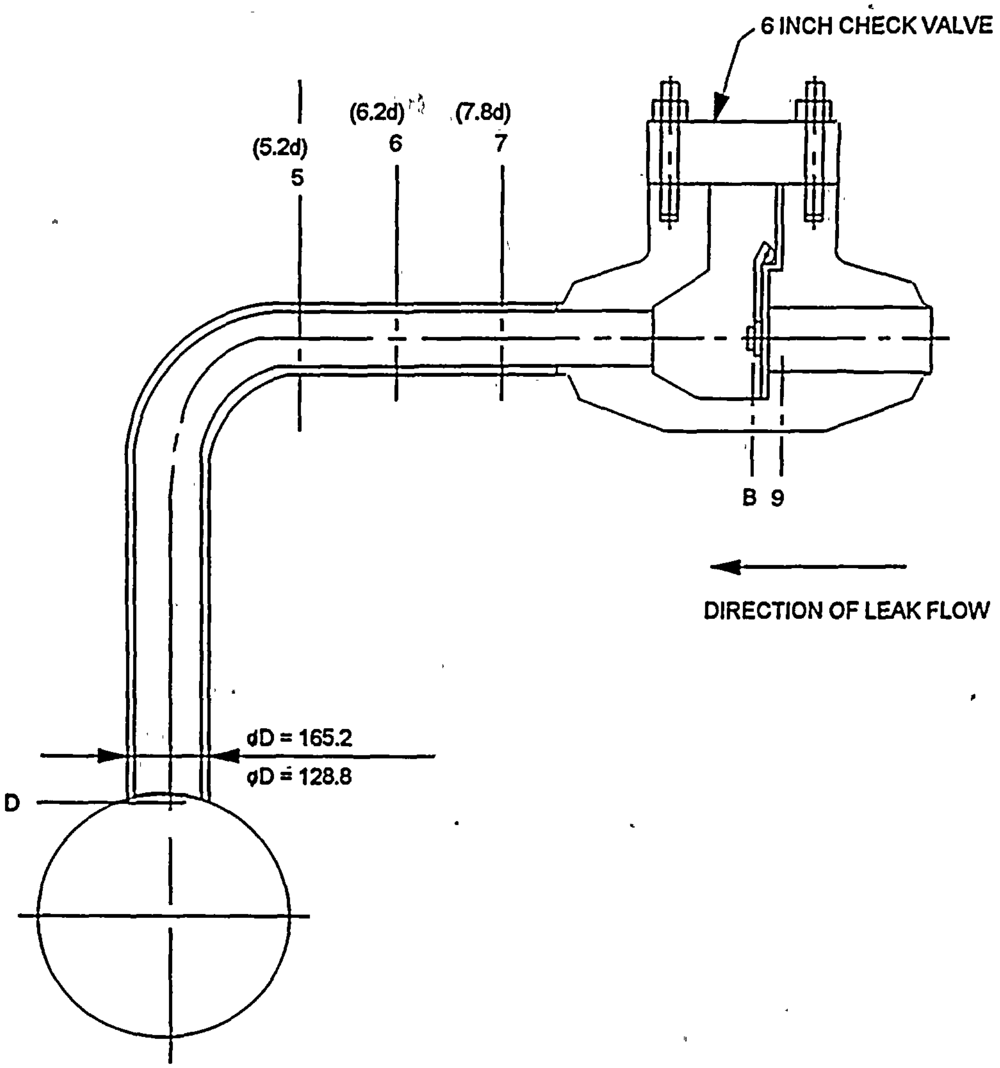


Figure 3-2 Wall Temperature Measurements from MHI Tests-Locations

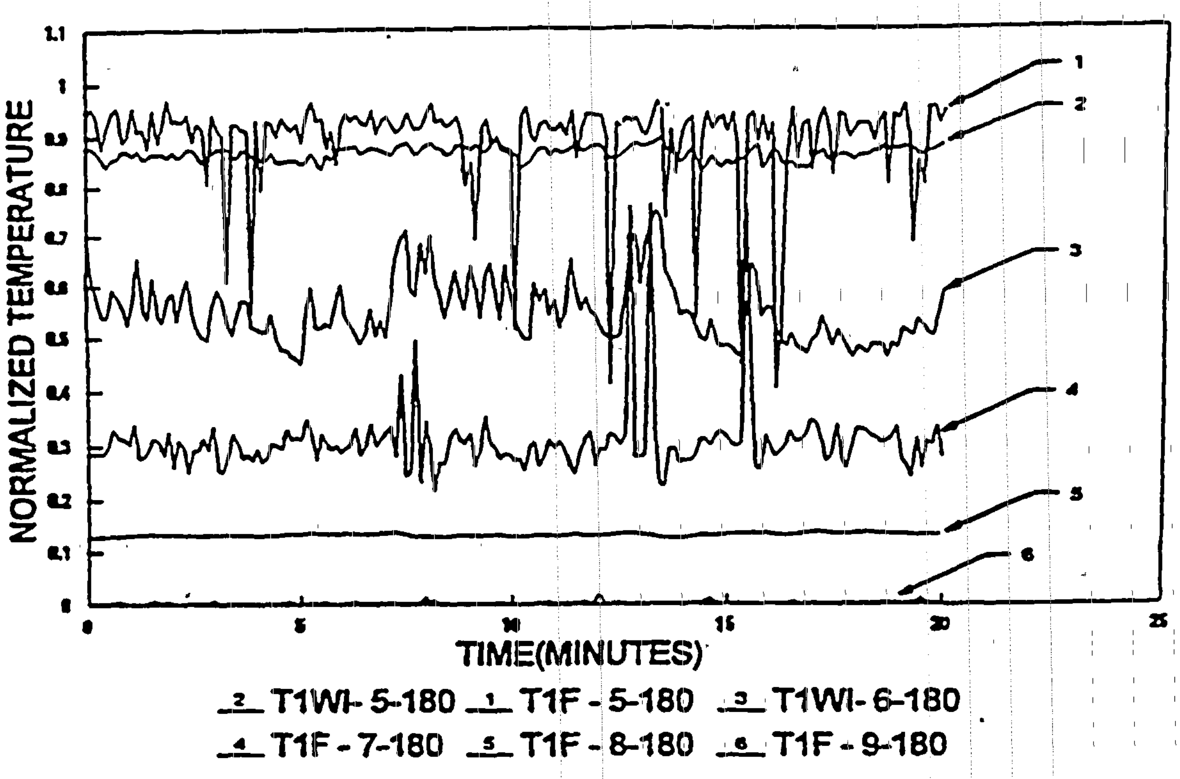


Figure 3-2 Wall Temperature Measurements from MHI Tests-Data

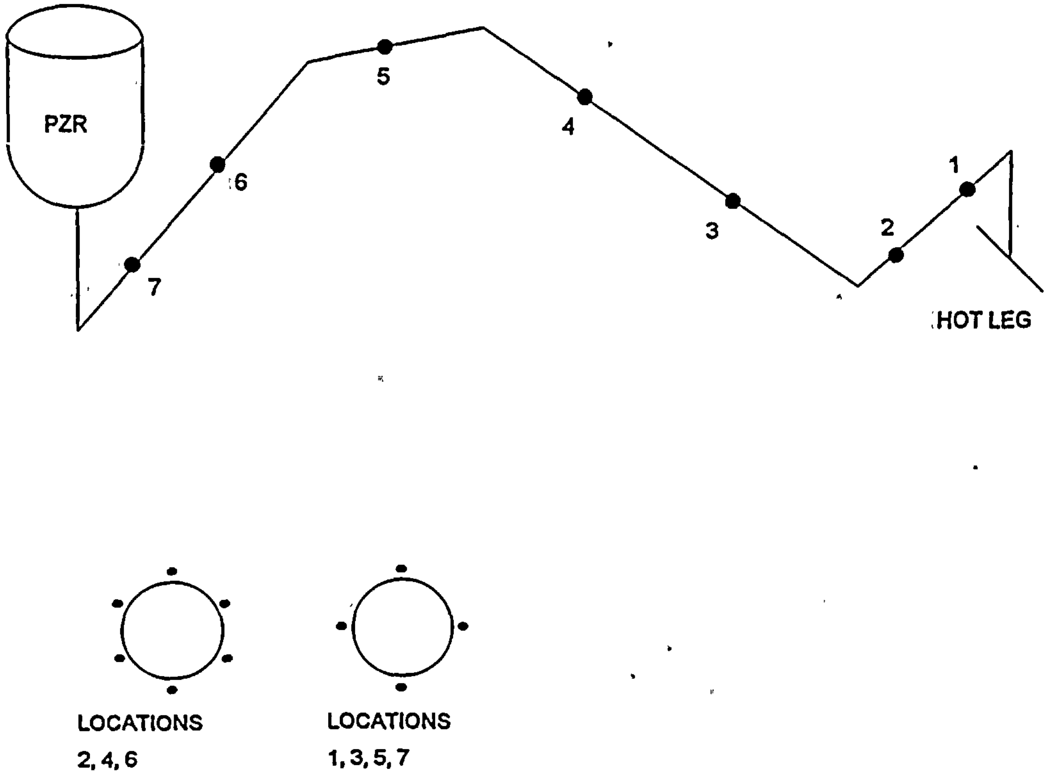


Figure 3-3 Surge Line Wall Temperature Measurements-Locations

BGE Calvert Cliffs Unit 1
Circumference Temperatures At Location #6

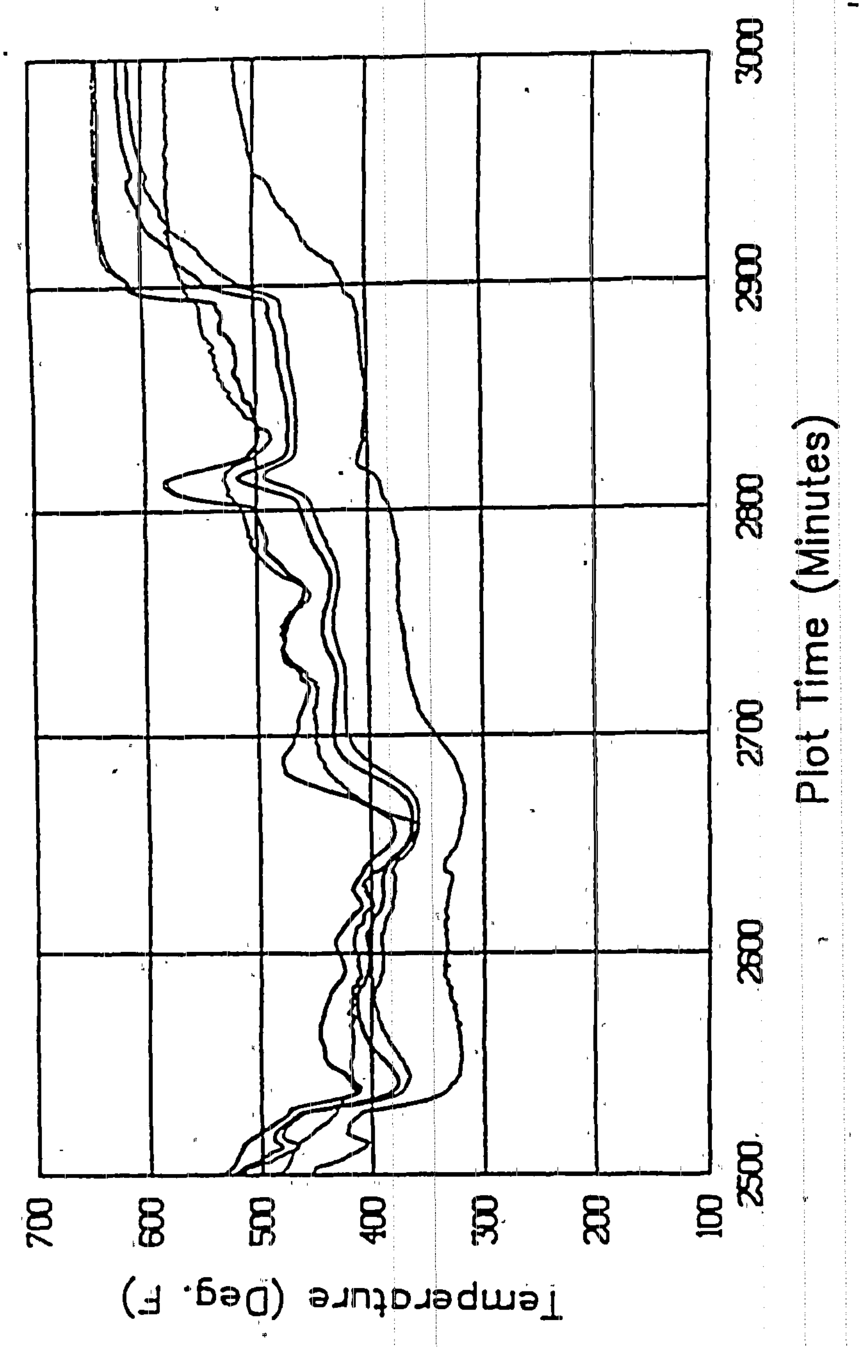


Figure 3-3 Surge Line Wall Temperature Measurements-Data

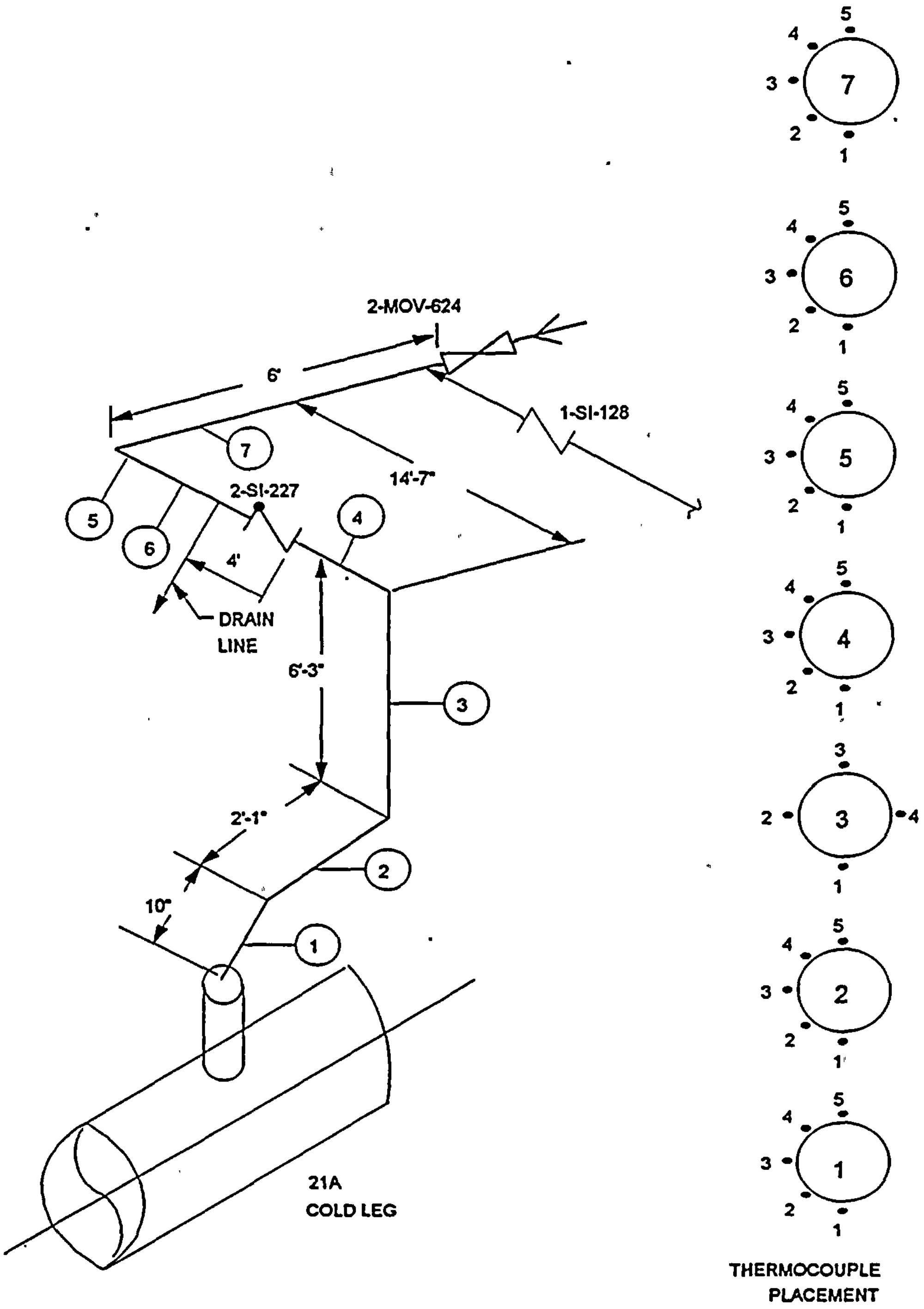


Figure 3-4 Representative Data: Calvert Cliffs 2 Safety Injection Line-Locations

BG&E Calvert Cliffs Unit 2
Heatup - SDC Piping - Location #6

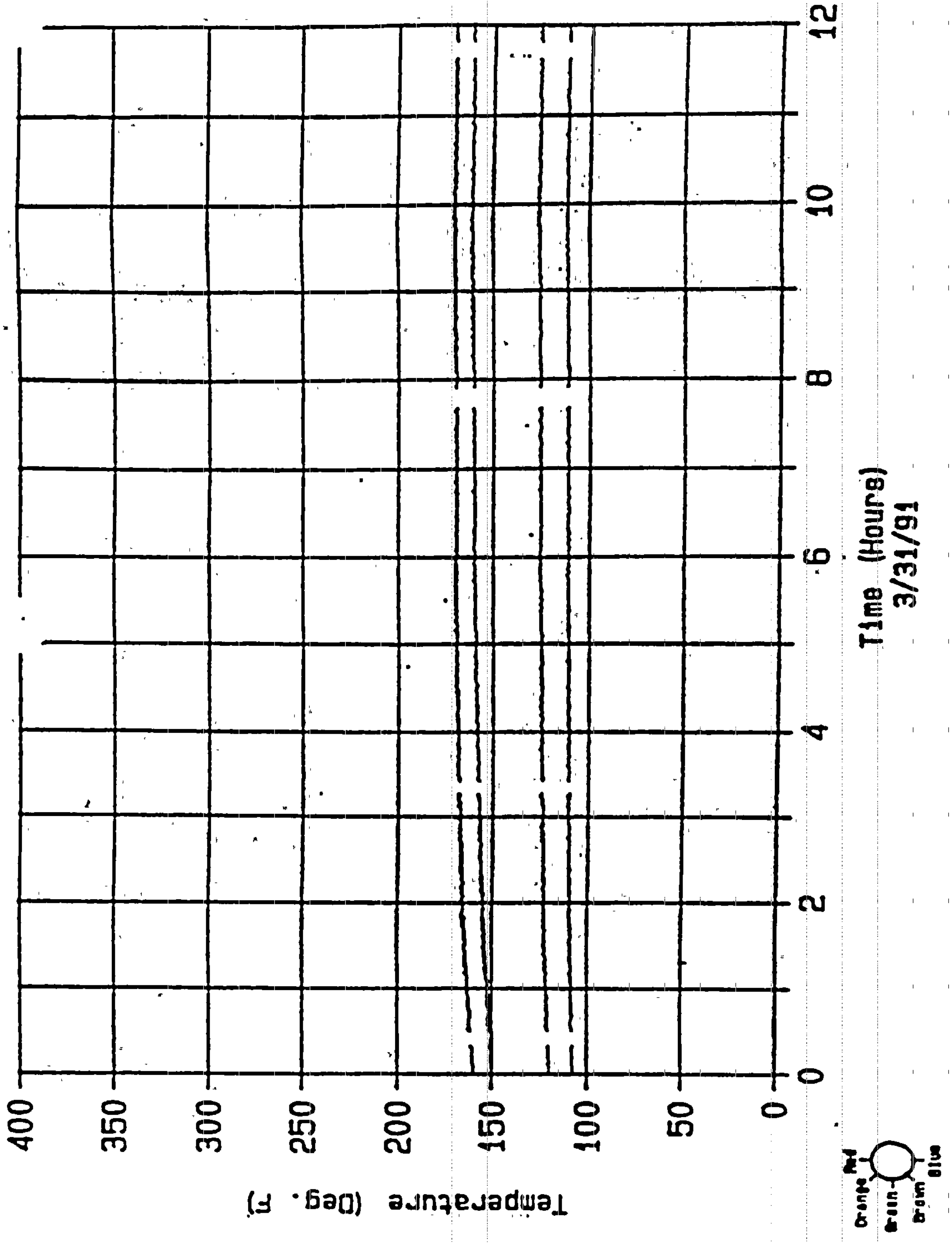


Figure 3-4 Representative Data: Calvert Cliffs 2 Safety Injection Line-Data

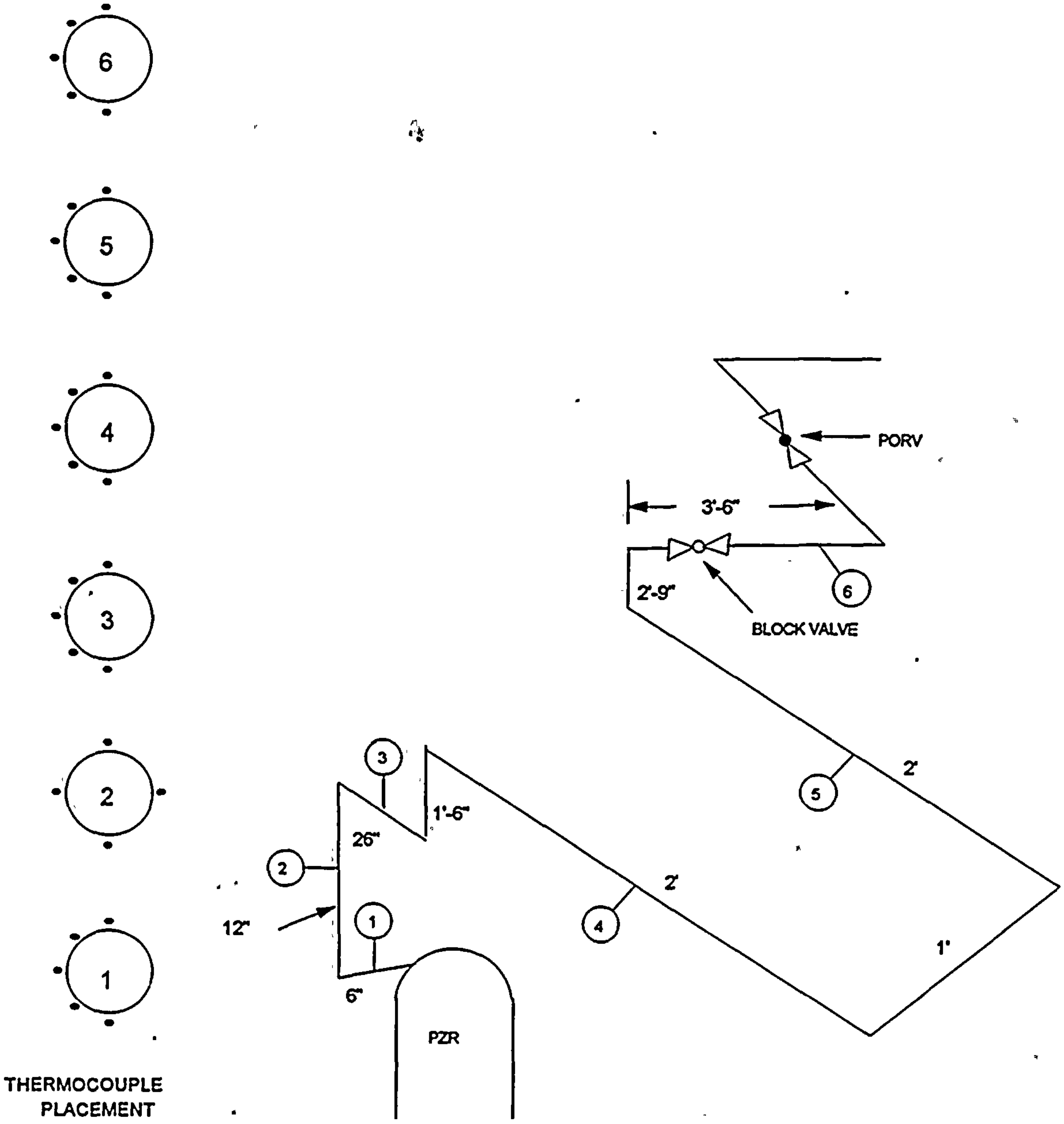


Figure 3-5 Representative Data: Calvert Cliffs 2 PORV Line-Locations

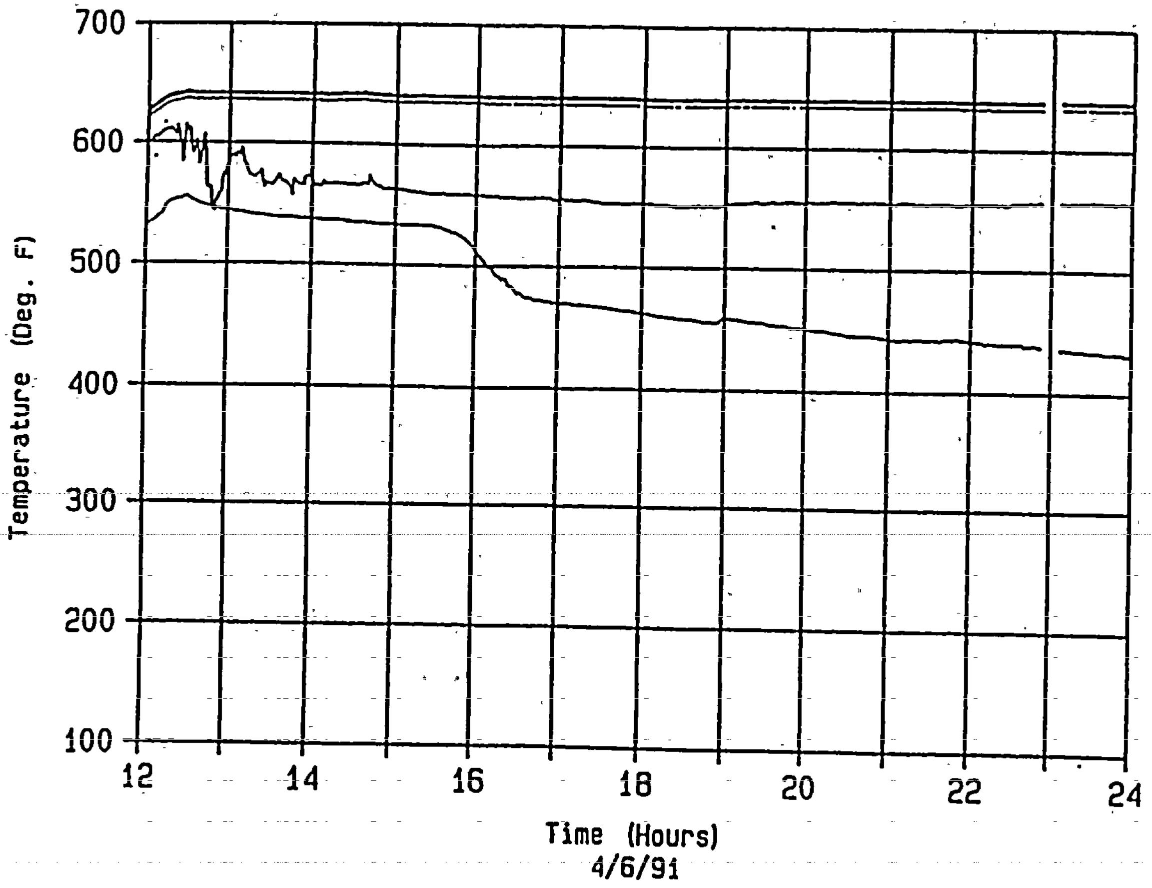


Figure 3-5 Representative Data: Calvert Cliffs 2 PORV Line-Data

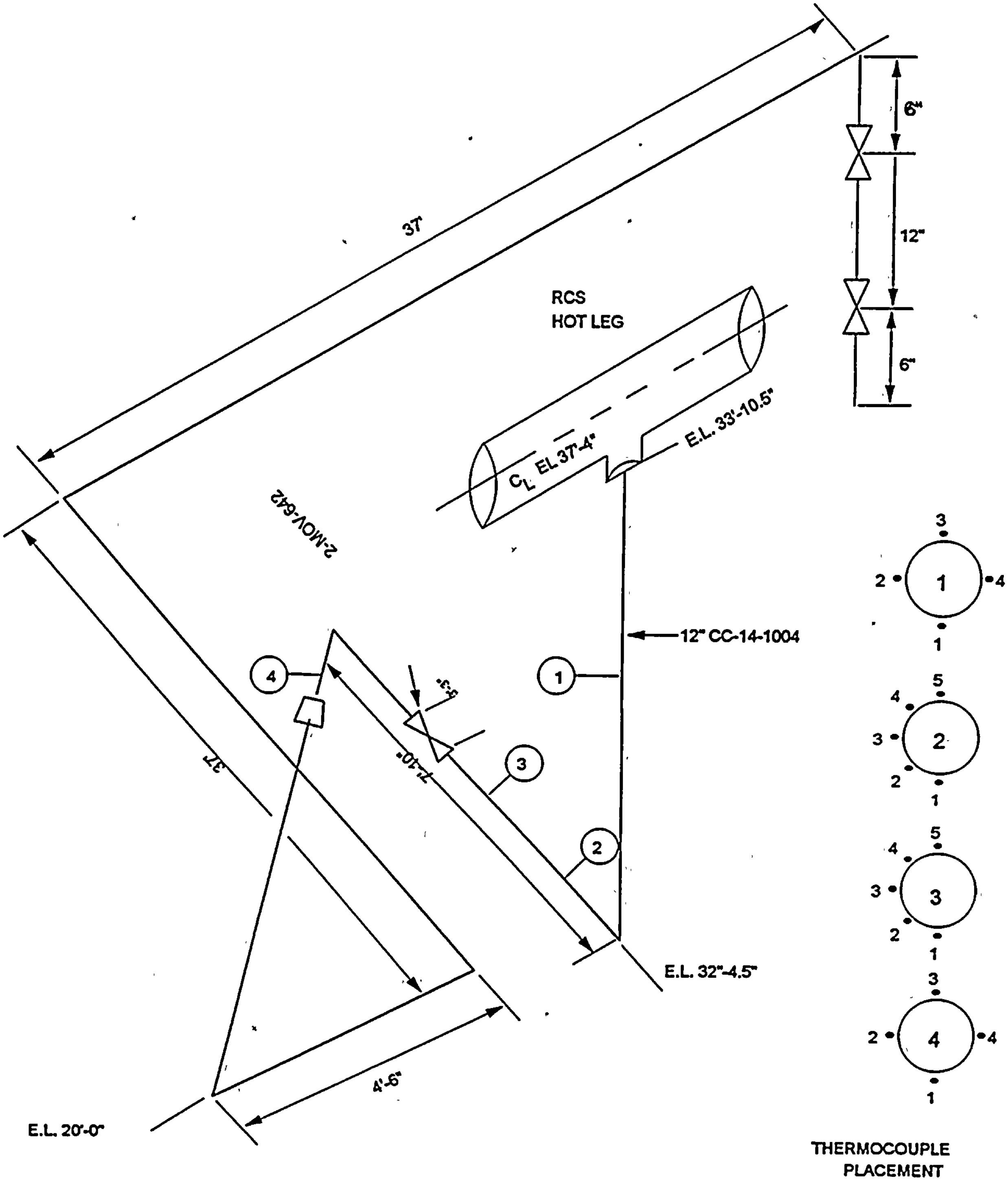
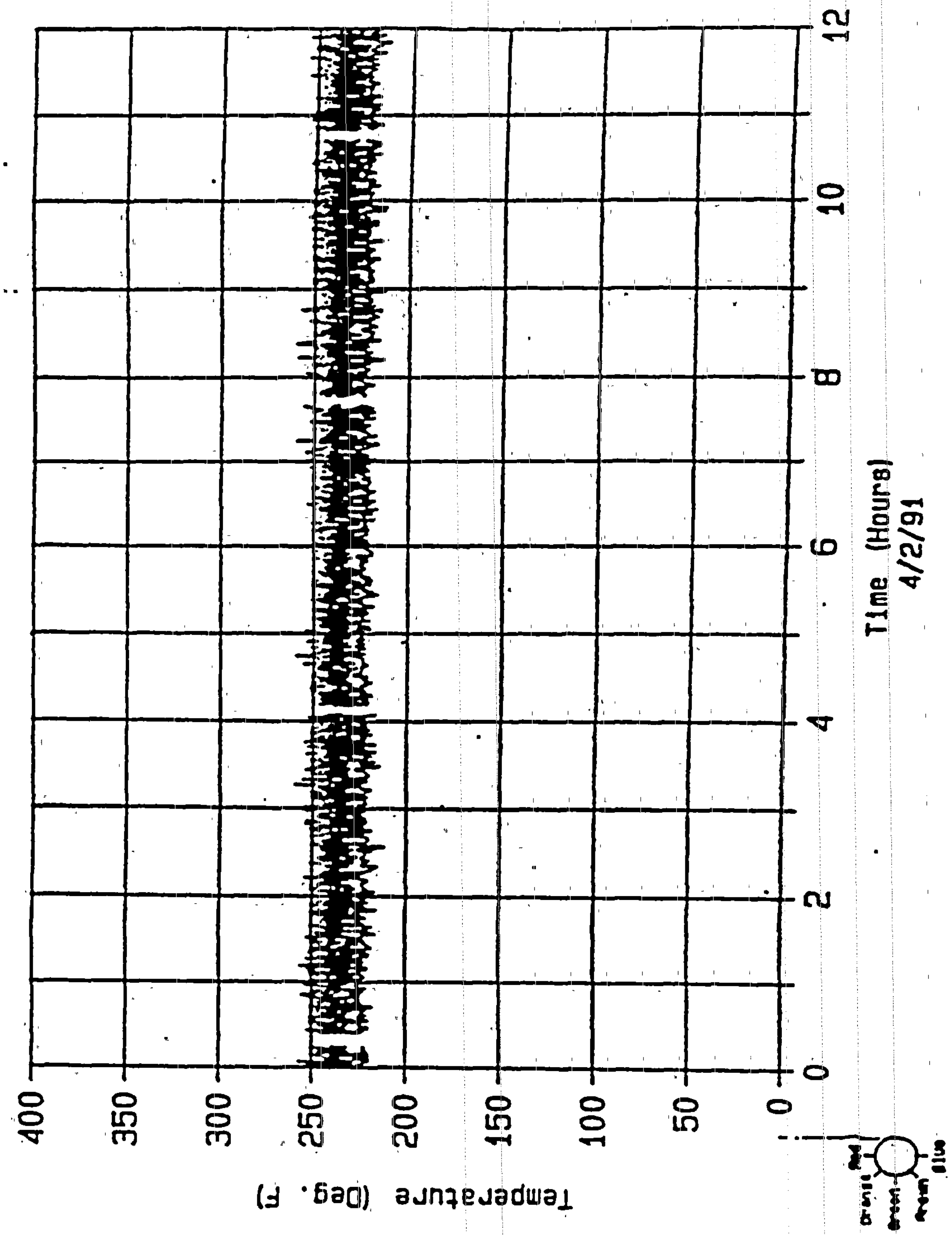


Figure 3-6 Representative Data: Calvert Cliffs 2 SDC Line-Locations



BG&E Calvert Cliffs Unit 2

Heatup - SDC Piping - Location #3

Figure 3-6 Representative Data: Calvert Cliffs 2 SDC Line-Data

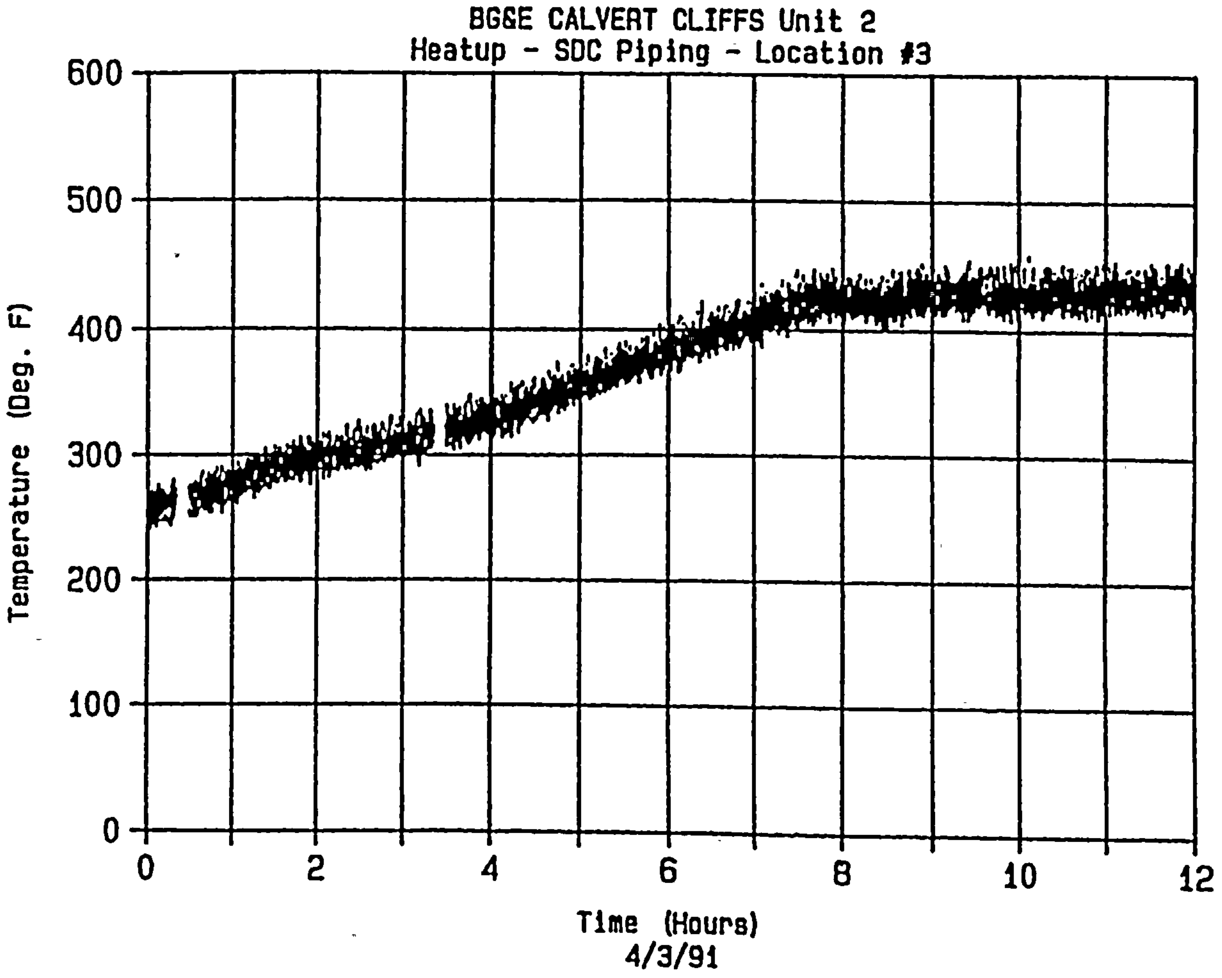


Figure 3-6 Representative Data: Calvert Cliffs 2 SDC Line-Data

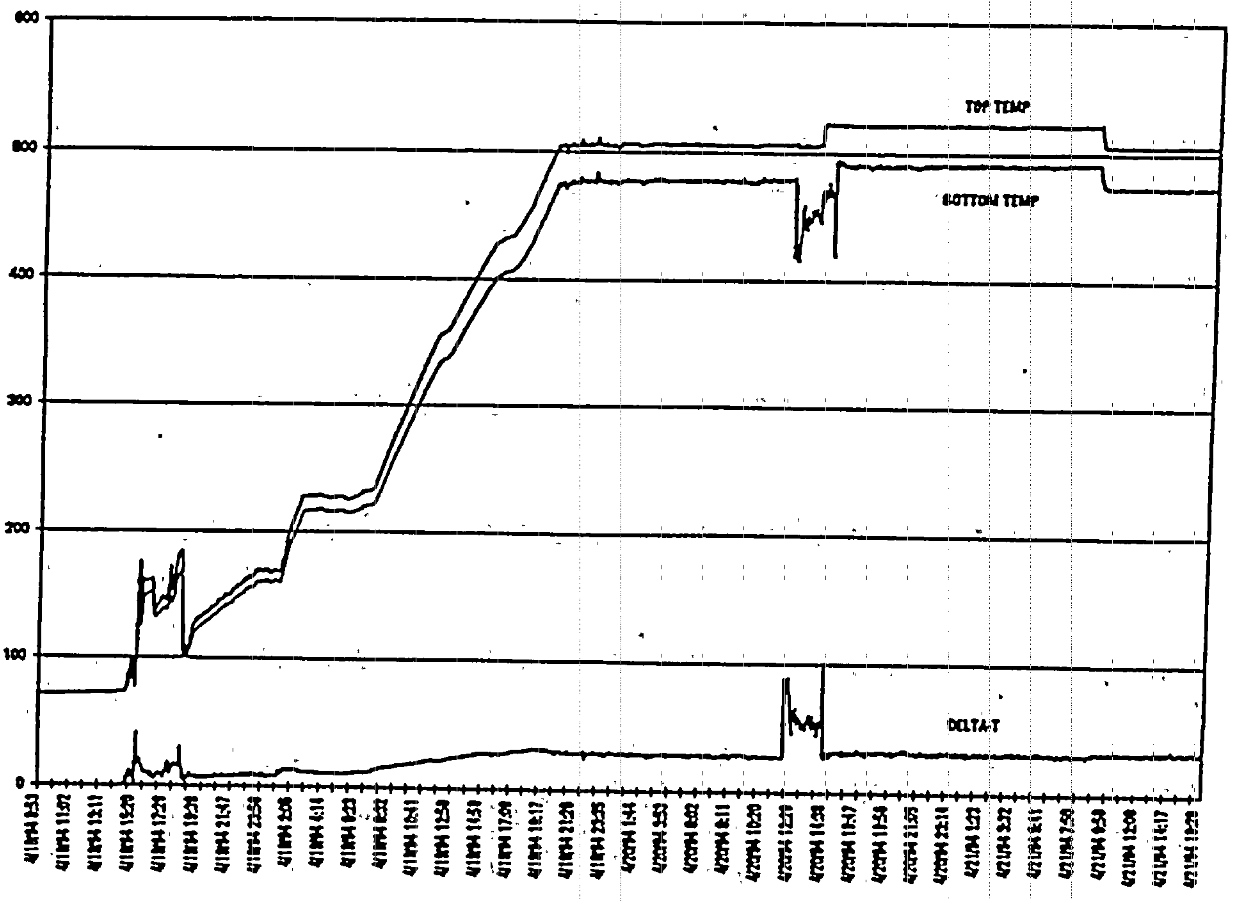


Figure 3-7 Representative Data: ANO-2 Aux Spray Line

4.0 EVALUATION, MODELING AND PREDICTION PROGRAMS

These programs were divided into two phases. The first phase was to use the pilot plant measurements to derive a model from which predictions of wall temperatures could be made for the remaining plants. The second phase was to use these thermal stratification loads to predict moments in either lines that would produce moments of the magnitude expected in lines of similar routing, or plant specific models of each line.

4.1 Safety Injection Lines

Evaluation of the wall thermocouple data (Reference CEOG-8) indicated that thermal stratification was primarily due to natural convection between the check valve which, because of turbulent mixing in the short line between the nozzle and the check valve, is close to the RCS temperature and the isolation check valve close to the Safety Injection Tank, which is close to containment temperature.

Two tasks were completed to develop a model to predict both fluid and wall temperatures (CEOG Task 741) and to determine the moments due to the predicted thermal stratification loads (CEOG Task 818). The participants in the two tasks are listed in Table 4.1-1. The reasons for non-participation in the task related to moments are also listed.

4.1.1 Geometry And Routing

The SI line connects the safety injection tanks to the cold leg of the Reactor Coolant System (Figure 4.1-1). The line runs from a safety injection nozzle, oriented in a vertical up position on the cold leg of the RCS. Typical lines have one or more long horizontal sections between vertical rises. Line sizes range from 12 to 14 inch nominal diameter and Schedules of 140 to 160. In normal operation, the safety injection tank is isolated from the cold leg by a check valve upstream of the cold leg injection nozzle. The motor operated valve used to isolate the safety injection tank is open during normal operation. In normal operation the RCS fluid ranges from 100°F at cold shutdown to 550°F at full power operation. Fluid in the SI tanks are typically at containment temperature of about 100°F.

4.1.2 Wall Temperatures

A series of wall thermocouples were placed at axial and circumferential locations on the S lines for BG&E Calvert Cliffs Unit 2, Figure 4.1-2. Wall temperatures were recorded during heat up, normal operation and cooldown. Typical data at the different axial locations are shown in Figure 4.1-3. In general wall temperatures between the RCS and the check valve are close to the RCS temperatures and indicate small variation with angular location. However, those between the check valve and the MOV, while lower than the RCS temperature due to the thermal resistance of the valve, have top-to-bottom variations in wall temperature of about 140°F.

Wall temperatures and temperature differences were observed to be directly related to RCS temperature. This observation and the absence of forced flow in the line, the wall temperature differences were credited to natural convection between a source of high temperature at the check valve and cold temperature close to the MOV.

4.1.3 Model

The large line diameter and high temperatures resulted in a Rayleigh number for natural convection on the order of magnitude of 10^{11}. A one-dimensional model (Reference 1), based on the intrusion layer behavior, Figure 4.1-4, observed in this range of Rayleigh numbers and small aspect ratios, was used to predict fluid and wall temperatures as a function of end conditions and line geometry. Representative predictions, compared with data, are shown in Figure 4.1-5.

4.1.4 Thermal Stratification Loads

As a result of the heat transfer analysis, the SI lines divided into the following categories: 1) Length of pipe from the RCS to the first check valve, short or long and, 2) Length of the horizontal section from the first check valve to a termination point, where the termination may be due to a second valve or a change in line orientation. Lines were further classified according to the length of the horizontal section, in which natural convection was assumed to dominate, and therefore, thermal stratification is assumed to exist. The results of this classification were three groups of lines, each of which corresponds to the three lines for which data were taken at Calvert Cliffs and ANO-2. The classifications are shown in Figure 4.1-6 and are listed by plant in Table 4.1-2.

Predictions of wall temperature distributions for all line classes, Figures 4.1-7, 4.1-8 and 4.1-9 were predicted according to the algorithm in Figure 4.1-10. Results are shown in Figure 4.1-11. The highest top-to-bottom temperatures for Class A lines were found for BG&E Lines 12B, 21A and 22B. The highest top-to-bottom temperatures for Class B lines was found at WSES-3, Line 2A. The highest top-to-bottom temperatures apply to all FP&L lines and WSES-3 Lines 1A and 2B. These temperature differentials were found to be a function of the stratified length and the number of elbows.

4.1.4.1 Class D lines

Due to their unique configuration, WSES-3 lines 1A, 2A, 1B, 2B were re-classified as Class D lines and were considered a special SI line case. These configurations have sections of piping between the cold leg and the check valve, which could make possible the existence of turbulent penetration-caused thermal stratification. Work reported by the EPRI-sponsored TASCS program indicated that, in lines similar to the SI lines, the turbulent penetration distance is from 15 to 25 length-to-diameter ratios (L/Ds), depending on the main line flow velocity, main branch temperature and relative line sizes.

4.1.5 Moments Due to Thermal Stratification

4.1.5.1 Class A and B Lines

The bounding line for Class A for structural evaluation was determined to be the APS (PVNGS) Unit 1 Loop 1A SI line and the bounding line for Class B was determined to be the ANO-2 SI Line 22. This determination was made based upon a review of the line configurations, calculated ΔTs and support type and number for each of the Class lines A and B, respectively. The combination of a long, stratified run of piping and the restraints for the PVNGS Unit 1 Loop 1A SI line and the ANO-2 Line 22 indicated that analysis of these lines for the variable ΔTs would produce forces and moments that would be bounding for the remaining Class A and B lines.

A structural analysis was performed for Class lines A and B. The Class A line analyzed was the PVNGS Unit 1 Loop 1A (Figure 4.1-12) and the Class B analyzed was the ANO-2 Line 22 (Figure 4.1.14). A stratification ΔT of 150°F was applied to the entire stratified length of piping for Class A. Class A was also analyzed applying the variable DTs which ranged from a maximum ΔT of 140°F to a minimum of 52°F. Similarly, Class B, ANO-2 Line 22, was analyzed applying variable ΔTs which ranged from a maximum of 68°F to a minimum of 32°F.

Three load cases were performed: linear thermal expansion, thermal stratification only and a combined case (linear thermal expansion and thermal stratification). The net combined moments due to thermal stratification for selected locations for lines Classes A and B are given in Tables 4.1-3 and 4.1-4. The results of this analysis maybe generically applied to the other Class A and B lines.

4.1.5.2 Analysis Methodology for Class D (WSES-3) lines

As done for Classes A and B, the ANSYS Computer Code was used to evaluate the bounding configuration for the one Class D line, WSES-3 Line 2A. Likewise, the bounding piping configuration was entered into the ANSYS Code as a series of straight runs and bends, as determined by the geometry provided in Figure 4.1-13. Class D line (WSES-3 Line 2A) was evaluated for the effects of a maximum ΔT, which is assumed to exist for the entire stratified section of piping, between the end of the turbulent penetration and the first check valve. The turbulent penetration length was assumed to be approximately 15 L/Ds.

Only one thermal stratification load case was performed for the Class D bounding line. In order to determine the effect of top-to-bottom wall temperatures, stratified temperatures were applied to the horizontal sections of the model using the BFE command. This command uses the top-to-bottom average temperature (T_{avg}) applied to the center of the pipe (i.e., the fluid) and the temperature at q=180° (T_{top} or T_{bot}, depending upon how a particular element was generated). The 0° location is internally calculated by ANSYS using a linear relationship based on these two values (Table 4.1-5).

4.1.6 Transient Description

4.1.6.1 Background

Stratification in the SI line was shown to occur as a result of the plant heatup transient and was found to be dependent primarily on the Cold Leg temperature (RCS T_{cold}). As Cold Leg temperature increases during heatup, turbulent penetration from the Cold Leg into the SI line sets up an axial temperature differential and resultant natural circulation loop (see Figure 4.1-1). Increasing the magnitude of the difference between RCS T_{cold} and ambient temperature will, accordingly, increase the amount of resultant natural circulation and the magnitude of the top-to-bottom differential temperature in the SI line.

As part of this effort, it was necessary to formulate a transient description which describes the SI line thermal stratification transient and assign a number of design occurrences. In order to accurately describe the SI line stratification transient, it will be necessary to determine which of the current design basis plant transient conditions will give rise to stratification and to what extent this stratification will occur.

4.1.6.2 Development of Transient Description

A list of typical design basis transients for the RCS are provided in Table 4.1-5. The time-temperature profiles for these transients were examined in order to determine the change in RCS T_{cold} associated with each transient. The predictive model was then used, with the ranges of RCS T_{cold}, to determine predicted temperature differentials in the SI line. The relationship between RCS T_{cold} and predicted SI line ΔT is presented in graphical form in Figure 4.1-15.

The majority of the design basis RCS transients have a minimal effect on SI line ΔT since they involve small changes in RCS T_{cold}. For this reason, plant heatup will be assumed to be the primary generator of SI line thermal stratification. Also, since the corresponding decrease in SI line ΔT comes about as a result of plant cooldown, the plant heatup/cooldown cycle will be assumed to constitute one full cycle of SI line thermal stratification. Therefore, the SI line thermal stratification transient will be assigned a number of design occurrences equal to 500 cycles.

4.1.7 Plant Specific Analyses

To evaluate the impact of the results of this effort on the participant plants, a plant specific analysis of the Safety Injection Nozzle and Class 1 piping was recommended as follows:

1. Load Comparison: In order to determine which loads are bounding and if further analysis is necessary, a comparison of the thermal stratified loads to the original linear thermal expansion loads of the original stress report for the nozzle and the Class 1 piping would be required.

2. Stress and Fatigue Analysis: Based on the results of the load comparison, a stress and fatigue analysis would be performed to determine maximum elastic stress levels and calculate fatigue usage factors.

3. Plant Specific Documentation: Revisions to Engineering Specifications and Addenda to Piping Analytical Reports, as required, to incorporate the new stress levels and fatigue usage factors.

Table 4.1-1

Participants in Safety Injection Line Tasks

Task	Participant	Plants
741	Arizona Public Service	PVNGS 1,2,3
	Entergy Operations	ANO2, WSES3
	Florida Power & Light	St. Lucie 1,2
	Northeast Utilities	MP2
	Omaha Public Power Dist	FCNS
818	Arizona Public Service	PVNGS 1,2,3
	Entergy Operations	ANO2, WSES3
	Florida Power & Light	St. Lucie 1,2
	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Omaha Public Power Dist	FCNS
	Maine Yankee	Maine Yankee

Table 4.1-2
Line Grouping

Line Class	Utility-Unit	Line Number	Size	Stratified Length (in)	Number of Elbows
A	APS-PVNGS 1,2,& 3	1A	14" Sch. 160	500	3
	APS-PVNGS 1,2,& 3	2A, 1B, 2B		400	3
	BG&E-1	11A	12" Sch. 160	550	2
	BG&E-2	21B		630	2
	BG&E-1&2	11B, 12A, 22A		330	1
	BG&E-1&2	12B, 21A, 22B		240	1
B	ANO-2	22	12" Sch. 140	550	3
		24		420	2
	WSES-3	1B		700	3
C	FP&L-2	2B1	12" Sch. 160	70	1
	ANO-2	21	12" Sch. 140	70	1
		23		80	0
	MY	53-1,53-2,53-3	14" Sch. 160	50	0
	FP&L-1&2	1A2, 1B2, 2A1, 2A2, 2B2	12" Sch. 160	40	0
	FP&L-1	1A1, 1B1	12" Sch. 160	20	0
D*	WSES-3	1A, 2A, 1B, 2B	12" Sch. 140	Section 2.1.1	

Table 4.1-3
PVNGS Unit 1 Loop 1A SI Line - Variable ΔT
Combined Moments or Selected Locations

Location	Node Number	Combined Moment (in-kips)			
		Mx	My	Mz	Mt
SI Nozzle Safe End	2	33.5	-16.6	368	370
Elbow	8	117	33.1	366	386
Elbow	15	954	391	544	1170
Tee	20	512	-944	968	1450
Elbow	26	300	-960	369	1070
Elbow	92	1030	-482	1870	2190

Table 4.1-4
ANO-2 SI Line 22 - Variable ΔT
Combined Moments For Selected Locations

Location	Node Number	Combined Moment (in-kips)			
		Mx	My	Mz	Mt
1st elbow upstream of SI nozzle	5	-229	349	-83.8	426
elbow	13	147	-493	-54.6	517
elbow	18	179	-370	-289	502
elbow	24	71.1	251	-410	486
elbow	30	70.9	210	-413	469
tee	28	193	177	-163	308
elbow	36	55	168	54	185

Table 4.1-5
Typical Design Basis Transients for the RCS

Transient	**Condition**	**Lifetime Occurrences**
Plant Heatup	Normal	500
Plant Cooldown	Normal	500
Plant Loading 5%/min.	Normal	15000
Plant Unloading 5%/min.	Normal	15000
10% Step Load Increase	Normal	2000
10% Step Load Decrease	Normal	2000
Normal Plant Variation	Normal	10^6
Reactor Trip	Upset	400
Loss of Reactor Coolant Flow	Upset	40
Loss of Load	Upset	40
Loss of Secondary Pressure	Emergency	5
Hydrostatic Test	Test	10
Plant Leak Test	Test	200
Safety Injection Check Valve Test	Test	160

Table 4.1-6
WSES-3 SI Line 2A - Maximum Uniform ΔT Thermal Stratification Moments For Selected Locations

Location	Node Number	Moments (in-kips)			
		Mx	My	Mz	Mt
SI Nozzle Safe End	1	-965	-147	1041	1427
Elbow	7	1047	100	-1066	1498
Straight Section	14	-1510	133	1134	1893
Elbow	17	1502	-81.6	-1076	1849
Elbow	26	1478	-378	-685	1672
Tee	40	120	205	-449	508
Anchor	60	36.8	-140	135	198

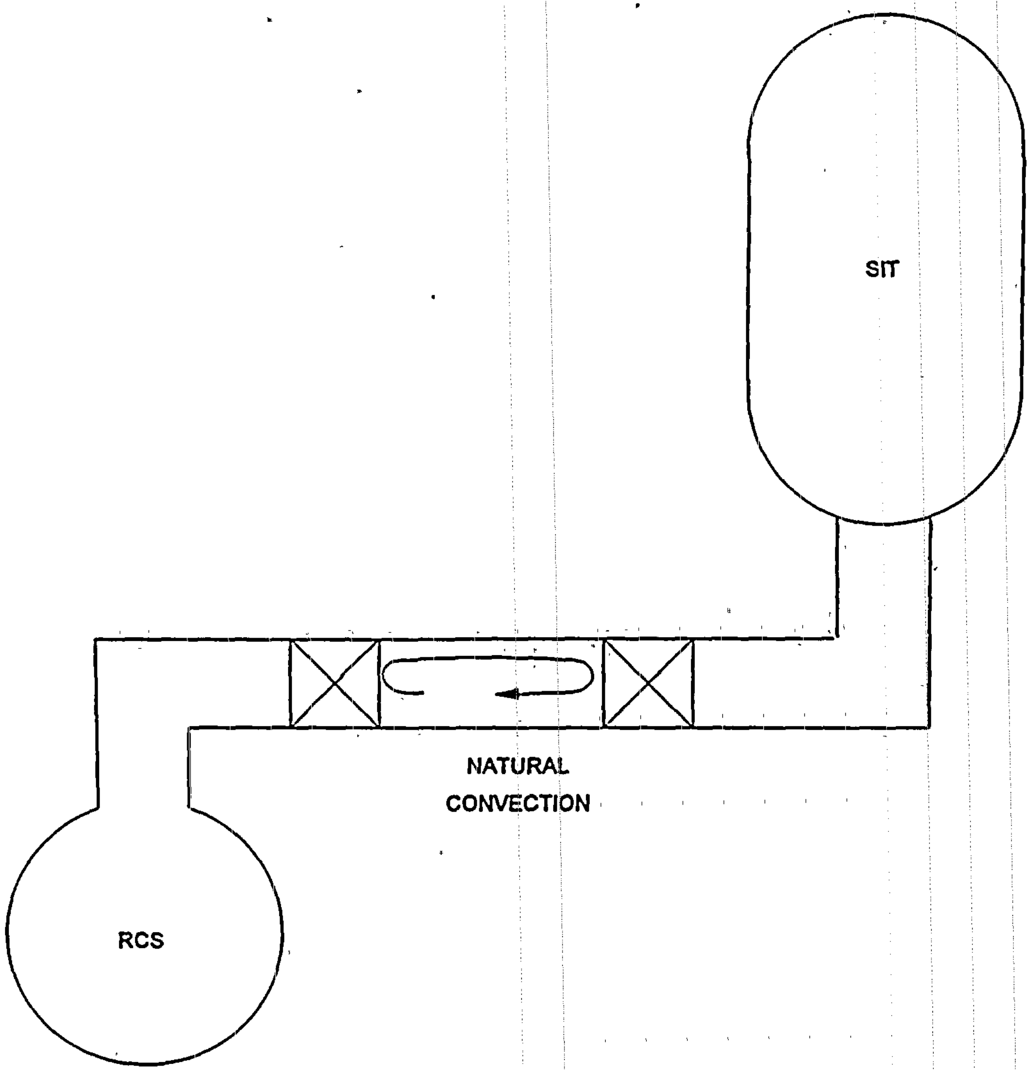


Figure 4.1-1 Safety Injection Line

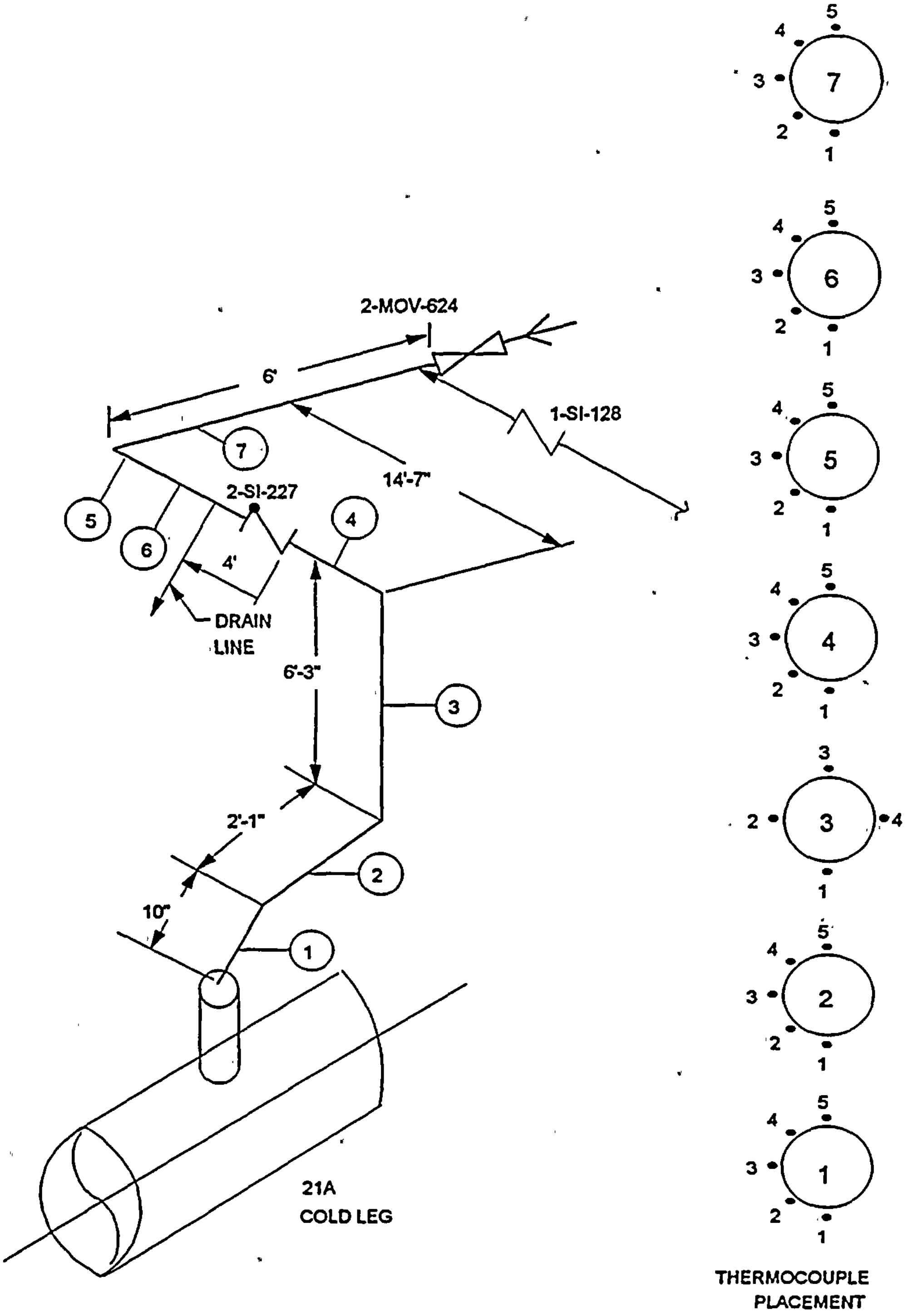


Figure 4.1-2 Instrumented Locations on Safety Injection Line

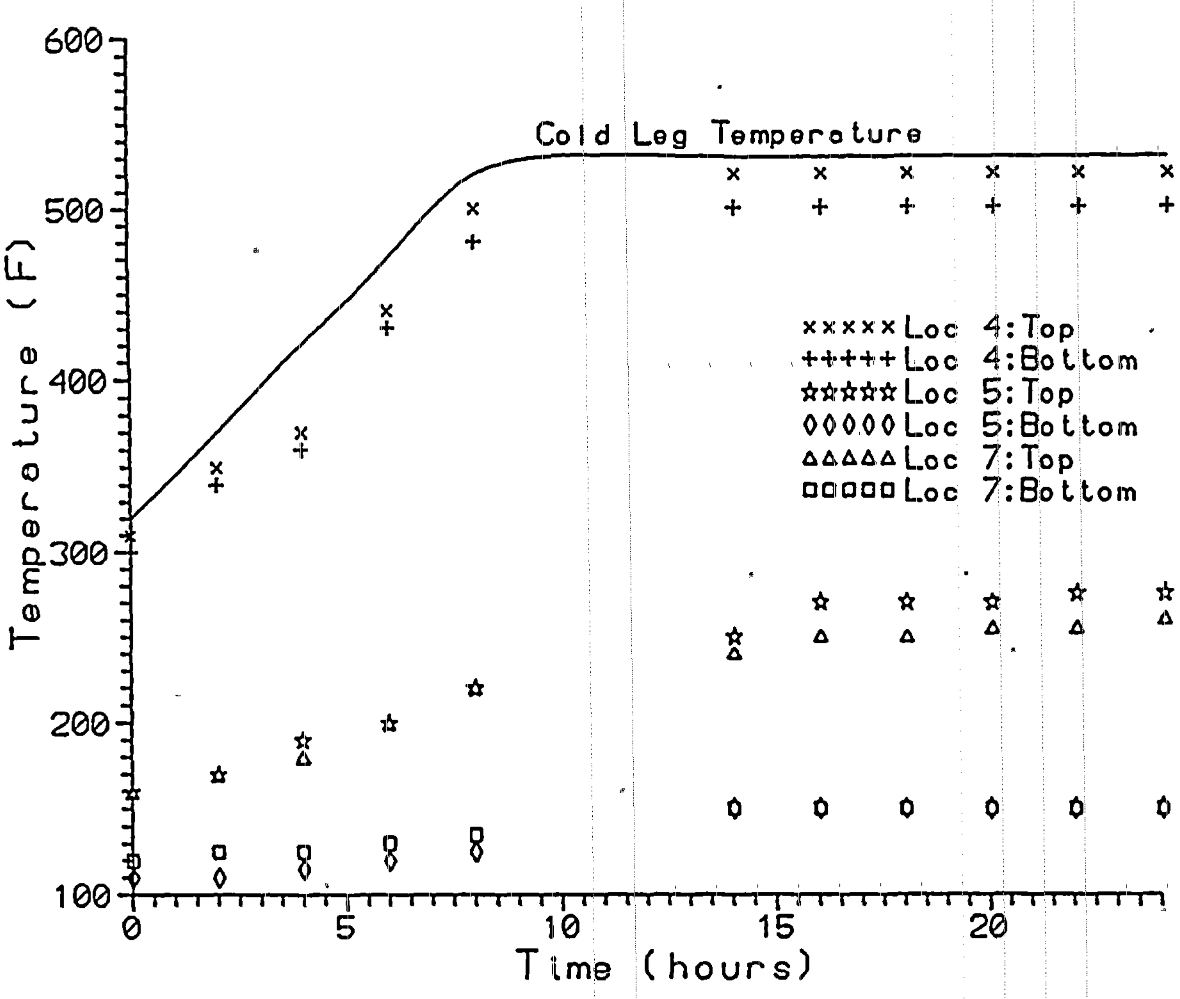


Figure 4.1-3 Safety Injection Line Wall Temperatures vs Time during Plant Heat Up

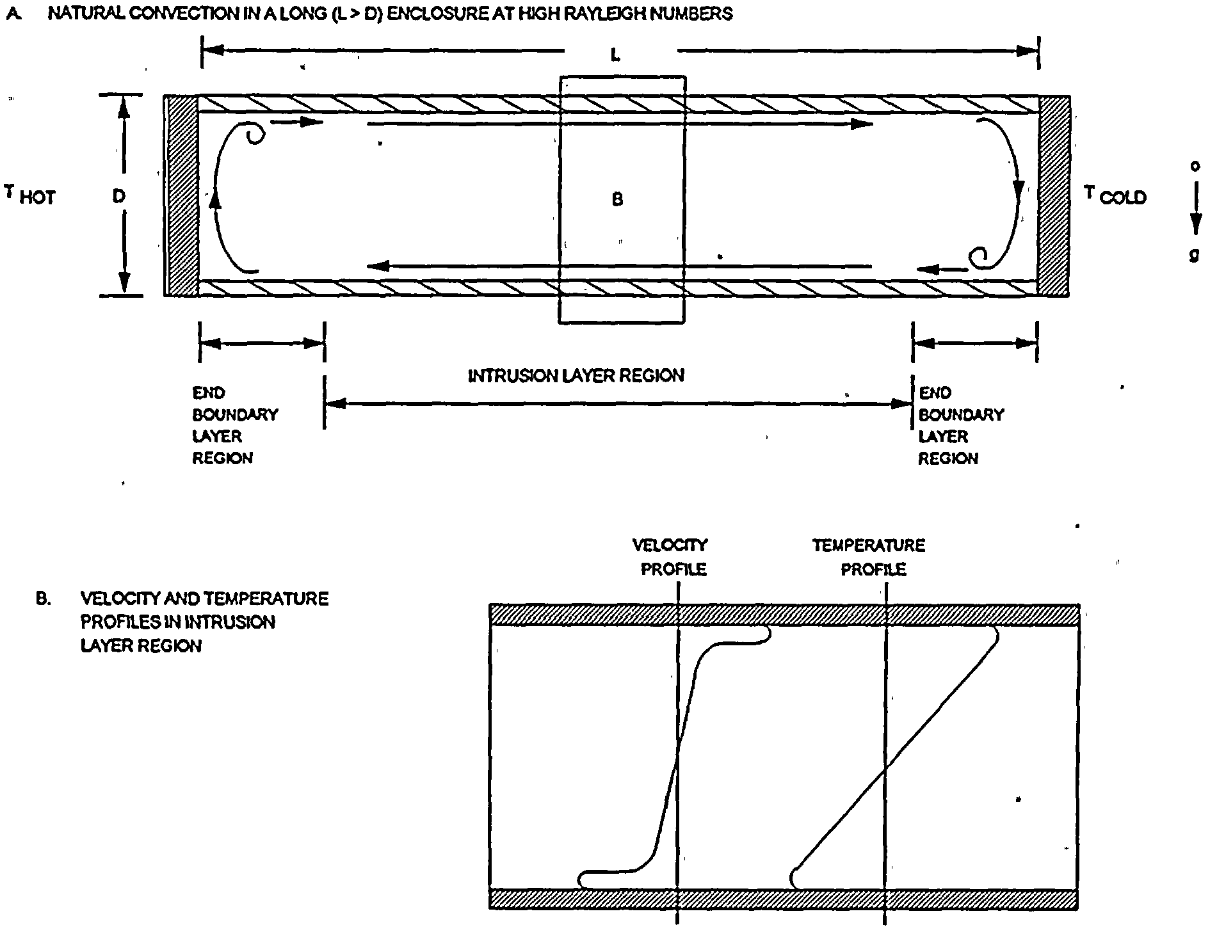


Figure 4.1-4 Model for Natural Convection at High Rayleigh Numbers

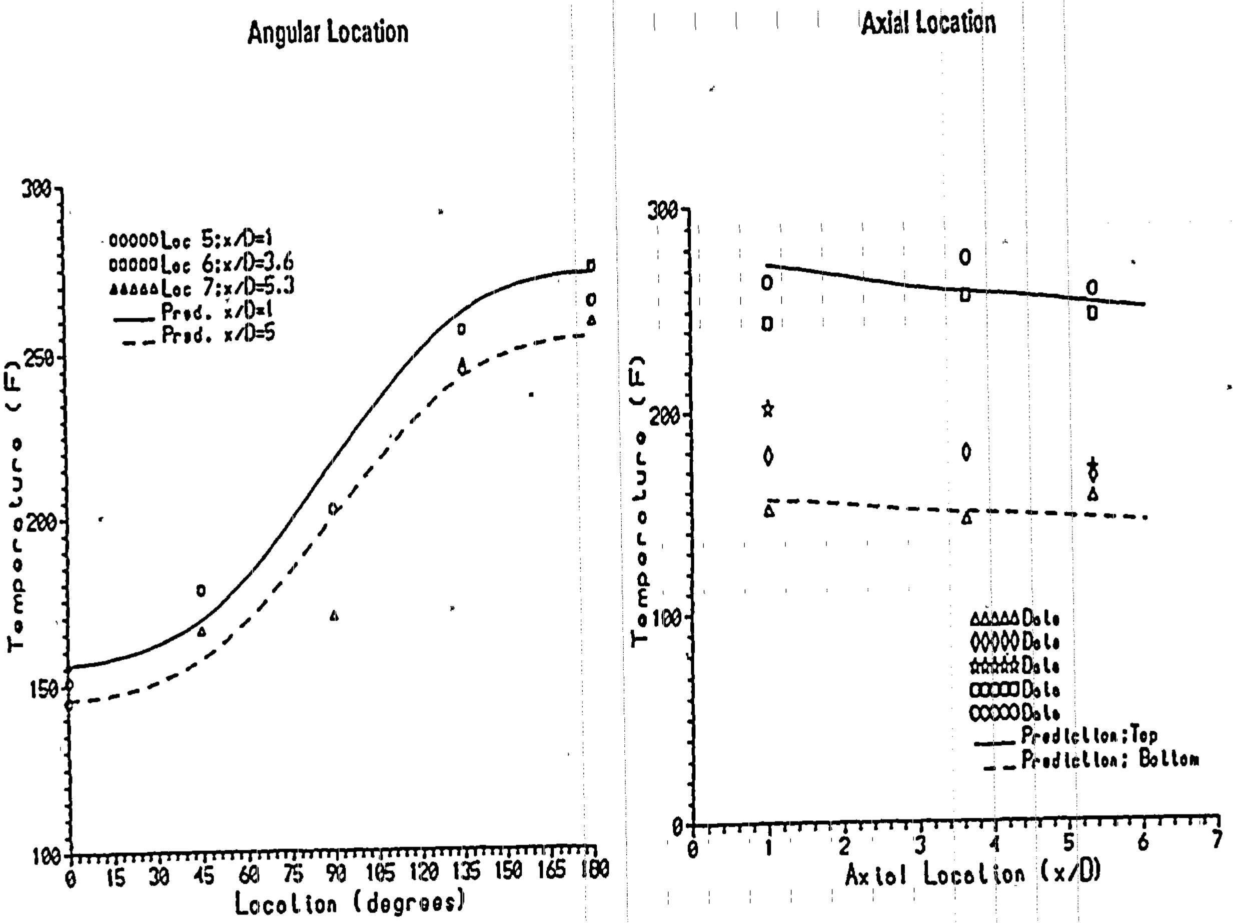
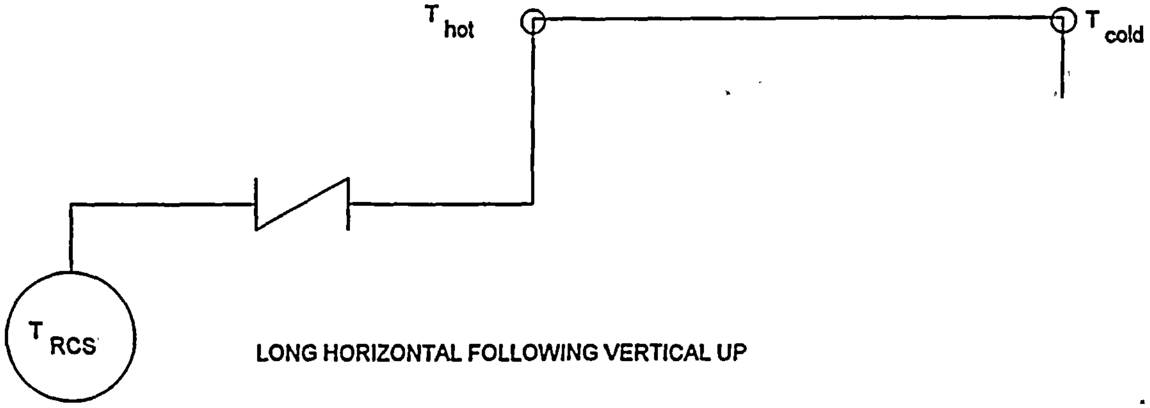
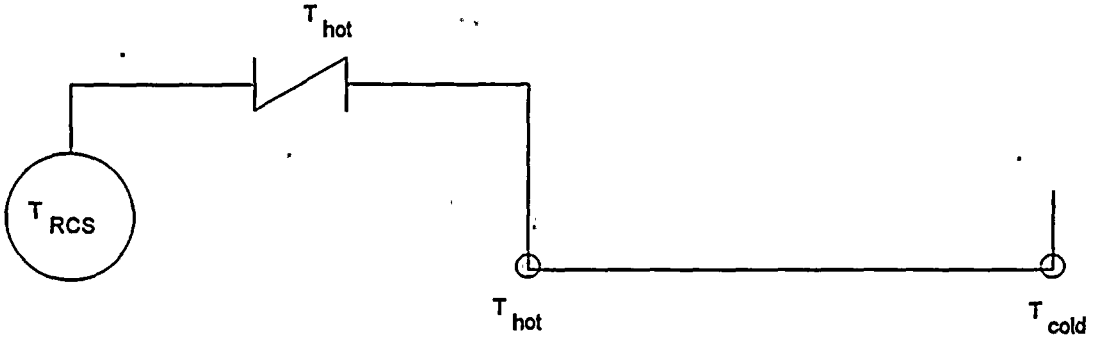


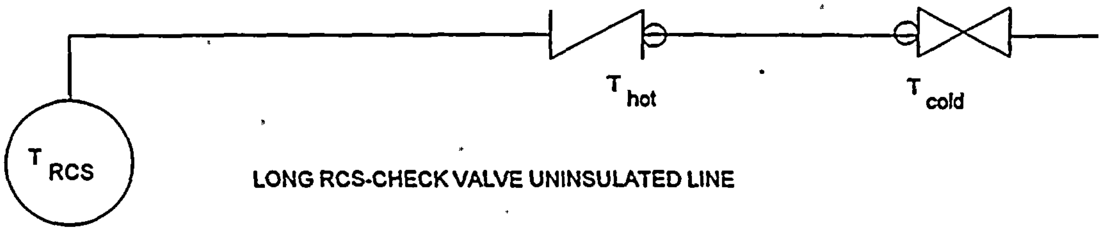
Figure 4.1-5 Wall Temperature Predictions vs Data



LONG HORIZONTAL FOLLOWING VERTICAL UP

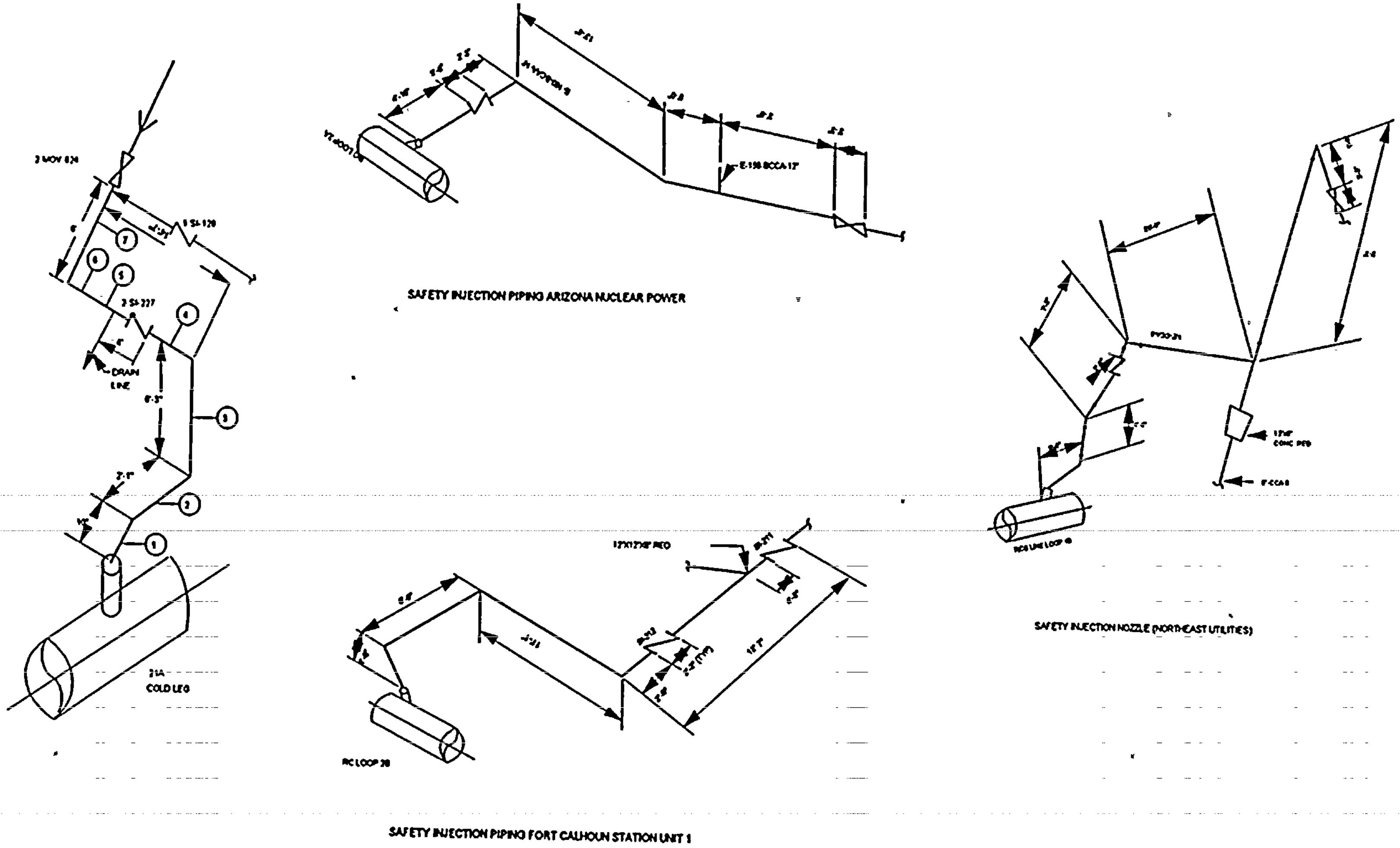


LONG HORIZONTAL FOLLOWING VERTICAL DOWN



LONG RCS-CHECK VALVE UNINSULATED LINE

Figure 4.1-6 Classification of Safety Injection Lines

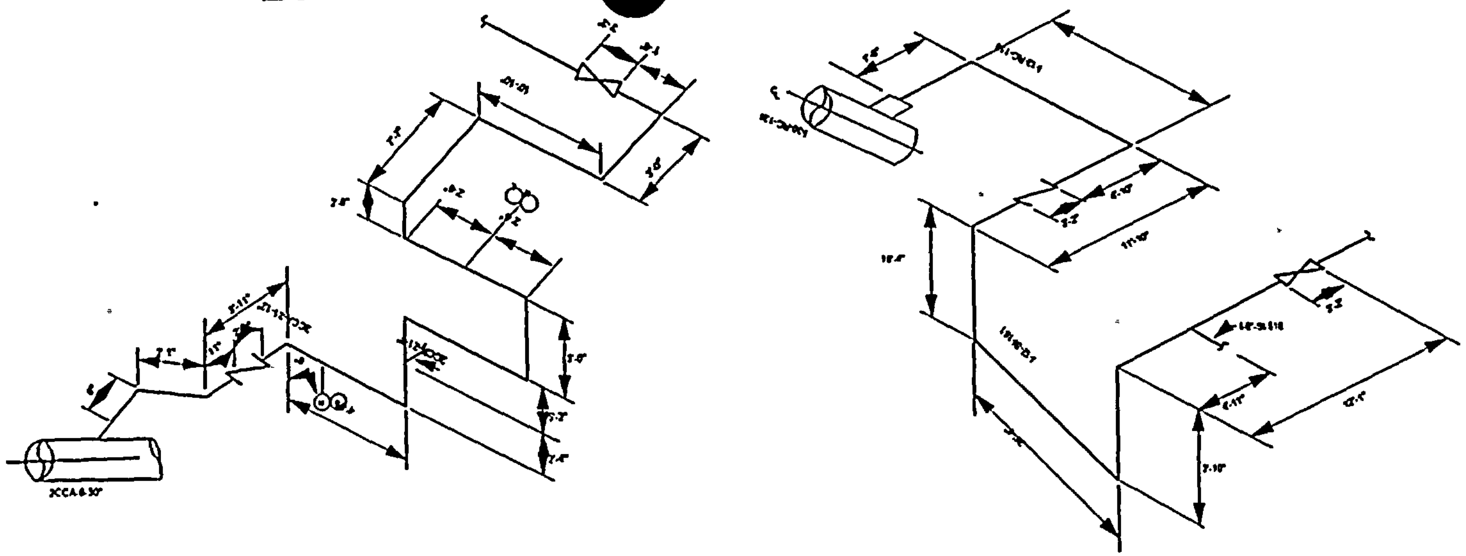


SAFETY INJECTION PIPING ARIZONA NUCLEAR POWER

SAFETY INJECTION NOZZLE (NORTHEAST UTILITIES)

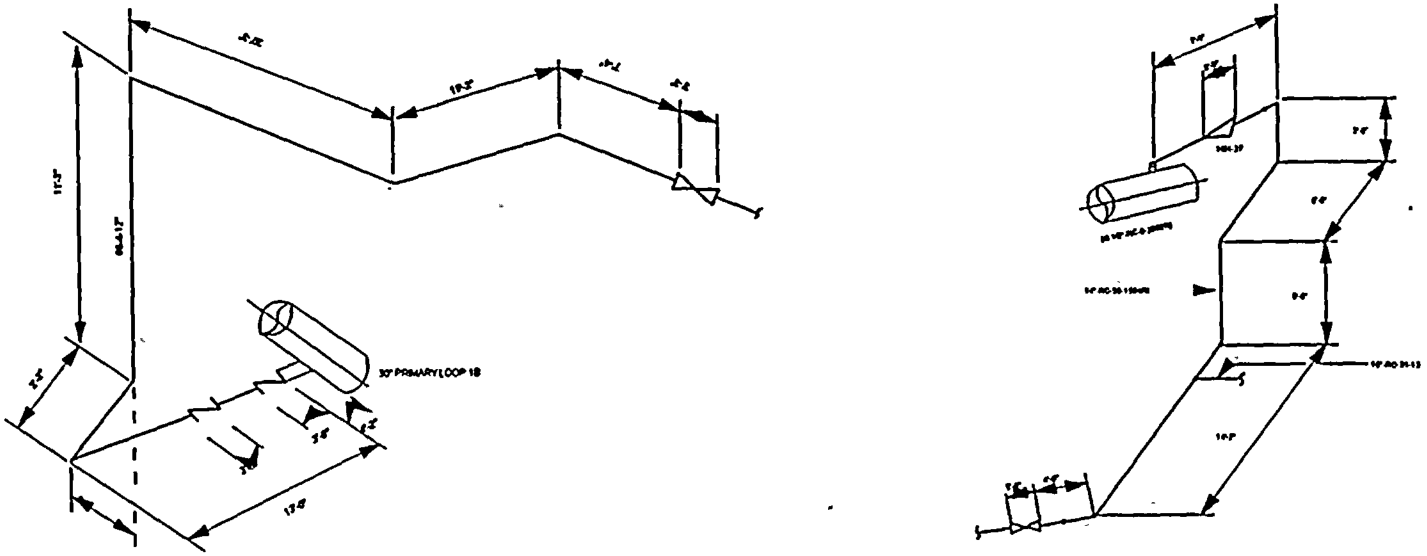
SAFETY INJECTION PIPING FORT CALHOUN STATION UNIT 1

Figure 4.1-7 Classification of SI Lines: Class A



SAFETY INJECTION PIPING ARKANSAS NUCLEAR ONE UNIT 2 LINE "B"

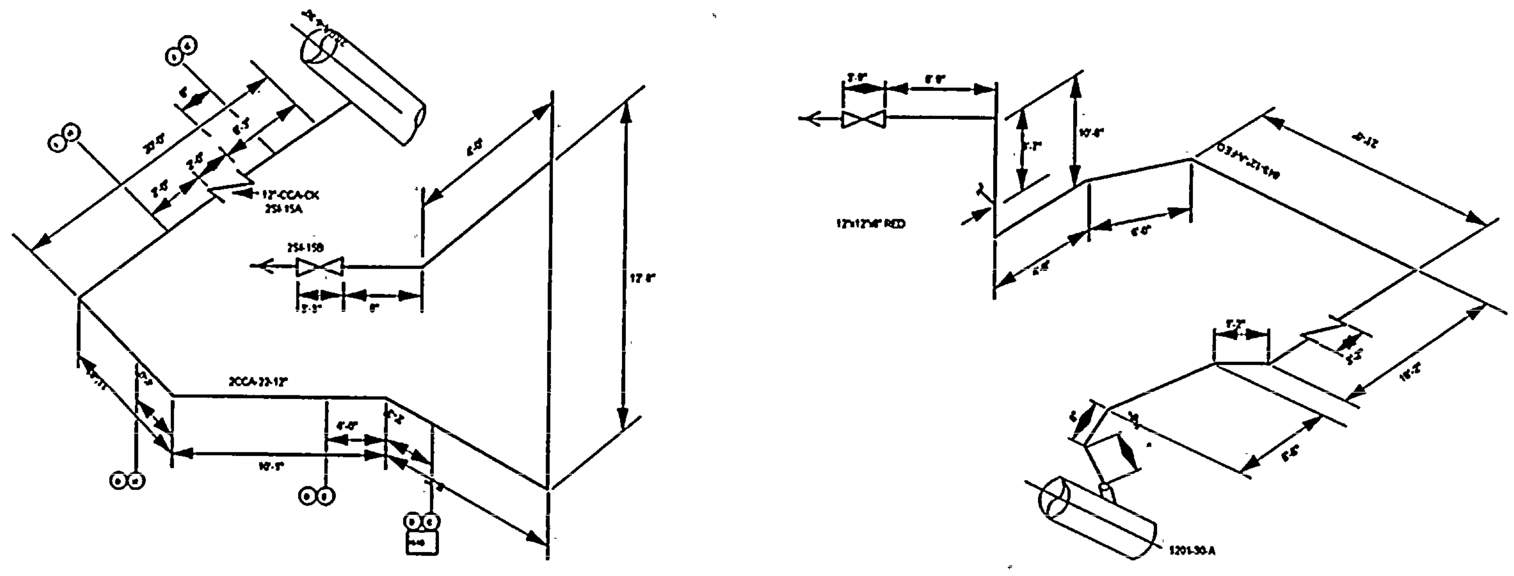
SAFETY INJECTION PIPING ST. LUCIE UNIT 2



SAFETY INJECTION PIPING PALISADES

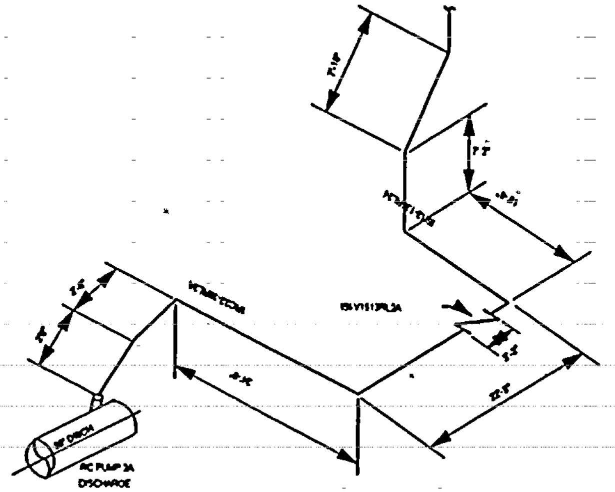
SAFETY INJECTION PIPING MAINE YANKEE

Figure 4.1-8 Classification of SI Lines: Class B



SAFETY INJECTION PIPING ARKANSAS NUCLEAR ONE UNIT 2 LINE "A"

SAFETY INJECTION PIPING SONGS UNITS 2 & 3



SAFETY INJECTION PIPING LOUISIANA POWER & LIGHT COMPANY

Figure 4.1-9 Classification of SI Lines: Class C

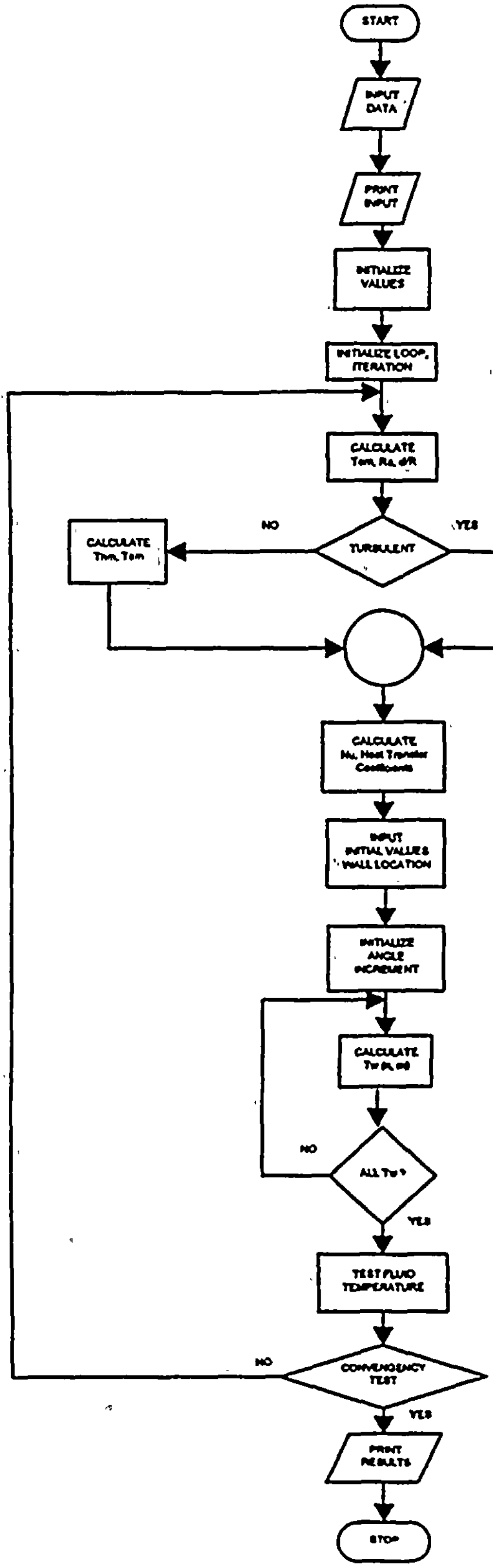


Figure 4.1-10 Flow Chart - Version 1.16

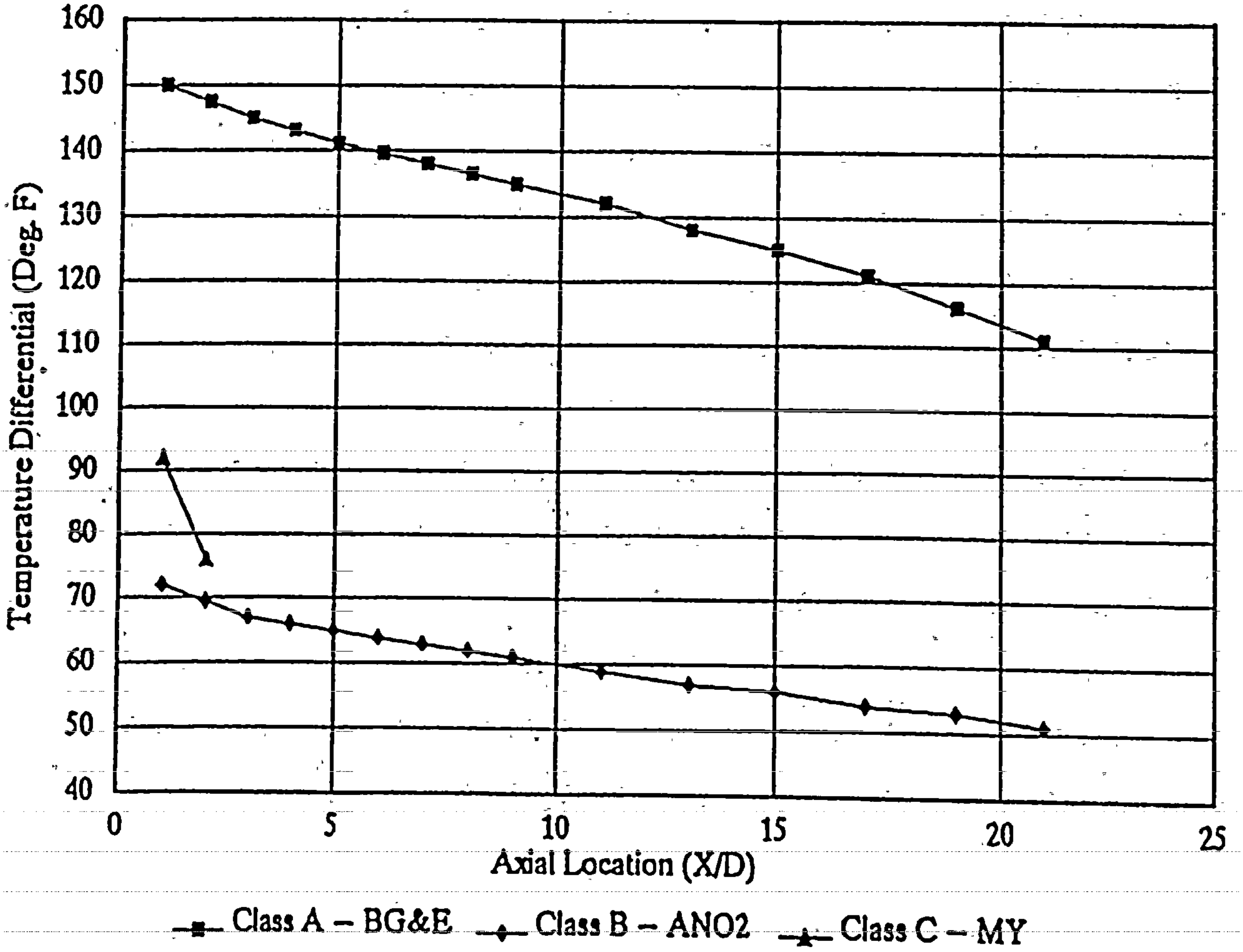


Figure 4.1-11 Predictions of Wall Temperature for SI Line Classifications

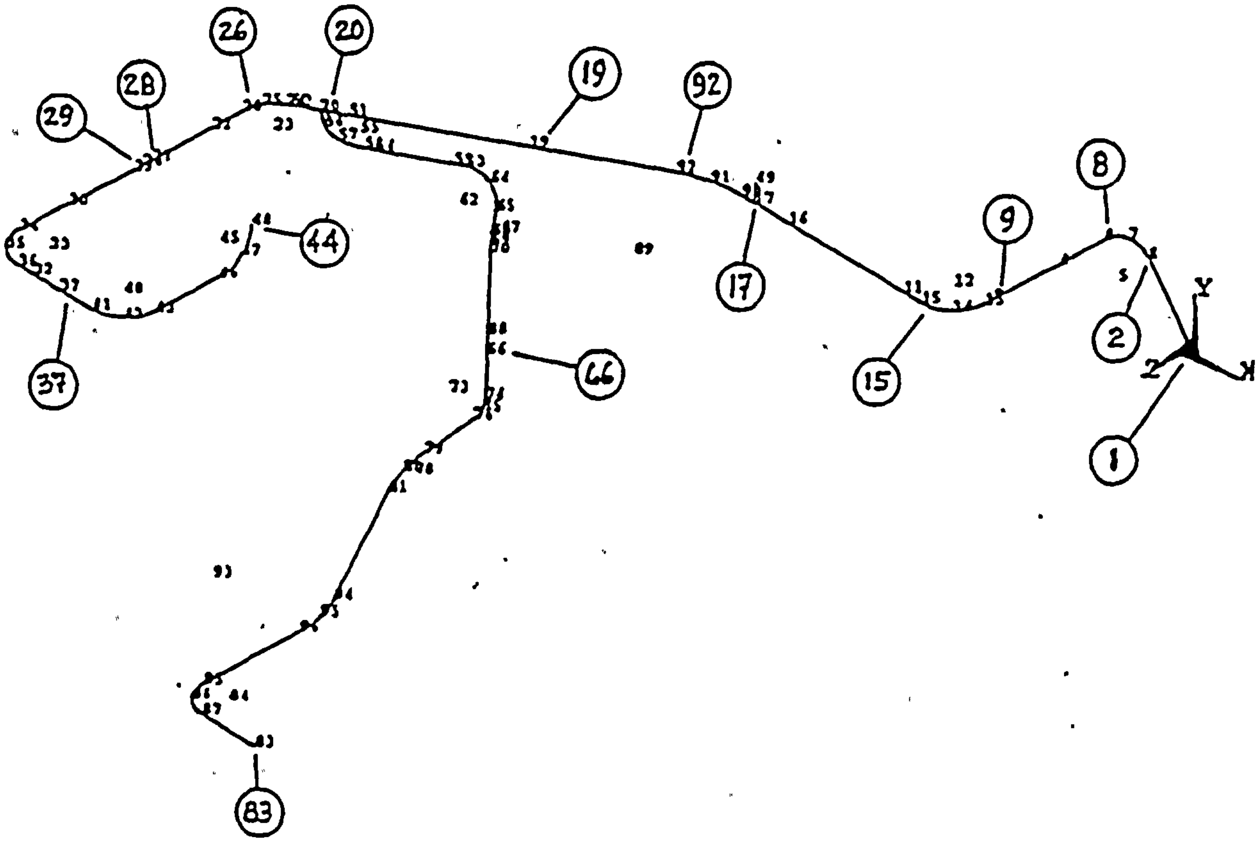


Figure 4.1-12 PVNGS Unit 1 Loop 1A SI - ANSYS Model

S.H. NODE #'s {28, 86, 83

R.R. NODE #'s {12, 14, 21, 23, 46, 61, 70, 76, 89, 103, 109, 115

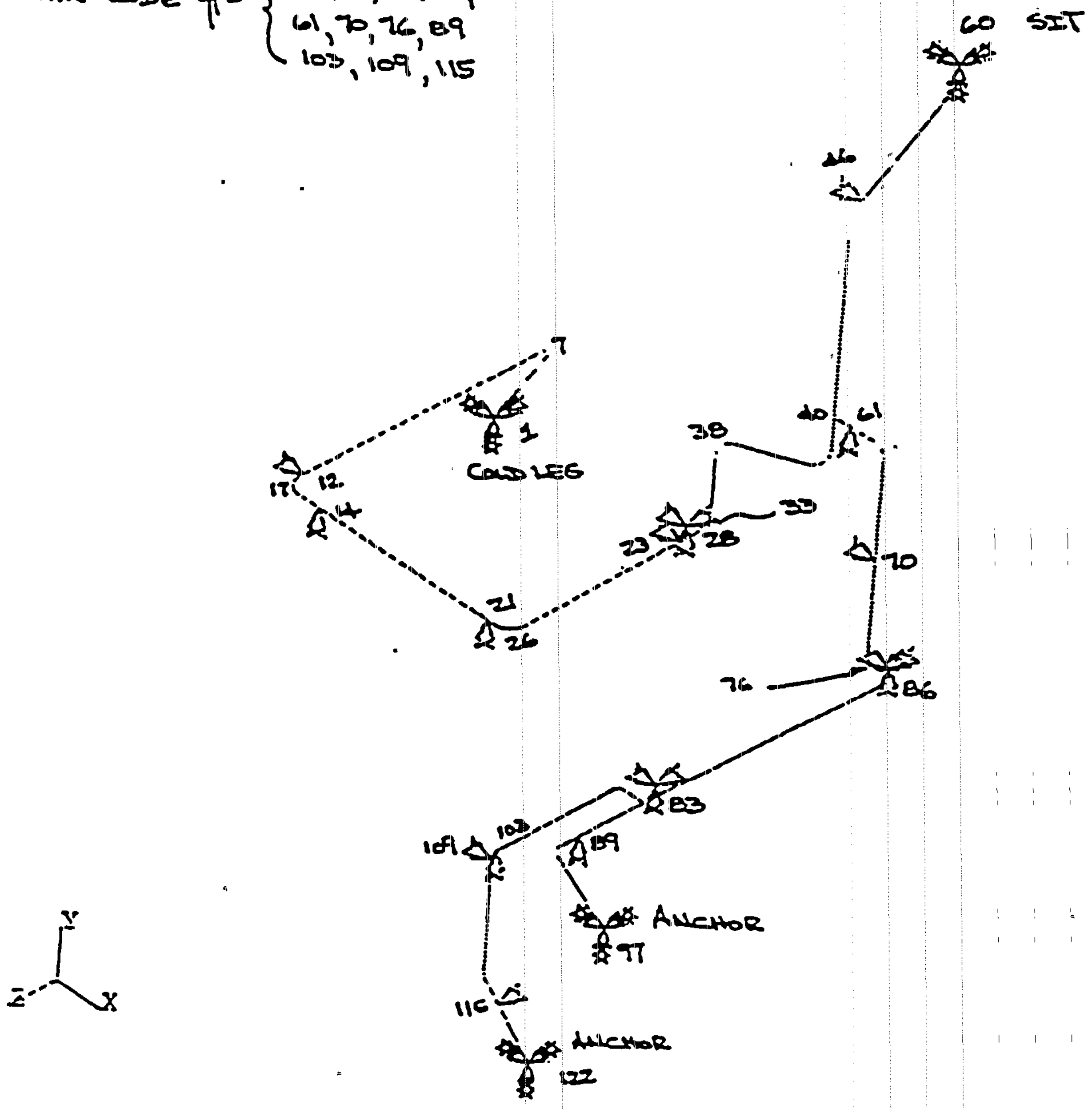


Figure 4.1-13 WSES-3 SI Line 2A - ANSYS Model

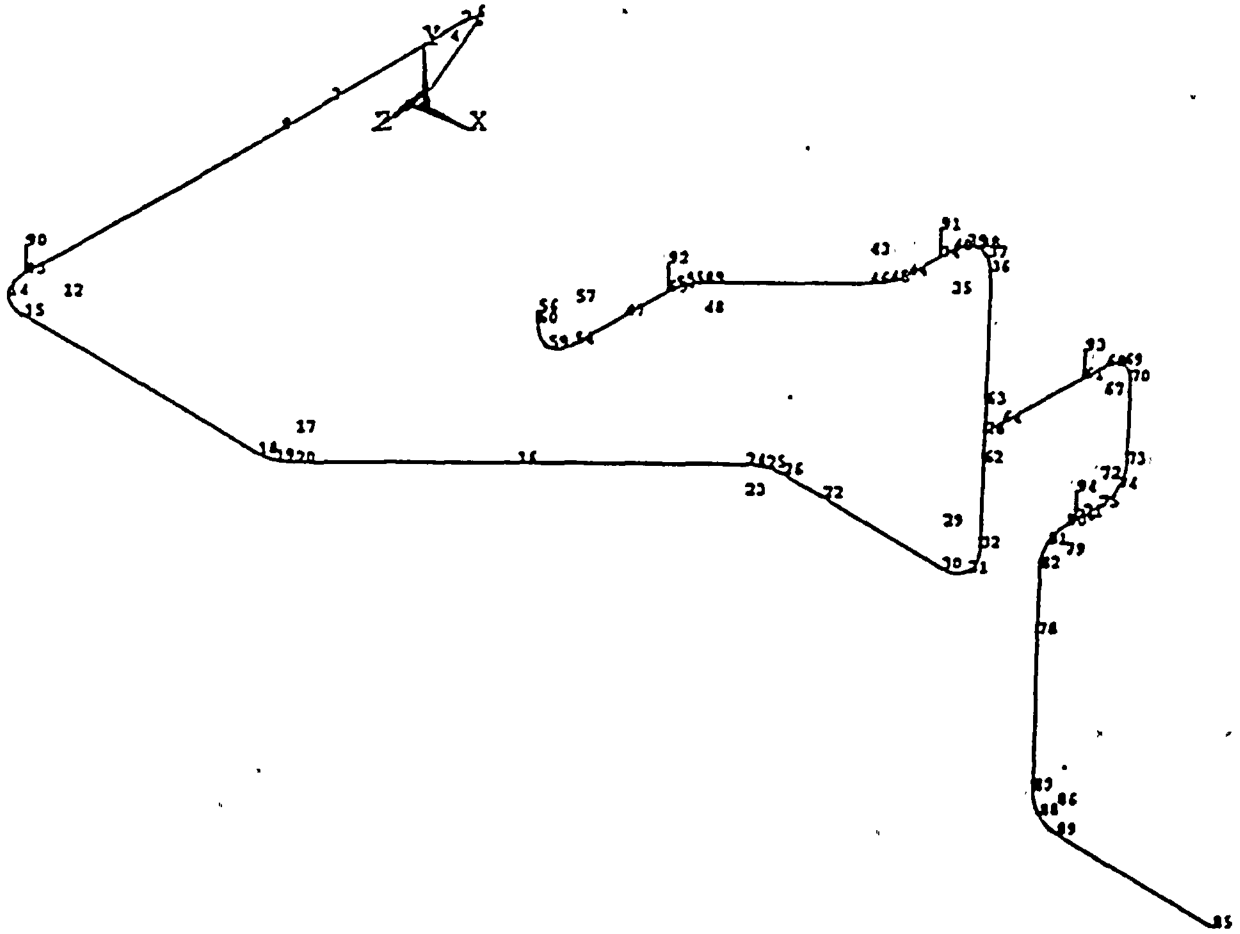


Figure 4.1-14 ANO-2 SI Line 22 - ANSYS Model

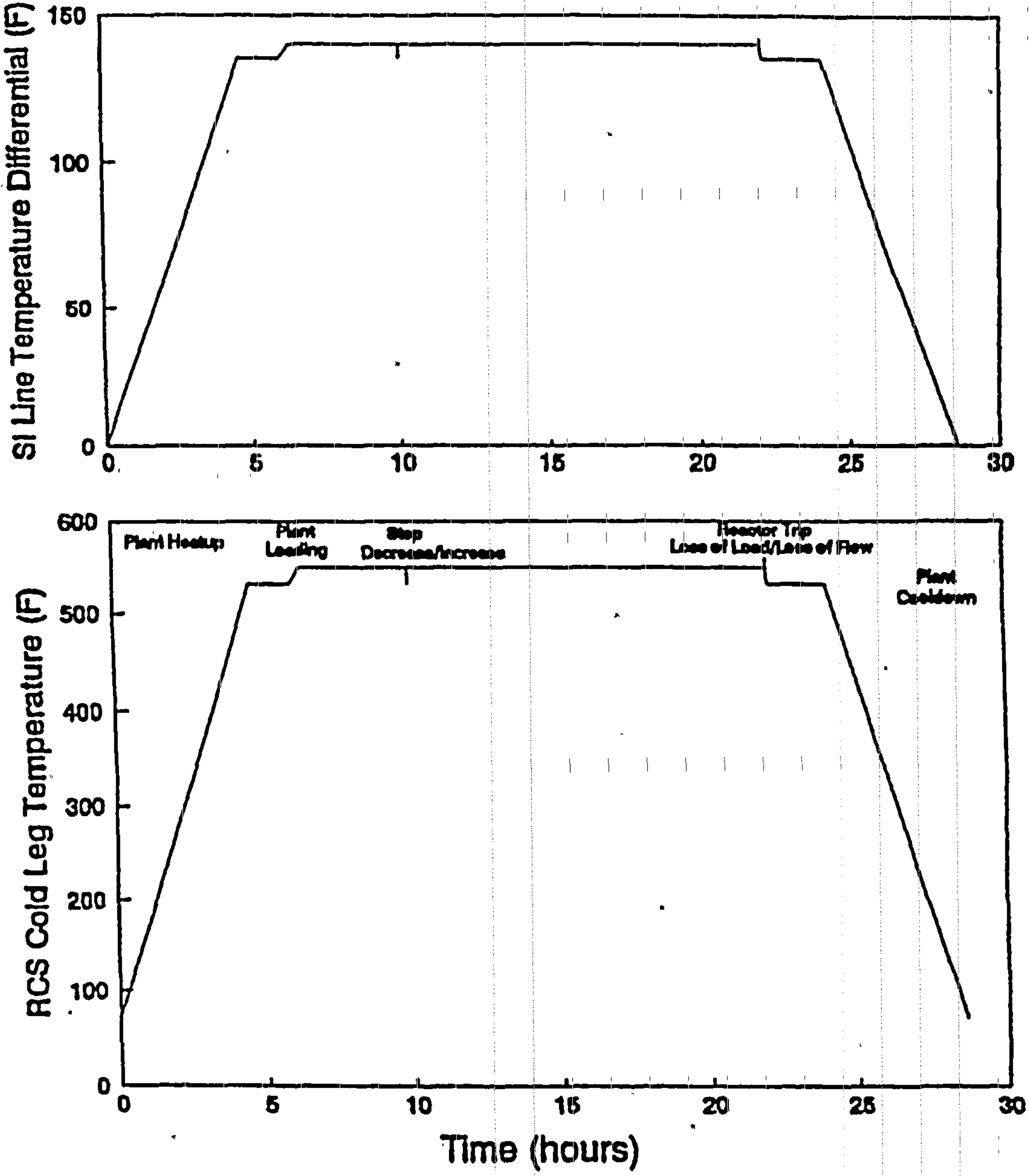


Figure 4.1-15 Thermal Stratification Transient for SI Line

4.2 Lines Connected to Pressure Operated Relief Valves

Thermal stratification in the lines from the pressurizer to the Pressure Operated Relief Valves (PORVs) is related to the presence of saturated steam and subcooled water in the horizontal section of the lines upstream of the valve. The line, being cooled to containment temperature at some distance from the pressurizer, provides the cooler surface upon which the steam can condense. Evaluation of the wall thermocouple data (Reference CEOG-8) indicate that possible run-back of the condensate into the PORV nozzle at the pressurizer results in a variation in wall temperature related to the thickness of the condensate layer (Figure 4.2-1).

Thermal stratification loads were determined by application of a model, developed in CEOG Task 773, based on the measurements taken at two plants; Calvert Cliffs unit 2 (BG&E) and ANO2 (Entergy Operations). The methodology was then applied, in CEOG Task 827, to plant specific FEA models of the PORV lines with which, using the thermal stratification loads, moments were determined. Participants in the tasks related to thermal stratification in the PORV lines are listed in Table 4.2-1.

4.2.1 Geometry and Routing

Relief valves, to protect the plant from over-pressure events, are connected to the top of the pressurizer through a series of lines ranging from nominal 3 to 6 inches and Schedule 120 to 160. Though the line routings differ between plants there is normally one or more horizontal sections close to the pressurizer. For full power operation the pressurizer contains saturated steam at about 650°F. However, even though the lines are normally insulated, the fluid in the lines can reach containment temperature about 10-15 feet from the pressurizer. Note that within this analysis PORV lines refers to all lines atop the pressurizer including Pressurizer Safety Valve (PSV) and Low Temperature Overpressure Protection (LTOP) lines.

4.2.2 Wall Temperatures

A set of thermocouples was used to monitor wall temperature in the horizontal section of lines shown in Figure 4.2-2. Wall temperatures recorded during heatup (Figure 4.2-3) showed top-to-bottom differences in wall temperature of 100°F.

Review of the top and bottom thermocouple readings indicate that during heatup saturated steam fills the upper section of the line while subcooled condensate accumulates along the bottom. Condensate level and temperature continues to increase until the condensate is close to the saturation temperature and an equilibrium condensate level is reached within the line at which point the difference in wall temperature approaches zero.

4.2.3 Model

This model was used to predict the variation in wall temperatures with axial and circumferential location. The model, Figure 4.2-4, assumed a variation of condensate level with distance from the pressurizer. Heat transfer was based on condensation in the steam region and natural convection in the condensate region. A fin-wall model was used to relate wall to fluid temperatures. An iterative procedure, Figure 4.2-5, was used to predict wall temperature distributions. Typical predictions, Figure 4.2-6, show an increase in wall temperature difference with distance from the pressurizer.

4.2.4 Thermal Stratification Loads

The PORV lines, unlike the Safety Injection lines in which the routings and line sizes were similar, have a variety of routings and line sizes. Routings for the plants considered are shown in Figure 4.2-7. Line diameters and schedules are listed in Table 4.2-1. Axial wall temperatures versus axial location away from the pressurizer, with the line assumed filled with subcooled water, are used as input for calculating plant-specific wall temperature distributions, for example Figure 4.2-7.

It was noted that the higher steam-water interface levels ($\theta > 90°$) have a greater effect on the wall ΔT. The higher the θ, the cooler the pipe bottom, and the greater the top-to-bottom temperature differential. This indicated that the assumption of a flat-interface steam would provide conservative results. Therefore, it was necessary to determine the value of the heat transfer rate that would result in highest ΔTs. Results similar to Figure 4.2-7, indicate that the highest ΔTs are obtained for values of θ between 150 and 160 and, more accurately, for a value of θ equal to 155°. Representative results for differences in top-to-bottom wall temperature are listed in Table 4.2-2.

4.2.5 Moments Due to Thermal Stratification

The ANSYS Computer Code, Version 5.0A, was used to evaluate the PSV, PORV and LTOP lines which are subjected to thermal stratification. In order to be modeled, each line was entered into the ANSYS Code as a series of straight runs, tees, reducers, valves and bends. These inputs are translated by ANSYS into a set of nodes and elements having the material properties and structural characteristics of the actual pipe segments.

For each line, two load cases are run: one linear thermal expansion case and one thermal stratification case. The linear thermal expansion case is considered to be the "benchmark" analysis and does not take into account the loads caused by thermal stratification. For all modeled lines, the temperatures of the pipe sections up to the first closed valve from the pressurizer were entered as a uniform temperature based on normal pressurizer steam operating conditions.

The thermal stratification load case was analyzed to determine the effect of top-to-bottom wall temperatures on the horizontally stratified sections of the piping. In place of where the uniform steam temperatures were originally applied, thermally stratified temperatures were applied to the horizontal sections of the model. Thermal anchor movements (i.e., rotations and displacements at the pressurizer) due to the thermal growth of the Pressurizer from ambient to normal operating conditions were also included. Depending on the location in the line, vertical sections were assumed to be either full of steam or full of water and, therefore, were not stratified.

A summary of these results comparing the stratified loads to the current linear expansion loads is presented in Tables 4.2-4 to 4.2-8 for each participant's piping system.

4.2.6 Plant Specific Analysis

From the results of this effort, it was concluded that the magnitude of the thermal stratified loads could be significant when compared to other design basis loads and that additional evaluation on the plant-specific basis may be necessary. Consequently, the effect of the moments resulting from thermal stratification should be evaluated on a plant specific basis as to their influence on current design basis (stress/fatigue) analyses and design code requirements. Attention should be given to the potential of spring hanger displacements exceeding travel limits (bottoming-out).

The methodology, used to calculate the stratified wall temperatures was based on data from a limited number of thermocouples from two line configurations. Temperatures based on this model are conservative. Thus, in cases where stress and fatigue allowables are exceeded, thermocouple data can be obtained on a plant-specific basis and used to substantiate an upper limit on the magnitude of any stratification, as well as on the affected length of a given run of piping.

Table 4.2-1
Participants in PORV Tasks

Task	Participant	Plants
773	Arizona Public Service	PVNGS 1,2,3
	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO2, WSES3
	Florida Power & Light	St. Lucie 1,2
	Maine Yankee	Maine Yankee
	Northeast Utilities	MP2
827	Arizona Public Service	PVNGS 1,2,3
	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO2, WSES3
	Florida Power & Light	St. Lucie 1,2
	Maine Yankee	Maine Yankee
	Northeast Utilities	MP2

Table 4.2-2
Summary of PORV/PSV Geometric Configurations

Participants:	BG&E		Entergy		FPL	MYAPCO	NU
1) PSV's							
Diameter (in.)	4		6		3	3	4
Schedule	120		160		160	160	120
Configuration Type	(1)		(2)		(3)	(4)	(1)
2) PORV or LTOP							
Diameter (in.)	4	2½	6	4	4	3	4
Schedule	120	160	120	120	160	160	120
Configuration Type	(5)		(6)		(7)	(7)	(8)

Description of configuration, by Type:

(1) From PRZ: a horizontal pipe with 2 "steps" to PSV (in vertical section); total distance to PSV is approximately 9 ft.
(2) PSVs mount directly to the vertical nozzles on top of the PRZ.
(3) From PRZ: a short vertical pipe to PSV.
(4) From PRZ: a short horizontal pipe (approximately 10 in.) to a 17 to 48 in. vertical pipe; configuration looks like a "step".
(5) From PRZ: a short horizontal pipe with 4 "steps" to the PORV; total distance to PORV is between 15 and 18 ft.
(6) From PRZ: approximately 4 ft. of vertical pipe to a 2 ft. horizontal section.
(7) From PRZ: a long horizontal pipe with a 2 ft. vertical pipe to a long horizontal section; total length is approximately 16 ft.
(8) From PRZ: a short vertical pipe to a 3 ft. 30° incline, to a 3 ft. horizontal pipe with a 29 in. vertical section and the PORV; total distance is approximately 10 ft.

Table 4.2-3
Wall Temperature Variation
for BG&E 4" Schedule 120, T_{prz} = 550°F

Axial Location [X/D]	Tcold °F (Table 10)	For heat transfer coefficient h_h=306, h_c=5.0		
		T_{top}	T_{bottom}	DT
1	473.1	547.0	494.4	52.6
2	409.3	545.0	455.1	89.9
3	356.6	543.4	422.8	120.6
4	312.6	542.0	395.7	146.3
5	276.2	540.9	373.4	167.6
6	246.1	540.0	354.9	185.1
7	221.1	539.2	339.5	199.7
8	200.4	538.6	326.8	211.8
9	183.2	538.0	316.2	221.8
10	169.0	537.6	307.5	230.1
11	157.2	537.2	300.2	237.0
12	147.4	536.9	294.2	242.7
13	139.3	536.7	289.2	247.5
14	132.6	536.5	285.1	251.4
15	127.0	536.3	281.7	254.6
16	122.4	536.2	278.8	257.3
17	118.6	536.0	276.5	259.5
18	115.4	535.9	274.5	261.4
19	112.8	535.9	272.9	262.9
20	110.6	535.8	271.6	264.2
21	108.8	535.7	270.5	265.3
22	107.3	535.7	269.6	266.1

Table 4.2-4
FP&L-1 PORV/PSV Thermal Loads Comparison

Location	Figure 1 (Attachment 2) Node Number	Moments (in-lbs)	Mx	My	Mz	Mt & M_{ratio}
PZR Nozzle	1	Thermal Expansion	7414	-3189	5965	10036
		Thermal Stratification	-495	-6122	81130	81362
		Ratio	-0.07	1.92	13.60	8.11
First TEE From Nozzle	8	Thermal Expansion	8085	-4225	21192	23072
		Thermal Stratification	12300	-9084	-11020	18848
		Ratio	1.52	2.15	-0.52	0.82
Reducer (EAST)	138	Thermal Expansion	-5512	571	-21192	21905
		Thermal Stratification	-10280	3634	11020	15502
		Ratio	1.86	6.36	-0.52	0.71
Elbow (East)	144	Thermal Expansion	-1184	-5108	-19101	19808
		Thermal Stratification	-6884	-5074	12660	15278
		Ratio	5.81	0.99	-0.66	0.77
Valve-1403 Outlet	36	Thermal Expansion	-1280	4579	7603	8967
		Thermal Stratification	-6076	11140	29010	31664
		Ratio	4.75	2.43	3.82	3.53
Valve-1405 Outlet	148	Thermal Expansion	-1184	1035	5525	5744
		Thermal Stratification	-6884	969	31130	31897
		Ratio	5.81	0.94	5.63	5.55
Elbow (East)	167	Thermal Expansion	9148	-10962	-16570	21873
		Thermal Stratification	12430	-16280	-38920	43981
		Ratio	1.36	1.49	2.35	2.01
Valve-1402 Outlet	74	Thermal Expansion	2108	-1395	6567	7037
		Thermal Stratification	52	-1830	21680	21757
		Ratio	0.02	1.31	3.30	3.09
Valve-1404 Outlet	174	Thermal Expansion	3085	13932	-160	14270
		Thermal Stratification	4590	20710	13960	25394
		Ratio	1.49	1.49	-87.38	1.78

Table 4.2-5
ANO-2 LTOP/PSV Thermal Loads Comparison

Location	Figure 2 (Attachment 2) Node Number	Moments (in-lbs)	Mx	My	Mz	Mt & M_{ratio}
PZR Nozzle	1	Thermal Expansion	44252	-16614	-29065	55489
		Thermal Stratification	40775	-24174	-34663	58724
		Ratio	0.92	1.46	1.19	1.06
First Tee From Nozzle	5	Thermal Expansion	-2915	-16614	-17640	24407
		Thermal Stratification	-21779	24174	-3917	32773
		Ratio	7.47	-1.46	0.22	1.34
Second Tee	16	Thermal Expansion	-2915	29547	14313	32960
		Thermal Stratification	-21779	26091	16689	37863
		Ratio	7.47	0.88	1.17	1.15
Hanger 2BCA-14-H11	29	Thermal Expansion	12895	4275	-10993	17476
		Thermal Stratification	-4906	-1042	-7182	8760
		Ratio	-0.38	-0.24	0.65	0.50
Hanger 2GCB-513-H1	36	Thermal Expansion	-4101	864	-7416	8518
		Thermal Stratification	-12522	-873	-5579	13736
		Ratio	3.05	-1.01	0.75	1.61
Hanger 2BCA-14-H6	67	Thermal Expansion	-5287	-12541	-7171	15383
		Thermal Stratification	10764	-9793	-5925	15712
		Ratio	-2.04	0.78	0.83	1.02
Hanger 2GCB-514-H1	71	Thermal Expansion	1239	95	-5020	5172
		Thermal Stratification	10938	1669	-5868	12524
		Ratio	8.83	17.54	1.17	2.42
Hanger 2FCC-2-H7	89	Thermal Expansion	-7515	15751	9928	20078
		Thermal Stratification	4402	13358	-143	14065
		Ratio	-0.59	0.85	-0.01	0.70
Hanger 2FCC-1-H21	210	Thermal Expansion	-4628	1627	5541	7400
		Thermal Stratification	-13829	1019	-1122	13912
		Ratio	2.99	0.63	-0.20	1.88

Table 4.2-6
MYAPCO - PORV Thermal Loads Comparison

Location	Figure 3 (Attachment 2) Node Number	Moments (in-lbs)	Mx	My	Mz	Mt & M_{ratio}
Relief Valve Nozzle	1	Thermal Expansion	4753	-1163	-1495	5116
		Thermal Stratification	-37763	-1320	13657	40178
		Ratio	-7.9	1.1	-9.1	7.85
Elbow @ SH-28	12	Thermal Expansion	-370	2051	-910	2274
		Thermal Stratification	-35879	5058	3020	36359
		Ratio	97.0	2.5	-3.3	15.99
SV-3004 Inlet	31	Thermal Expansion	-2945	-1368	2434	4058
		Thermal Stratification	14672	-3012	-9826	17913
		Ratio	-5.0	2.2	-4.0	4.41
SV-3004 Outlet	37	Thermal Expansion	4513	1368	-3532	5892
		Thermal Stratification	-6984	3012	1579	7768
		Ratio	-1.5	2.2	-0.4	1.32
Anchor H-7 (South)	110	Thermal Expansion	-11084	-4061	5661	13091
		Thermal Stratification	-17343	-28686	4310	33797
		Ratio	1.6	7.1	0.8	2.58
Elbow @ SH-24	160	Thermal Expansion	1776	-1702	695	2556
		Thermal Stratification	3456	-2761	2731	5198
		Ratio	1.9	1.6	3.9	2.03
SV-3005 Inlet	200	Thermal Expansion	-3912	1107	-114	4067
		Thermal Stratification	17309	2700	-2062	17639
		Ratio	-4.4	2.4	18.1	4.34
SV-3005 Outlet	206	Thermal Expansion	6287	-1107	-87	6384
		Thermal Stratification	-5580	-2700	3329	7036
		Ratio	-0.9	2.4	-38.3	1.10
Elbow @ SH-26	234	Thermal Expansion	150	-910	10192	10234
		Thermal Stratification	-27	-896	10159	10198
		Ratio	-0.2	1.0	1.0	1.00

Table 4.2-7
BG&E-2 PORV/PSV Thermal Loads Comparison

Location	Figure 4 (Attachment 2) Node Number	Moments (in-lbs)	Mx	My	Mz	Mt & M_{ratio}
PZR Nozzle	1	Thermal Expansion	-6803	23684	12325	27552
		Thermal Stratification	12223	33442	35017	49940
		Ratio	-1.8	1.4	2.8	1.81
1st Elbow From Nozzle	6	Thermal Expansion	12038	-29653	-11823	34117
		Thermal Stratification	-6840	-44682	-32218	55509
		Ratio	-0.6	1.5	2.7	1.63
Straight Run Stratified	12	Thermal Expansion	-10894	27561	3839	29884
		Thermal Stratification	4465	42092	11244	43796
		Ratio	-0.4	1.5	2.9	1.47
2nd Elbow	11	Thermal Expansion	-13852	30785	2024	33819
		Thermal Stratification	2342	47209	11923	48748
		Ratio	-0.17	1.5	5.9	1.44
3rd Elbow	16	Thermal Expansion	-2407	-13842	-19976	24422
		Thermal Stratification	-16067	-20319	-23689	35102
		Ratio	6.7	1.5	1.2	1.44
Tee	13	Thermal Expansion	-1638	-12507	2818	12925
		Thermal Stratification	-9770	-18200	19518	28419
		Ratio	6.0	1.5	6.9	2.20
Valve	19	Thermal Expansion	3741	-7279	-7032	10790
		Thermal Stratification	3224	-7228	465	7928
		Ratio	0.9	1.0	-0.07	0.73
Elbow	29	Thermal Expansion	-5816	17686	12871	22634
		Thermal Stratification	-2241	31220	12996	33891
		Ratio	0.4	1.8	1.0	1.50
Elbow	50	Thermal Expansion	13523	3630	-21747	25865
		Thermal Stratification	11669	7770	-24769	28461
		Ratio	0.9	2.1	1.1	1.10

Table 4.2-7 (Cont.)
BG&E-2 PORV/PSV Thermal Loads Comparison

Location	Figure 4 (Attachment 2) Node Number	Moments (in-lbs)	Mx	My	Mz	Mt & M_{ratio}
Elbow Stratified	59	Thermal Expansion	-17755	1385	9737	20297
		Thermal Stratification	-14776	7879	49385	52147
		Ratio	0.8	5.7	5.1	2.57
Straight Run Stratified	60	Thermal Expansion	19660	-2911	-14338	24507
		Thermal Stratification	16413	-10290	-53338	56747
		Ratio	0.8	3.5	3.7	2.32
Elbow Stratified	70	Thermal Expansion	4429	4064	18349	19309
		Thermal Stratification	4238	6230	56070	56574
		Ratio	1.0	1.5	3.0	2.93
Straight Run Stratified	80	Thermal Expansion	-5065	-5765	4671	8984
		Thermal Stratification	-3945	-7870	-23593	25182
		Ratio	0.8	1.4	-5.0	2.80
PORV Valve	88	Thermal Expansion	-4382	-4869	4777	8107
		Thermal Stratification	-2909	-6509	-16691	18150
		Ratio	0.7	1.3	-3.5	2.24
Elbow	85	Thermal Expansion	-5065	-5022	-15146	16741
		Thermal Stratification	-3945	-6741	-40619	41363
		Ratio	0.8	1.3	2.7	2.47
Tee	47	Thermal Expansion	2741	4171	-21711	22277
		Thermal Stratification	419	5450	-10977	12263
		Ratio	0.2	1.3	0.5	0.55
Elbow	119	Thermal Expansion	-40120	7495	2598	40897
		Thermal Stratification	-37890	7316	3200	38722
		Ratio	0.9	1.0	1.2	0.95
Anchor	127	Thermal Expansion	-28798	218	-4376	29129
		Thermal Stratification	-25117	-234	-4035	25440
		Ratio	0.9	-1.1	0.9	0.87

Table 4.2-8
NU - PORV/PSV Thermal Loads Comparison

Location	Figure 5 (Attachment 2) Node Number	Moments (in-lbs)	Mx	My	Mz	Mt & M_{ratio}
Relief Valve Nozzle	1	Thermal Expansion	9237	-8102	10498	16161
		Thermal Stratification	-3874	-41196	43040	59704
		Ratio	-0.4	5.1	4.1	3.69
RC-404 Inlet	25	Thermal Expansion	3289	-5274	5248	8135
		Thermal Stratification	-37	-8898	14772	17245
		Ratio	0.0	1.7	2.8	2.12
Reducer to RC-403	68	Thermal Expansion	-4768	411	-2643	5467
		Thermal Stratification	-1419	-1902	21313	21445
		Ratio	0.3	-4.6	-8.1	3.92
RC-402 Inlet	77	Thermal Expansion	3395	-579	876	3554
		Thermal Stratification	2200	-6011	-4692	7937
		Ratio	0.6	10.4	-5.4	2.23
RC-200 Inlet	135	Thermal Expansion	5743	-1466	870	5991
		Thermal Stratification	396	-1368	2487	2865
		Ratio	0.1	0.9	2.9	0.48
Nozzle (RC-200)	160	Thermal Expansion	5755	-3859	6245	9328
		Thermal Stratification	3140	-4377	8180	9794
		Ratio	0.5	1.1	1.3	1.05
RC-201 Inlet	198	Thermal Expansion	-10079	3230	-6273	12303
		Thermal Stratification	-2512	4251	-5966	7745
		Ratio	0.2	1.3	1.0	0.63
Nozzle (RC-201)	220	Thermal Expansion	15171	5029	7627	17709
		Thermal Stratification	19993	7735	10650	23937
		Ratio	1.3	1.5	1.4	1.35
Element @ PSVH-30/31	225	Thermal Expansion	64813	-14547	-80455	104325
		Thermal Stratification	56184	-13761	-70975	91561
		Ratio	0.9	0.9	0.9	0.88

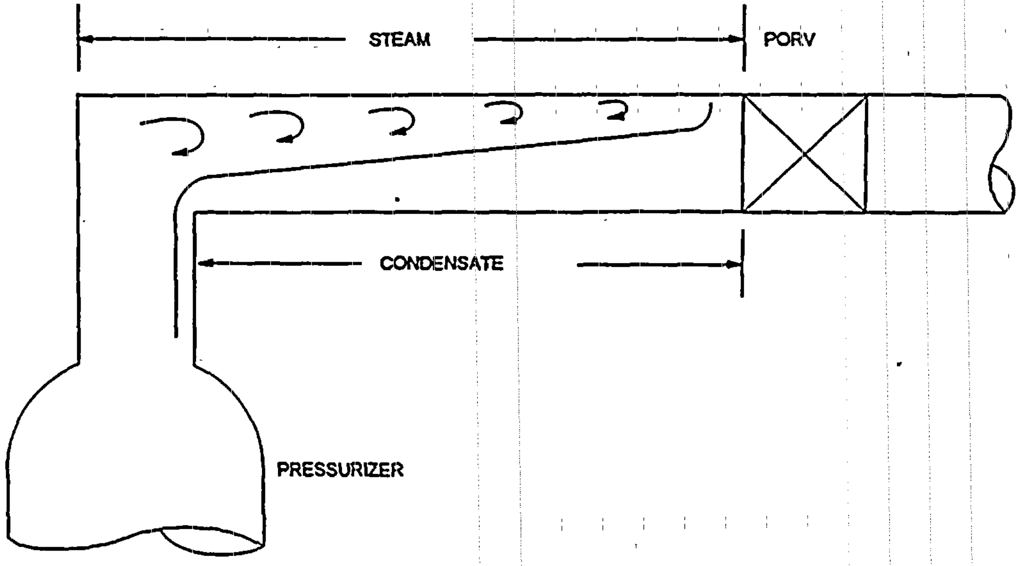


Figure 4.2-1 Thermal Stratification in PORV Lines

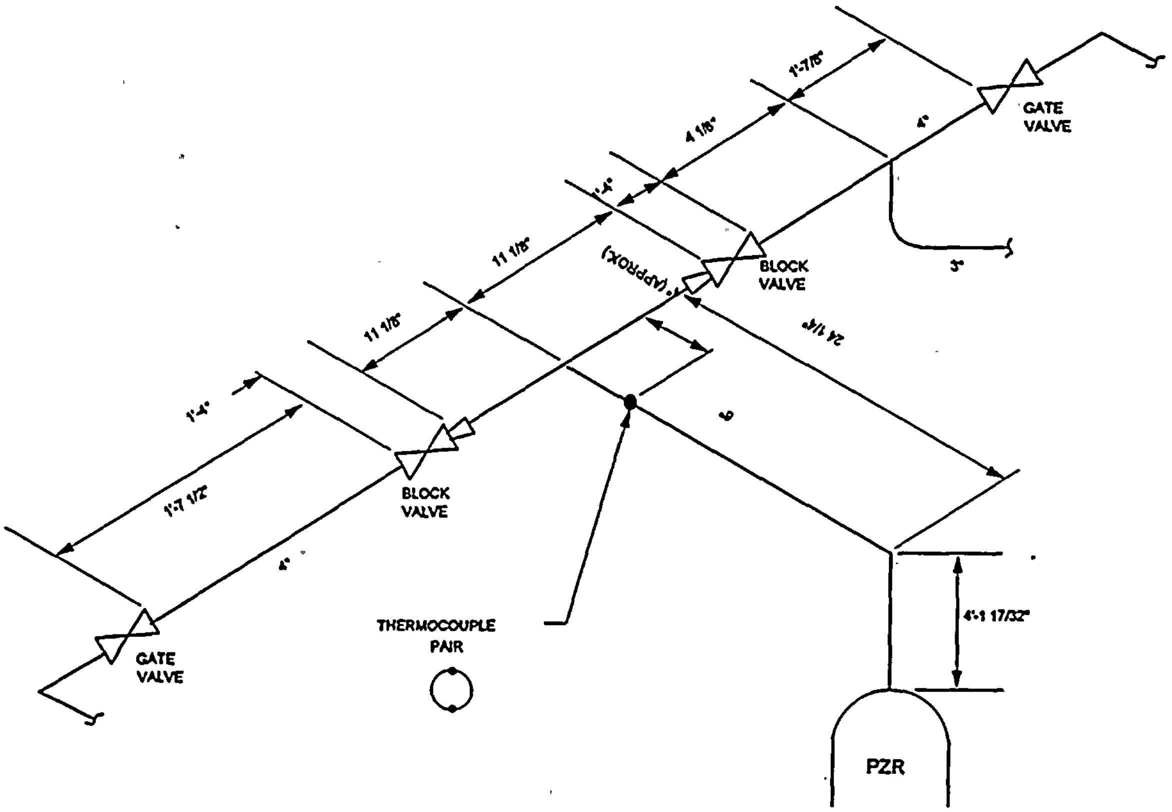
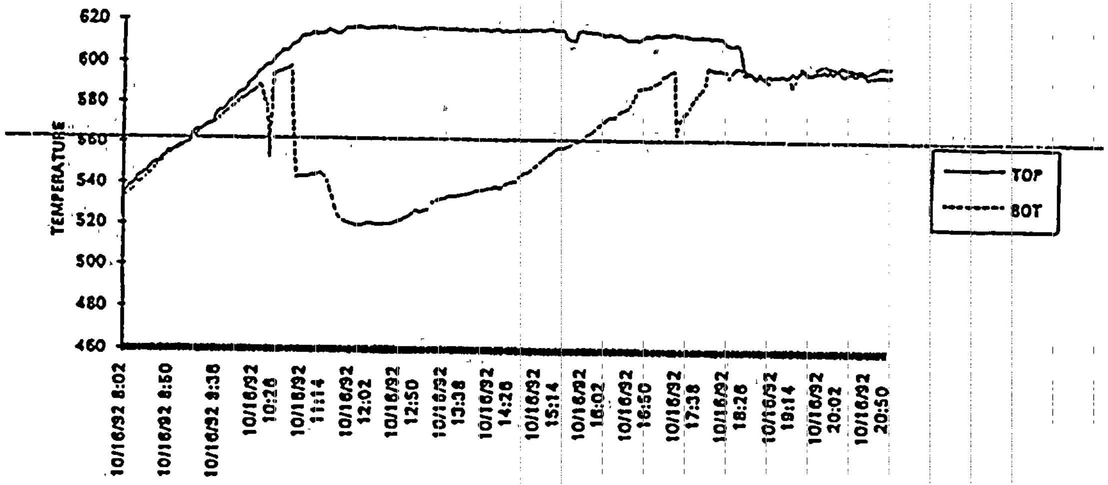
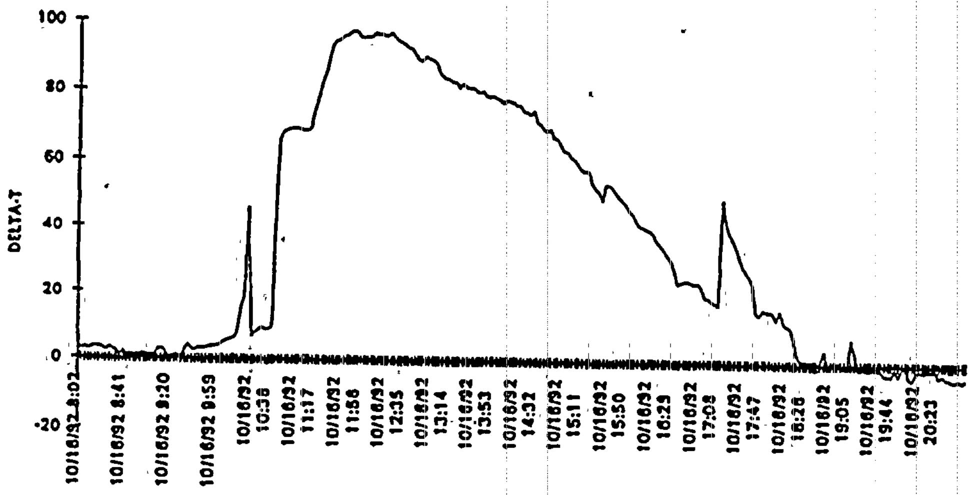


Figure 4.2-2 Instrumented Location on ANO2 Pressure Operated Relief Valve Line



Wall Temperature



Difference in Top and Bottom Temperatures

Figure 4.2-3 ANO2 PORV Line Wall Temperature vs Time During Plant Heat Up

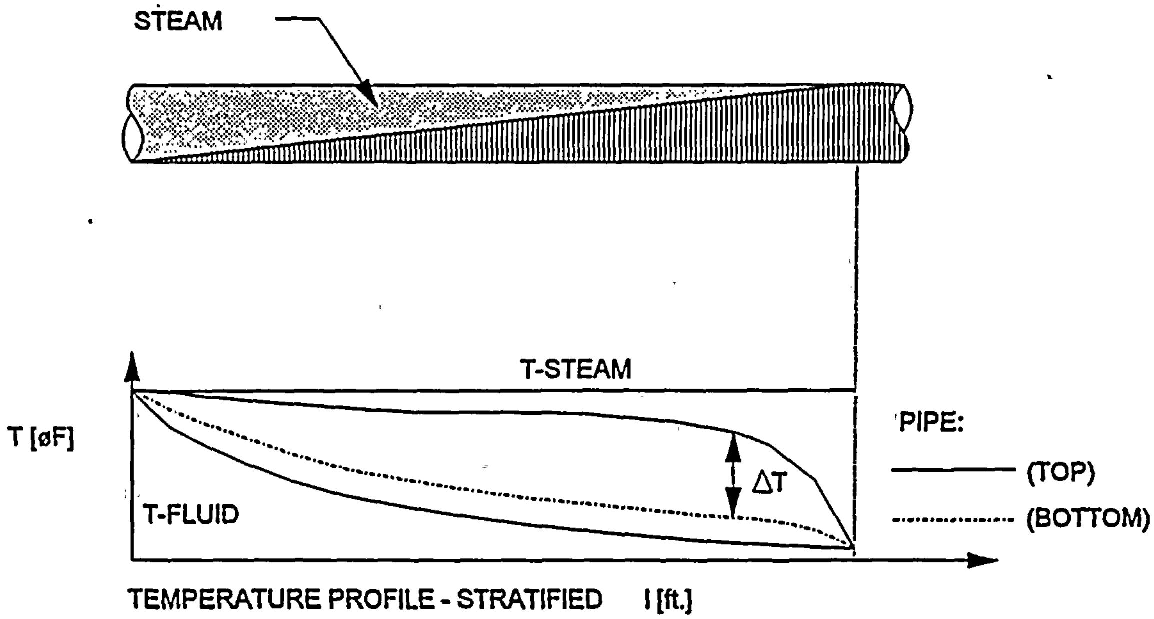


Figure 4.2-4 Model for Two Phase Flow in PORV Lines

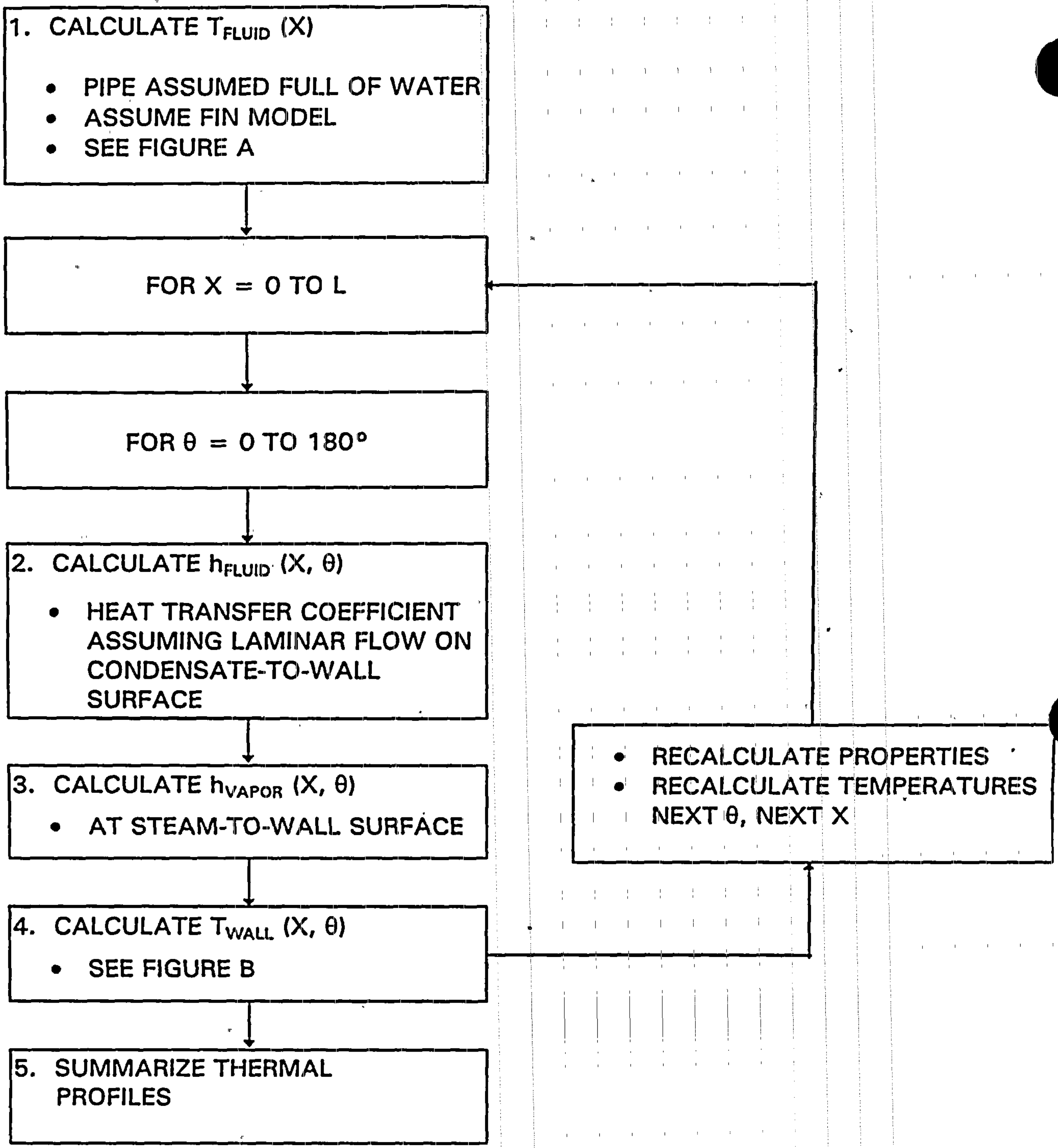


Figure 4.2-5 Procedure for Calculating Fluid and Wall Temperatures for PORV Lines

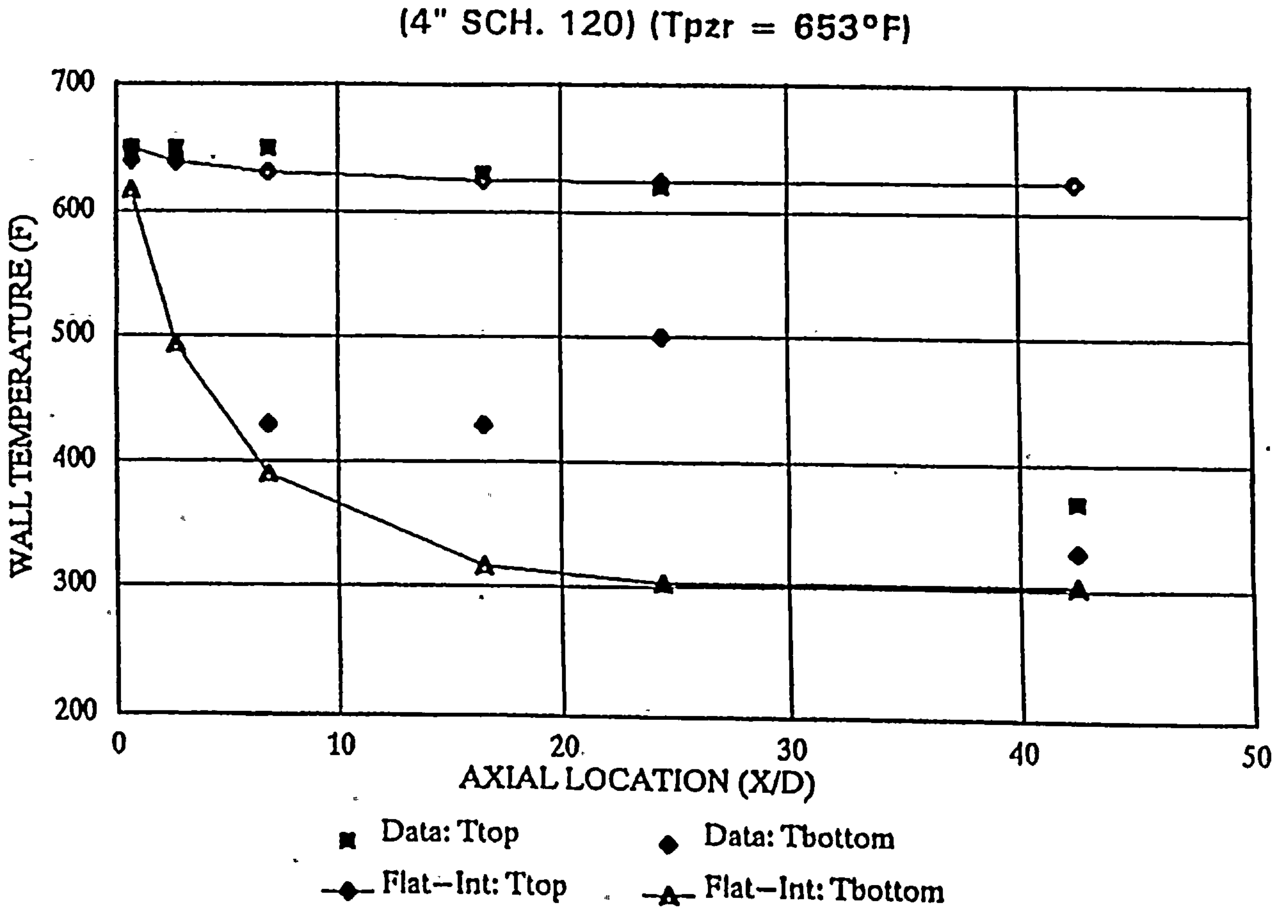
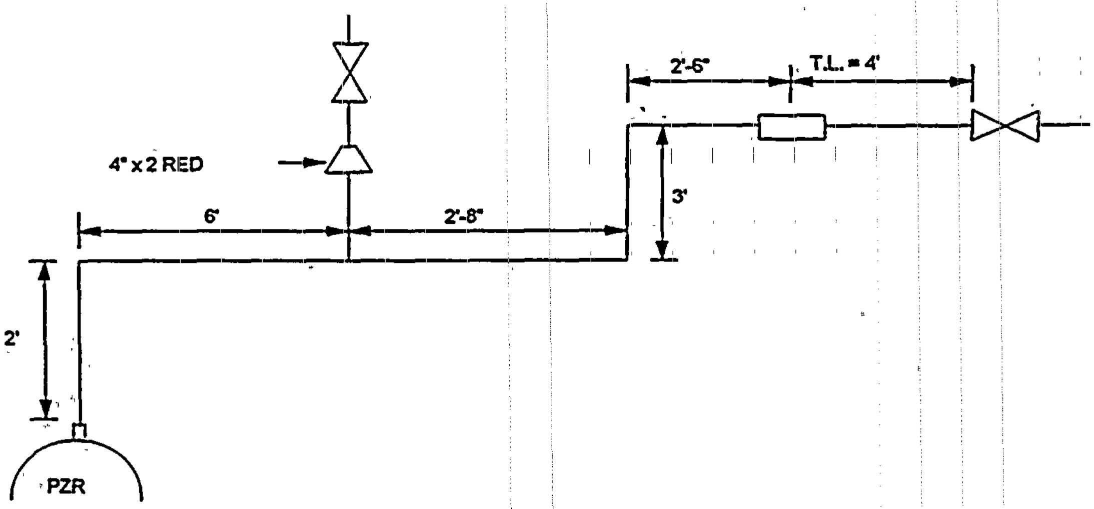


Figure 4.2-6 Wall Temperature Predictions

BG&E CALVERT CLIFFS UNIT 1



BG&E CALVERT CLIFFS UNIT 2

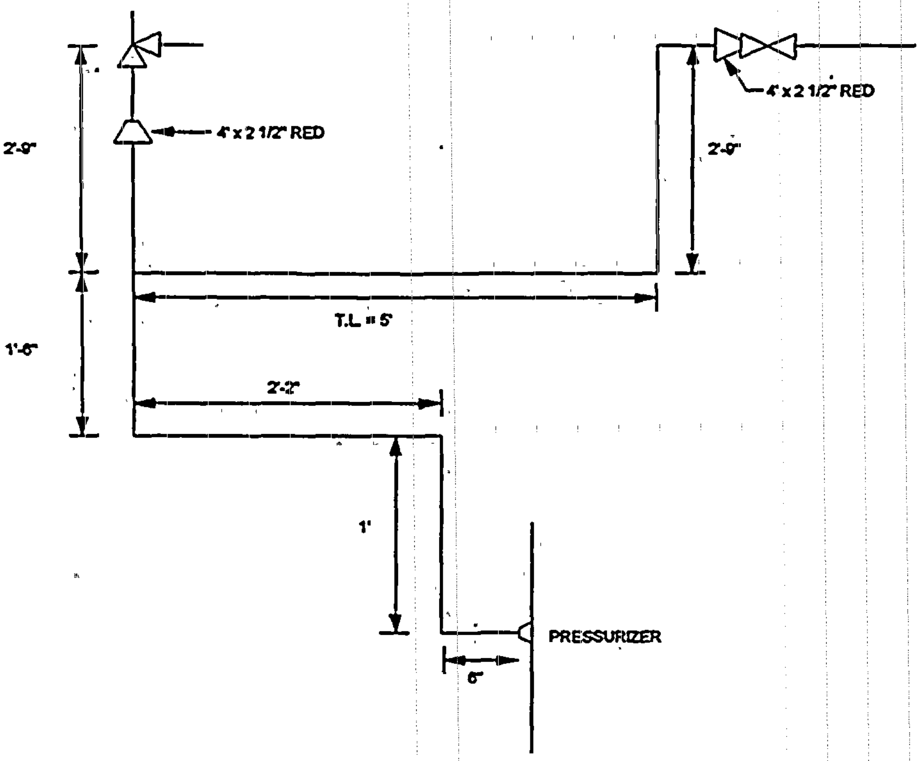


Figure 4.2-7 PORV Line Configurations

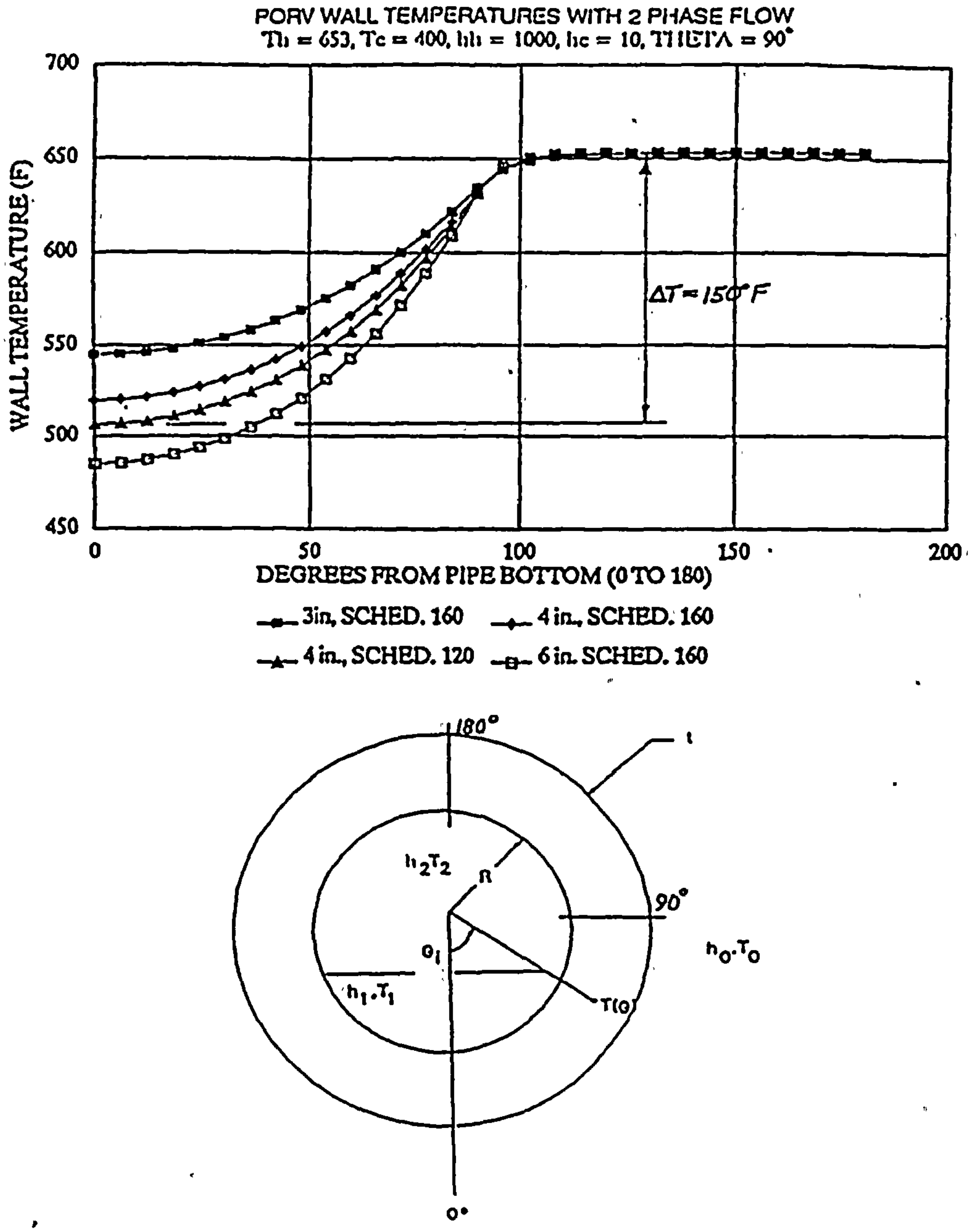
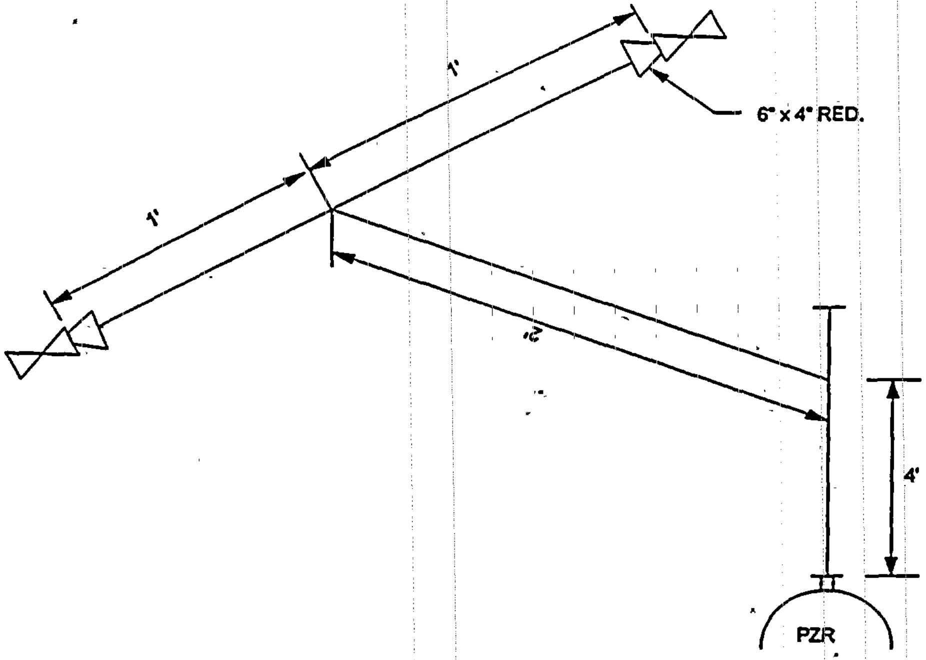
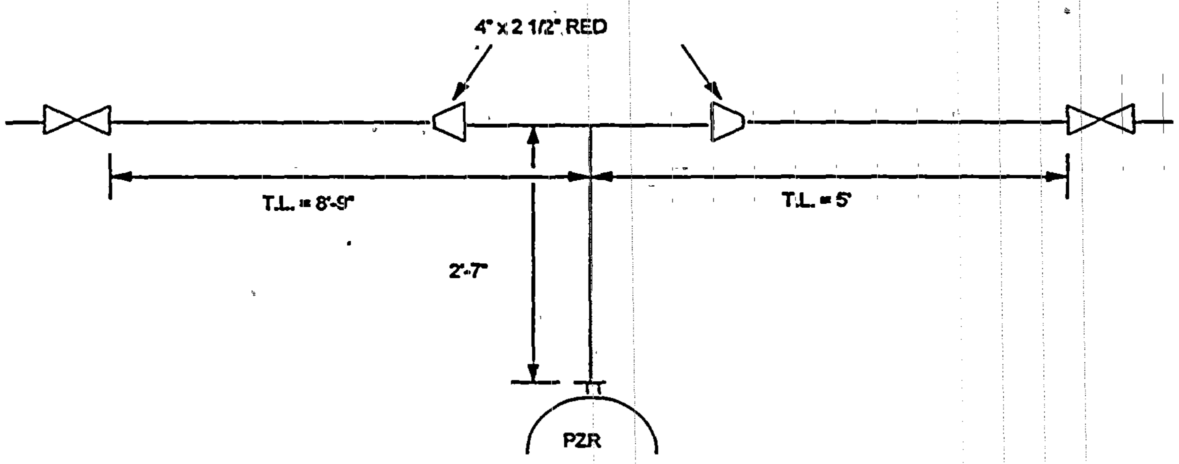


Figure 4.2-8 Predictions for Circumferential Variation in PORV Wall Temperatures

ARKANSAS NUCLEAR ONE UNIT 2



FP&L ST. LUCIE UNIT 1



4.3 Shutdown Cooling System Lines

Evaluation of the results for the BG&E line (Reference CEOG-8) indicated no thermal stratification in the shutdown cooling line. However, subsequent measurements at ANO2 (Reference 6) indicated large differences in top to bottom wall temperatures with operating conditions. Thermal stratification in the shutdown cooling line was found to be related the variation of turbulent penetration length with operating conditions upsetting the equilibrium in the natural convection driven heat transfer in the horizontal sections of the line downstream of the turbulent penetration (Reference CEOG-17). The time required to re-establish a new equilibrium pattern resulted in a lag in the cooler fluid temperatures at the bottom of the line as compared with the hotter temperatures at the top. This lag was the cause of the differences in wall temperatures. A schematic of the SDC arrangement showing the turbulent penetration and natural convection that exist during steady state, are shown in Figure 4.3-1.

The maximum differences in wall temperatures (345°F) measured for the SDC line at ANO2 were larger than those measured in the surge line (300248F). Thus, whereas the surge line results had been used as a basis for the Justification for Continued Operation (JCO) for the Safety Injection and PORV lines, a new JCO was necessary for the SDC lines. This JCO was based on a stress and fatigue analysis based on what was assumed to be a conservative distribution of wall temperatures, based on the ANO2 measurements. Support for the JCO, documented in Appendix D, was to be based on the moments resulting from thermal stratification loads done under CEOG Task 772.

In a subsequent program, CEOG Task 813, a model was developed to predict wall temperatures and to ascertain if the wall temperature distributions assumed in CEOG Task 772 bounded those based on the predictive model.

The participants in these two tasks are listed in Table 4.3-1.

4.3.1 Geometry And Routing

The shutdown cooling line is used during refueling to remove decay heat from the core. This line runs from the SDC nozzle, oriented in a vertical down position on the RCS hot leg, to the suction side of the Low Pressure Safety Injection (LPSI) pumps. The line consists of a number of long (L/D >1) horizontal and vertical runs with nominal diameters of from 12 to 16 inches and a 140 Schedule. The line, during normal operation, is isolated from the LPSI pumps by a motor operated valve, located between 20-30 diameters from the SI injection nozzle. RCS fluid temperatures vary from about 600°F during full power operation to containment temperature at the MOV locations.

4.3.2 Wall Temperatures

Two SDC line arrangements are shown in Figure 4.3-2. Both lines have long horizontal runs which, for ANO-2, starts at L/D = 16 and for PVNGS at L/D = 20. Both lines were instrumented at the locations shown. Representative values of wall temperature vs time during heatup (Figure 4.3-3) show evidence of a change in characteristics at the point at which four pump operation is initiated. However, whereas all the top thermocouples for ANO-2 show a marked increase in temperature, in PVNGS only those in the vertical section at an L/D = 15 indicate this increase in temperature.

The axial variation in top and bottom wall temperatures, Figure 4.3-4, show a large difference in wall temperatures prior to four pump operation. However, initiation of four pump operation results in a large difference in top-to-bottom wall temperatures for ANO-2 but only a minor change for PVNGS.

4.3.3 Model

Though the details are not well understood, turbulent penetration has been defined as the mechanism by which momentum and energy are transferred from a main flow to the secondary flow in a branch line. The L/D of branch line to which this transfer takes place has been placed at about 15-25 based on the isothermal tests reported by EPRI (Reference 2).

Work by Robert and Mattei (Reference 3) and Robert (Reference 4) describes the complex, three dimensional flow pattern and the non-isotropic nature of the turbulence for the non-isothermal tests performed. Noted is the almost abrupt change in fluid temperature at the limit of the thermal turbulent penetration length. As noted by Robert, (Reference 4) this length maybe related to a global Richardson number, defined by Turner (Reference 5) as,

$$Ri = \frac{g\beta(T_o - T_\infty)}{V_x^2}$$

where β is the coefficient of thermal expansion, T_o the temperature of the main flow, T_∞ a reference temperature, and V_x the local velocity at axial location x in the line. The relationship between the local velocity and the velocity, v_o , in the main line, using the EPRI (Reference 2) data, can be expressed as,

$$\frac{V_x}{V_o} \cong \frac{1}{(x/D)^p}$$

Taking the turbulent penetration distance, L_{tp}, as the axial location where the abrupt change from main to branch line temperature is noted, the expression for Richardson number is re-written as,

$$\frac{L_{tp}}{D} \cong \frac{g\beta(T_o - T_\infty)}{V_o^2}$$

The data from Lubin, et al., (Reference 12) and ANO2 and PVNGS are shown in Figure 4.3-5 as a function of Richardson number. This relationship implies that an increase in RCS velocity, V_o, will result in an increase in penetration distance.

This relationship also agrees with the observations reported by Lubin and Hammer (Reference 6) of the change in wall temperature difference with an increase or decrease in RCS temperature.

A one-dimensional model, Figure 4.3-6, was formulated that assumed conduction through the fluid as the primary mode of heat transfer past the turbulent penetration distance. The effect of a change in turbulent penetration length due to a change in operating condition was assumed to disrupt the existing natural convection pattern in the horizontal section. Predictions based on this model and compared to data are shown in Figure 4.3-7.

4.3.4 Thermal Stratification Loads

The structural evaluation was based on what was assumed to be conservative values of thermal stratification loads. Based on the limited set of data available at the time of the analysis, it was assumed that thermal stratification resulted in a constant difference in top-to-bottom wall temperatures and that this difference was uniform over the first horizontal section of the line. Further more, based on the observation that the bottom wall temperatures stayed almost constant while the top temperature could vary , thermal stratification loads were taken over a range of temperatures for the hotter (top) fluid and a constant colder (bottom) fluid.

SDC line routings were similar in that the initial nozzle, vertical and horizontal sections were then followed by either the MOVs or a vertical up or down section. Line configurations were divided into the three classifications, and plant within these classifications, defined as (Figure 4.3-8):

Class A	Short vertical section followed by a short horizontal section terminating at the center of the second valve (BG&E, MYAC, OPPD).
Class B	Two or more short vertical sections followed by short and long horizontal sections terminating at the valve (FP&L, Entergy WSES-3).
Class C	Short vertical section followed by a long horizontal section (ANO-2, PVNGS).

Wall temperature distributions assumed for the structural analysis are also shown in Figure 4.3-9.

Test results showed that thermal stratification in the SDC lines occurred only in the horizontal sections downstream of the turbulent penetration distance. Furthermore, the distribution in fluid and, thus, wall temperature differences are not strongly dependent on axial distance along the line. The maximum differences in fluid and, assuming infinite heat transfer coefficients, wall temperature were found to be the difference in RCS and ambient temperature. However, test results showed that the variation in wall temperature was dependent on the number of operating pumps. However, changes in wall temperature were evident with changes in RCS temperature that could occur without a change in pump operation. These data showed that while the top temperature could vary the bottom temperature remained close to the cold sink (ambient) temperature. Thus thermal stratification loads were taken over a range of temperatures for the hotter (top) fluid and a constant colder (bottom) fluid. Wall temperature distributions assumed for the structural analysis are also shown in Figure 4.3-9.

4.3.5 Moments Due to Thermal Stratification

The criteria for bending moments due to thermal stratification indicates an increase in the moment with the length of line over which the stratification occurs. Thus, Class C lines should have the highest moments. ANSYS models were done for all three line classifications. The routings were based on: Maine Yankee for Class A, WSE-3 for Class B and ANO-2 for Class C.

The analysis included consideration of linear thermal expansion, thermal stratification and the combined linear expansion and thermal stratification. Results, Table 4.3-1 show that thermal stratification moments can be higher than linear thermal expansion. The variation in moment with thermal stratification load is shown in Figure 4.3-10.

4.3.5.1 Justification of Assumed Thermal Stratification Loads

Test results showed that thermal stratification in the SDC lines occurred only in the horizontal sections downstream of the turbulent penetration distance. Furthermore, the distribution in fluid and thus wall temperature differences is not strongly dependent on axial distance along the line. The maximum differences in fluid and, assuming infinite heat transfer coefficients, wall temperature were found to be the difference in RCS and ambient temperature. Test results showed that the variation in wall temperature was dependent on the number of operating pumps. The maximum difference in wall temperatures occurred under four pump operation. In these conditions the turbulent penetration length reaches its largest value due to the RCS velocity being the highest, of about 15 diameters into the line.

Plants with a combined vertical and horizontal length of pipe less than 15 diameters to the MOV, turbulent penetration will reach the valve mixing the fluid and eliminating therma stratification.

Plants with vertical and horizontal length of pipe greater than 15 diameters may have thermal stratification if the penetration can extend on partially into either the first or second horizontal sections.

Based on these subsequent observations, the plants with lines categorized as Class A , the turbulent penetration should mix with any cooler fluid, resulting in little or no stratification. Thus, the assumed loads are clearly conservative.

Plants within Class B only differ from Class A in having a vertical rise after the first vertical and horizontal sections. These being between 11 and 16 diameters in length, as with Class A, turbulent penetration should mix with cooler fluid resulting in little or no stratification. Here again, the assumed thermal stratification loads are conservative.

Plants within Class C include only ANO2 and APS, the plants upon which the measurement program was done. ANO2, having the vertical and horizontal sections of about 27 diameters in length, the turbulent penetration cannot extend the full length of these sections, thus resulting in the stratification measured. However, APS with the vertical and horizontal section only about 13 diameters in length, the turbulent penetration can mix with the fluid to the next vertical section where the fluid can be stable in the vertical direction. Hence the stratification loads assumed for ANO2 are realistic while for APS can be considered conservative.

4.3.5.2 Bounding Calculation of Usage Factor to Support JCO

A fatigue usage factor was calculated, based on two assumptions, that was used in the analysis supporting the JCO for the participating plants. The first assumption, confirmed in Task 813, was that the temperature differences recorded at ANO2 would be the upper bound for subsequent measurements. It was further assumed that the routing of the SDC line at ANO2 represented in bounding configuration in that its stiffness was such that it would result in the largest values of stratification loads. This was based on the observation that the horizontal length subject to stratification was for the lines in Class C, bounded by ANO2. The second assumption was that the contribution to the usage factor for the remaining design basis loads are of a magnitude similar to those for ANO2.

Stratification in the SDC line was observed to occur with changes in hot leg flow and/or temperature. The fatigue usage was calculated based on the number of plant heat-ups and cool downs as well as reductions in power, including trips. The number of expected cycles for 40 years of operation :e.g. 210 total for heatups plus cooldowns and 1292 reductions in power, were based on extrapolation of the operating data for ANO2.

The current design basis usage factor of .398 was increased to .704 with the inclusion of the above thermal stratification events. The difference of .306 can be linearly prorated by participants and added to current design basis usage factor for these events. A more accurate estimate could also be obtained using the moments associated with the classification of the SDC line for the specific plant.

4.3.6 Plant Specific Calculations

Based on the methodology provided, the participants that did not instrument their lines could calculate the stratified temperatures which may be occurring in their SDC piping systems, based on the operating conditions and line configurations of their plants. These could be in plant specific analysis.

As an alternative, the values of moments based on the Class A, B and C analyses could be used to determine how these compare with other design basis loads. These comparisons, along with the margins in stress levels and usage factor can be used to judge the importance of thermal stratification loads.

Table 4.3-1
Participants in SDC Tasks

Task	Participant	Plants
772	Arizona Public Service	PVNGS 1,2,3
	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO2, WSES3
	Florida Power & Light	St. Lucie 1,2
	Maine Yankee	Maine Yankee
	Omaha Public Power Dist	FCNS
813	Arizona Public Service	PVNGS 1,2,3
	Entergy Operations	ANO2, WSES3
	Florida Power & Light	St. Lucie 1,2
	Omaha Public Power Dist	FCNS

Table 4.3-2
Forces and Moments for SDC Line Classifications vs Thermal Stratification Loads

Summary results: Classes A, B & C							
		Thermal Expansion			Thermal Expansion & Stratification		
Case	Node No.	Mxo (in-lbf)	Myo (in-lbf)	Mzo (in-lbf)	M_x (in-lbs)	M_y (in-lbs)	M_z (in-lbs)
A_{400}	2	67708	77307	-172931	-1,209,745	-31,682	2,190,801
A_{350}	2	-1033713	-19907	182079	-1,033,714	-19,907	1,820,790
A_{250}	2	66835	84707	-170581	-712,839	6,133	1,241,648
A_{150}	2	66230	89561	-169091	-385,574	31,238	705,193
B_{400}	5	1710	5581	481961	2,678	7,799	-1,897,630
B_{350}	5	1510	5567	496068	2,216	7,855	-1,580,723
B_{250}	5	1115	5540	524174	1,303	7,957	-959,195
B_{150}	8	-7266	6779	-847601	-6,413	9,100	-471,321
C_{400}	2	-147457	112904	18256	-2,376,374	303,922	1,348,784
C_{350}	2	-143304	106537	16079	-2,112,858	286,141	1,183,736
C_{250}	2	-135104	94016	11774	-1,598,426	252,372	862,979
C_{150}	2	-127016	81723	7525	-1,103,437	218,971	554,728

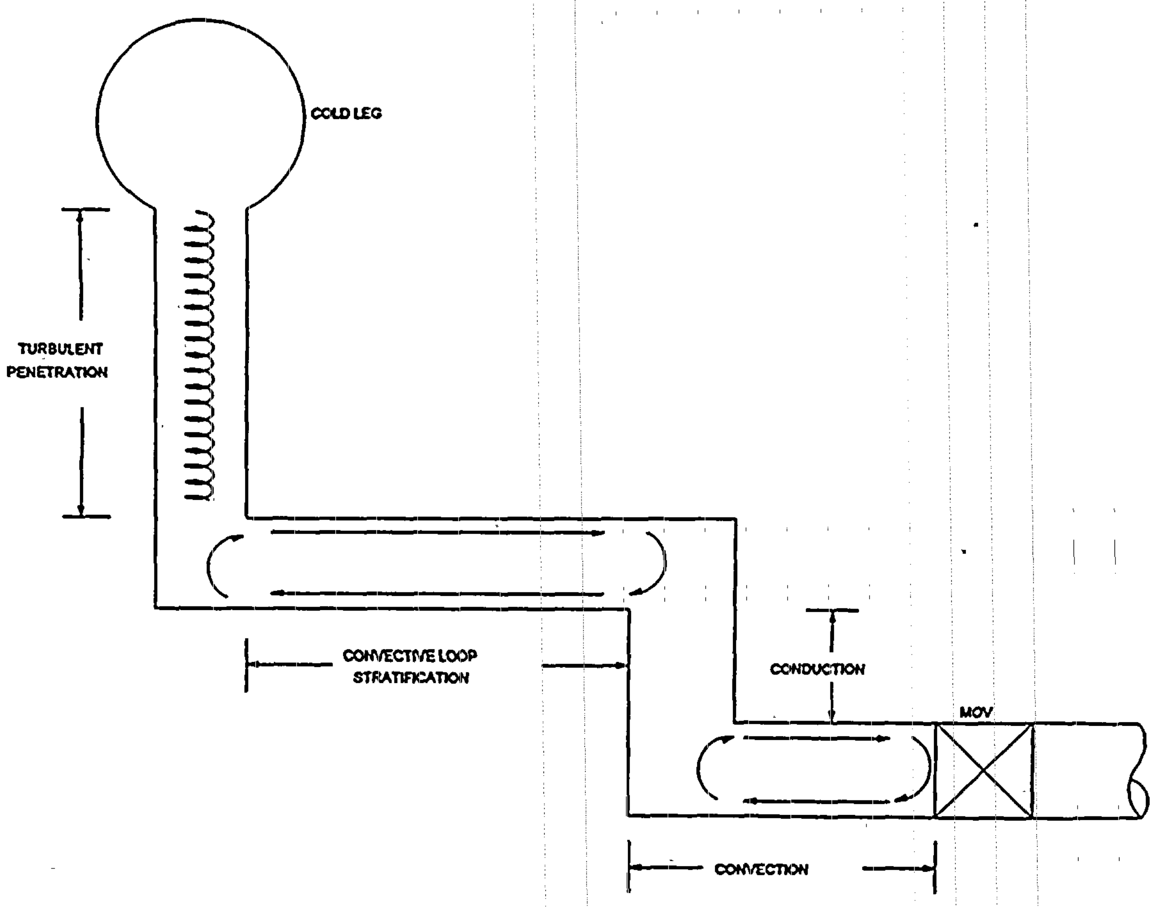


Figure 4.3-1 Thermal Stratification in Shutdown Cooling Lines

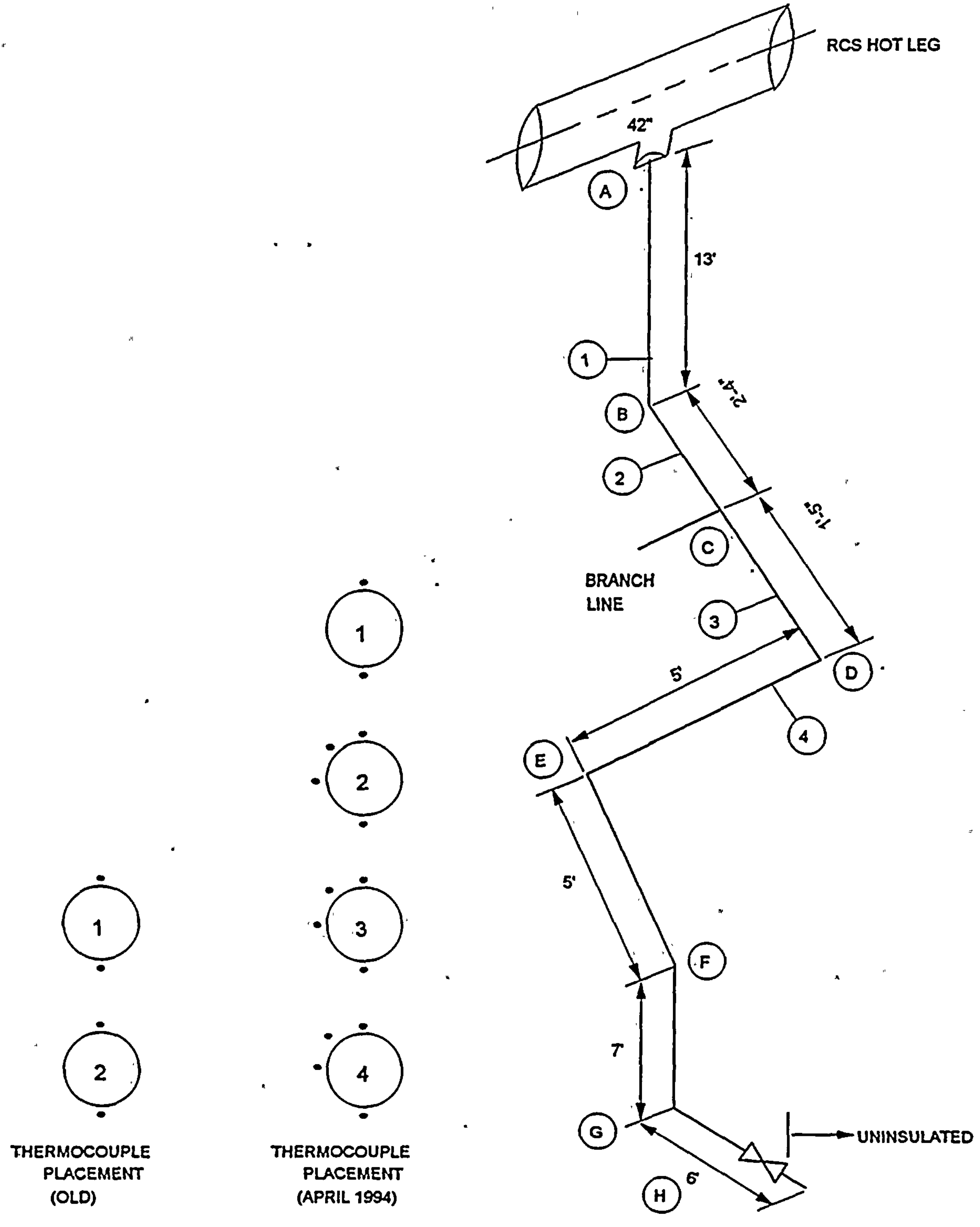
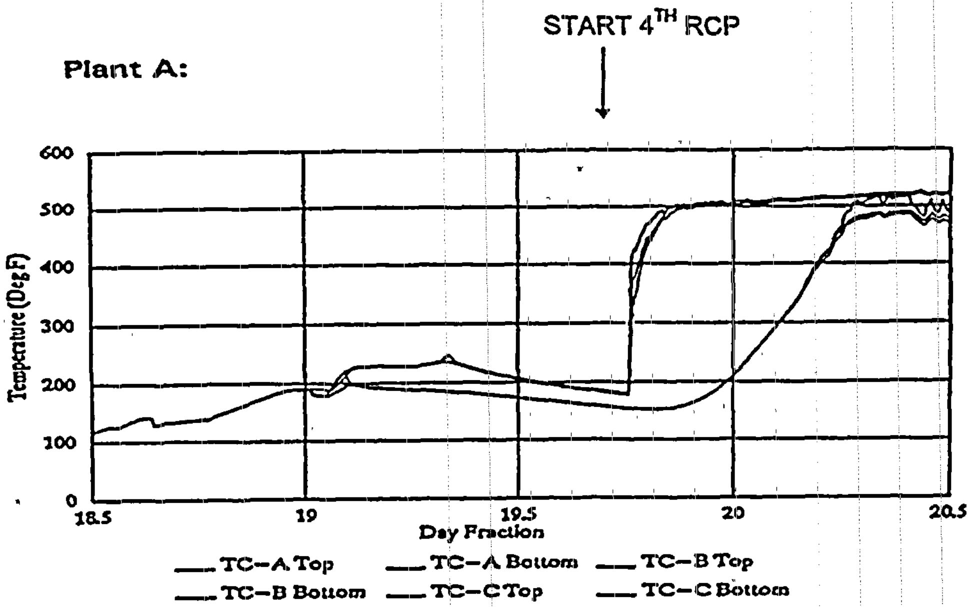


Figure 4.3-2 Instrumented Locations on Shutdown Cooling Lines - ANO-2

Plant A:



Plant B:

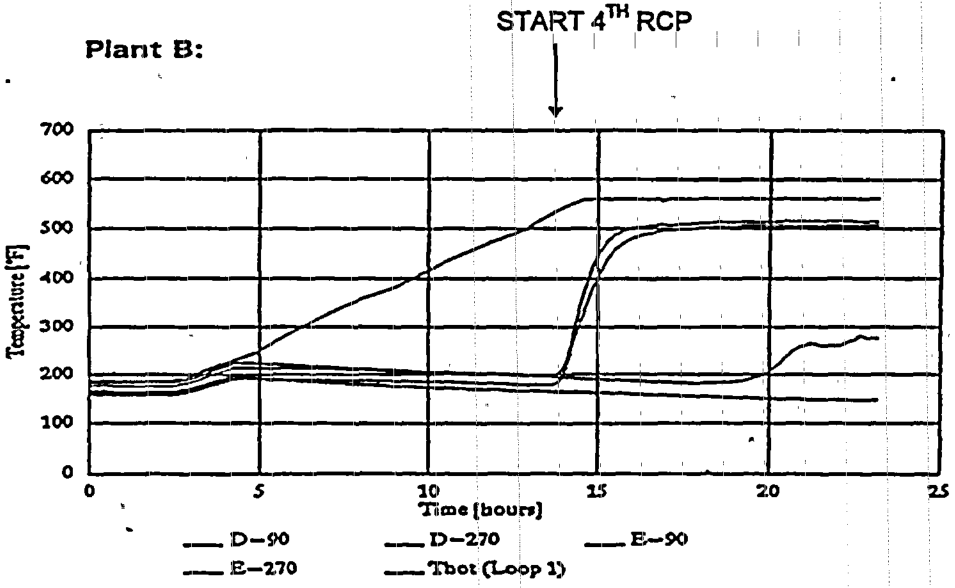


Figure 4.3-3 SDC Lines Wall Temperature vs Time during Heat Up

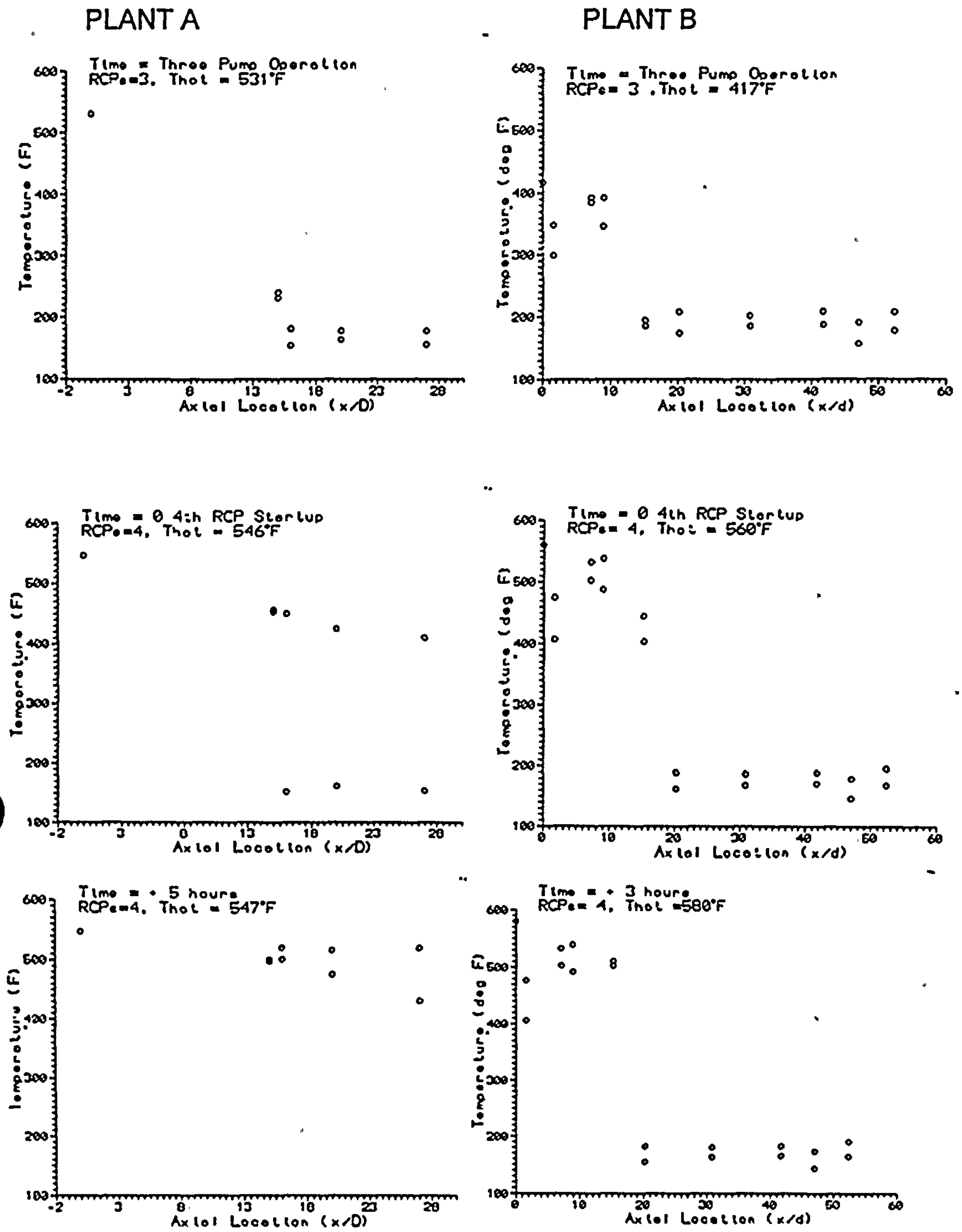


Figure 4.3-4 Wall Temperatures at Top and Bottom Locations vs Axial Location; Three to Four Pump Operation During Heatup

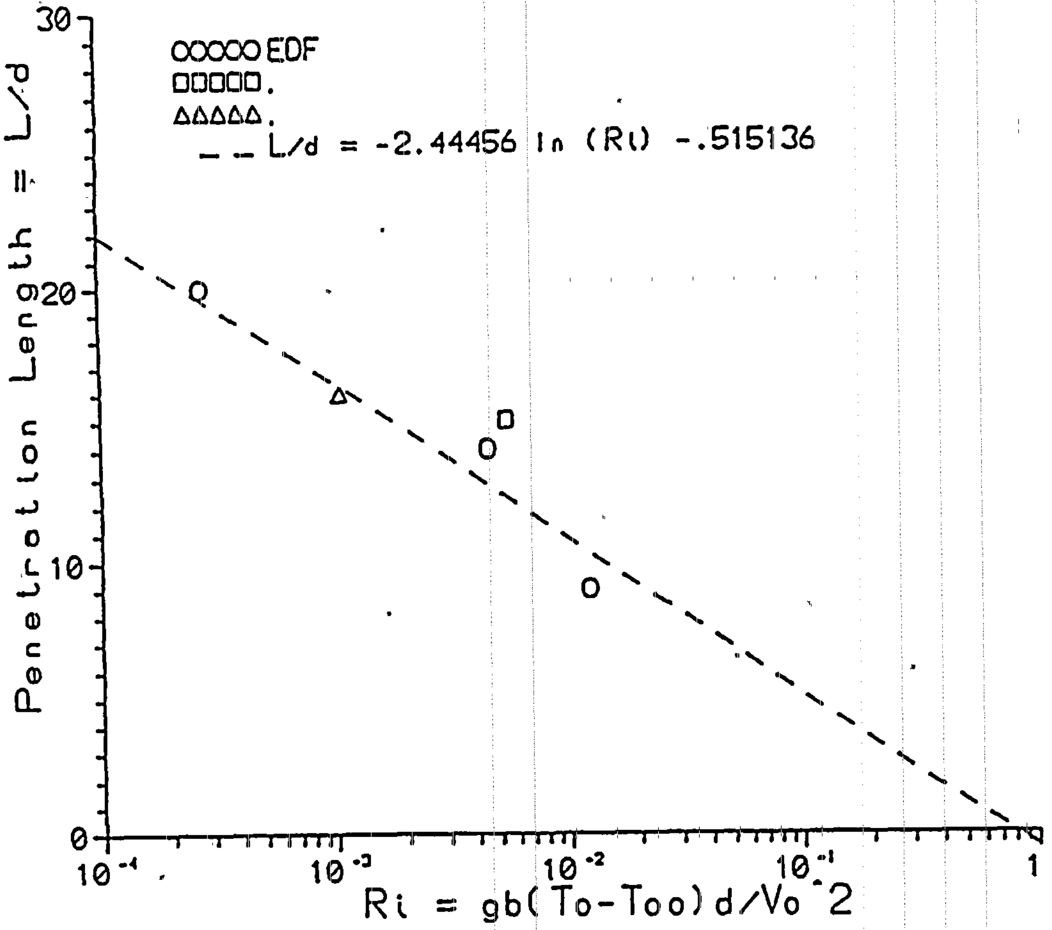


Figure 4.3-5 Turbulent Penetration Length vs Richardson Number

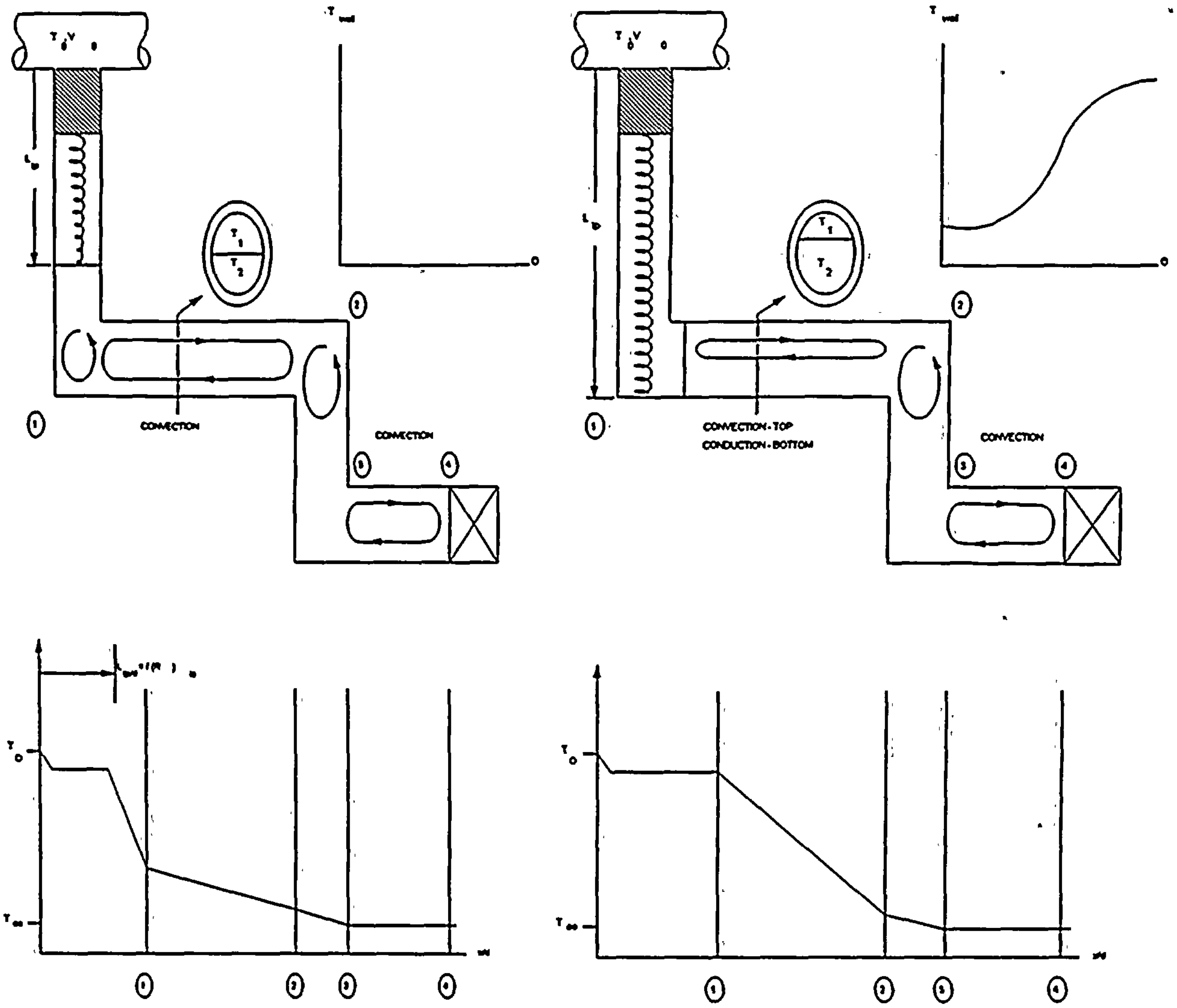
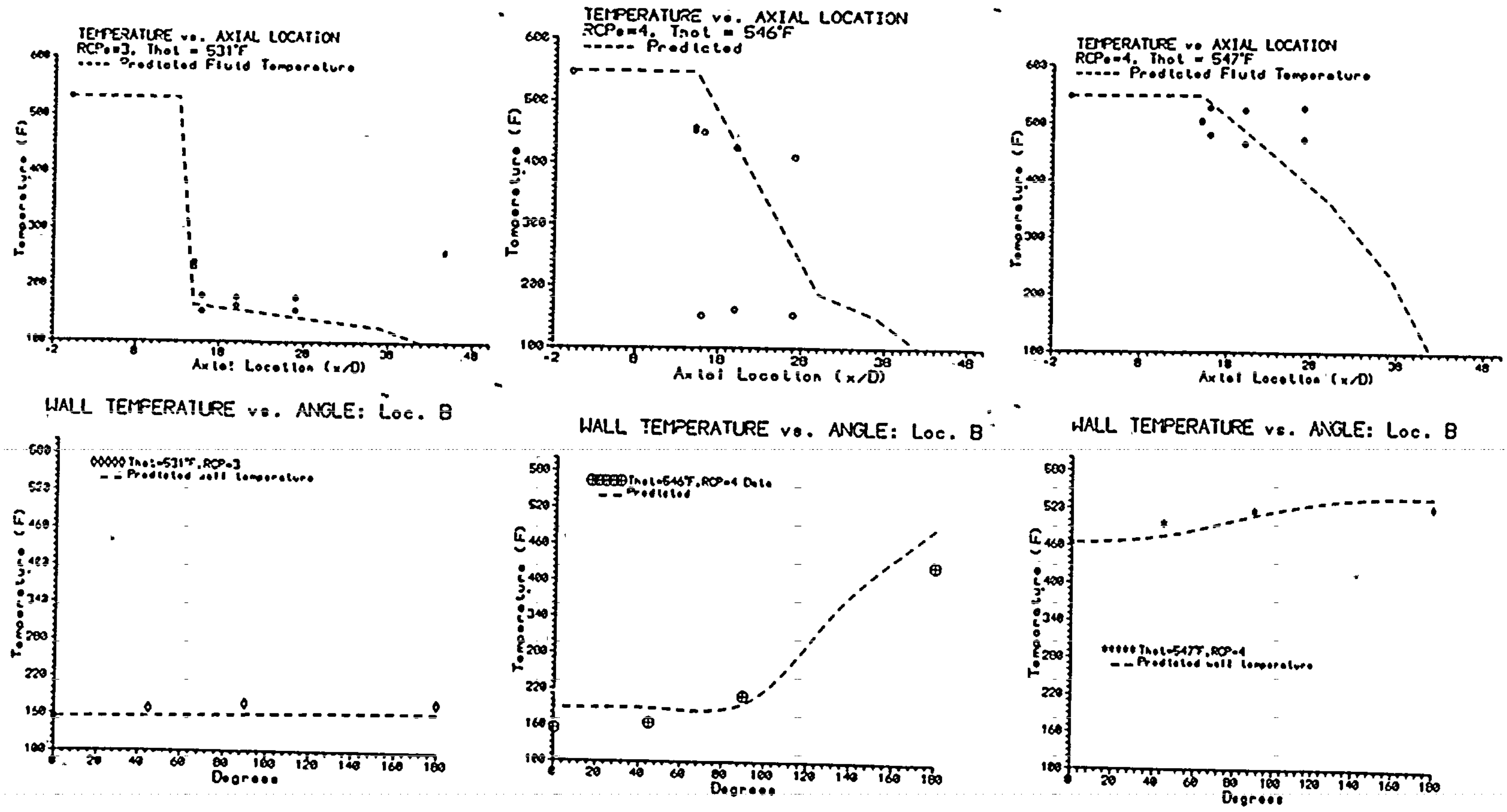


Figure 4.3-6 Model for Prediction of Wall Temperatures with Change in Turbulent Penetration Length



Steady State :
Three Pump Operation

Change in Operating Conditiopn:
Turn on Fourth Pump

Steady State:
Four Pump Operation

Figure 4.3-7 Predictions and Data; Wall Temperature vs Axial Location

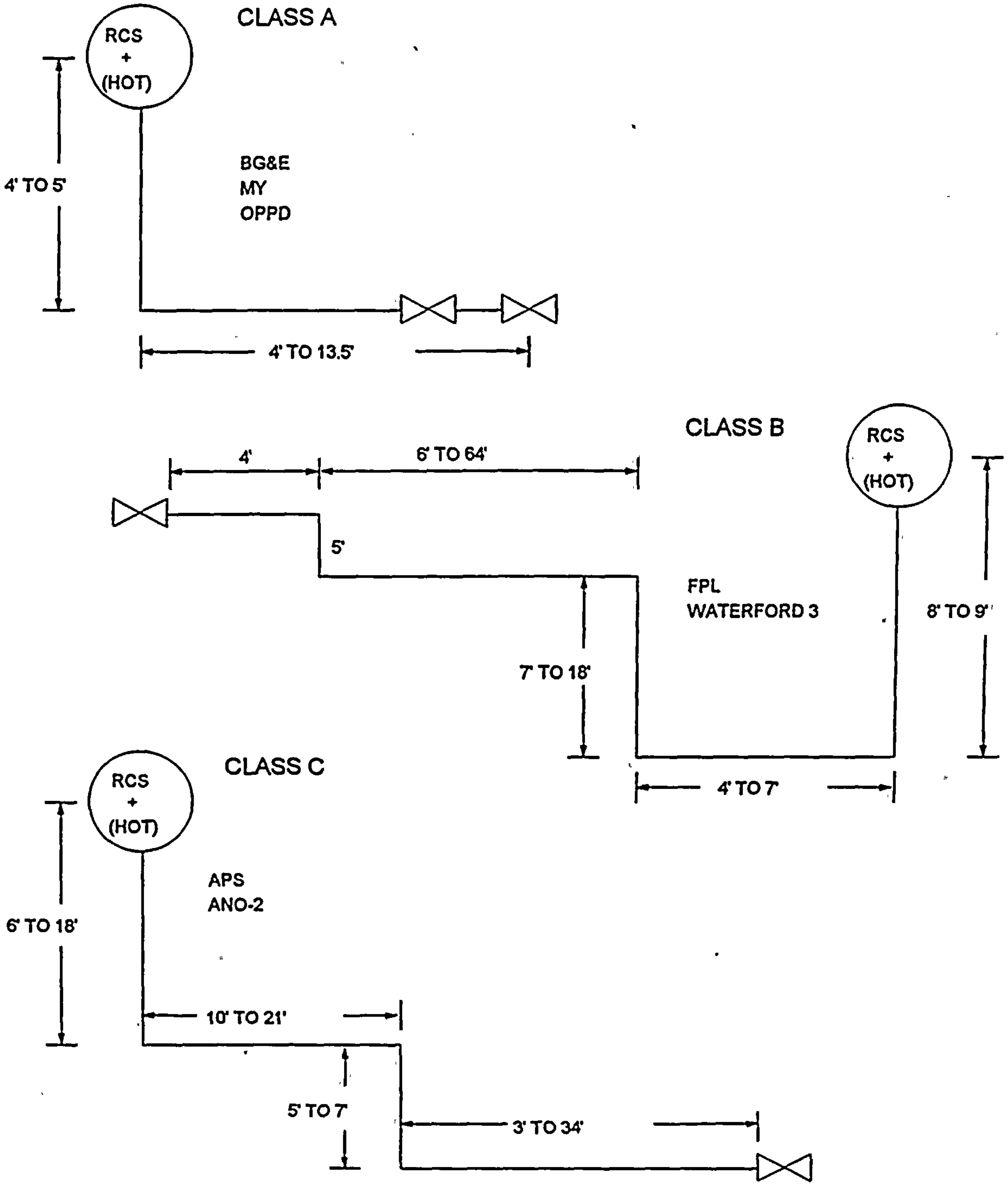
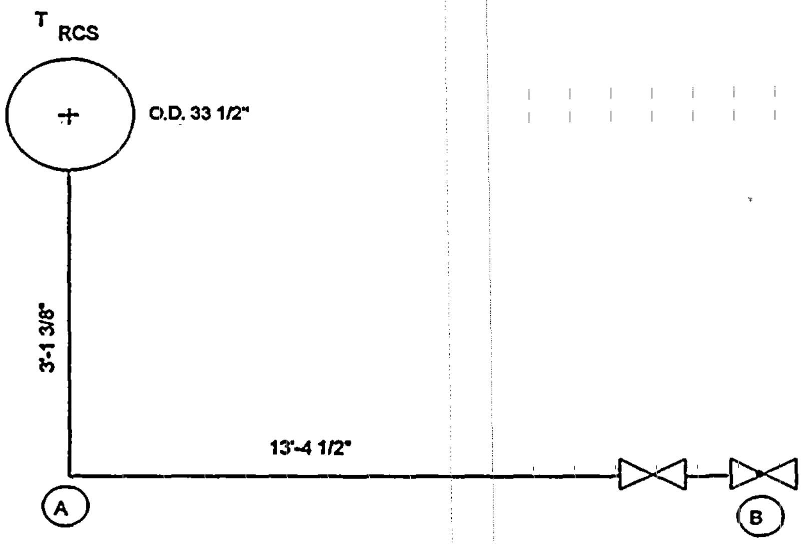
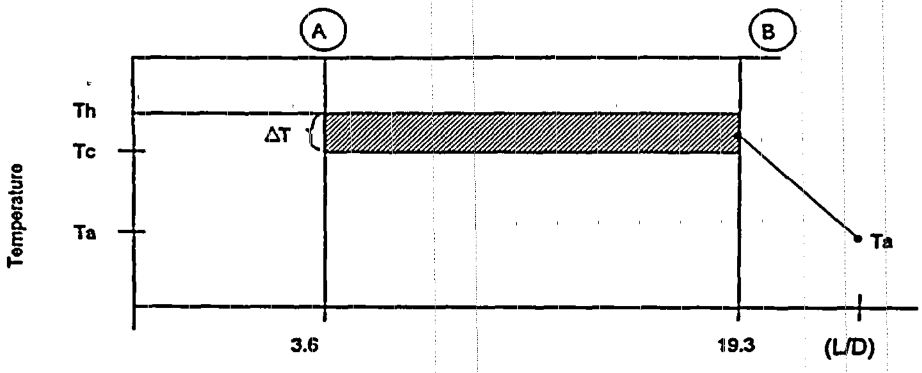


Figure 4.3-8 Classification of Shutdown Cooling Lines

CLASS A - MAINE YANKEE - SDC LINE

OD = 12"
ID = 10.25"



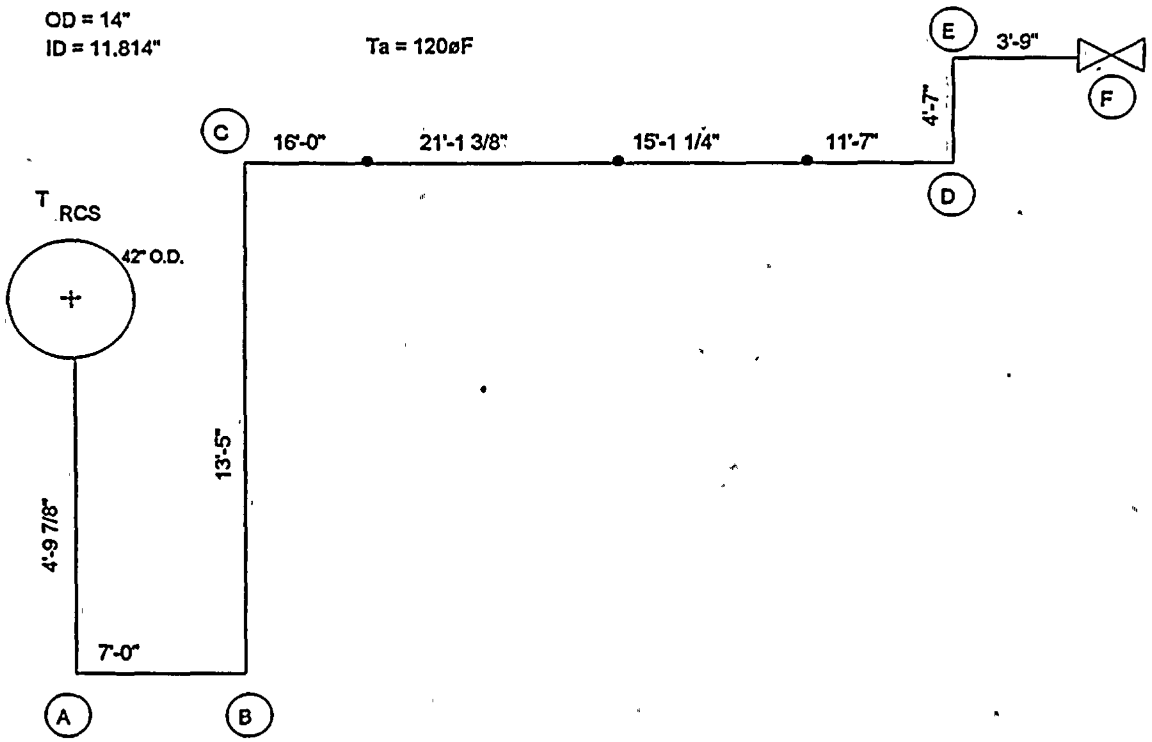


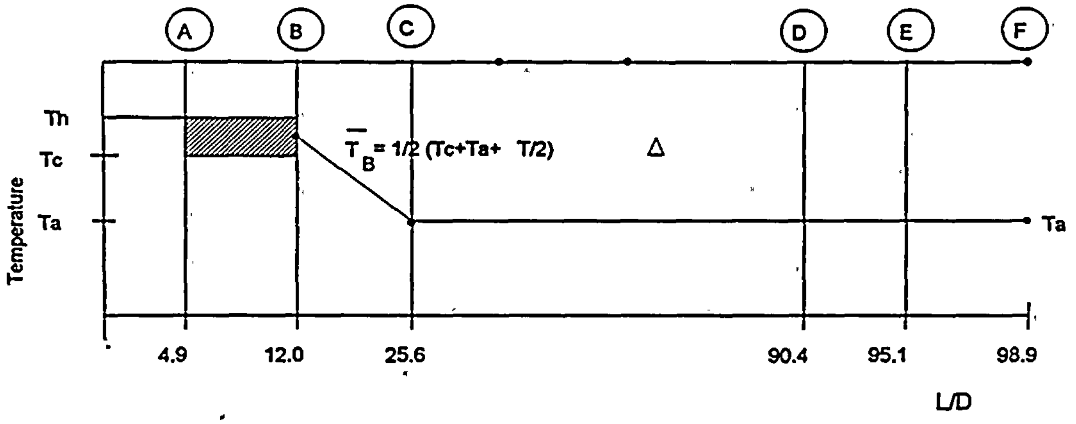
FOR TΔ	T_h A-B	T_c A-B	T_a @ B
400	550	150	120
350	500	150	120
250	400	150	120
150	300	150	120

CLASS B - SDC LINE

OD = 14"
ID = 11.814"

Ta = 120øF





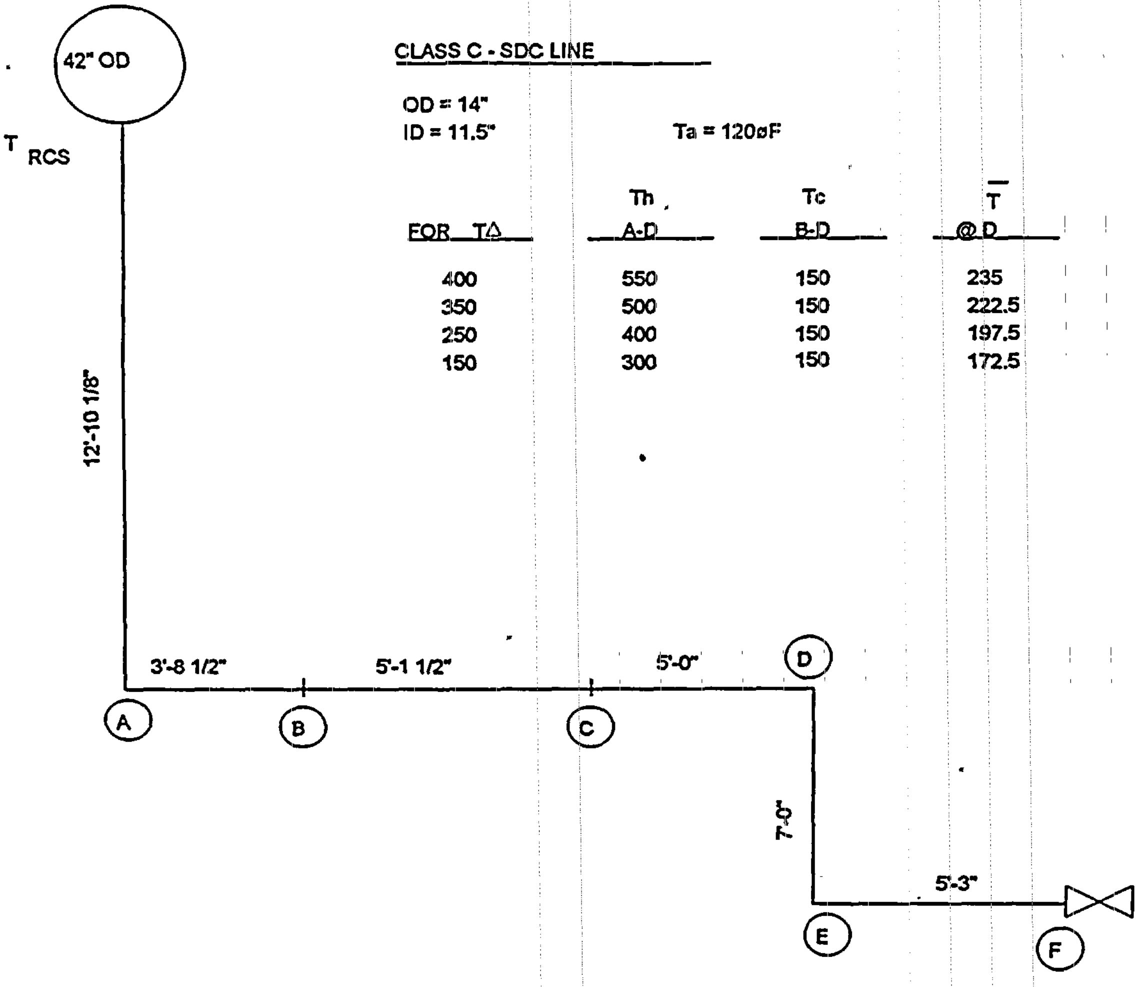
FOR TΔ	T_h A-B	T_c A-B	$\overline{T}_B$
400	550	150	235
350	500	150	222.5
250	400	150	197.5
150	300	150	172.5

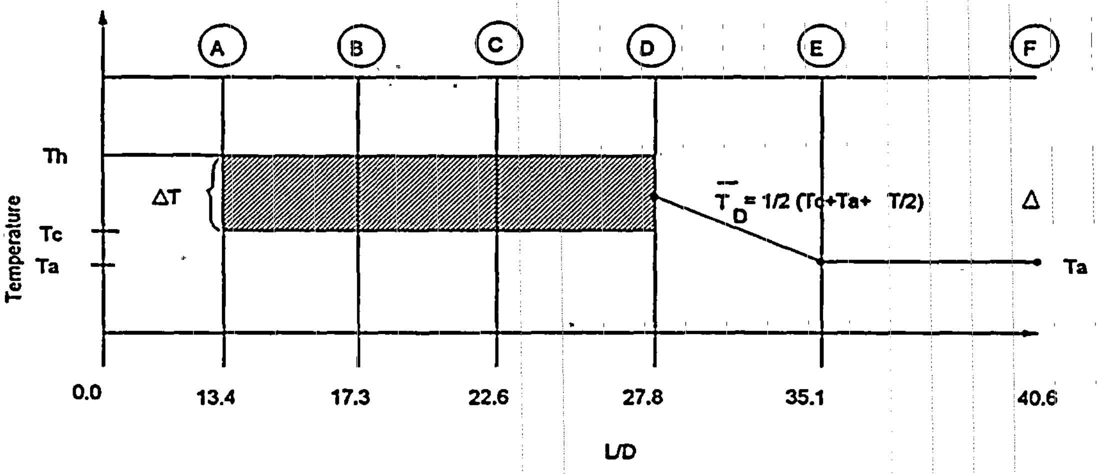
CLASS C - SDC LINE

OD = 14"
ID = 11.5"

Ta = 120°F

FOR TΔ	Th A-D	Tc B-D	$\bar{T}$ @ D
400	550	150	235
350	500	150	222.5
250	400	150	197.5
150	300	150	172.5





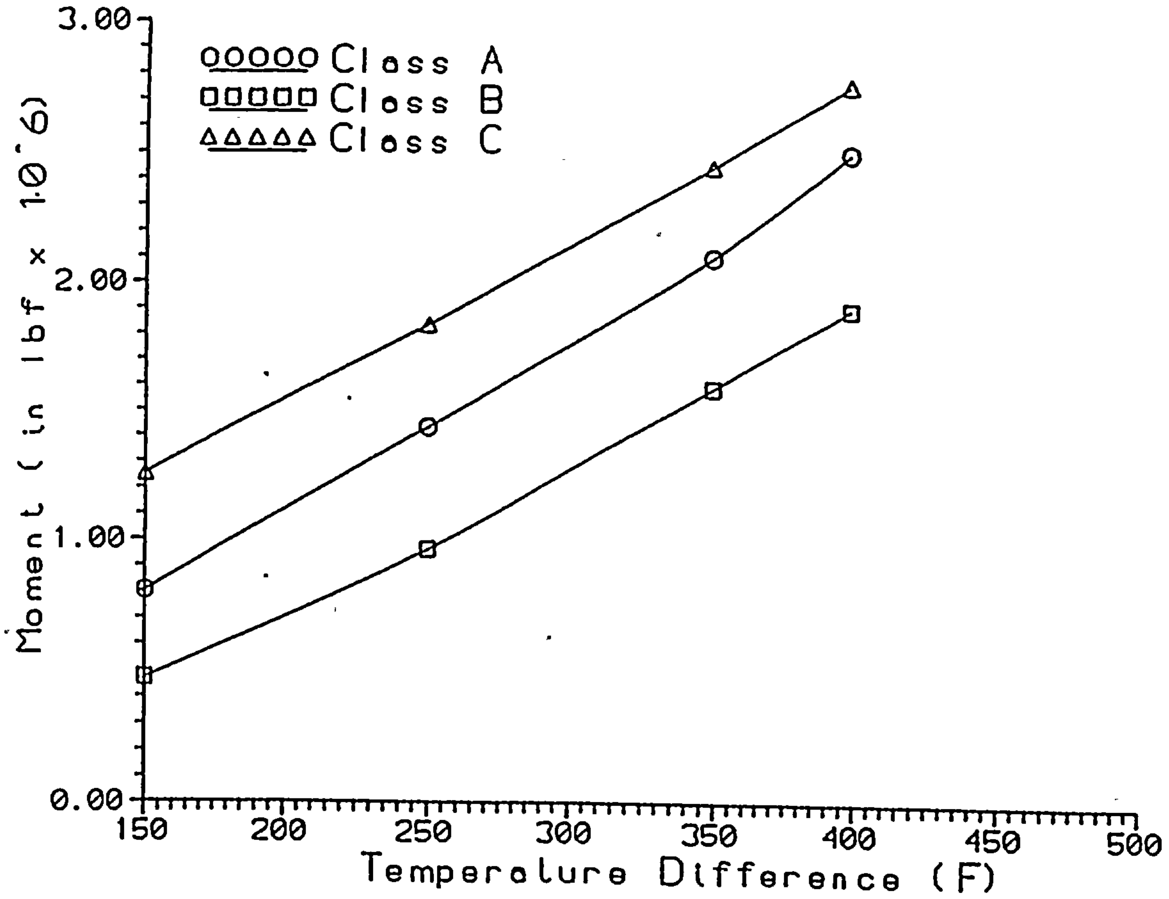


Figure 4.3-9 Bending Moment for Line Classification vs. Top to Bottom Difference in Wall Temperature

4.4 Auxiliary Spray Lines

NRC Bulletin 88-08 identified leakage into or out of the Reactor Coolant System (RCS) as the source of thermal stratification that resulted in cracks in unisolable lines. In initial responses to NRC Bulletin 88-08, several utilities identified the auxiliary spray system as being susceptible to this phenomena because of higher charging system pressures and the potential for in-leakage. CEOG Task 578 (Reference CEOG-6) concluded that the auxiliary spray line may have the potential for flow (steam-water) stratification at some units. However, for a number of plants (i.e., Calvert Cliffs 1 & 2, ANO-2, Maine Yankee, and Fort Calhoun), it was concluded that steam-water stratification would not occur.

After responses to Bulletin 88-08 were submitted, thermocouple data were reported which indicated differential temperatures greater than 50°F in the auxiliary spray lines at Palo Verde Unit 3 and ANO Unit 2. This stratification has been presumed to be of hotter water, from the pressurizer, over cooler water, caused by in-leakage from the charging system.

The purpose of CEOG Task 886 (Reference CEOG-19) was to evaluate thermal stratification in the pressurizer auxiliary spray lines of participating plants and to determine loads caused by thermal stratification. Participants are listed in Table 4.4-1.

4.4.1 Geometry and Routing

The auxiliary spray system is used to reduce pressurizer pressure at times when main spray is not available (such as during plant shutdown). Auxiliary spray is provided via the charging pumps. During normal plant operation, the auxiliary spray line is isolated from the charging system by a single control valve (or two valves in parallel). Figure 4.4-1 contains a simplified diagram which shows the typical auxiliary spray line connections.

Figures 4.4-2 through 4.4-3 contain simplified isometric drawings for each of the configurations under consideration, and show the orientation and approximate run lengths of each auxiliary spray line. Rigid restraints are indicated as "RR", with corresponding direction(s) of constraint.

4.4.2 Wall Temperatures

The stability of the flow in a line of the same fluid at two different temperatures is controlled by the balance between gravitational body forces and inertial forces between the two streams. This ratio is represented by a global Richardson number, Ri,

$$\mathrm{Ri} = \frac{g(\rho_c - \rho_h)Di}{\rho_{avg}(Vc - Vh)^2} = \frac{g\beta(Th - Tc)Di}{(Vc - Vh)^2}$$

where ρ_c and ρ_h are the densities of the cold and hot fluid, respectively, V_c and V_h are the velocities of the cold and hot fluid, respectively, ρ_{avg} is the density at the average temperature, and D_i is the line inner diameter (Figure 4.4-2). Substitution of the coefficient of thermal expansion, β, results in the second form of the equation, where T_h and T_c are the temperatures of the hot and cold fluids. Richardson numbers greater than one denote a stable stratification of the flow.

Cracks found in the safety injection nozzle at Farley Unit 2 were attributed to loads due to thermal stratification (Reference 2). This thermal stratification was found to be due to in-leakage of colder fluid upstream of a check valve into the hotter reactor coolant system (RCS) fluid in the horizontal section of line between the RCS and the check valve some six (6) line diameters away. Crack initiation and growth has been shown to be related to high cycle fatigue caused by the aperiodic mixing due to turbulent penetration of the fluid in the main line with the leakage film in the branch line. This aperiodic mixing was hypothesized as being related to the instability of the turbulent penetration of the main stream fluid into the branch line with periods ranging from about 1-2 minutes. The mixing of the hotter main line fluid with the colder leakage fluid resulted in cyclical variations in wall temperature that were assumed to have been a possible cause of the cyclic fatigue. This behavior has been termed Thermal Cycling (EPRI, Reference 2).

In the case of the auxiliary spray lines, the junction of the charging and auxiliary spray lines is typically located several hundred line diameters upstream from the junction of the main and auxiliary spray lines. All can be considered far enough away from the junction with the main spray line that any leakage fluid moving though the line is cooled to containment temperature before it reaches the horizontal section upstream of this junction.

Furthermore, this higher pressure leakage fluid will most likely be mixed with the cooler fluid already in the lines from flow through sections of line in which the stratified flow is unstable (Ri <1). This leakage will result in this colder fluid being forced into the horizontal sections upstream of the junction with the main spray line.

This colder fluid, it is assumed, forms a stable leakage type flow in the lower area of the horizontal section. Bending of the line is due to this thermal stratification of the flow. Treating the piping as a beam, moments at the fixed end of a beam due to thermal stratification are proportional to the difference in top to bottom wall temperatures and the length of the stratified section. In keeping with the scope of this task, conservative values of thermal stratification loads (Figures 4.4-2,4.4-3) for each of the candidate lines are used, based on the following assumptions:

1. Stratification occurs over the entire length of the horizontal section just upstream of the junction with the main spray line.

2. The flow in the bottom section of the line is at a uniform temperature equal to that of the containment (T_{cold} = 120°F).

3. The flow in the upper section of the line is at a uniform temperature equal to that of the main spray flow (T_{hot} = 550°F).

4. The wall temperatures are equal to the fluid temperatures. Thus the top-to-bottom difference in fluid temperatures of 430°F is equal to that of the wall.

4.4.3 Model

4.4.3.1 ANSYS Structural Evaluation

An ANSYS evaluation was performed in order to provide maximum moment loadings due to a range of stratification ΔTs (i.e., top-to-bottom temperature differentials) applied to sections of the auxiliary spray line for each Task 886 participant. The stratification ΔTs considered are: 430°F, 250°F, and 0°F.

In order to determine moment loadings due to stratified conditions in the auxiliary spray lines, each of the lines is modeled from the main spray tee (or, in the case of OPPD, the 4"x2" reducer) to an upstream anchor or appropriate restraint. Schematics of the ANSYS models are shown in Figures 4.4-4 to 4.4-11.

4.4.3.2 Thermal Stratification Loads

The stratification cases analyzed are based upon having a steady-state leakage flow through the auxiliary spray piping into the main spray line. Stratified conditions may occur where this cooler leakage meets the hotter main spray flow. Conservatively, the sections of piping which are considered to be stratified include the uppermost horizontal sections of 2"auxiliary spray piping, just upstream of the main spray-auxiliary spray tee. Additionally, for some configurations, there is a transition from the 2" auxiliary spray piping to the 4" main spray piping using a 4"X 2" reducer and a short section of 4" piping; this reducer and 4"piping section are also considered to stratified.

Three stratification (i.e., ΔT) cases are evaluated. All cases include linear thermal expansion. Case 1 constitutes the most conservative conditions for inleakage-caused stratification at steady-state, in which the bottom of the stratified is at an ambient temperature of 120°F, and the top of the stratified piping is at the Normal Operations main spray temperature of 550°F. Case 2 is an intermediate stratification case, with a ΔT of 250°F. Case 3 is the "no stratification" case, with a uniform temperature of 550 °F. This latter case includes only the influence of linear thermal expansion and is done to obtain what represents the baseline values of moments and displacements at the support of the lines.

4.4.3.3 Cyclic Load Considerations

4.4.3.3.1 Turbulent Penetration and Thermal Cycling

TASCS program (Reference 2) reported cyclical effects caused by a mixing of the flow due to turbulent penetration. This secondary flow caused by flow in the main spray line will result in a mixing of the main spray flow and any leakage flow near the junction of the main and auxiliary lines. Calculations, based on the model of Strauch, et al (Reference 9), show that bypass flow rates in the main spray line of 1.5 gpm are below the flow rates at which turbulent penetration occurs. Thus, any thermal stratification in the auxiliary spray line would be undisturbed and the behavior due to turbulent penetration effects should not be a problem.

For flow in the main spray line above this value, thermal cycling can occur in two ways.

A. Interaction of turbulent penetration and leakage film.

TASCS (Reference 2) and Nakamori (Reference 8) reported that the leading edge of the leakage film can be caused to undergo an almost periodic advance and retreat upon interacting with the turbulent penetration. Data show a period of from one to two minutes with the higher values occurring at the higher leak rates.

The time constant for a circular line, with thickness t, can be approximated as (Krieth, Reference 8):

$$\tau = \frac{t^2}{\alpha}$$

where α is the thermal diffusivity of the material.

For the two inch, Schedule 160 Stainless Steel line the time constant is about 20 seconds. This, being a factor of three to six times lower than the period of advance and retreat for the penetrations, will result in accompanying variations in through wall temperatures.

The mixing of the colder leakage film by the hotter fluid brought into the line by the turbulent penetration is a function of the length to which the penetration will occur. Per Lubin & Brown (Reference 12) the length for turbulent penetration is inversely proportional to a Richardson number based on the temperature difference between the hotter fluid, T_o, and the colder fluid, T_∞, the diameter of the main spray line, D, and the velocity, Vo, of the flow in the main line:

$$Ri = \frac{g\beta(To - T_\infty)D}{Vo^2}$$

where α is the coefficient of thermal expansion and g the acceleration of gravity.

Preliminary calculations indicate that for typical main spray flow rates of up to 375 gpm and assumed leakage rates of up to .10 gpm, in lines with stratified lengths longer than about 40 diameters, the leakage film will reach an equilibrium temperature with the hotter upper layer fluid before being reached by the turbulent penetration. Thus thermal cycling due to interaction of the penetration with leakage film should not occur. Lines with longer stratified sections; Calvert Cliffs Units 1 and 2, Fort Calhoun, and St. Lucie Units 1 and 2 should not experience this type of thermal cycling. However, plants with shorter stratified sections: e.g., ANO-2, APS and WSES-3, this type of thermal cycling could occur.

B. Mixing of turbulent penetration and leakage film

The second effect is a complete mixing of the main spray fluid and leakage fluid when the turbulent penetration can extend beyond the leading edge of the leakage film, in the limit extending the full length of the horizontal section. This could result in considerable reductions in thermal stratification temperatures (Figure 4.4-12) and resultant moments.

Depending on the rate of bypass flow and design flow in the main spra lines turbulent penetration can result in a change in the therma stratification moment coincident with the startup and stopping of the main flow (Figure 4.4-12).

For plants with stratified sections longer than 40 diameters, design values of main spray flows do not result in turbulent penetration extending the length of the horizontal sections. Therefore thermal cycling, related to main spray actuation, should not occur. Once again, plants with shorter stratified sections: e.g. ANO-2, APS and WSES-3, could experience this type of thermal cycling.

4.4.3.3.2 Thermal Striping

Thermal striping (Figure 4.4-13) refers to the variations with time of fluid and wall temperatures observed in thermally stratified flows representative of typical surge lines; e.g. Wolf (Reference 10). The observed variations (Fujimoto, Reference 13) have periods ranging from about 10 seconds (frequency of .10 hertz) to one second (frequency of 1 hertz), with the lower values observed closer to the wall. Fluid temperatures can vary from about 10% to as much as 50% of the difference between hot and colder temperatures, with the higher values occurring at locations away from the fluid-wall interface.

Striping is related to the formation of waves at the interface between the two fluids. The relationship for the frequency of these types of waves is given as,

$$f\text{wave} = \sqrt{\frac{g}{4\pi\lambda}\,\frac{\Delta\rho}{\rho}}$$

where $\Delta\rho$ is the difference in density between the hotter and colder fluid, the average density, g the acceleration of gravity and λ the wavelength. For typical values, and taking the wavelength as proportional to the line (inner) diameter, the frequency of striping for the auxiliary spray lines is about 2 hertz. Taking the same 10:1 reduction in frequency near the wall results in a wave period of about 5 seconds near the wall.

Striping has been found to be more aperiodic (random) than periodic (deterministic). Thus the above frequency can be considered a mean value.

The time constant for a circular line for the two inch, Schedule 160 Stainless Steel line the time constant is about 20 seconds. This being a factor of four higher than the mean period for temperature fluctuations, changes in wall temperature should be limited to close to the inner surface and not greatly influence the through wall temperatures.

Likewise temperature fluctuation measurements show the dominance of low amplitude fluctuations over those of larger amplitude(Wolf, Reference 10), Figure 4.4-14. Thus not only is the temperature reduced as the wall is approached but large amplitude fluctuations should be infrequent. Thus the maximum difference in fluid temperatures of 430°F should result in fluctuations near the wall of about 43°F. When included with the above comparison between period for these fluctuations and time constant of the wall for temperature changes, these differences should not have a significant impact on the high cycle fatigue behavior of the lines.

4.4.5 Moments

Table 4.4-2 presents the maximum total moment for the 430 F° ΔT case for each configuration, as well as the nodal location at which this moment occurred. Additionally, this table includes the total moment at the same node for the remaining two cases.

4.4.6 Plant Specific Data

Thermocouple data recorded at ANO-2 and Palo Verde show thermal stratification with ΔT up to approximately 100 F° and 120 F°, respectively. In each case, it appears that this maximum ΔT correlates with the sustained operation of one or two charging pumps during plant heatup.

In case of Palo Verde stratification temperature difference is non-periodic with time. Data for ANO-2 show possible cyclical variation coincident with periods of an increase in charging pump flow. However, the small magnitude of these fluctuations indicate only a small or no influence of turbulent penetration causing thermal cycling.

4.4.7 Plant Specific Evaluations

Limited plant data provides an indication of the magnitude of stratification in two of the configurations. Table 4.4-3 presents a ranking of configurations, in order from most susceptible to least susceptible to significant thermal stratification loads.

The information in the table above indicates that two configurations, ANO-2 and Palo Verde, have the smallest loads due to thermal stratification. This conclusion is reached based on the apparent maximum recorded ΔT, and the relatively low resultant bending moments which would be produced by this ΔT. A comparison of these loads with the remaining design basis loads should indicate the influence of thermal stratification on values of maximum stress and fatigue usage.

Due to the absence of comparable data, the same conclusion cannot reached for the remaining configurations (Calvert Cliffs 1 and 2, Fort Calhoun, St. Lucie 1 and 2, and Waterford 3). However, the temperature differences recorded at ANO-2 and Palo Verde are of the magnitude expected when the influence of the conservative assumptions are accounted for.

The influence of these assumptions and the existing data imply that the remaining plants may reasonably expect wall temperature differences less than the maximum temperature difference assumed in the analysis. A plot of the bounding thermal moment as a function of wall temperature differences are shown in Figure 4.4-18. A second order polynomial fit of the three sets of calculations at 430°F, 250 °F and 0 °F is also documented.

When combined with the added loads due to normal and upset operation these curves can be used to determine the maximum difference in wall temperature that can be accommodated by the auxiliary spray lines for each of the plant specific configurations. In the case of these limits being in the range of 100 °F to 120 °F, available plant data can be referenced to justify the use of these temperatures. Plant specific measurements of wall temperatures can be obtained to confirm that the actual wall temperature differences are lower than the limiting values.

Table 4.4-1
Participants in Auxiliary Spray Line Tasks

Task	Participant	Plants
886	Arizona Public Service	PVNGS 1,2,3
	Baltimore Gas & Electric	Calvert Cliffs 1,2
	Entergy Operations	ANO-2, WSES-3
	Florida Power & Light	St. Lucie 1,2
	Omaha Public Power Dist	FCNS

Table 4.4-2
Moments versus Temperature Difference

Unit	**Total Moment (in-lb)***			
	Node	**Case 1 (430 F° ΔT)**	**Case 2 (250 F° ΔT)**	**Case 3 (0 F° ΔT)**
ANO-2	1	30200	17300	3880
APS	1	13300	10900	4610
BGE 1	17	26800	17900	5600
BGE 2	17	39500	23800	1840
FPL 1	5	50000	26800	5870
FPL 2	3	47900	26500	3540
OPPD	5	50900	29500	489
WSES-3	1	15700	8460	2210

Table 4.4-3

Maximum Moments for Auxiliary Spray Lines

Unit	Total Moment (in-lbf) due to Bounding (430 F°) ΔT	Maximum Recorded ΔT (in F°)
Fort Calhoun	50900	Not Available.
St. Lucie 1	50000	Not Available.
St. Lucie 2	47900	Not Available.
Calvert Cliffs 2	39500	Not Available.
Calvert Cliffs 1	26800	Not Available.
Waterford 3	15700	Not Available.
ANO-2	30200	100
Palo Verde	13300	120

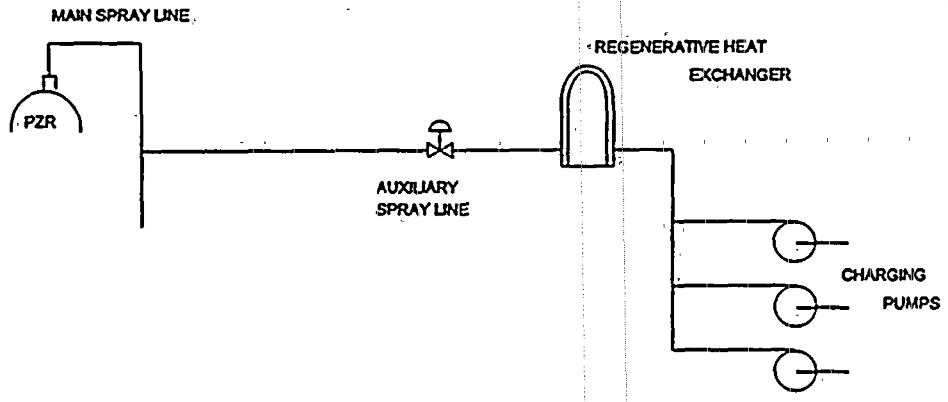


Figure 4.4-1 Simplified Diagram of Auxiliary Spray System

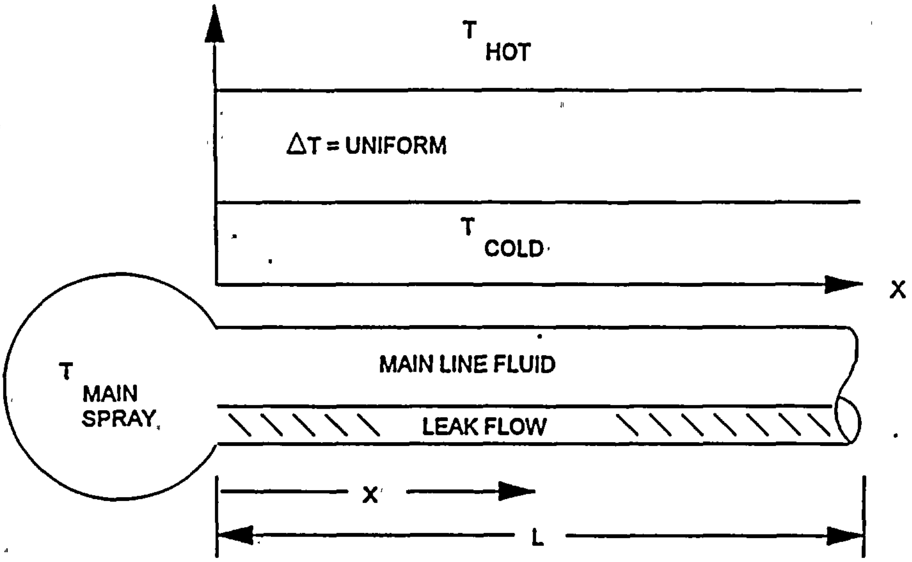


Figure 4.4-2 Auxiliary Spray Line Stratification

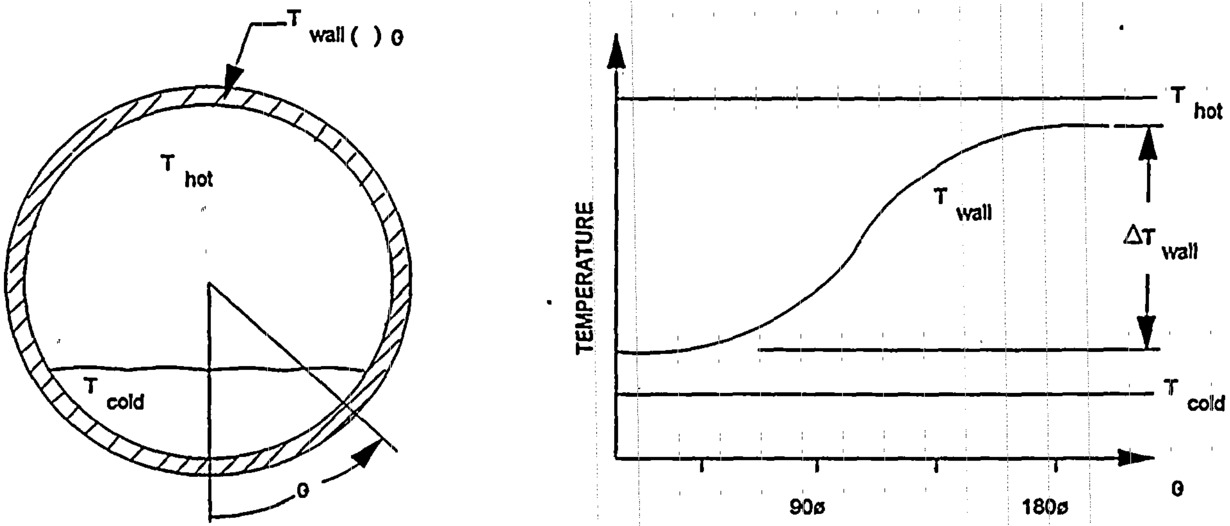


Figure 4.4-3 Variation of Wall Temperature

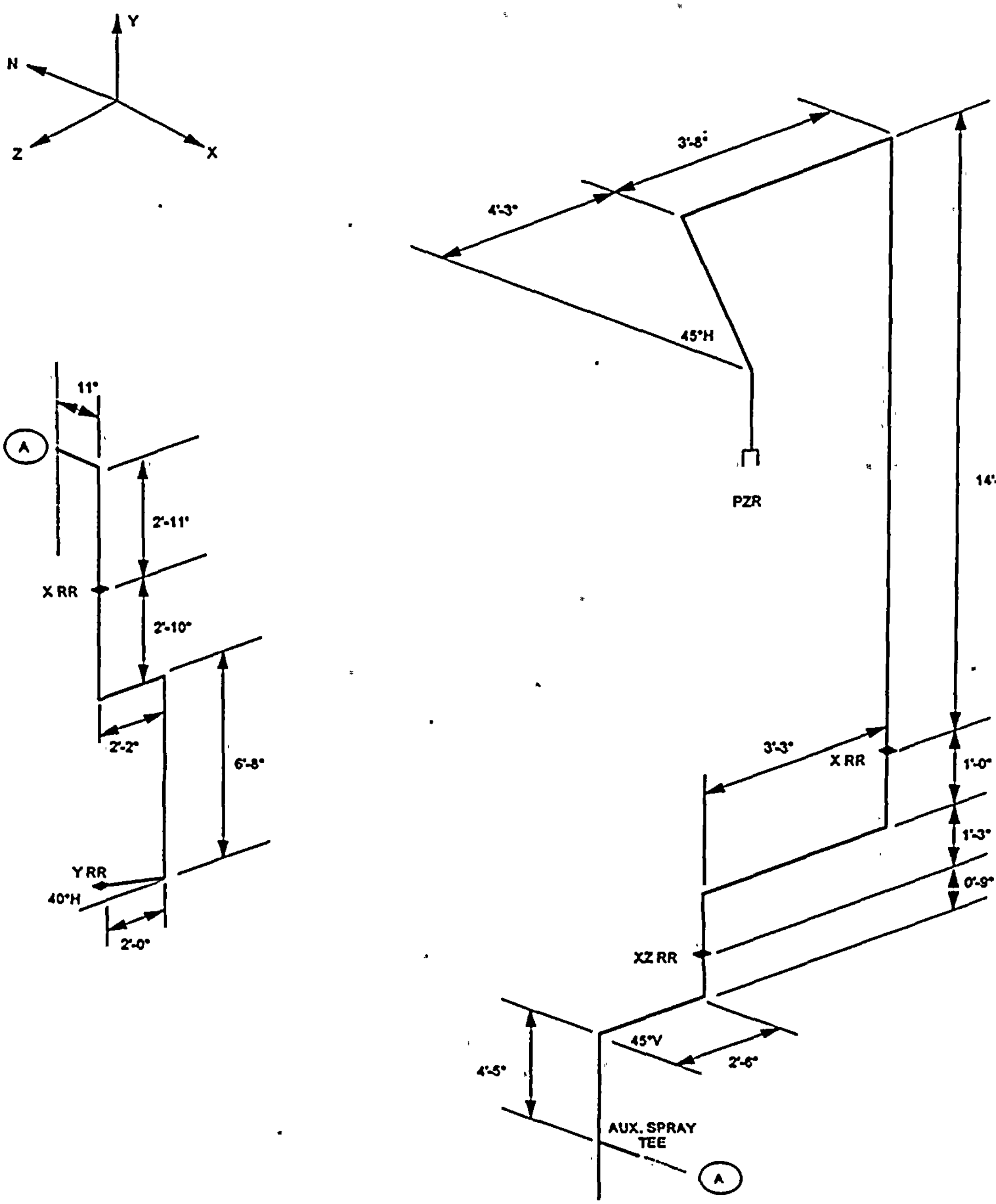


Figure 4.4-4 Simplified Drawing For ANO-2

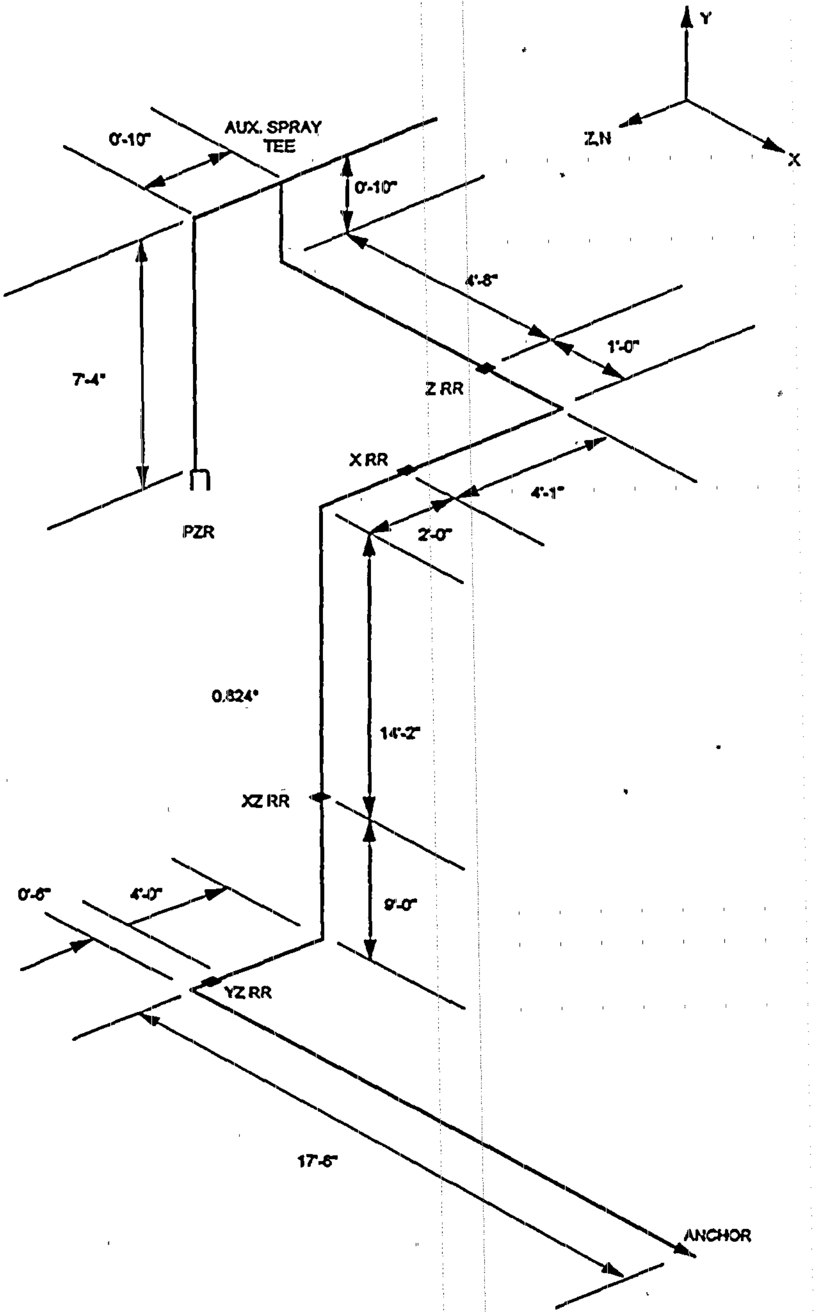


Figure 4.4-5 Simplified Drawing For Calvert Cliffs Unit 1

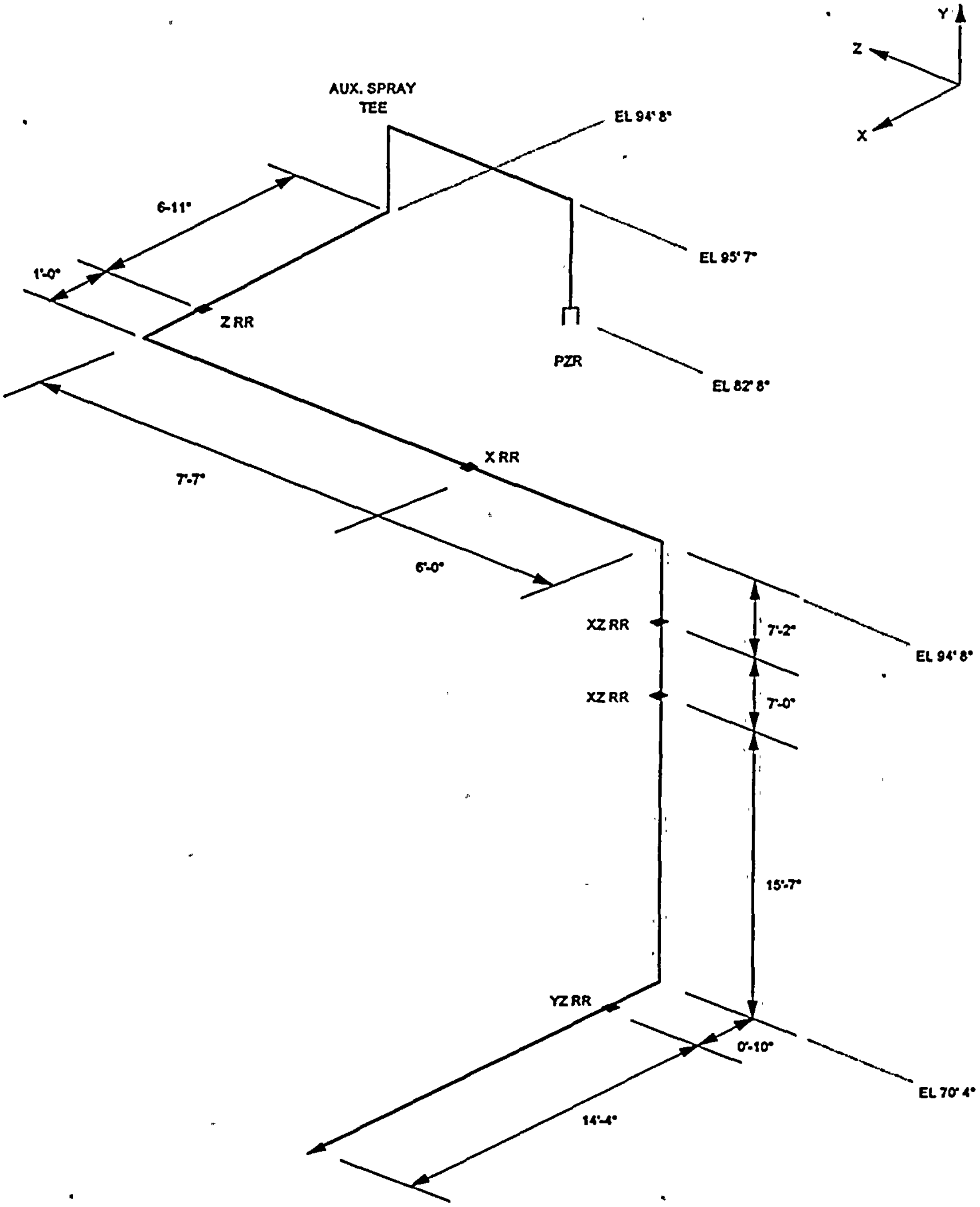


Figure 4.4-6 Simplified Drawing For Calvert Cliffs Unit 2

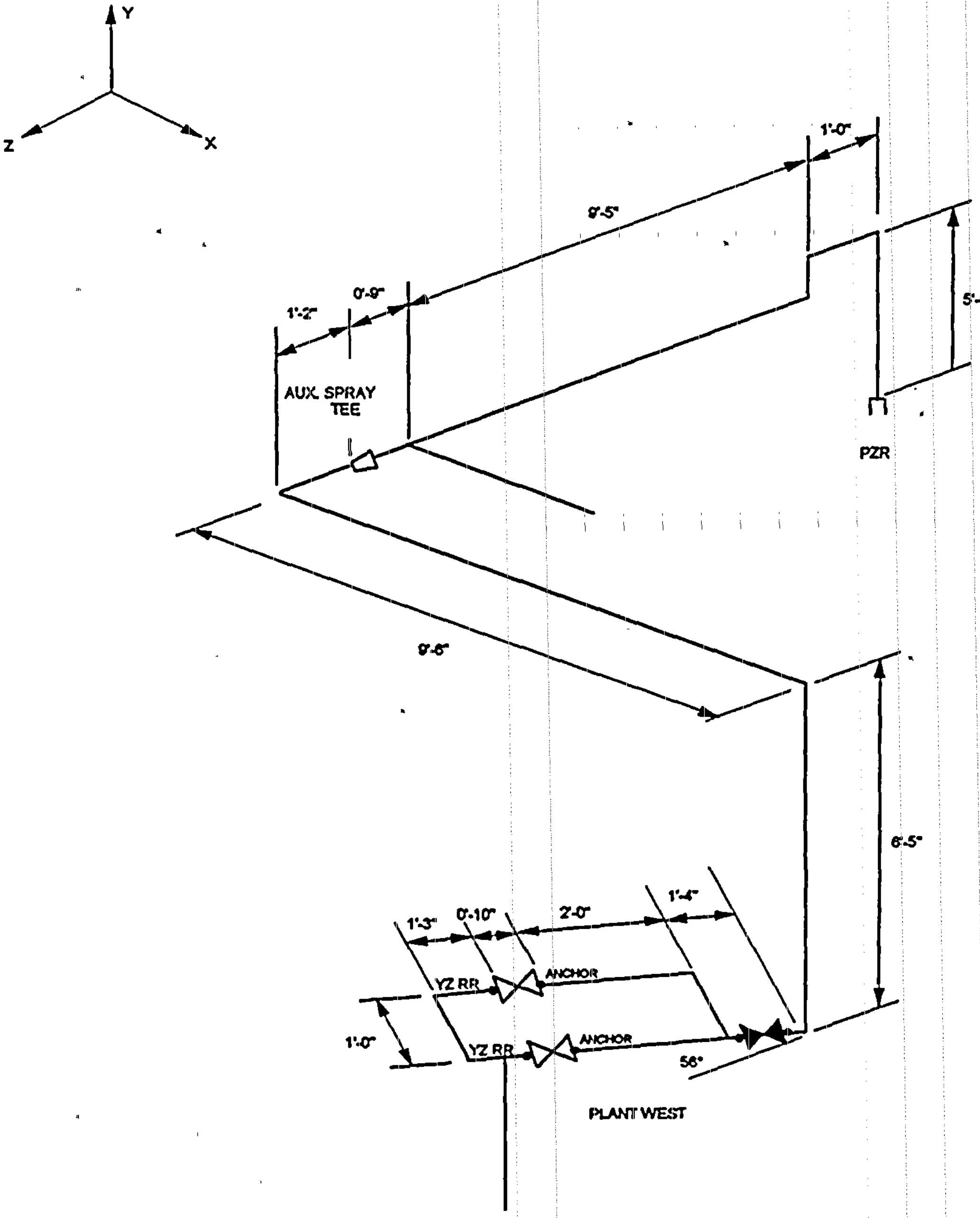


Figure 4.4-7 Simplified Drawing For Fort Calhoun Station

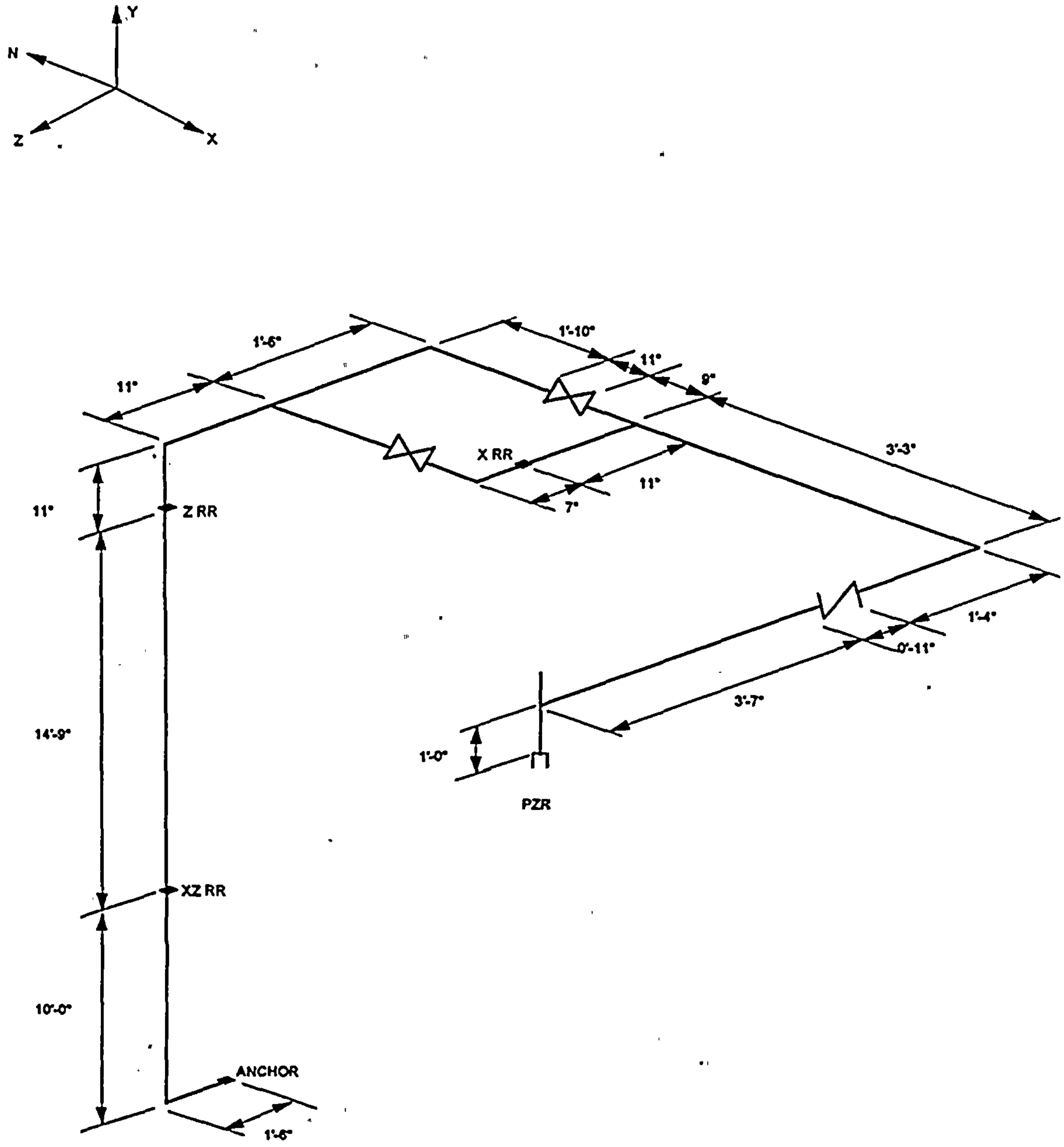


Figure 4.4-8 Simplified Drawing For Palo Verde (Typical)

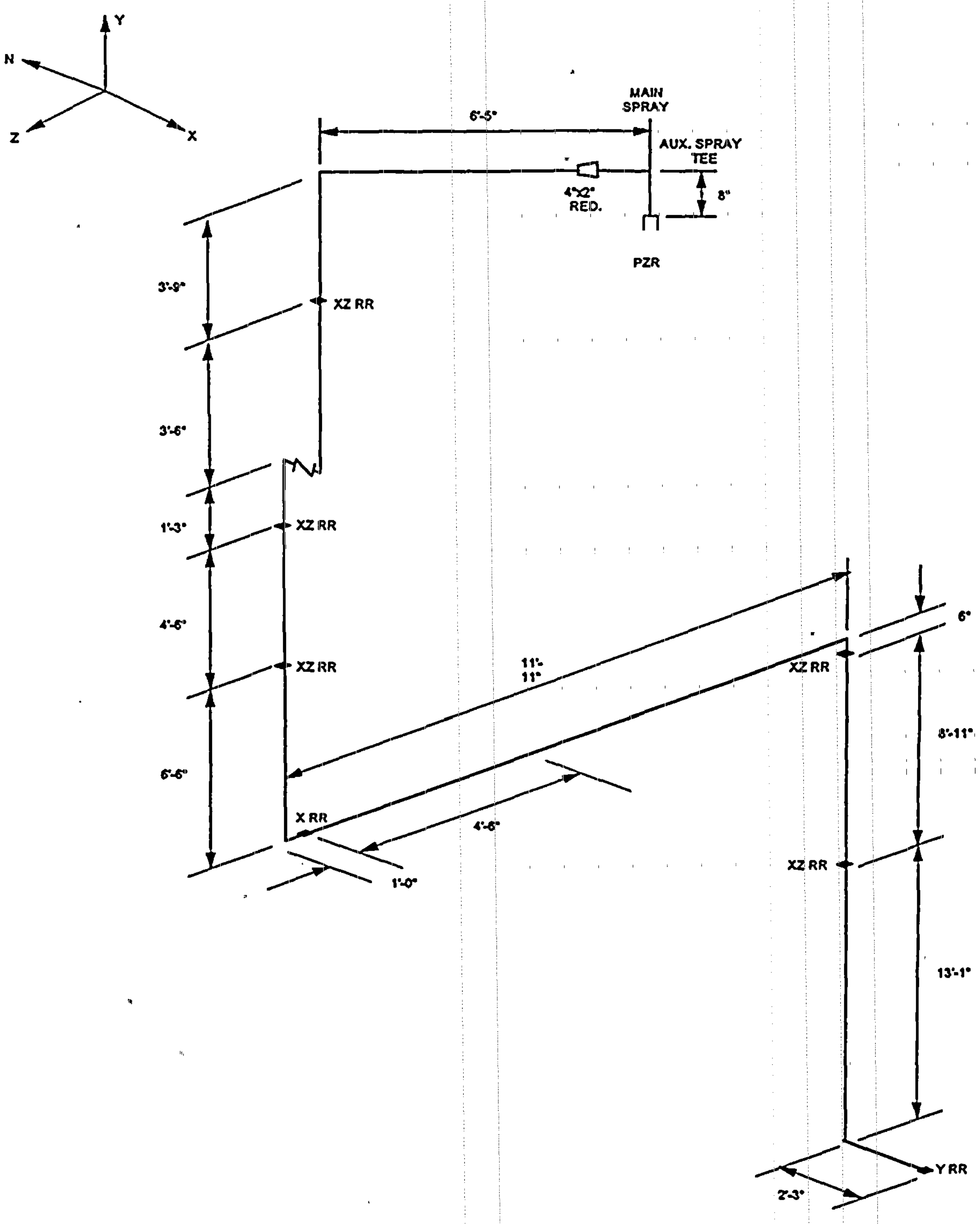


Figure 4.4-9 Simplified Drawing For St. Lucie Unit 1

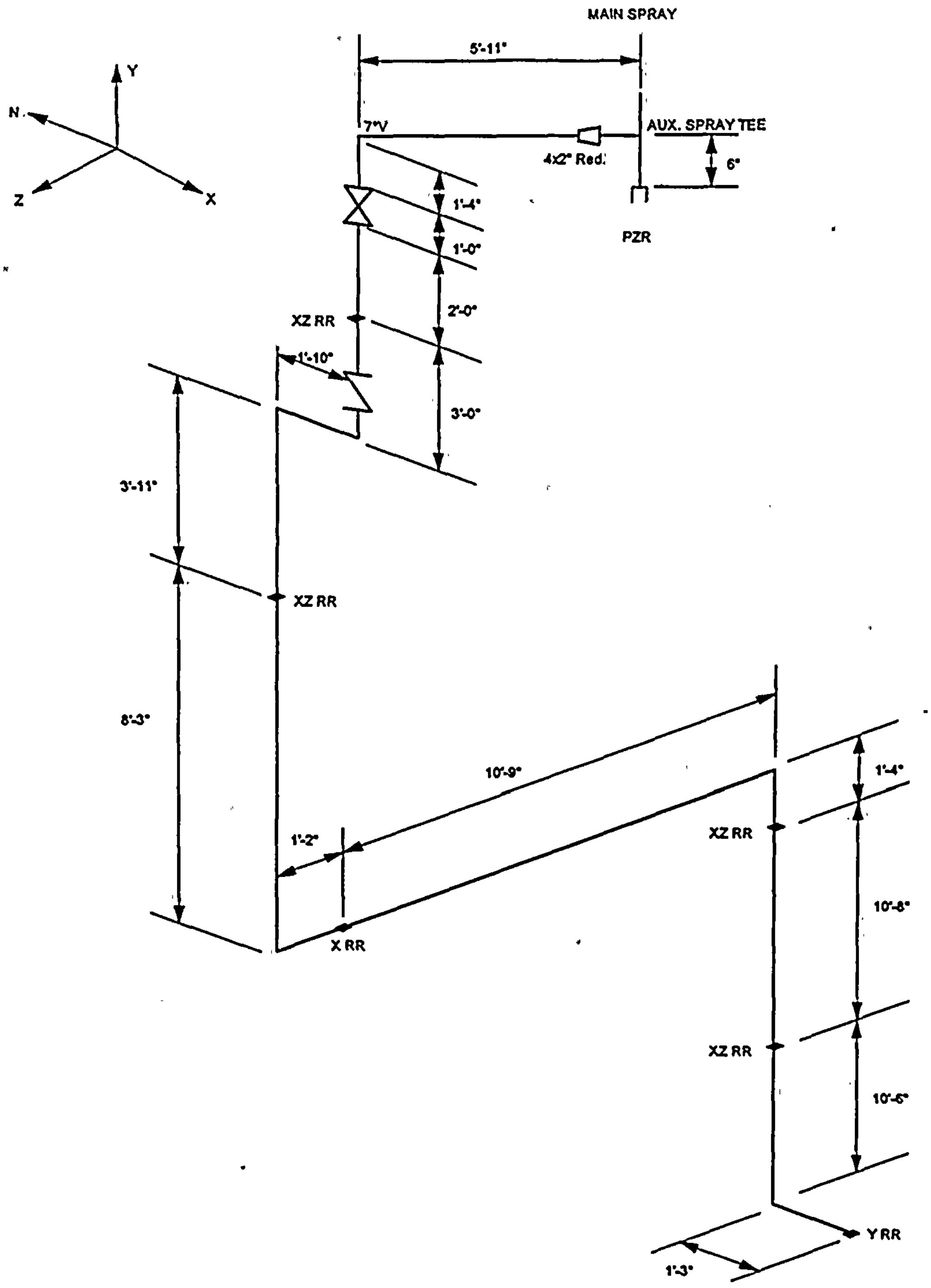


Figure 4.4-10 Simplified Drawing for St. Lucie Unit 2

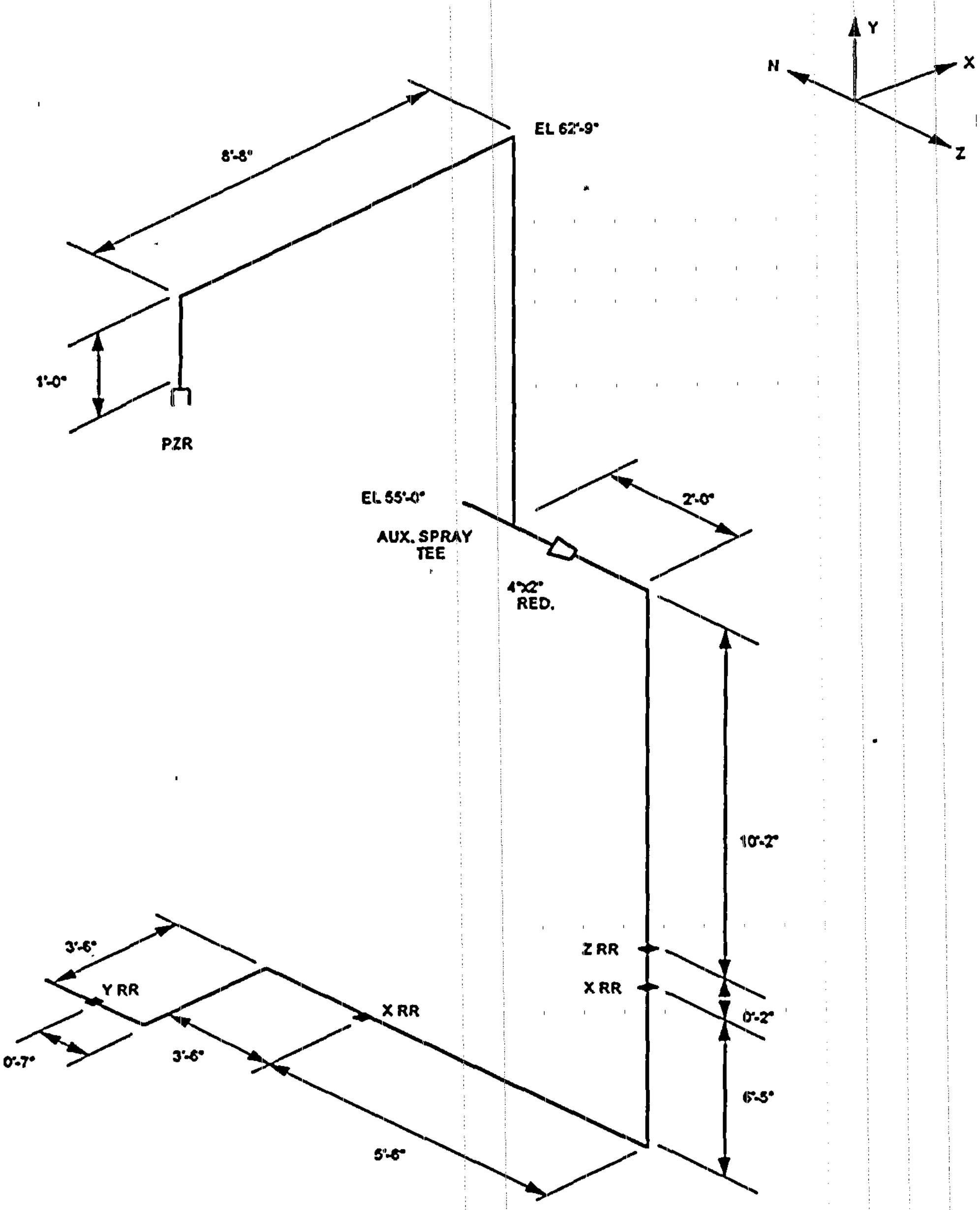


Figure 4.4-11 Simplified Drawing for Waterford Unit 3

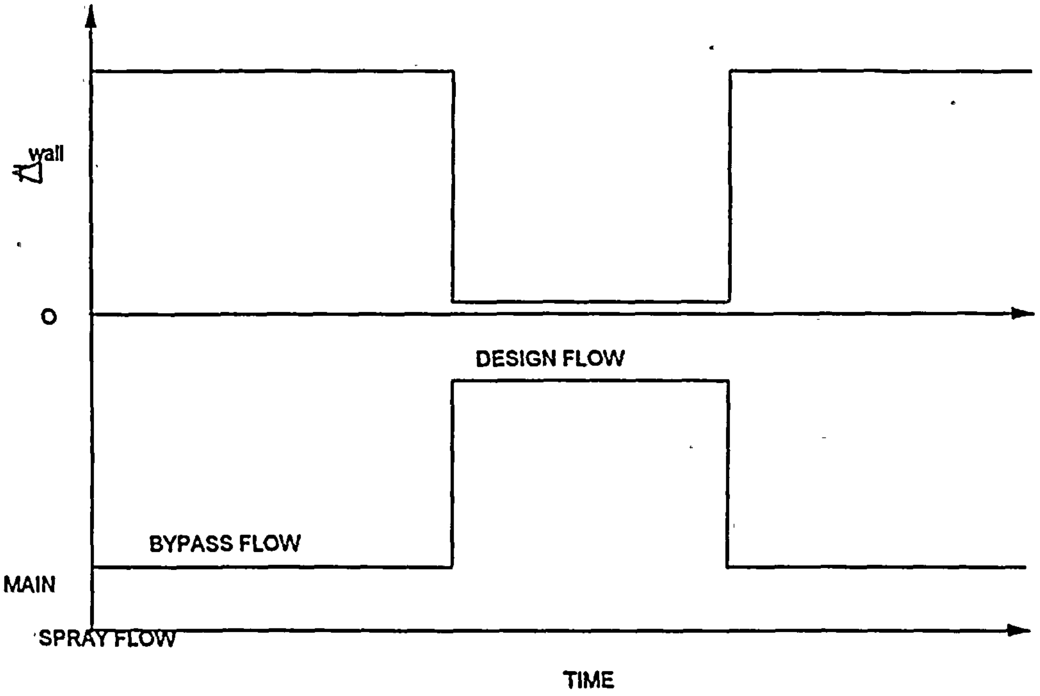


Figure 4.4-12 Variation in Stratified Flow Wall Temperature Difference with Main Spray Flow

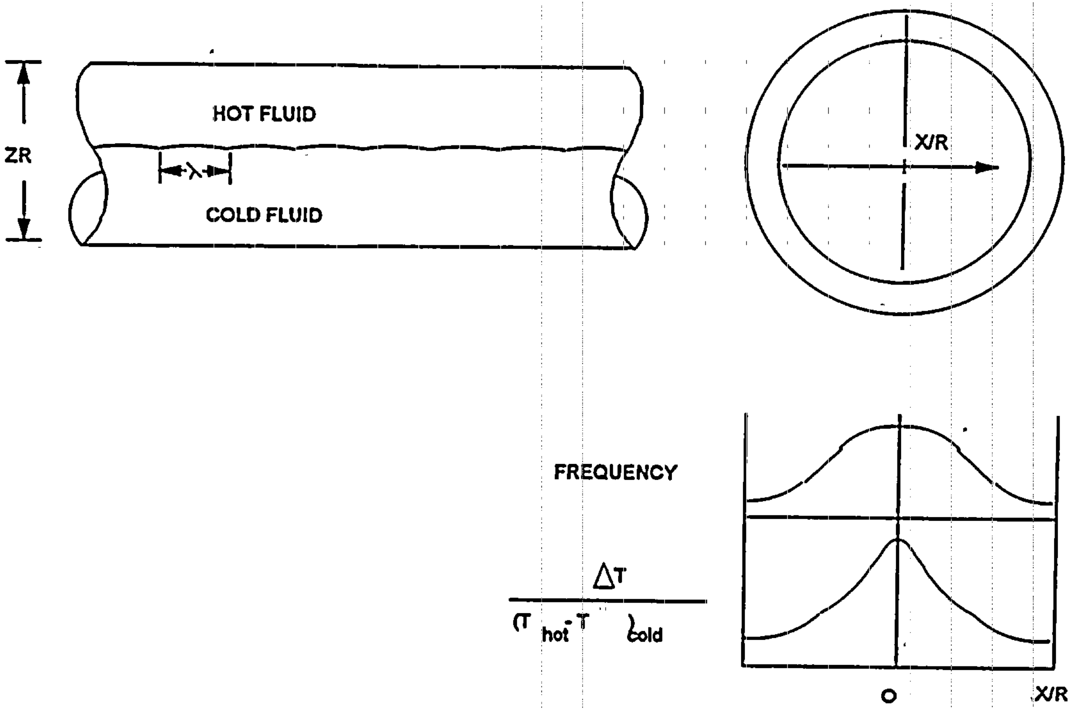


Figure 4.4-13 Thermal Striping

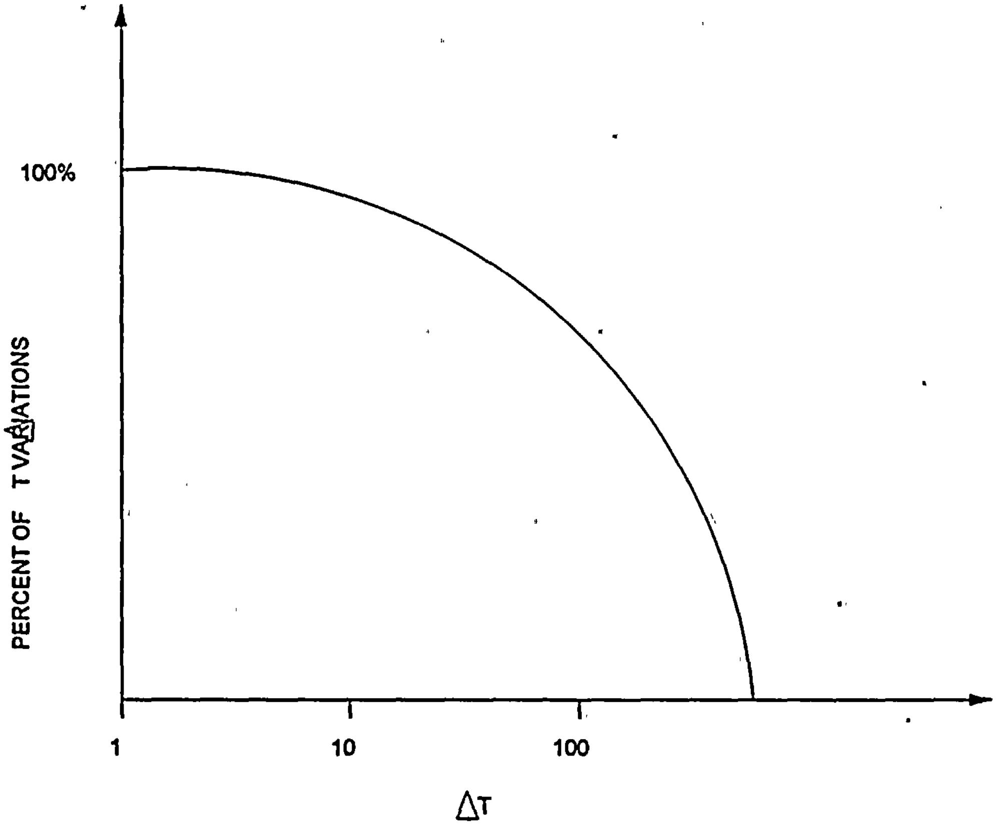


Figure 4.4-14 Spectrum of ΔT Variations

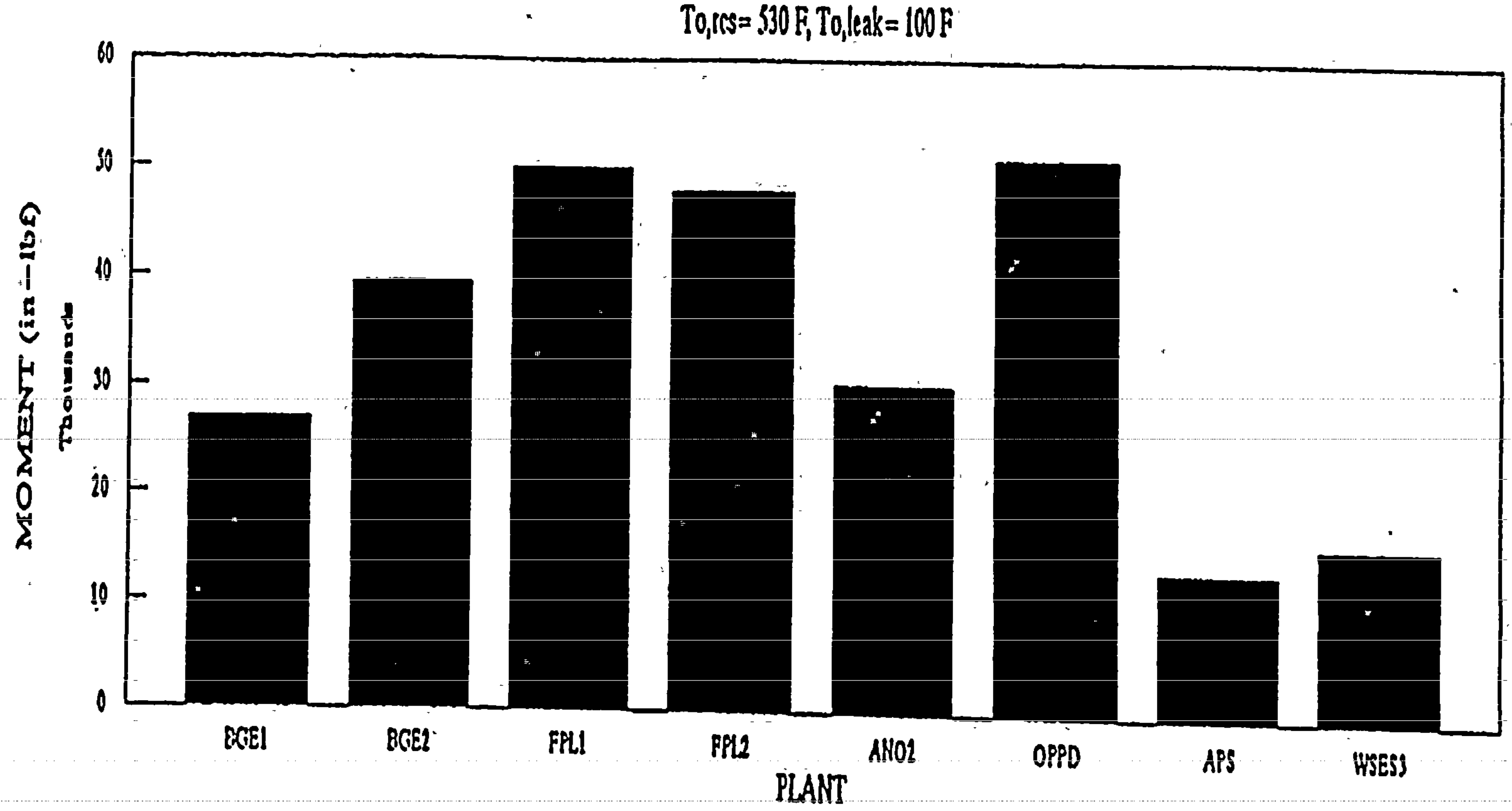


Figure 4.4-15 Thermal Stratification Moment at Temperature Difference of 430°F

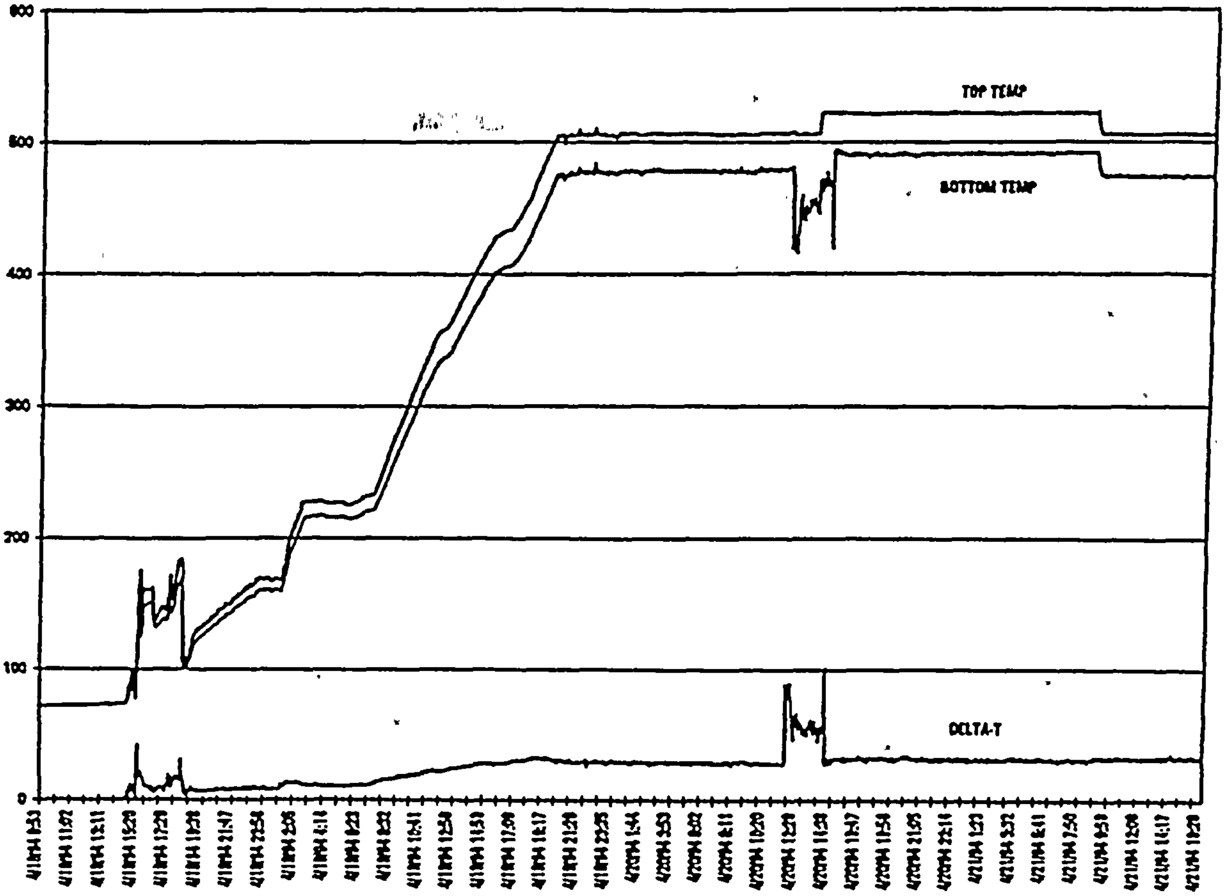


Figure 4.4-16 ANO-2 Plant Heatup Data

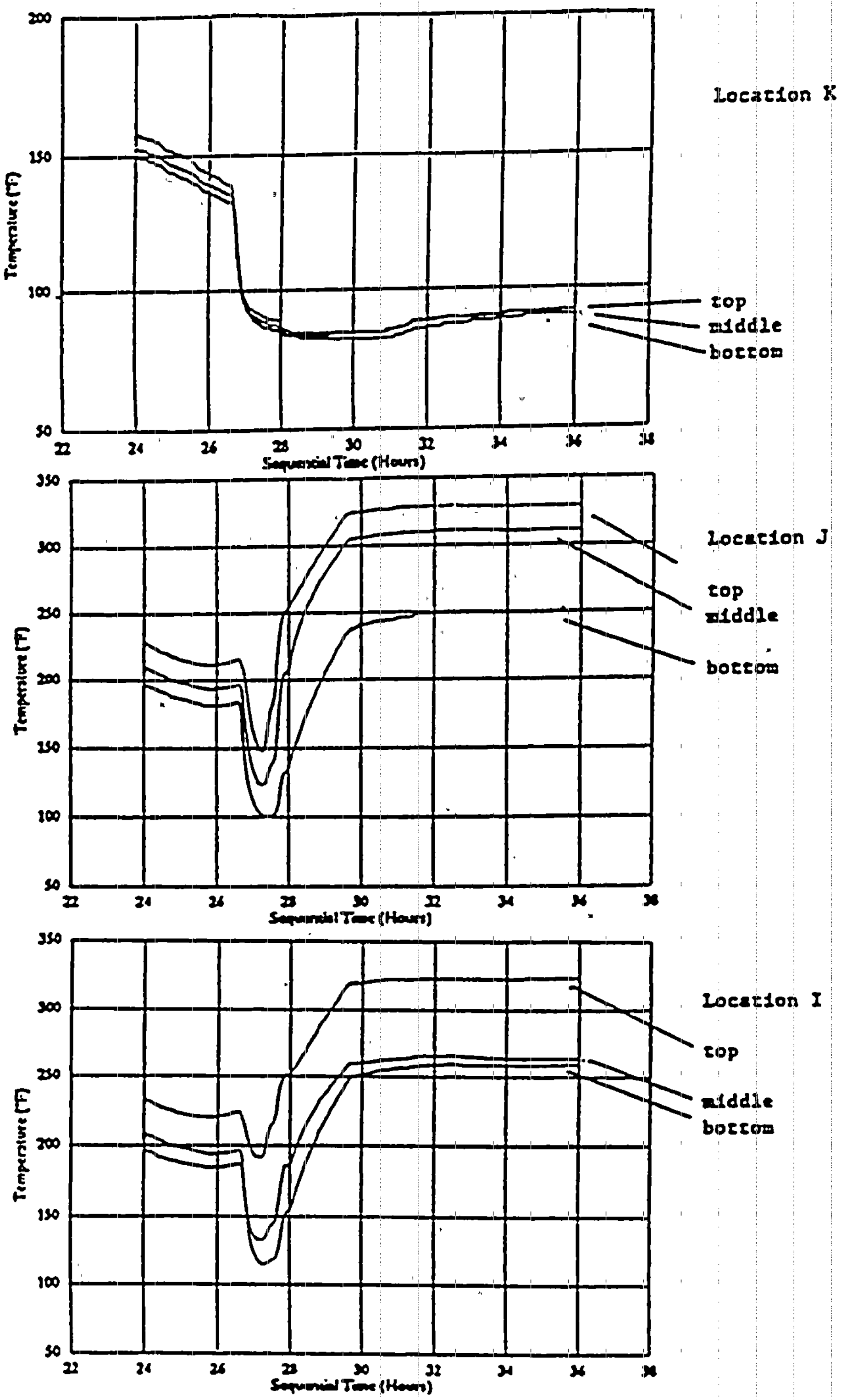


Figure 4.4-17 Palo Verde Plant Heatup Data

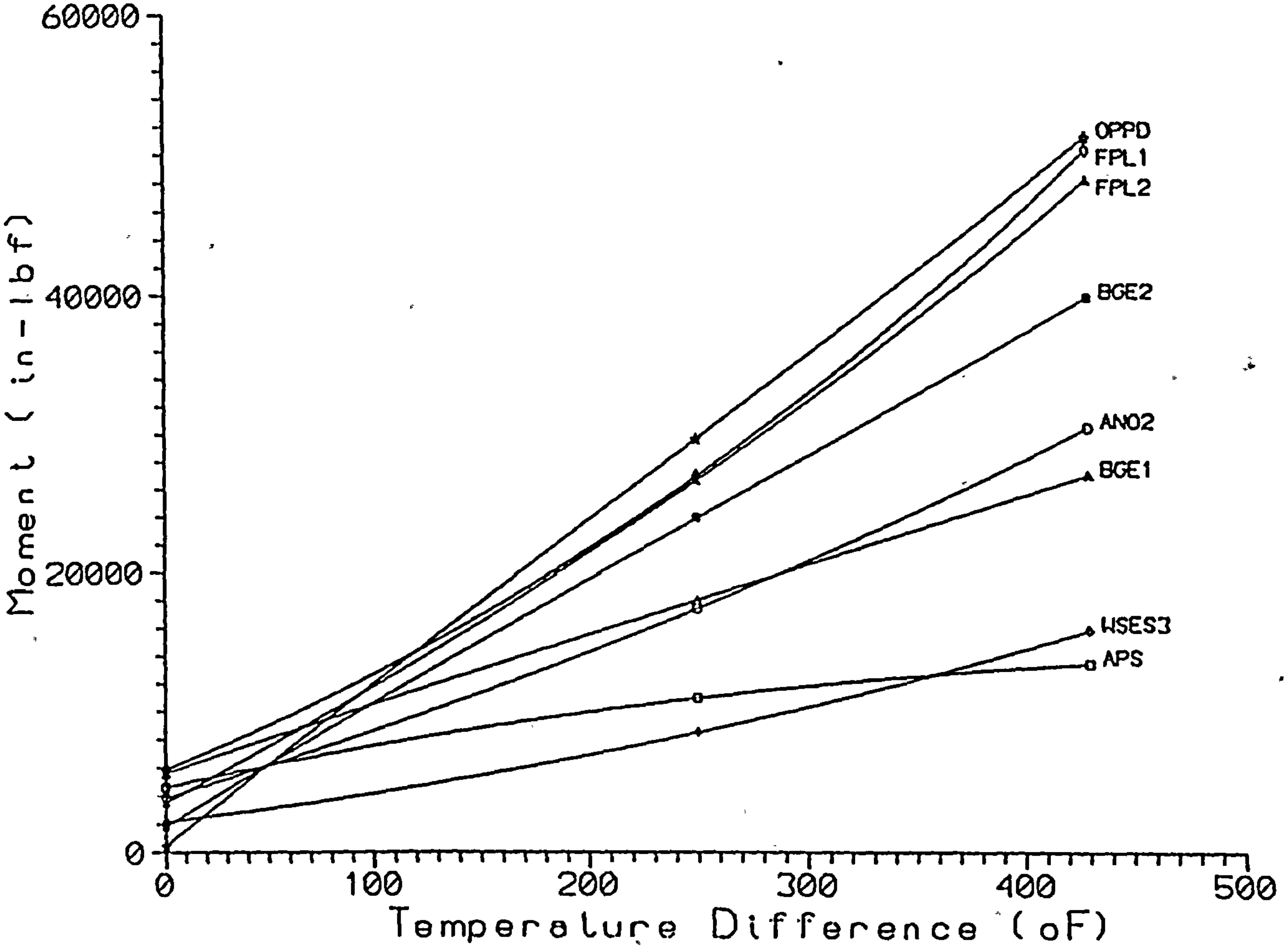


Figure 4.4-18 Thermal Stratification Moment vs Wall Temperature Difference

4.5 Branch Lines

Branch lines have been defined as lines intersecting one or more of the system lines reviewed in the previous sections. Of the candidate lines, the hot leg injection line, which branches off of the shutdown cooling line, was identified as being susceptible to thermal stratification caused by outleakage. The leak in this case would be of the assumed hotter, higher pressure, fluid in the SDC line past the isolation check valve into the normally stationary, cooler, lower pressure, fluid in the line to the Safety Injection Tanks.

A review of the configuration of the SDC lines in a number of plants showed that, depending on the length and routing of these lines, and the operating conditions, the coolant in these lines may not be at temperatures close to those of the RCS. Furthermore, these branch lines may intersect the SDC lines at a variety of axial locations down stream of the SDC-Hot Leg nozzle location. In addition, the leakage of hotter into colder fluid tends to be unstable. Thus, confirmation of stratification in the hot leg injection line was left to the discretion of the individual plants.

As typical of a number of plants, pressure transducers can be placed down stream of the check valves as a means of detecting leakage from the higher pressure RCS coolant in the SDC line into the cooler, stationary fluid in the hot leg branch line. Leakage would tend to pressurize the line at pressures close to that of the RCS: e.g. 2250 psia. Such measurements taken at Entergy Operations ANO2 indicated this pressure to be close to that of the Safety Injection Tanks, 900 psia. Furthermore, the recorded pressures remained constant showing only minor variations with changes in operating conditions. It was concluded that there was no thermal stratification due to leakage.

4.6 Drain Lines

A re-examination of the influence of line size on differences in wall temperature, Section 2, indicated that two inch lines, such as the drain lines, could have differences in wall temperatures due to stratification larger than 50°F. While no instances of problems related to thermal stratification have occurred in drain lines of CE plants, this section summarizes one recently reported incident and its implications to CE plants.

4.6.1 Drain Line Crack due to Thermal Stratification

Reference 15 documented the through wall crack found in the non-isolable section of a 2 inch drain line at Three Mile Island Unit 1, Figure 4.6-1 . Downstream of this section is a horizontal run of line in which the flow, due to the normally closed valves, is stagnant. The line is one of four, all oriented in a vertical down direction from the cold leg. Approximately eight inches of the lines and the RCS cold leg nozzles, are insulated. Though all four lines are nominally similar, the crack was in only one line, in the weld between the elbow and drain line, Figure 4.6-2.

The crack was initiated on the inside of the line, Figure 4.6-3. Metallurgical examination identified fatigue as the mechanism for crack growth, with the crack initiation possibly due to a slight surface defect, though none was evident in the as build radiographs. The post failure examination indicated both "beach" marks, related to thermal expansion for the 41 heat up and cool down cycles of the plant, and striations where the crack propagated through the heat affected zone. Based on spacing between striations approximately 44,000 cycles occurs for the crack to propagate through the wall.

Based on the post failure evaluation, it was hypothesized that failure resulted from a small crack , that existed early in life, which was the cause of the changes in stress levels necessary to cause the beach marks, and, approximately 100,000 stress cycles 60 ksi in magnitude that caused the crack to grow to the outer diameter. The latter would require a temperature difference of about 440°F between the top and bottom of the elbow. Though several mechanisms were considered the only plausible reason was related to thermal stratification caused by to turbulent penetration. The turbulent penetration would have a cyclical behavior, Figure 4.6-4, with a period of about 30 seconds, for the wall to experience cyclical changes in top and bottom temperatures.

Measurements recorded differences in wall temperatures of 40-60°F, Figure 4.6-5, in the horizontal section of the line. However, temperature variations of as high as 100°F, confirmed the presence of turbulent penetration in the vertical section. Test conditions were not at hot standby (four pump operation) conditions. Thus, test conditions did not result in the needed variations in temperature. However, it was hypothesized that higher flow rates in the cold leg during normal operation and, in addition, the lines being uninsulated, resulting in the source of cooler fluid being close to the bottom of the vertical section, could have resulted in higher differences in wall temperature. Data taken with the horizontal sections insulated did result in higher values of fluid temperatures.

4.6.2 Application to CE Plants

Results of the TASCS program identified a mechanism in which interaction of the turbulent penetration and a leakage film resulted in cyclical variations in wall temperature. However, no mention is made in Reference 15 of leakage through the isolation valves. This implies a possible source of cyclical behavior not documented in the TASCS study. The line being uninsulated than allows the fluid to cool down to containment conditions providing an alternate source of cooler temperature fluid. Insulation of these lines would increase the fluid temperature in sections of line close to the hot and cold legs, thus reducing variations in wall temperature that might result from turbulent penetration.

Without further analysis and/or experimental data the cyclical behavior the mechanism for crack initiation and growth for the GPU TMI-1 drain line cannot be substantiated. Thus, based on line size only drain lines cannot be eliminated from consideration. However, with drain lines only subject to outleakage, either natural convection or turbulent penetration could result in wall temperature differences larger than 50°F.

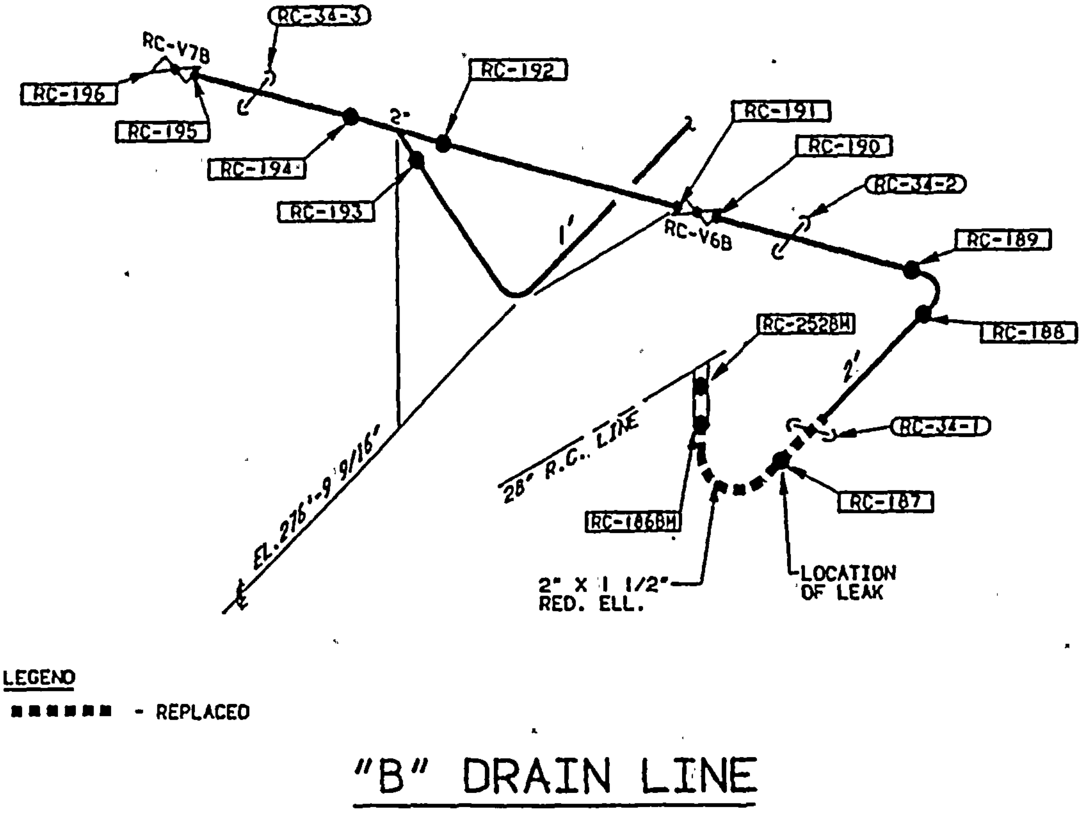


Figure 4.6-1 TMI-1 B Drain Line Routing

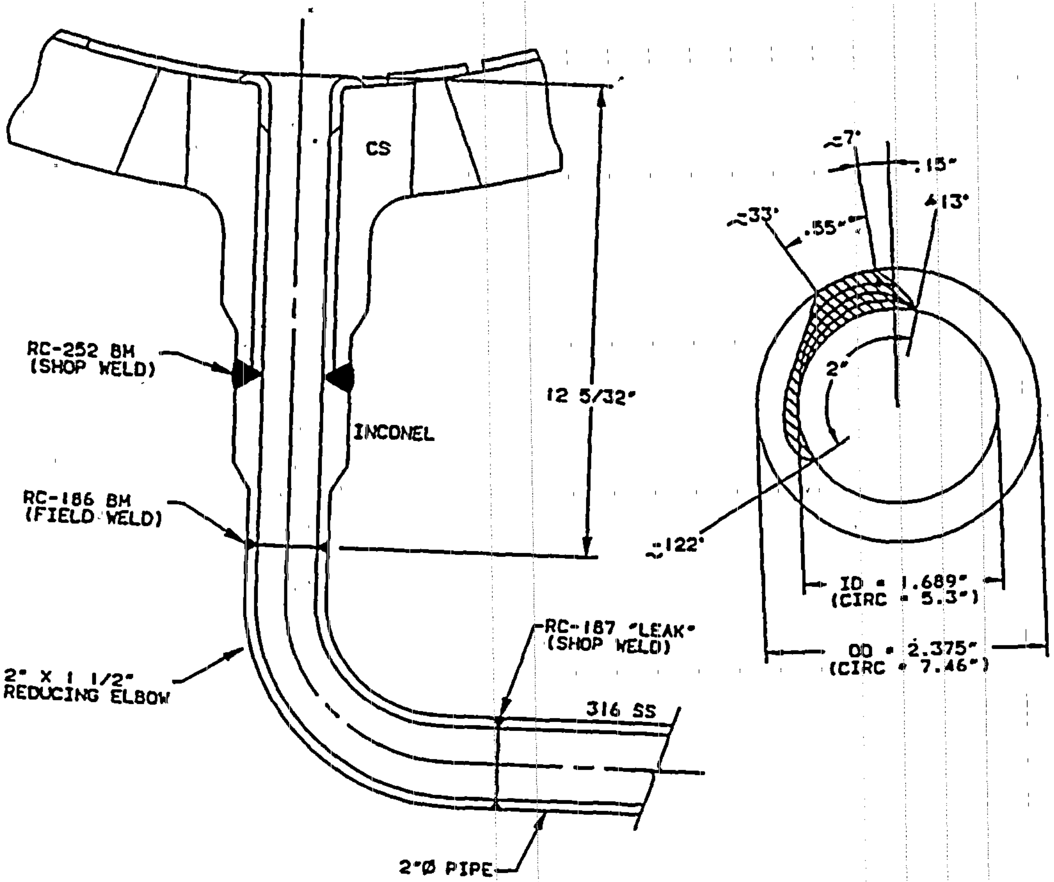


Figure 4.6-2 TMI-1 B Drain Line Nozzle, Elbow & Drain Line Crack Geometry

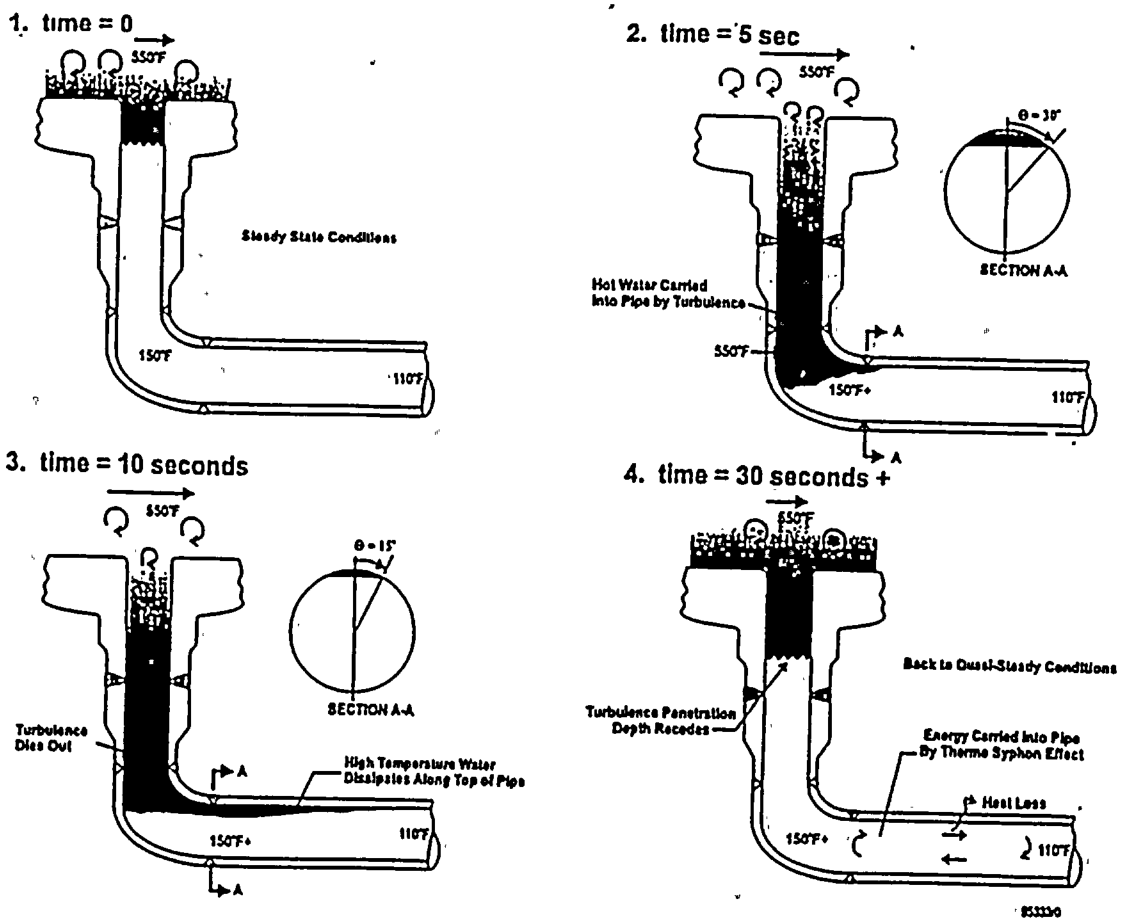
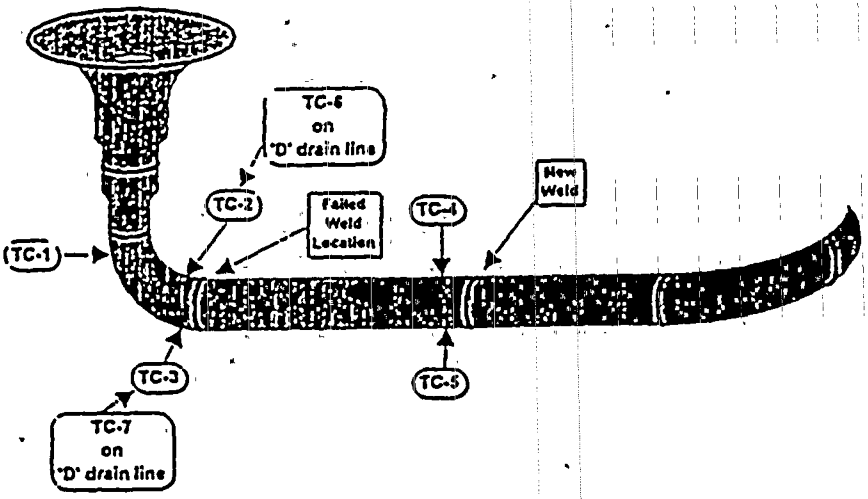


Figure 4.6-3 TMI-1 Turbulent Penetration into Drain Line

TMI-1 RCS 'B' & 'D' Drain Line Thermocouple Locations



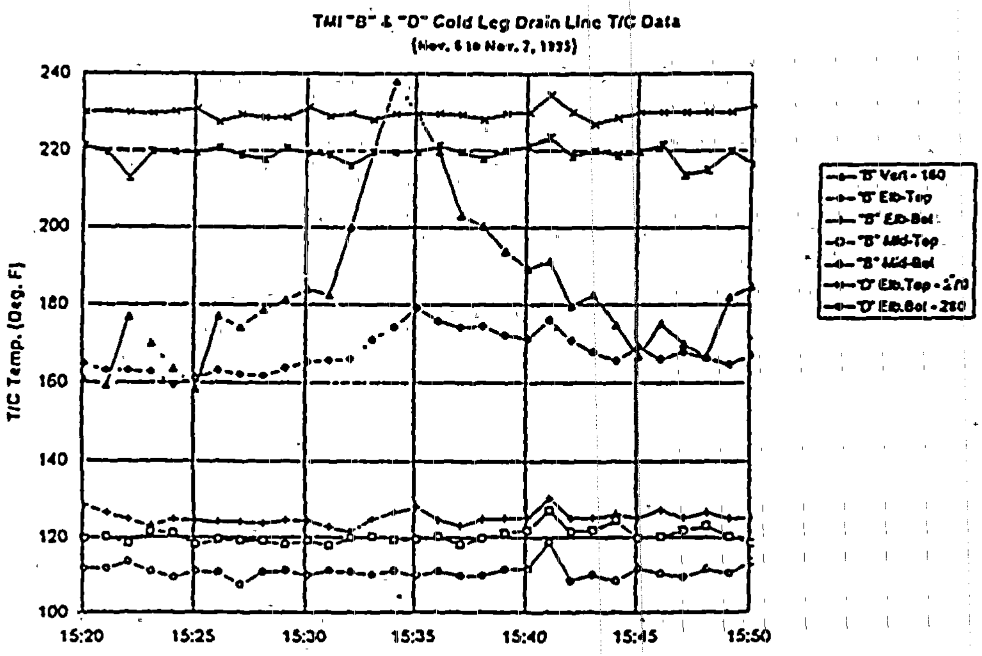


Figure 4-6-4 TMI-1 B Drain Line Thermocouple Locations and Sample Data

5.0 EVALUATION OF THERMAL STRATIFICATION LOADS ON FATIGUE

5.1 Fatigue Evaluation

Bulletin 88-08 was due primarily through events in which thermal stratification was the result of the leakage of a colder into the area of a hotter fluid. The resultant cracks were attributed to cyclical stresses related to either operating conditions or turbulent penetration. The course of the CEOG identification programs, with the exception of the auxiliary spray lines, the thermal stratification was found in a number of Class 1 lines that were found to be related to a variety of quasi-steady transients associated with plant operation; e.g. heatup and/or cooldown.

The mechanical loads due to these thermal stratification transients were not included in the design basis of the plant. The third required action of NRC Bulletin 88-08 requires that plant of plant licenses "plan and implement a program to provide continued assurance pipe stresses will not result in fatigue failure." NRC Bulletin 88-11 cites the requirement of 10CFR50.55.a that requires Class 1 piping satisfy Sections III of the ASME Code. Should this information be used as the basis for an amendment to the license, 10CFR50.71.e requires the FSAR be updated.

There is no specific directive that plant specific documentation is to be updated to include the effect of these loads on stress intensities and cumulative fatigue factors. However, an evaluation should be completed to determine the influence of these previously unconsidered loads on cumulative fatigue usage factor. Furthermore, some level of documentation should be added to the design report of record recording the results of this evaluation.

5.2 Influence of Thermal Stratification Loads on Fatigue

As set forth in 10CFR50.55(a), the methods and criteria on service limits of Section III of the ASME Boiler and Pressure Vessel Code are the basis for determining the influence of the loads due to thermal stratification. Per Bulletin 88-08, of particular importance is the continued integrity of the piping against fatigue failure.

Fatigue is based on the ability of the piping and connecting nozzles to experience the number of cycles and magnitudes of the design basis transients for the design life of the plant. The limit for fatigue life, expressed as the Cumulative Usage Factor, is required to be less than one for transient operation. The method of determining this is to consider the stress values for each of the loads (Section III, NB-3653.1) and then (Section III ;NB-3653.6(C)) determine values of alternating stress, allowable cycles and usage factor for each combination of transient events.

Values of Cumulative Usage Factor are, thus, dependent of magnitude of the loads, the stresses resulting from these loads, and the incremental value of usage factor due to sets of loads for each of the transients. The most accurate method of making this determination is to apply the loads to a Finite Element Model of the line, including supports. However, the influence of the thermal stratification loads on the piping can be used to determine if a full FEM analysis needs to be done. This involves the following two steps.

Screening: The objective is to determine the importance of the thermal stratification loads when compared to those for the remaining Design Basis events. Should the loads be insignificant (e.g. and order of magnitude smaller than existing loads) the influence of thermal stratification can be assumed to be small. Should this not be the case the next step is as follows.

Contribution to CUF: Objective is to calculate the incremental value of usage factor due to thermal stratification in combination with the design basis value of CUF at the worst (highest value) location (s). Should the incremental value result in the CUF being less than one, thermal stratification can be judged as not significant. However, should the value be close to or exceed one, the following design analysis would have to be completed.

Design Analysis: Perform a complete piping and fatigue analysis for piping including thermal stratification loads. Use react loads to analyze effect on nozzles and pipe supports.

An example of this procedure is included in Appendix D. Results of the evaluation should be documented and included in the Design Analysis of record for the line.

6.0 SUMMARY

NRC Bulletin 88-08 required owners of operating nuclear plants to ensure that conditions under which loads due to thermal stratification in lines connected to the RCS were adequately addressed. The CEOG has these actions in the following programs as follows.

Action 1: Review System to identify any section of piping subjected to similar conditions (that of thermal stratification).

Task 578 was to evaluate the potential for temperature oscillations due to systems connected to the RCS while Task 626 was to identify and evaluate systems where outleakage from the RCS was possible and make recommendations for systems and locations to be visually inspected.

Systems with large diameter lines in which little or no flow existed under normal operating conditions; e.g. Safety Injection, PORV and SDC, Pressurizer main and auxiliary spray systems, were identified as being most susceptible to thermal stratification. The main spray had been evaluated in a prior CEOG program (Task 482). Of the remaining systems, only the auxiliary spray system could be subject to inleakage into the RCS while the others could be subject to outleakage from the RCS.

Action 2: Inspect those pipes that may be subjected to excessive thermal stresses.

Based on guidelines documented in Task 732, identified locations were visually inspection for signs of leakage and/or unanticipated line movement.

Action 3: Plan and implement a program to provide continued assurance those pipes will not be subjected to stresses that could cause fatigue failure.

In addition to visual inspections, wall temperature measurements were recommended for the line identified as susceptible to thermal stratification. The measurements, done in accordance with the recommendations of Task 626, were done on the SI, SDC, PORV and Auxiliary Spray lines. All showed evidence of differences in wall temperature greater than 50°F. With the exception of the auxiliary spray line, none showed evidence that the stratification was related to outleakage from the RCS. Analyses were completed for each of these lines in which, first, a methodology was developed to predict fluid and wall temperature distributions and then these distributions were applied to calculate forces and moments.

Safety Injection Lines: Stratification was associated with natural convection in long (L>>D) horizontal sections of these lines between the isolation valve and the safety injection tank. Lines were divided into classes, based on geometric arrangement. Predicted temperature distributions (Task 741) were used to determine forces and moments (Task 813) for the lines in each class.

Pressurizer Safety and Relief Piping: The long length of the PORV lines allowed steam from the pressurizer to condense in the line and run back towards the pressurizer. The wall temperatures were evaluated based on a model of the condensate run-back (Task 773). These temperatures were used to compute moments for each line configurations (Task 826).

Shutdown Cooling Lines: Original wall measurements (Task 588) indicated small differences in top-to-bottom wall temperatures. Subsequent measurements in the ANO2 line with a longer vertical section, indicated substantial differences in wall temperature, related to operating conditions. Plants were divided into classes, based on length of vertical legs and following horizontal sections. Wall temperature distributions, based on those observed at ANO2 were used to estimate the moments due to thermal stratification at other plants (Task 772). These moments were used as a basis for a Justification for Continued Operation. A program to establish the cause and relationship of these distributions (Task 818) verified that the assumed temperature distributions were conservative for plants with short (L/D < 15) vertical lines.

Auxiliary Spray Lines: Increase in pressure due to initiation of charging flow was found to be related to variations in measured wall temperatures in two pilot plant applications. A conservative leakage model was used to estimate differences in wall temperatures due to stratification and resulting moments (Task 886). In addition, lines with short horizontal sections (L/D<40) upstream of the junction with the main spray line were identified as possibly being susceptible to turbulent penetration induced cycling.

These measurements and predictions, when compared combined with existing design base loads can be used as the basis for plant specific responses to Action 3.

7.0 NOMENCLATURE

α = coefficient of linear expansion of the line

ΔTw = difference in top-to-bottom wall temperatures

D = Outside diameter of the line.

t = Line thickness

E = Young's modulus

I = Moment of inertia about neutral axis; $1/64(D^4-(D+2t)^4)$

L = Length over which the ΔT_w is applied

k = Spring constants of the connected lines

K = Spring constants of the stratified section; $K_y = EI/2l^2$, $K_\theta = EI/L$

β =Coefficient of thermal expansion for the fluid

ΔT =Temperature difference of the hot and cold fluids

ΔV =Relative velocity between the hot and cold layers

Ri =Local Richardson Number

Rig =Global Richardson Number

k =Cofficient of Thermal Conductivity (equation for N2L)

m =Leakage Flow Rate

8.0 GENERAL REFERENCES

1. Lubin, B.T., Kim, J.H., "Prediction of Wall Temperatures in Long Lines Undergoing Natural Convection at High Rayleigh Numbers," IHTC-10, International Heat Transfer Conference, Brighton, UK, 1994.

2. Thermal Stratification, Cycling and Striping (TASCS) , EPRI, TR-103581, March 1994.

3. Robert, M., Mattei, J.D., "Thermal-Hydraulic Phenomena in a Zero Flowrate Pipe Connected to a High Flow Rate, High Temperature Circuit," Porch. of the International Symposium on Engineering Turbulence Modeling and Measurements, Sept. 24-28,1990, Dubrovnik, Yugoslavia (Elsevier, 1990).

4. Robert, M., "Corkscrew Pattern in Piping System Dead Legs,"NORTH 5, Salt Lake, UT, September 1992

5. Turner ,J.S., Bouyancy Effects in Fluids, Cambridge Univ- Press, 1973.

6. Lubin, B.T., Martin, J.W., Hammer, P.I., "Structural Evaluation of a Shutdown Cooling Line Subjected to Thermal Stratification due to Turbulent Penetration," ASME PVP, June. 1994.

7. Roark, R.J., Young, W.C., Formulas for Stress and Strain, McGraw Hill (5th Ed).

8. Nakamori, N., Hanzawa, K., "Valve Maintenance Guideline to Prevent Thermal Fatigue Damage of the Reactor Pressure Boundary Piping," PVP-Vol-313-2, pgs.95-102, ASME 1995.

9. Strauch, P.L., et al, "Evaluation of Isolation Valve Leakage in Alternate Charging Piping," PVP-Vol-313-1, pgs.53-59, ASME 1995.

10. Wolf, L., et al, "Results of HDR-experiments for Pipe Loads Under Thermally Stratified Flow Conditions," Nuclear Engn Design V137 (1992) Pgs 387-404.

11. Krieth, F., Principles of Heat Transfer, International Textbook Co, 1958.

12. Lubin, B.T., Brown, J. , "Thermal Stratification in Lines Connected to a Reactor Coolant System," ASME PVP-Vol 313-1,1995.

13. Fujimoto, T., et al, "Experimental Study of Stripping at the Interface of the Thermal Stratification,"ASME-AICHE 20th Heat Transfer Conference, August 1981, Pg. 73.

14. Letter from C.M.Thompson (NRC Project Manager) to W.F.Conway (APS), October 18, 1991 , Subject: NRC Bulletin 88-08, "Thermal Stresses in Piping Connected to Reactor Coolant System" ,NRC dockets 50-528, 529 and 53

15. GPU Nuclear Corporation, "TMI-1 Assessment of B Drain Line Leak and Implications to Other RCS Connected Lines,"Report 102, Rev 0 December 14, 1995.

9.0 CEOG REPORTS RELATED TO THERMAL STRATIFICATION

PRESSURIZER SPRAY LINE

CEOG-1	CE NPSD-261, Pressurizer Spray System Thermal Fatigue Evaluation" (CEOG Task 482)

NRC BULLETIN 88-11

CEOG-2	CE NPSD-546-P, Pressurizer Surge Line Flow Stratification Evaluation" Vols 1,2 (CEOG Task 587)
CEOG-3	CEN-387-P, Rev 1-P, Pressurizer Surge Line Flow Stratification Evaluation" Vols 1,2 (CEOG Task 662)
CEOG-4	CEN-387-P, Rev 1-P-A, "Pressurizer Surge Line Flow Stratification Evaluation" (CEOG Task 662)
CEOG-5	CEN-387, Rev 1-A, "Pressurizer Surge Line Flow Stratification Evaluation" (CEOG Task 662)

NRC BULLETIN 88-08

CEOG-6	CE NPSD-489, Evaluation of Thermal Stresses in Piping Connected to CE-Designed Reactor Coolant Systems" (CEOG Task 578)
CEOG-7	CE NPSD-579, Evaluation of Thermal Stresses in Piping Connected to CE-Designed Reactor Coolant Systems" (CEOG Task 626)
CEOG-8	CE NPSD-686-P, "A Program to Resolve Concerns Resulting from NRC Bulletin 88-08 Report on Phase III" Vols I, II, III (CEOG Task 588)

CEOG-9 CE NPSD-736, "Justification for Continued Operation; Phase VI of a CEOG Program to Address Thermal Stratification in Piping Connected to the RCS" (CEOG Task 732, Activity A.2)

CEOG-10 CE NPSD-744, "A Program to Address Thermal Stratification in Piping Connected to the RCS; Walkdowns of Potentially Affected Piping" (CEOG Task 732, Activity A.1)

CEOG-11 CE NPSD-760, "Guidelines for Temperature Data Collection" (CEOG Task 732, Activity A.3)

CEOG-12 CE NPSD-907, "Temperatures in Safety Injection Lines due to Thermal Stratification; Final Technical Basis Report" (CEOG Task 741)

CEOG-13 CE NPSD-915, "Prediction of Temperatures in Safety Injection Lines Subject to Thermal Stratification Due to Natural Convection" (CEOG Task 741)

CEOG-14 CE NPSD-924, "A Methodology to Predict Wall Temperature Distributions in Thermally Stratified Pressurizer Safety and Relief Piping "(CEOG Task 773)

CEOG-15 CE NPSD-933, "Justification for Continued Operation Addressing Thermal Stratification in the Shutdown Cooling Piping" (CEOG Task 772)

CEOG-16 CE NPSD-963, "Temperature Distributions and Structural Analysis of Safety Injection Piping Subject to Thermal Stratification" (CEOG Task 818)

CEOG-17 CE NPSD-979, "Thermal Stratification in the Shutdown Cooling Piping" (CEOG Task 813)

CEOG-18	CE NPSD-1003, “Temperature Distributions and Structural Analysis of Pressurizer Safety and Relief Valve Piping Subject to Thermal Stratification”(CEOG Task 827)
CEOG-19	CE NPSD-1020, “Thermal Stratification in Pressurizer Auxiliary Spray Piping”(CEOG Task 886)

APPENDIX A
LINES CONNECTED TO THE RCS

A-1 Arkansas Nuclear One-Unit 2

LINE NUMBER	DESCRIPTION
2CCA-11-1/2"	Sample Line
2CCA-21-12"	Safety Injection/Shutdown Cooling
2CCA-22-12"	Safety Injection/Shutdown Cooling
2CCA-14-3"	Pressurizer Spray
2BCA-5-1/2"	Sample Line
2CCA-12-2"	Letdown Line
2CCA-B-3"	Pressurizer Spray
2CCA-29-2"	To Reactor Drain Tank
2CCA-27-2"	Charging Line from Regenerative Hx
2CCA-32-2"	To Reactor Drain Tank
2CCA-23-12"	SI & Shutdown Cooling (line D)
2CCA-24-12"	SI & Shutdown Cooling (line C)
2CCA-26-2"	Charging Line from Regenerative Hx
2CCA-30-2"	To Reactor Drain Tank
2CCA-31-2"	To Reactor Drain Tank
2CCA-25-14"	Shutdown Cooling
2 ft 4700	RCS Pressure Instrumentation Lines (SGB)
2CCB-69-3/4"	RV Head Gasket Drain
2CCA-17-3/4"	RV Head Vent
2CCA-11-1/2"	Sample
2 ft 4600	RCS Pressure Instrumentation Lines (SGA)
2CCA-1-12"	Surge Line
2CCA-28-2"	To Reactor Drain Tank
2CCA-15-3/4"	Main Spray Bypasses

LINE NUMBER	DESCRIPTION
2CCA-15-3"	Spray Valve Piping
2CCA-15-4"	Spray Header to Pzr.
2BCA-2-3/4"	Sample from Pzr.
2FCC-2-6"	PSV 4634
2FCC-1-6"	PSV 4633
2FCC-1-10"	PSVs to Quench Tank
2FCC-4-2"	RCP Seal Relief To Quench Tank
2BCA-14-6"	Pzr. to PORVs
2BCA-14-4"	PORV 4730/4740 Piping
2GCB-514-4"	PORV 4741 Piping
2FDC-2-6"	Relief 4742
2FDC-1-6"	Relief 4732
2BCA-14-3"	To MV-4693 (PORV Bypass)
2FCC-2-6"	From MV-4698
2TCD-40-1/4"	Drainline
2CCA-18-3/4"	Ref. Level Indicator
2CCD-72-3/4"	TRMP Reac. AP Monitoring Station
2CCA-25-3"	HPSI Header 1
2CCA-25-3"	HPSI Header 2
2CCA-12-2"	Drain (Off Cold Lg (1B))
2CCB-54-1/2"	Sample Line

A-2 Calvert Cliffs Units 1 & 2

PLANT: Calvert Cliffs Unit 1

LINE NUMBER	DESCRIPTION
3/4" CC-11-1004	Spray Line Piping
12" CC-4-1010	Safety Inject. Tank No. 11B
2" CC-9-1004	RC Drain Tank No. 11
2" CC-9-1003	RC Drain Tank No. 11
2" CC-5-1005	CVCS Charging Line
12" CC-4-1009	Safety Inj. Tank No. 11A
3" CC-11-1001	Pressurizer Spray
12" CC-4-1011	Safety Inj. Tank No. 12-A
2" CC-3-1004	CVCS Letdown Line RHX No. 11
2" CC-9-1005	RC Drain Tank No. 11
2" CC-9-1006	RC Drain Tank No. 11
2" CC-5-1004	CVCS Charging Line
12" CC-4-1012	Safety Inj. Tank No. 12B
12" CC-14-1004	Shutdown Cooling
SG No. 12 Pressure Tap	(1-PDT-1210)
2" CC-9-1007	RC Drain Tank No. 11
3/4" CC-9-1008	To Local Refueling Level Indicator
S/G No. 11 Pressure Taps	(1-PDT-111A) (1-PDT-111B)
Surge Line 12"	
3/4" CC-5-1005	Elbow in Spray Line
2" CC-5-1003	Aux. Spray Line From CVCS
2 1/2" CC-10-1008	Safety Valve/PORV

PLANT: Calvert Cliffs Unit 1

LINE NUMBER	DESCRIPTION
4" GC-8-1008	"
1/2" GC-8-1010	"
6" GC-8-1013	"
4" GC-8-1007	"
1/2" GC-8-1009	"
4" GC-8-1002	"
4" GC-10-1002	"
6 GC-8-1003	"
1/2" GC-8-1011	"
3/4" CC-10-1012	"
4" GC-8-1001	"
2-1/2" CC-10-1003	"
1/2" GC-8-1010	"
4" GC-8-1006	"
2-1/2 CC-10-1007	"
3/4" CC-10-1009	"
4" CC-10-1001	"
4" CC-10-1005	"

PLANT: Calvert Cliffs Unit 1

LINE NUMBER	DESCRIPTION
12" CC-4-2009	Safety Inj. Cold Leg 21B
3" CC-11-2002	Spray Line Piping
2" CC-9-2004	RC Drain Cold Leg 21B
2" CC-9-2003	RC Drain Cold Leg 21A
2" HC-2-2217	RC Drain Cold Leg 21A
3" CC-11-2001	Spray Line Piping
2" CC-5-2005	Charging Line
2" CC-5-2004	Charging Line
12" CC-4-2010	Safety Inj. Tank No. 21A
1" CC-9-2008	Local Refueling Level Indicator
2" CC-9-2007	RC Drain Hot Leg 21
S/G No. 21 Pressure Taps	(2-PDT 111A) (2-PDT 111B)
12" CC-4-2011	Safety Inj. Tank No. 22B
2" CC-9-2006	RC Drain Tank No. 21
2" CC-3-2004	Letdown Line to CVCS
12" CC-4-2012	Safety Inj. Tank No. 22A
3/4" CC-11-2004	Spray Line Piping
2" CC-5-2003	Aux. Spray
3/4" CC-11-2005	Spray System
3/4" CC-10-2009	Safety Valve/PORV
4" CC-10-2006	"
4" CC-10-2002	"
2-1/2" CC-10-2004	"
2-1/2" CC-10-2008	Safety Valve/PORV
2-1/2" CC-10-2003	"

PLANT: Calvert Cliffs Unit 1

LINE NUMBER	DESCRIPTION
4" CC-10-2001	"
4" CC-10-2005	"
4" CC-11-203	"
2-1/2" CC-10-2007	"
6" GC-8-2006	"
1/2" GC-8-2011	"
4" GC-8-2001	"
1/2" GC-8-2010	"
6" GC-8-2003	"
3/4" GC-8-2014	"
1/2" GC-8-2012	"
1/2" GC-8-2009	"
4" GC-8-2002	"
6" GC-8-2013	"
6" GC-8-2007	"
4" GC-8-2008	"
10" GC-8-2005	"
S/G No. 22 Pressure Taps	(2 PDT-121A) (2 PDT-121B) (2 PDT-121C)
12" Surge Line	
12" CC-14-2004	Shutdown Cooling Line Hot Leg 22

A-3 St.Lucie Units 1 & 2

PLANT: **St. Lucie Unit 1**

LINE NUMBER	DESCRIPTION
3/4-RC-136	RVGVS
3/4-RC-160	RV PI
3/4-RC-161	RV PI
12-RC-151	ST Line to Loop 1A1
1-RC-218	ΔP across RCP 1A1
1-RC-217	ΔP across RCP 1A1
2-RC-113	To Waste Management (WM)
1-RC-117 to 120	SG 1A1 Pressure Taps
3/4-RC-132 to 135	RCS 1A Pressure Taps
2-RC-145	RWLIS
3/4-RC-143	Sample
12-RC-162	Loop 1A SDC Line
2-RC-116	To WM
1-RC-219	ΔP across RCS 1A2
1-RC-220	ΔP across RCP 1A2
2-RC-148	Loop 1A2 Charging
12-RC-154	Loop 1A2 SI Line
12-RC-153	Loop 1B2 SI Line
3-RC-141	Spray Line from Loop 1B2
1-RC-223 1-RC-224	ΔP across RCP 1B2
2-RC-125	To WM
1-RC-137 to 140	SG 1B1 Pressure Taps
3/4-RC-126 to 129	RCS 1B Pressure Taps

PLANT: St. Lucie Unit 1

LINE NUMBER	DESCRIPTION
12-RC-147	Loop 1B SDC Line
1-RC-158	Drain
2-RC-106	Drain
12-RC-108	Surge Line
12-RC-152	Loop 1B1 SI Line
2-RC-150	Loop 1B1 Charging
1-RC-222 1-RC-221	ΔP across RCP 1B1
2-RC-142	Letdown
2-RC-122	To WM
3-RC-109	Spray Line from Loop 1B1
3/4-RC-103	Spray bypass
4-RC-103	Sprayline to Pzr
1-RC-130	Pzr instrumentation
1-RC-107	Pzr instrumentation
6-RC-827	PSV V1200
6-RC-823	PSV V1201
6-RC-829	PSV V1202
10-RC-822	PSV Line to Quench Tank
2-RC-834	Charging relief to Quench Tank
1-RC-835, 836	SI Relief to Quench Tank
6-RC-824	PORV Line to Quench Tank
6-RC-837	Flange off PORV Line
2-RC-283	From RVGVS to PORV Line
1/2-RC-831, 833	PORV Tap

PLANT: **St. Lucie Unit 1**

LINE NUMBER	DESCRIPTION
4-RC-101	PORV Line
2-1/2-RC-157	PORVs
2-1/2-RC-156	PORVs
4-RC-825	PORV Line
4-RC-826	PORV Line
3/4-RC-131	RVGVS
3/4-RC-100	Sample
2-RC-149	Aux. Spray Line
3/4-RC-146	Sample
	3/4" RCP seal injection lines
	ICI Nozzles

PLANT: St. Lucie Unit 2

LINE NUMBER	DESCRIPTION
12-RC-151	Loop 2A1 Safety Inj. & Shutdown Cooling
1-RC-218 3/4-RC-263/V1446	RCP 2A1 Pressure Taps
1-RC-217 3/4-RC-261/V1445	RCP 2A1 Pressure Taps
2-RC-113/V1235	To Waste Management
2-RC-116/V1234	To Waste Management
1-RC-219 3/4-RC-265/V1448	RCP 2A2 Pressure Taps
1-RC-220 3/4-RC-267/V1419	RCP 2A2 Pressure Taps
2-RC-148	Charging Line
12-RC-154	Loop 2A2 Safety Inj. & Shutdown Cooling
12-RC-162 10-RC-301	Loop 2A2 Shutdown Cooling
2-RC-106/V1215	Drain
3/4-RC-143 3/4-RC-208/V1213	Sample
2-RC-106 3-SI-190	Hot Leg Inj.
3/4-RC-144/V1214	RWLIS
3/4-RC-135/I-SO-01-16 3/4-RC-207/V1216	RCS Instr.
3/4-RC-134/I-SO-01-15 3/4-RC-206/V1217	RCS Instr.
3/4-RC-133 3/4-RC-205/V1218	RCS Instr.
3/4-RC-132 3/4-RC-204/V1219	RCS Instr.

PLANT: St. Lucie Unit 2

LINE NUMBER	DESCRIPTION
12-RC-152	Loop 2B1 Safety Inj. & Shutdown Cooling
3-RC-109	Loop 2B1 Spray Line
2-RC-150	Loop 2B1 Charging Line
1-RC-222 3/4-RC-273	RCP 2B1 Pressure Taps
2-RC-142	Letdown Line
2-RC-122/V1450	Drain
2-RC-125/V1449	Waste Management
1-RC-223 3/4-RC-277/V1428	RCP 2B2 Pressure Taps
1-RC-224 3/4-RC-278/V1430	RCP 2B2 Pressure Taps
12-RC-153	Safety Inj. & Shutdown Cooling Loop 2B2
3-RC-141	Spray Line - Loop 2B2
12-RC-147 3-RC-191	Loop 2B Shutdown Cooling Hot Leg Inj.
12-RC-108	Surge Line
3/4-RC-126/I-SO-01-09 3/4-RC-209/V1224	RCS Instrumentation
3/4-RC-127/I-SO-01-10 3/4-RC-210/V1225	RCS Instrumentation
3/4-RC-128/I-SO-01-11 3/4-RC-211/V1226	RCS Instrumentation
3/4-RC-129/I-SO-01-12 3/4-RC-212/V1227	RCS Instrumentation
1-RC-117 to 120	SG 2A1 Pressure Instrumentation
3/4-RC-161	RV Leak Detection

PLANT: St. Lucie Unit 2

LINE NUMBER	DESCRIPTION
3/4-RC-164	RV Leak Detection
3/4-RC-136	RVGVS
3/4-RC-137 to 140	SG 2B1 Pressure Instrumentation
3/4-RC-307	Spray Bypass
3/4-RC-304	Spray Bypass
4-RC-103	Spray Header to Pzr
4-RC-101	PORV Header from Pzr
6-RC-827	PSV V1200 Piping
6"-RC-828	PSV V1201 Piping
6"-RC-829	PSV V1202 Piping
10"-RC-822	PSV Header to Quench Tank
1"-RC-836, 835	SI Relief to Quench Tank
2"-RC-834	Charging Relief
1"-RC-856	RVGVS to Quench Tank
8"-RC-312	PORV header to Quench Tank
10"-RC-315	Quench Tank Header
3"-RC-309	PORVs

PLANT: St. Lucie Unit 2

LINE NUMBER	DESCRIPTION
3"-RC-310	PORVs
8"-RC-311	PORV Header to Quench Tank
10"-RC-302	Loop 2A2 Shutdown Cooling
2"-RC-158	Drain
	3/4" RCP seal injection lines
	ICI Nozzles

A-4 Maine Yankee

LINE NUMBER	DESCRIPTION
2502-12"	Surge Line
1504-3"/RC271	Loop 1 iso. vlv connections
1504-3/4"/HCV-121	Loop 1 iso. vlv connections
1504-2"/HCV-110	Loop 1 iso. vlv connections
1504-3/4"/RC212	Loop 1 pressure instrumentation
1504-3/4"/RC214	Loop 1 pressure instrumentation
1504-3/4"/RC216	Loop 1 pressure instrumentation
1504-3/4"/RC218	Loop 1 pressure instrumentation
1504-3/4"/RC219	Loop 1 pressure instrumentation
1504-3/4"/RC217	Loop 1 pressure instrumentation
1504-3/4"/RC215	Loop 1 pressure instrumentation
1504-3/4"/RC213	Loop 1 pressure instrumentation
1504-2/RC240	Drain Instrumentation
1504-3/4"/RC243	Refueling Level
1504-3"/RC273	Loop 3 iso. vlv. connections
1504-1"/HCV-125	Loop 3 iso. vlv. connections
2502-8"HCV109	Loop 3 iso. vlv. connections
1504-2"/HCV112	Loop 3 iso. vlv. connections
1504-3/4"/RC260	Loop 3 iso. vlv. connections
1504-3/4"/RC238	Loop 3 iso. vlv. connections
1504-3/4"/RC236	Loop 3 iso. vlv. connections
1504-3/4"/RC234	Loop 3 iso. vlv. connections

LINE NUMBER	DESCRIPTION
1504-3/4"/RC239	Loop 3 Pressure Instrumentation
1504/3/4"/RC237	Loop 3 Pressure Instrumentation
1504-3/4"/RC235	Loop 3 Pressure Instrumentation
1504-3/4"/RC233	Loop 3 Pressure Instrumentation
1504-3/4"/HCV-126	Loop 3 iso. vlv connections
1504-2"/RC242	Drain connections
1504-14"	Loop 3 SI and RHR
1504-3"/RC263	Loop 3 Charging Line
1504-12"	Shutdown Cooling (Residual Heat Exch.) Loop 2
2502-8"/HCV-108	Loop 2 iso. vlv. connections
1504-2"HCV-114	Loop 2 iso. vlv. connections
1504-3/4"/RC-124	Loop 2 iso. vlv. connections
1504-3"/RC-129	Loop 2 iso. vlv. connections
1504-14"	Loop 2 SIS & RHR
1504-3"/RC-262	Loop 2 Charging Line
1504-3/4"	Containment Sump
2502-8"/HCV-107	Loop 1 iso. vlv. connections
1504-3/4"/HCV-122	Loop 1 iso. vlv. connections
1504-3"/RC-128	Loop 1 iso. vlv. connections
1504-3"-206	Spray Line (PCV-101T)
1504-3/4"/RC-269	Spray bypass
1504-4"	Spray header to Pzr.
1504-2"	Aux. Spray connection
1504-3"/RC-208	Sprayline (PCV-101V)
1504-3/4"/RC-268	Spray bypass

LINE NUMBER	DESCRIPTION
1504-1"	Pzr. instrumentation
1503-3"/RC-351	PSV
1503-3"/RC-352	PSV
1503-3"/RC-353	PSV
301-10"	PSV/PORV header to quench tank
1504-3/4"/RC-248	PSV line to sample
1504-3/4"/RC-266	Sample
1504-3/4"/RC-203	Sample
1504-3/4"/HCV-145	PORV header
1504-3/4"/HCV-146	PORV header
1504-2-1/2"/PCV-102X	PORVs
1504-2-1/2"/PCV-102Y	PORVs
1504-2-1/2"/RC-261	Loop 1 Letdown
1504-14"	Loop 1 SI and RHR
1504-2"/HCV-111	Loop 2 iso. vlv. connections
1504-3/4"/RC-171	Loop 2 iso. vlv. connections
1504-3/4"/RC-170	Loop 2 iso. vlv. connections
	1" RCP seal injection lines
	ICI Nozzles

A-5 Fort Calhoun

LINE NUMBER	DESCRIPTION
3/4" RC 2501R/RC100	RVGVS
12" SI 2501R	Safety Injection & Shutdown Cooling Loop-2B
2" RC-2501/RC-112	To WD
RC-118/158	SG Loop 2-B Pressure Taps
RC-120/148	SG Loop 2-B Pressure Taps
RC-121/153	SG Loop 2-A Pressure Taps
RC 113/157	SG Loop 2-A Pressure Taps
2" RC-2501R	To Letdown Loop 2A
2" RC-250R/RC-113	To WD Loop 2A
2" RC-2501R	Charging Line Loop 2A
3" RC-2501R/PCV 1031	Spray Line Loop 2A
3/4" RC-2501R/RC-133	Bypass Spray Line Loop 2A
3/4" RC-2501R/RC-139	Sample Line Hot Leg Loop 2
12" SI 2501R	Shutdown Cooling Hot Leg Loop 2
12" SI 2501R	Safety Injection/Shutdown Cooling Loop 2A
12" SI 2501R	Safety Injection/Shutdown Cooling Loop 1B
3/4" RC 2501R/RC-101	RV Level Indication Loop 1A
2" RC 2501R	Charging Line Loop 1A
12" SI 2501R	Safety Injection & Shutdown Cooling Loop 1A
2" RC 2501/RC-124	To WD Loop 1A

PLANT: Fort Calhoun Station

LINE NUMBER	DESCRIPTION
RC 110/RC-134	SG Pressure Taps Loop 1A
RC 108/156	SG Pressure Taps Loop 1A
3" RC 2501/PCV 103-2	Spray Line Loop 1B
3/4" RC 2501/RC-131	Spray Bypass
10" RC 2501R	Surge Line
3/4" RC 2501R/RC-138	Sample Line
2" RC 2501R/RC-128	Refueling Level Indicator Connection
RC 153/RC-109	SG Pressure Taps Loop 1B
RC 155/107	SS Pressure Taps Loop 1B
RC 103 to 106	SG Pressure Taps Loop 1B
2"RC 2501R/RC 123	To WD
RC-114 to 117	Loop Pressure Instrumentation
4"-RC-2507R	Spray Line Header to Pzr.
2"-RC-1508R	Aux. Spray Line
1"-RC-2507R/RC143 - 146	Pzr. Instrumentation
1"-RC-2507R/RC0147, 149, 150	Pzr. Instrumentation
4"-RC-2507R/RC-141	Pzr. to PSV
4"-RC-2507R/RC-142	Pzr. to PSV
6"-RC-301R/RC-141	PSV to Quench Tank Header
6"-RC-301R/RC-142	PSV to Quench Tank Header
8"-RC-301R	Quench Tank Header
3" RC-2507R	PORV Header
3/4"-RC-2507R/RC	Sample

PLANT: **Fort Calhoun Station**

LINE NUMBER	DESCRIPTION
102,126	
2-1/2"-RC-2507R/HCV-151	PORVs
2-1/2"-RC-2507R/HCV-150	PORVs
4"-RC-301R	PORV Header
6"-RC-301R	PORV Header to Quench Tank
1/2"-RC-301R	PORV Bypass
8"-RC-301R	Relief Header to Quench Tank
1-1/2"-RC-301R	Relief Header
3/4" RC-2501R/RC-127	Sample
	ICI Nozzles

APPENDIX B

CALCULATION OF DIFFERENCES IN WALL TEMPERATURE CAUSED BY DIFFERENT THERMAL STRATIFICATION MECHANISMS

Thermal stratification of a fluid is the result of a number of different flow and thermodynamic conditions. Each, however, must be of a configuration in which the body forces, related to mass density, are greater than the inertial forces, related to the relative velocity between the successive depths in the fluid.

As pertains to NRC Bulletin 88-08, the following four mechanisms have been found to result in thermal stratification of the flow:

1. Natural Convection
2. Two phase fluid
3. Turbulent Penetration
4. Leakage

All of these mechanisms can be represented as the hotter, low density layer over the colder, higher density layer, separated by a interface at angular location . Heat transfer occurs from the upper layer, at temperature T_h and heat transfer coefficient h_h, to the wall. This heat is conducted through the wall, the primary resistance to conduction being in the circumferential direction. Though heat is lost by convection to the ambient, the presence of insulation makes this heat loss normally low . The majority of the heat is lost by convection from the wall to the fluid, at temperature T_c with a convection coefficient hc. This one dimensional, axisymmetric model, Figure B-1, is solved for the following relationship between wall temperature and angular location (Reference)

$$T_{w,top} = T_{oc} + [(T_{oh}-T_{oc}) N_h \mathrm{Sinh}(N_h L_h) \; / \; B]$$

$$T_{w,bottom} = T_{oh} - [(T_{oh}-T_{oc}) N_c \mathrm{Sinh}(N_c L_c) \; / \; B]$$

$$\text{where } B = N_h \mathrm{Cosh}(N_c L_c) \mathrm{Sinh}(N_h L_h) + N_c \mathrm{Cosh}(N_h L_h) \mathrm{Sinh}(N_c L_c)$$

Parameters N and To are defined as follows:

$N_c = [(h_c + h_{amb}) / k\,t\ ]_{.50}$ $T_{oc} = (h_c T_c + h_{amb}\,T_{amb}) / (h_c + h_{amb})$

$N_h = [(h_h + h_{amb}) / k\,t\ ]_{.50}$ $T_{oh} = (h_h T_h + h_{amb}\,T_{amb}) / (h_h + h_{amb})$

and the lengths L , with Oi the interface angle in radians, as;

$L_c = D/2\,\theta_i$ $Lh = D/2\,(\pi/2 - \theta_i)$

Evaluation of the equations was based on values of heat transfer coefficients, hot and cold fluid temperatures and interface locations derived in the related CEOG programs, as listed in Table B-1.

Results , evaluated in spread sheet format, for selected values of tube sizes, schedule and heat transfer mechanisms are shown in Figure B-2. Turbulent penetration, with the high heat transfer rates from the hotter fluid and the cooler fluid occupying a significant surface area results in the highest difference between top and bottom temperatures. In addition, while the 50°F screening point for natural convection, leakage, turbulent penetration and two phase flow indicate temperatures above this screening value could occur for diameters below one inch.

Variations for the same heat transfer mechanism are shown in Figure B-3. For larger diameter tubes, reductions in temperature difference of about 60% are evident in going from Schedule 40 to Schedule 160.

Table B-1: Values of Heat Transfer Parameters from CEOG Programs

HEAT TRANSFER MECHANISM	Natural Convection	Leakage	Turbulent Penetration	Two-Phase
Thot	300	540	500	650
Tcold	100	200	150	400
h_{hot}	10	10	35	200
h_{cold}	10	100	15	5
Interface Angle	90°	15°	125°	155°
h_{avg}	10	17.5	21	32
Reference	CEOG-13	CEOG-19	CEOG-17	CEOG-18

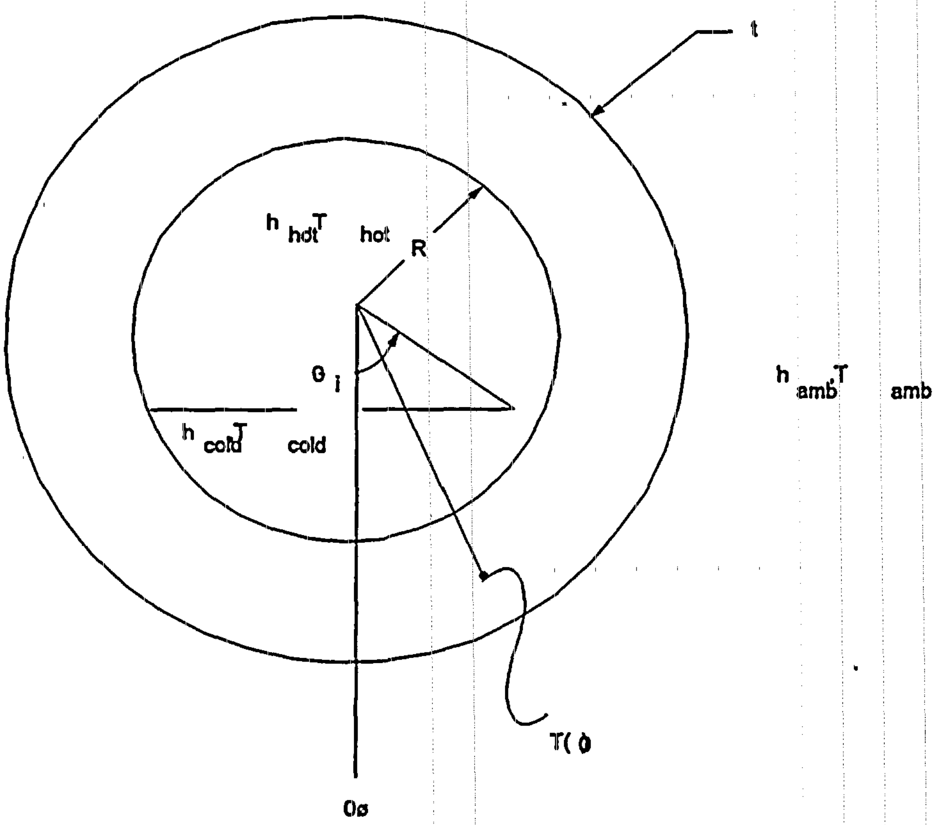


Figure B-1: One Dimensional Conduction Model for Thermal Stratification in a Circular Pipe

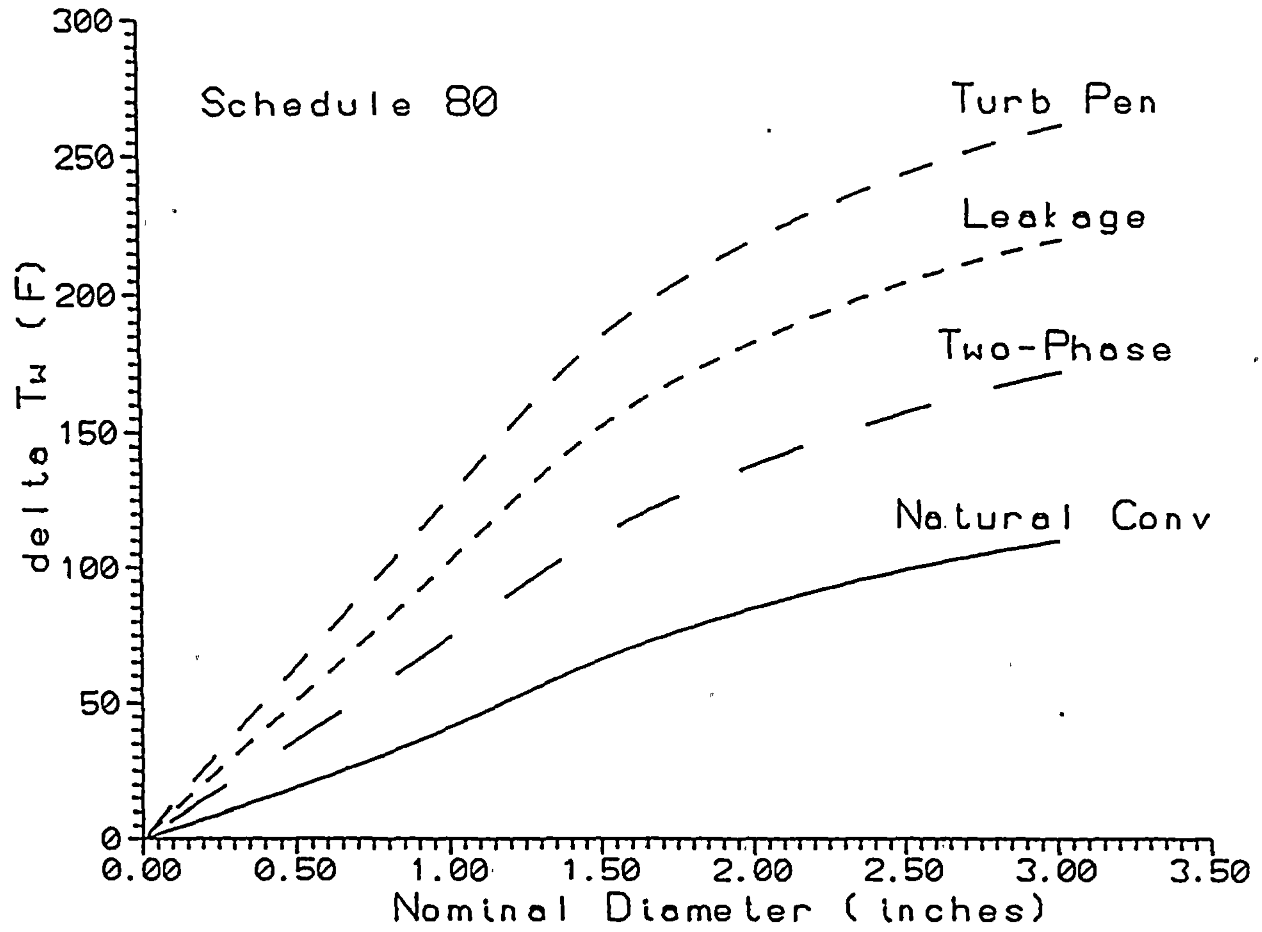


Figure B-2: Wall Temperature Difference a Schedule 80 Pipe & Different Heat Transfer Mechanisms (Th = 540°F, Tc = 100°F)

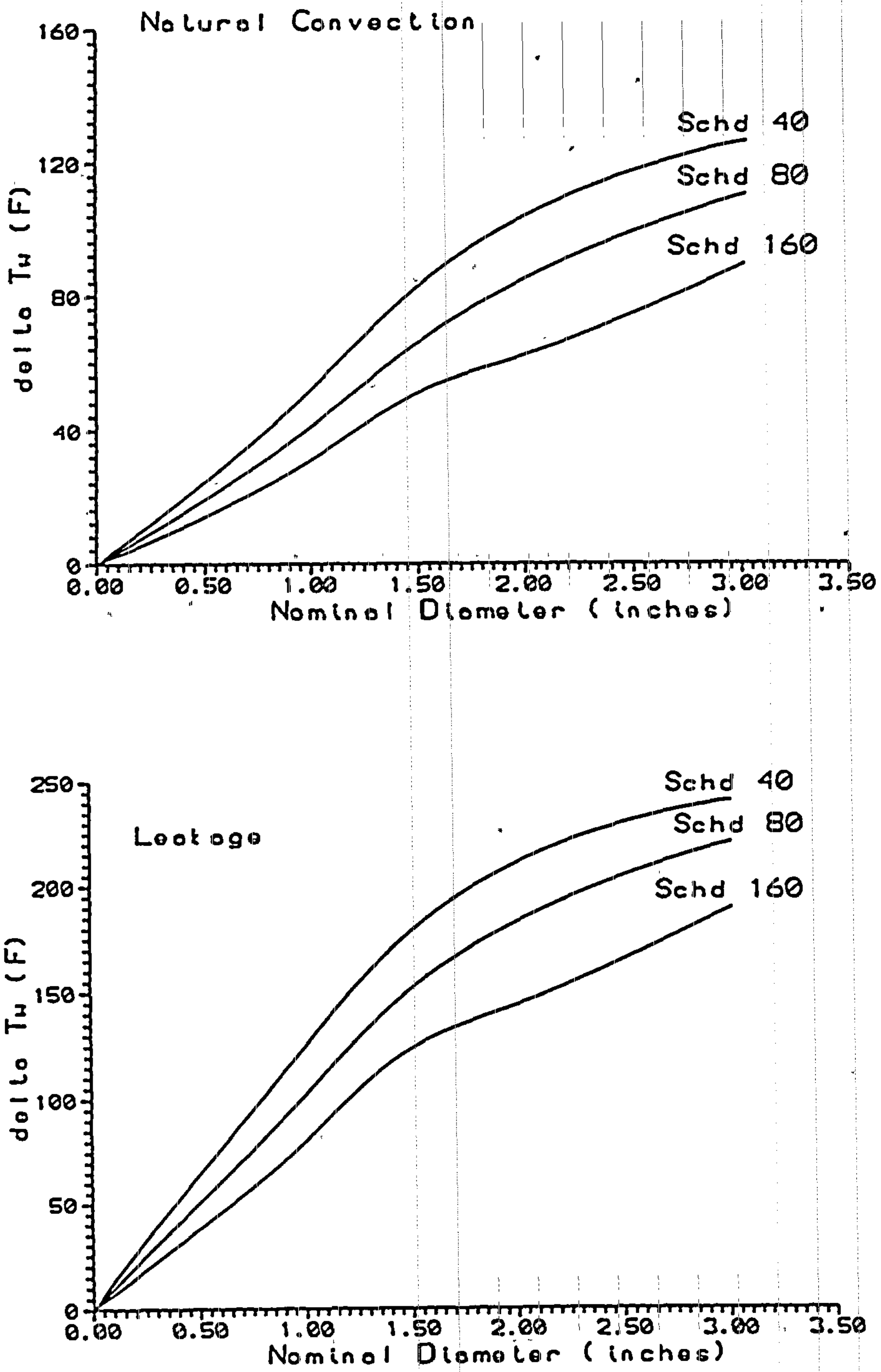
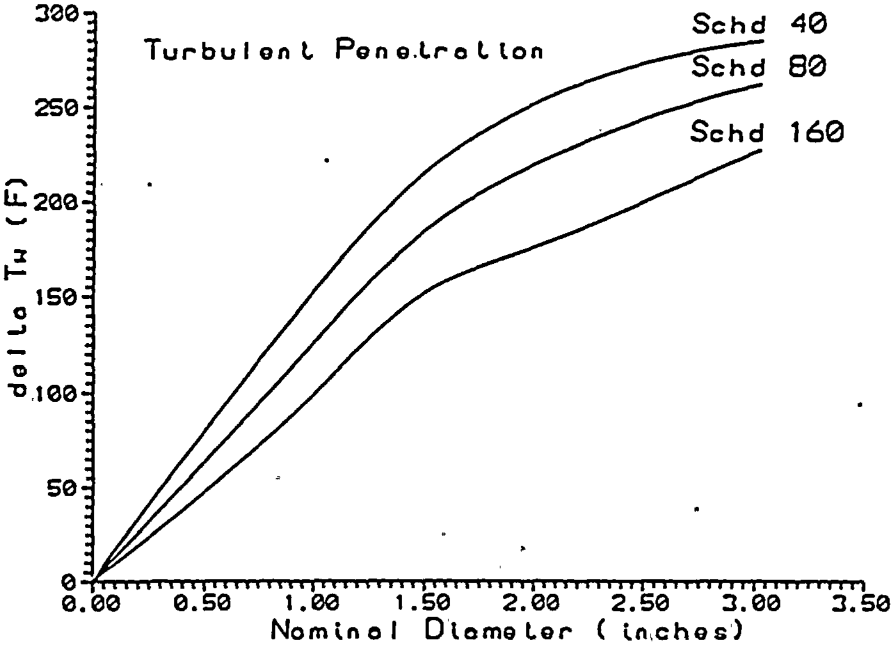
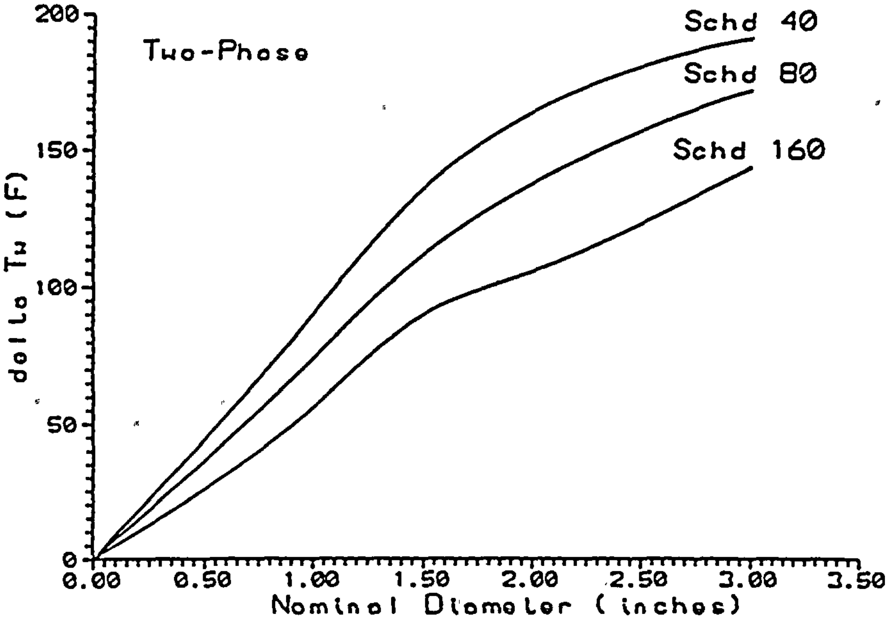


Figure B-3: Wall Temperature Difference for Different Schedule Pipes & Heat Transfer Mechanisms (Th = 540°F, Tc = 100°F)


Turbulent Penetration
Schd 40
Schd 80
Schd 160
delta Tw (F)
0
50
100
150
200
250
300
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Nominal Diameter (inches)


Two-Phase
Schd 40
Schd 80
Schd 160
delta Tw (F)
0
50
100
150
200
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Nominal Diameter (inches)

APPENDIX C
JUSTIFICATION FOR CONTINUED OPERATION PHASE VI OF A CEOG PROGRAM TO ADDRESS THERMAL STRATIFICATION IN PIPING CONNECTED TO THE RCS

Executive Summary

Top-to-bottom temperature differentials ≥ 50°F have been observed in a Power-Operated Relief Valve (PORV) line and in a Safety Injection (SI) line at a CE-designed plant. They were measured during the heatup of the plant to Hot Standby conditions. These temperature differentials are considered to be the result of the existence of a thermally stratified layer within each of the respective lines.

Due to general similarities in piping configurations, system temperatures, and operations between the pilot plant and ____. there is the potential that these conditions exist within the corresponding systems at ___. Thus, these piping systems may be subjected to unacceptable thermal stresses. This Justification for Continued Operation provides a technical assessment of these potential conditions in view of the concerns raised in NRC Bulletin 88-08, Thermal Stresses in Piping Connected to Reader Coolant System."

These differential temperatures have not been formally analyzed for design basis purposes for the PORV or SI line. However, ____considers that, if they do exist at ____,the structural integrity of the Reader Coolant System (RCS) pressure boundary will not be immediately compromised and that a significant safety hazard to the public will not exist. Accordingly, continued operation of ___ is considered to be justified.

Description of Conditions

As part of the Combustion Engineering Owners Group (CEOG) continuing effort to address the concerns of NRC Bulletin 88-08, a PORV line and a SI line at a CE-designed plant were instrumented with surface-mounted thermocouples. The thermocouples were circumferentially placed at various locations on each of the lines - primarily on horizontal sections of the piping runs. Temperatures were recorded while the plant heated up from Cold Shutdown to Hot Standby conditions.

PORV Line

The [normally closed] PORV helps to provided overpressure protection for the RCS. The instrumented section of the PORV piping at the pilot plant is a 4-inch, stainless steel line running from the top of the pressurizer to the PORV. The configuration of this line includes both horizontal and vertical runs of pipe; as well as a [normally open] block valve (see Figure 1). Thermocouples were placed at several locations on this length of piping, including on either side of the block valve. Data collected from these thermocouples indicate that top-to-bottom temperature differentials (ΔTs) developed in a horizontal section of the PORV piping, reaching a maximum of 220°F as the plant approached Hot Standby conditions. (The thermocouples measured the outside wall temperatures; these temperatures are assumed to be on the same order as the temperatures of the respective internal fluid.) The maximum ΔT occurred at Location 3 (see Figure 1). Other locations had smaller differences in top-to-bottom temperatures.

The observed temperature distributions are attributed to the presence of steam in the upper portion of the pipe, with subcooled water along the lower portion of the pipe. The presence of the water is explained as follows: once the [saturated steam] bubble in the pressurizer forms, the piping up to the PORV fills with steam. However, at points away from the pressurizer, this steam loses energy to the containment ambient environment, condenses on the inner pipe walls, and sub-cools. The resulting condensate runs back to the pressurizer along the bottom of the pipir The measured ΔTs are, thus a result of the difference in temperature between the steam in the upper region of the pipe and sub- cooled water at the lower portion of the pipe.

SI Line

The SI System provides a means for the direct injection of highly borated water into the Cold Legs, from storage tanks, for the purpose of emergency reactivity control; it is also used for normal shutdown cooling operations. The instrumented portion of the SI piping at the pilot plant is a 12-inch stainless steel line running from the SI nozzle on one of the Cold Legs to the first block valve. The configuration of this line includes both horizontal and vertical runs of pipe, as well as a check valve (see Figure 2). Thermocouples were placed at several locations on this length of piping, including either side of the check valve. Data collected from these thermocouples indicate that top-to-bottom ΔTs developed in the horizontal sections of the SI piping, reaching a maximum of 140°F as the plant approached Hot Standby conditions. The location where the maximum ΔT occurred was Location 6 (see Figure 2); less significant thermal stratification was observed at Locations 5 and 7.

The observed temperature distributions are attributed to a natural convection counterflow produced by the temperature difference between the ends of the affected piping (between the two valves). The higher temperature end was at the SI check valve, kept relatively hot by RCS turbulent flow; the lower temperature end was at the block valve, kept relatively cold by conduction to the ambient environment.

Engineering Evaluation

The structural integrity of the PORV and SI lines, in consideration of the ΔTs, is a function of both the frequency of occurrence of the stratified conditions and the magnitude of the expected stresses. A discussion of both of these issues is presented below.

Frequency of Occurrence

The pilot plant data indicates that the ΔTs in the PORV and SI lines begin to develop as the plant heats up; gradually, as the relative difference between RCS temperatures and ambient temperature increases, so does the degree of stratification. Once steady-state Hot Standby conditions are reached, the temperatures in the piping also reach steady-state conditions. It is noted that no thermal cycling was indicated, including flow disturbances created by plant operations (e.g., testing of SI check valves).

There was no evidence for the establishment of the thermally stratified layers by any mechanism other than the relative RCS-ambient ΔT (e.g., no influence from leakage was detected). This being the case, the resulting thermal stresses created within the piping develop at a frequency essentially equal to the frequency of the heatup cycles in plant operations. This is significant because it alleviates the concern that the piping is subjected specifically to high-cycle fatiguing.

General similarities in piping configuration, system temperatures, and operating procedures between the pilot plant and ____suggest the possibility that these conditions are duplicated at ____. However, given the number of heatup cycles that have occurred at the potential number of occurrences for these stratified conditions is low with respect to the design number of heatup cycles. Fe systems were designed for 500 heatup cycles.)

Magnitude of Stresses

The ΔTs that were measured are on the order of 220°F for the PORV line and 145°F for the S line. Similar or lower ΔTs would be expected at ___. While these conditions of stratification will subject the respective lines to thermal stresses, it is not expected that these stresses will immediately compromise the structural integrity of the RCS. A detailed discussion of the expected stresses in each line is presented below.

PORV Line

A preliminary evaluation of the steam-water stratification in the pilot plant's PORV line was made by comparison to the formal analysis of steam-water stratification which was performed for the pressurizer spray line in 1984 as part of CEOG Task 482 (Report No. CE NPSD-261, December 1984). This formal analysis was of a 4-inch, stainless steel spray line subjected to several thermal transients. These transients include steam-water stratified conditions, with ΔTs ranging from 175°F to 600°F. The results of this conservative analysis indicate a relatively high number of allowable cycles for the stresses that developed for even worst stressed location in the line. For example, the limiting number of cycles for all components in the line for the 175°F ΔT condition was 4000.

A review of the descriptions of the spray line transients reveals that the stratified conditions occurred as step changes: from full flow conditions-to-stratified conditions-to-full flow conditions. The stratified spray transients induce not only bending stresses (from top-to-bottom differential expansion), but because of the step changes, significant through-wall radial gradient stresses are induced as well. Bending stresses would still be created in the stratified PORV lines. However, the development of the stratified conditions in the PORV line parallels the gradual plant heatup and, therefore, typically would not create significant

radial gradient stresses. Additionally, the formal analysis of the spray line conservatively assumed that the entire horizontal section of the spray line was at the maximum ΔT condition, whereas the length of PORV piping experience the maximum ΔT is relatively short. Consequently, the total stress ranges in the PORV line at the pilot plant, excepting differences in geometry and pipe support characteristics, should be less than what was determined for the spray line for a comparable ΔT. For the pilot plant and, by similitude, also for the PORV lines at ______, this should result in a comparatively greater number of allowable cycles.

SI Line

A preliminary evaluation of the water-water stratification in the SI line was made by comparison to the formal analysis of single-phase water stratification performed for the pressurize surge line in CEOG Task 662 (Report No. CEN-387-P, Rev. I-P, December 1991). This formal analysis was of a 12-inch, stainless steel surge line subjected to several thermal transients. These transients included stratified conditions, with ΔTs ranging from 90°F to 340°F. The results of the conservative analysis indicate a relatively high number of allowable cycles for the stresses that developed for even the worst stressed location in the line. For example, the limiting number of cycles for all components in the surge line for the 150°F ΔT condition was approximately 6000.

A review of the descriptions of the surge line transients reveals that the stratified conditions occurred as step changes. However, the development of the stratified conditions in the SI line parallels the gradual plant heatup and, therefore, would not create the radial gradient stresses typically induce by step changes. Additionally, the formal analysis of the surge line conservatively assumed that the entire horizontal section of the surge line was at the maximum ΔT condition, whereas the length of SI piping experiencing the maximum ΔT is relatively short. Consequently, the total stress ranges in the SI line at the pilot plant, excepting differences in geometry and pipe support characteristics, should be less than what was determined for the surge line for a comparable ΔT. For the pilot plant and, by similitude, also for the SI lines at ____, this should result in a comparatively greater number of allowable cycles.

Compensatory Actions

As part of ____'s efforts to resolve generic concerns regarding stratification in NSSS piping system, ____will continue to support the CEOG's participation in the EPRI TASCS (Thermal Stratification, Cycling, and Striping) program.

More immediately, _____ is also part of an ongoing CEOG program that includes the development of guidelines for each CEOG utility for the collection of In-service inspection Data, incident reports and material data pertinent to the subject lines. This program also provides guidelines for performing walk-downs of the lines in an effort to find evidence, if any, of piping deformation due to stratification, including deformed hangers or supports, crushed insulation, indications of excessive piping movement, etc.

Conclusion

The stratified conditions in both the PORV and SI lines at the pilot plant may be duplicated in [illegible] PORV and SI lines at _______ Based on the above engineering assessment, these conditions will not immediately compromise the structural integrity of the RCS at _______and, thus, the public health and safety will be maintained. Therefore, continued operation of is considered to be justified.

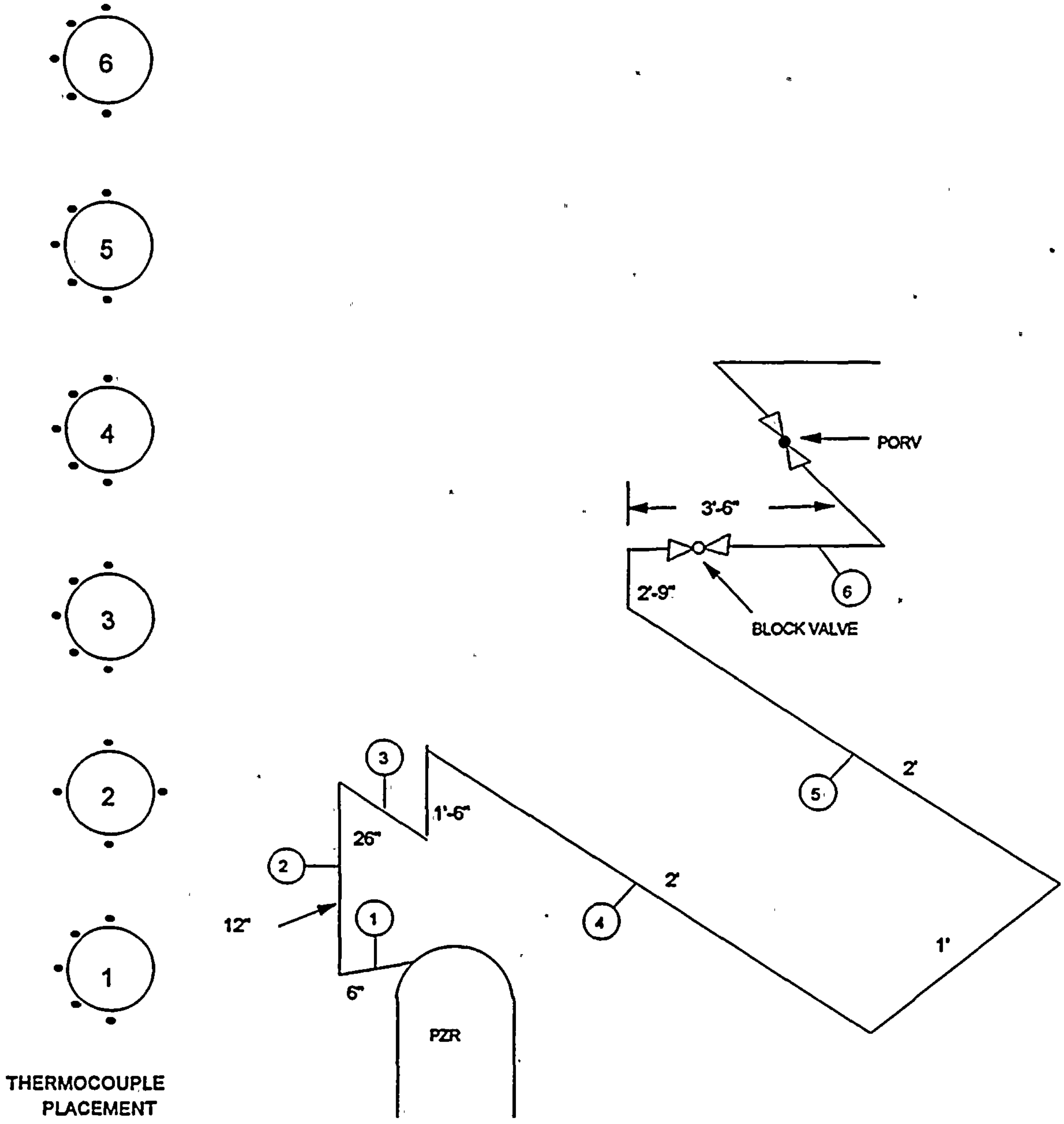


Figure 1 PORV Piping Thermocouple Location
(from ABB/CE Report No. CEN NPSD-868-P, Vol. 1, p. 15)

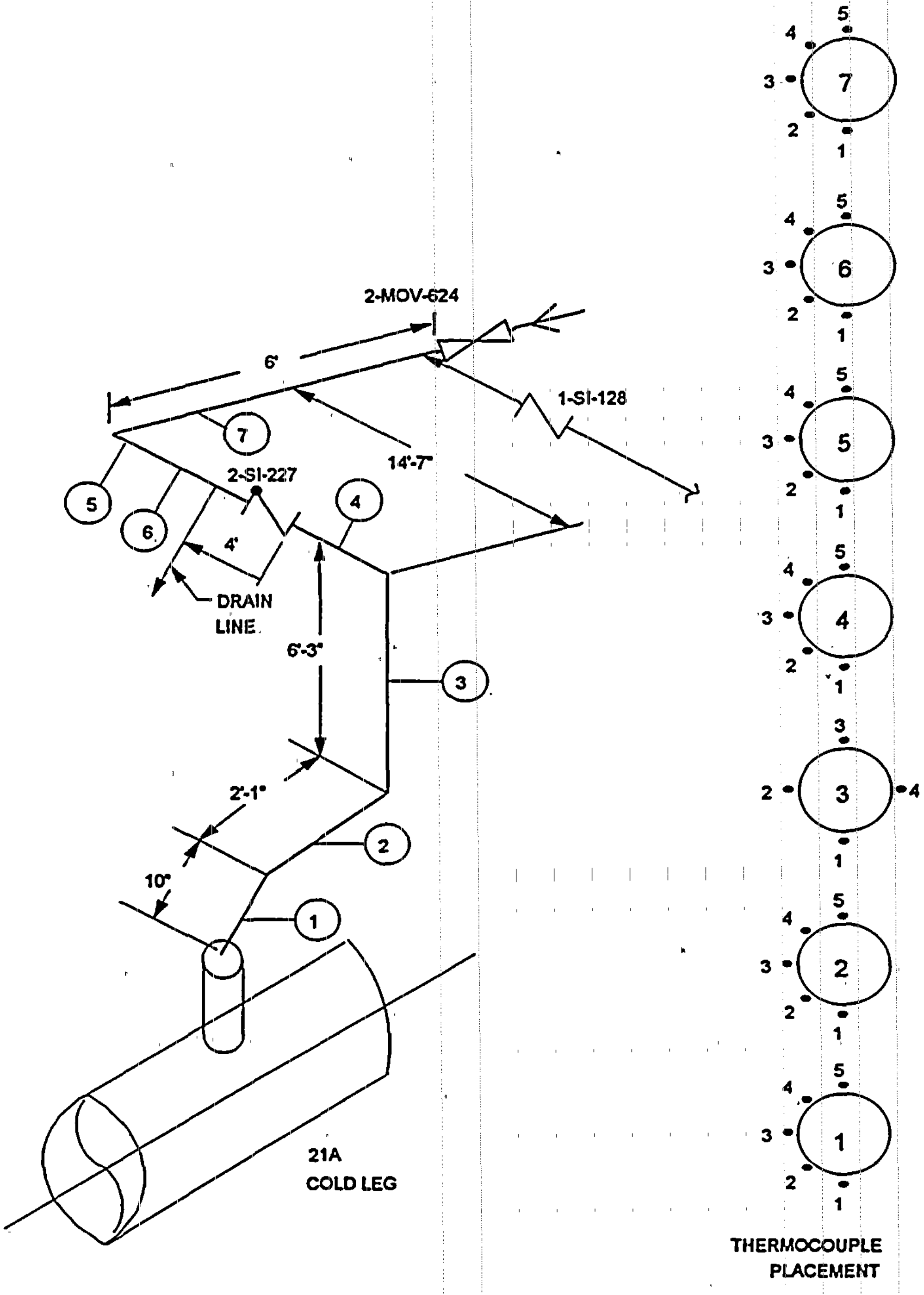


Figure 2 Safety Injection Piping Thermocouple Location
(from ABB/CE Report No. CEN NPSD-686-P, Vol. 1, p. 17)

APPENDIX D
JUSTIFICATION FOR CONTINUED OPERATION ADDRESSING THERMAL STRATIFICATION IN COOLING THE SHUTDOWN COOLING PIPE

2.0 Sample Justification for Continued Operation

Executive Summary

Top-to-bottom temperature differentials greater than 50°F have been observed in the shutdown cooling (SDS) lines at an ABB-CE designed plant. These temperature differentials measured during plant heatup and power reduction conditions. These temperature differentials provided evidence of the existence of a thermally stratified layer within the line.

Piping configuration analyses have been performed to confirm the general similarities in the system temperatures, and operations between the pilot plant and _______. Hence, there is the potential that these conditions may exist within the corresponding system at _______. Thus, these piping systems may be subjected to unacceptable thermal stresses. This Justification for Continued Operation provides a technical assessment of these potential conditions in view of the concerns raised in NRC Bulletin 88-08, "Thermal Stresses in Piping Connected to the RCS".

A bounding analysis of the thermally stratified conditions of the SDC line has been performed to assure the structural integrity of all ABB-CE designed plants. Consequently, considers that, if these conditions do exist at the structural integrity of the Reactor Coolant System (RCS) pressure boundary will not be compromised and that a significant safety hazard to the public does not exist. Accordingly, continued operation of ___________ is considered to be justified.

Description of Conditions

As part of the Combustion Engineering Owners Group (CEOG) continuing effort to address the concerns of Bulletin 88-08, the SDC at a CE-designed plant was instrumented with surface-mounted thermocouples. Thermocouples were located on several location on the top and bottom of the line, primarily on

horizontal section of the piping runs. Temperatures were recorded during power reduction and plant heatup from cold shutdown.

Shutdown Cooling Line

In combination with the safety injections (SI) system, the SDC is designed to provide emergency core cooling following reactor coolant or main steam line pipe breaks, and to be used for normal plant shutdown (e.g., during refueling or maintenance operations).

The instrumented section of the SDC line at the pilot plant is a 14-inch stainless steel line running from one of the RCS hot legs to the safety injection nozzles. The configuration of this line includes both horizontal and vertical runs of pipe up to a motor operated valve (MOV) which is normally closed. Thermocouples were placed at several locations on this length of piping. Data collected from these thermocouples indicated top-to-bottom temperature differentials (ΔTs) in a horizontal section of the SDC piping from 100"F to 1500F during normal plant heatup, and up to 345°F during plant power reductions.

The observed temperature distributions are attributed to a mechanism called turbulent penetration. Turbulent occurs when now in the RCS line (main line) creates a secondary flow in connecting line (branch line). The variation in the SDC line ΔTs are related to variations in heat transfer coefficients between the different fluid temperatures and the adjacent walls of the line.

Turbulent penetration has been found in lengths to diameter (L/D) ratios between 15 and 25 in typical branch lines for temperatures of 550°F to 620°F and velocity of approximately 50 ft/sec. Turbulent penetration would result in adequacy mixing and nearly uniform temperatures (at RCS values) in piping shorter than 15 L/D. As a result, the presence of turbulent penetration phenomena is a function of both the line configuration and ratios L/D (see Figure 1). The value of L/D applies to the first combined vertical and horizontal section of the SDC lines. They are three different SDC line configurations in ABB-CE designed plants. These three configurations are classified as follows (See Figure 2):

Class A: Short vertical section followed by a short horizontal section terminating at the center of the second valve.
Class B: Two or more short vertical sections followed by short and long horizontal sections terminating at the valve.
Class C: Short vertical section followed by long horizontal sections.

The most bounding case of these three configurations modeled to determine the stratified thermal loadings. Class C is the most bounding case with respect to the thermal stratified conditions because it has more horizontal piping subjected to potential flow stratification.

The expected degree of stratification for Classes A and B lines is much less, based on actual data, than for the bounding Class C. Therefore, the analysis, which assumes worst case Class C stratification temperatures to exist on the horizontal portion of lines A and B, is conservative and bounding.

Engineering Evaluation

The structural integrity of the SDC line, in consideration of the assumed boundary ΔT, is a function of both the frequency of occurrence of the stratified conditions and the magnitude of the expected stresses. A discussion of both of these issues is presented below.

Magnitude of Stresses

The measured ΔTS are of the order of approximately 100°F to 150°F during heatup and up to 345°F during a period of plant power reduction for the SDC line. An analysis was performed using a bounding ΔT of 400°F. While these stratification conditions will subject the respective lines to thermal stresses, it is not expected that these stresses will compromise the structural integrity of the RCS.

Thermal Stresses in the Shutdown Cooling Line

In order to evaluate the magnitude of the stresses due to thermal stratification, all three plant configurations were modeled considering top-to-bottom temperatures differences of 400, 350, 250 and 150°F, and were conservatively assumed to be stratified in the first section of horizontal run as follows:

Class A: Stratified for L/D between 3 and 19 (See Figure 3).
Class B: Stratified for L/D between 5 and 12 (See Figure 4).
Class C: Stratified for L/D between 11 and 26 (See Figure 5).

The results of these analyses showed that Class C is the most bounding line with respect to the thermally stratified loads (See Attachment 1). The stress ranges incorporating the thermal stratified conditions were used to evaluate the structural integrity of the SDC line (See Attachment 2).

Frequency of Occurrence

The pilot plant data indicates the presence of thermal stratification, downstream of the first elbow of the SDC line, during power reduction and plant heatup from cold shutdown. There is no evidence for the establishment of the thermally stratified layers by any mechanism other than turbulent penetration and geometry dependency (e.g., no influence for leakage was detected). This being the case, the resulting thermal stresses created within the piping develop at a frequency essentially equal to the frequency of the heatup and cooldown cycles in plant operations, and the plant power loading and unloading conditions.

The increase in fatigue due to thermally stratified conditions for the pilot plant were determined taking into consideration the frequency of occurrence of these stratified transients to-date, and the maximum number of cycles over the intended life of the plant (i.e., 40 years). Fatigue usage factor calculations were performed by adding the maximum number of occurrences at the pilot plant times the number of operating years for the oldest ABB-CE designed plants (i.e., 20 years), and for an estimated forty (40) year life by duplicating the number of occurrences. (See Attachment 2).

The results of the piping configuration analysis, general similarities in the operating conditions between the pilot plant and _________suggest the possibility that these conditions are duplicated at ______. This analysis establishes the structural integrity of the SDC at the pilot plant. As a result, the structural integrity of the SDC line as ________ is also established.

Compensatory Actions

As part of the CEOG efforts to resolve generic concerns regarding stratification in NSSS piping systems, the applicability of CEOG Task 732, "A Program to Address Thermal Stratification in Piping Connected to the RCS - Walkdowns of Potentially Affected Piping," CE-NPSD-744, has been extended to the shutdown cooling line. This program was originally developed for the power-operated relief valve (PORV) and the SI lines. It includes the guidelines for the collection of In-Service Inspection data, incident report, and material data pertinent to the subject lines. This program also provides guidelines for performing walk-downs of the lines to find evidence, if any, of piping deformation due to stratification, such as deformed hangers or supports, crushed insulation or indications of excessive piping movement (See Attachment 3).

Conclusions

The stratified conditions in the SDC line at the pilot plant may be applicable to the SDC line at _________. Based on the above engineering evaluation, these conditions will not compromise the structural integrity of the SDC line at and, thus, the public health and safety will be maintained. Therefore, continued operation of ________ is considered to be justified.

STRATIFICATION DUE TO TURBULENT PENETRATION

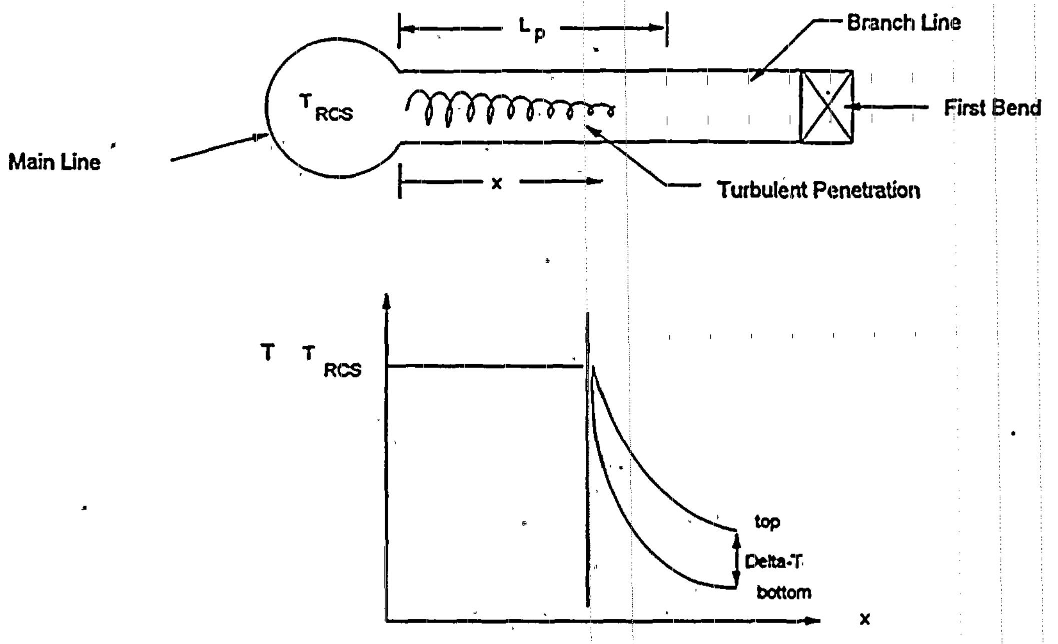


Figure 1 Stratification Due to Turbulent Penetration

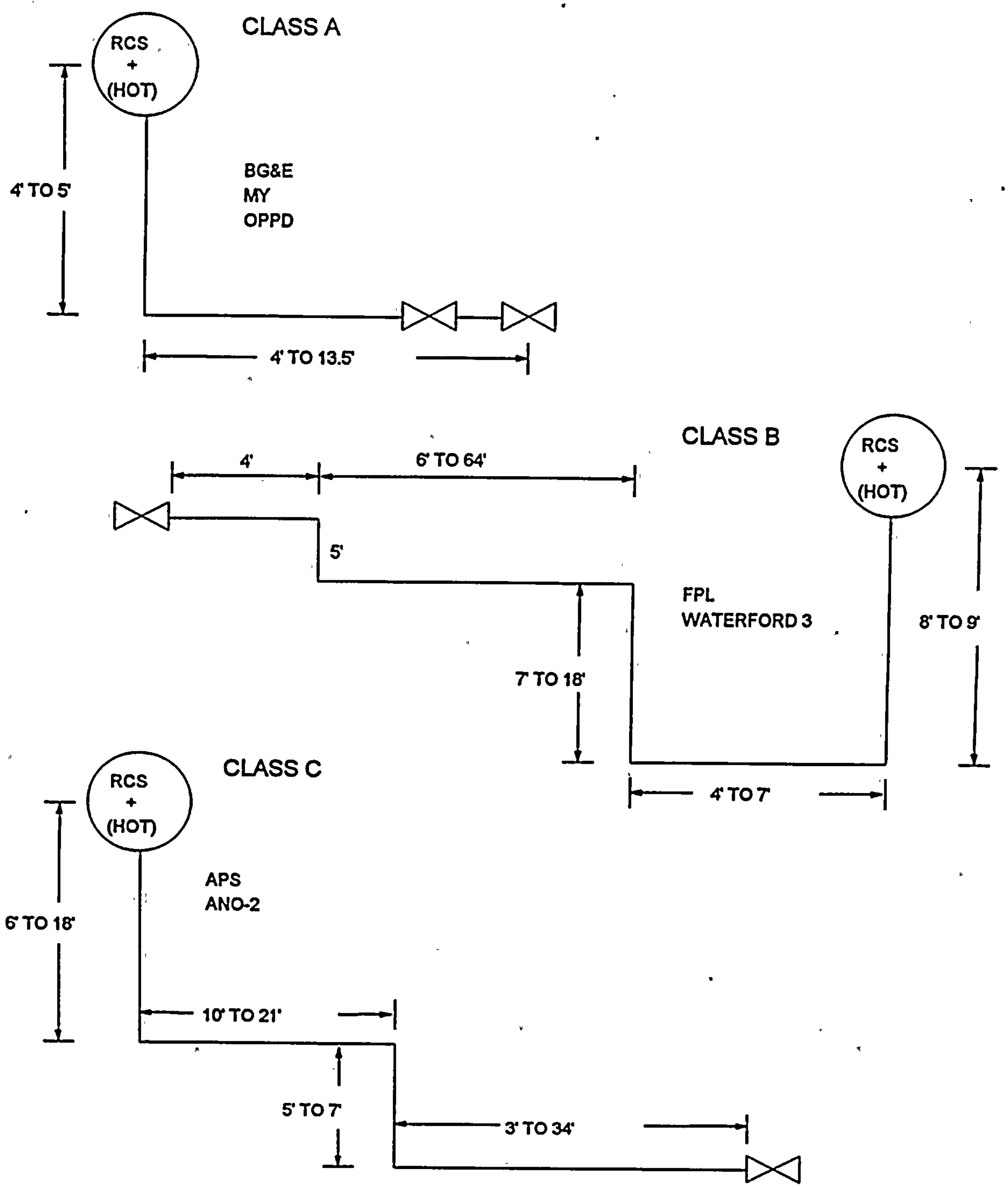
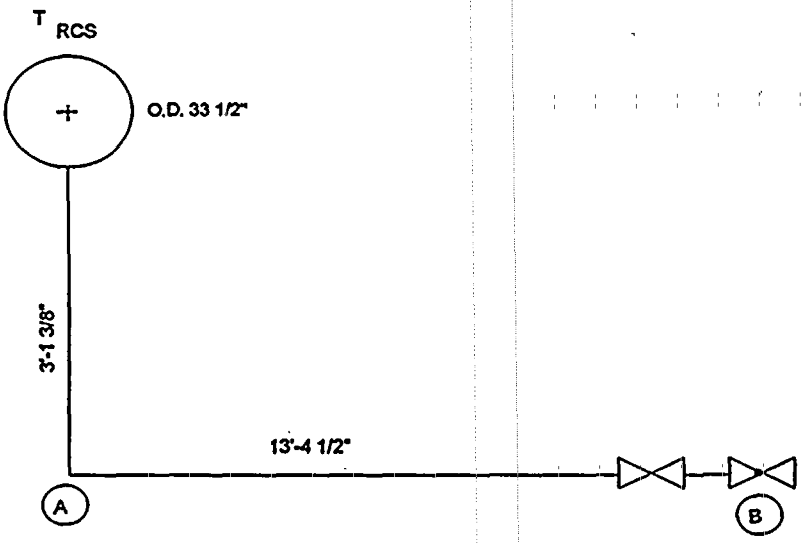
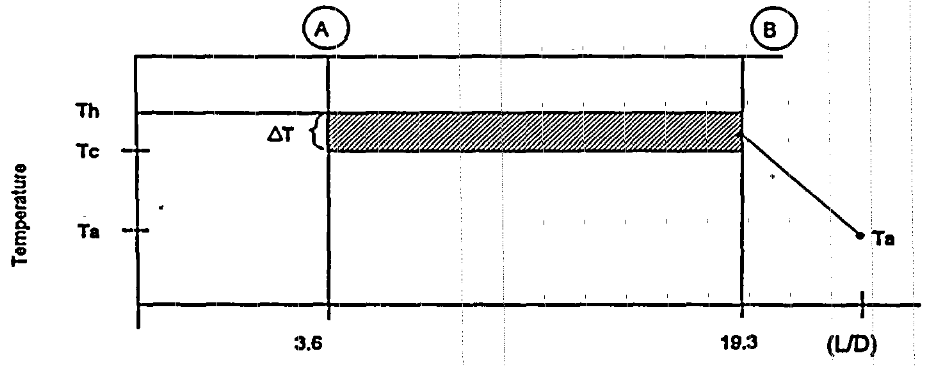


Figure 2 Three Types of SDC Lines in the CEOG

CLASS A - MAINE YANKEE - SDC LINE

OD = 12"
ID = 10.25"

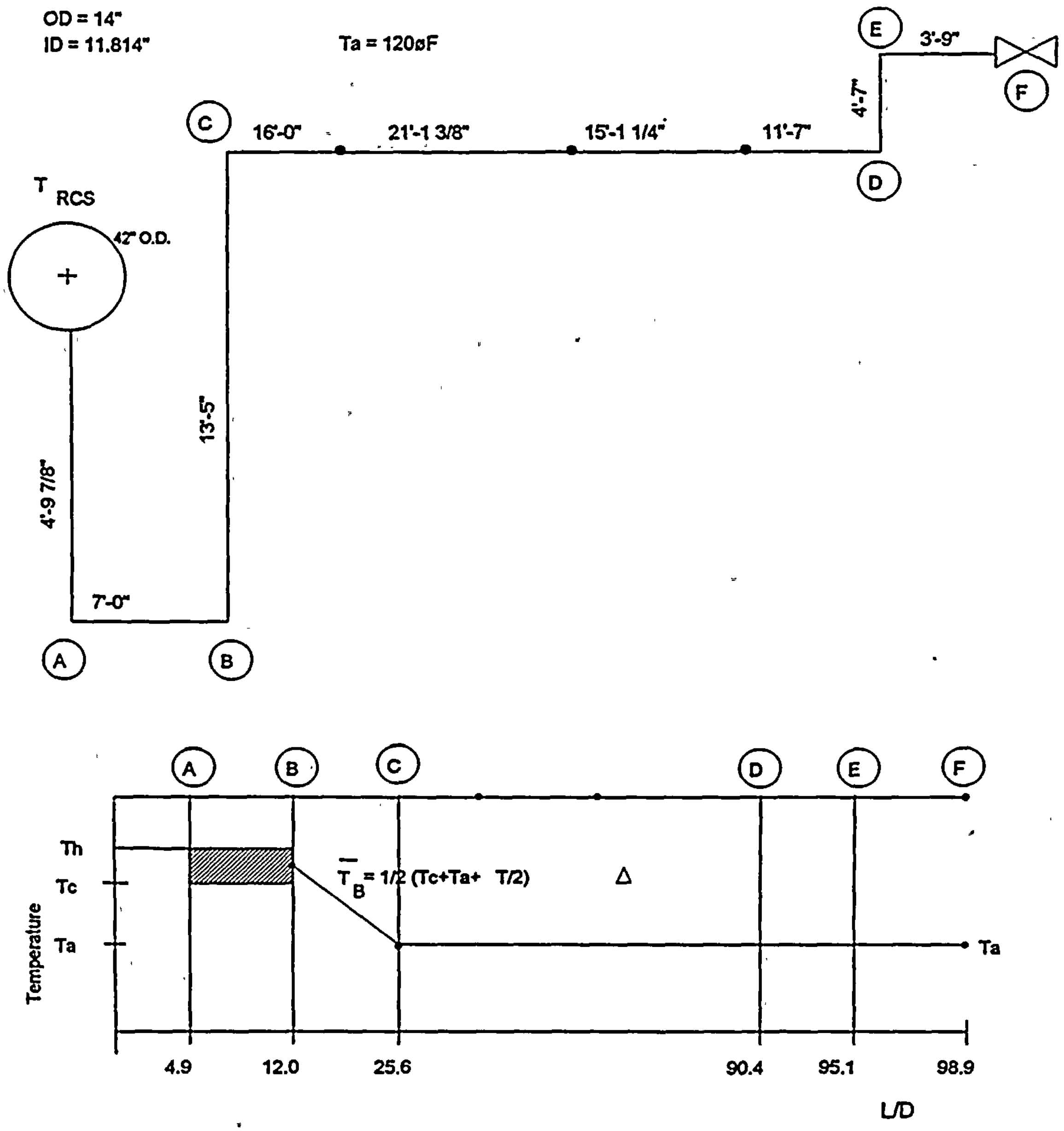




FOR TΔ	T_h A-B	T_c A-B	T_a @ B
400	550	150	120
350	500	150	120
250	400	150	120
150	300	150	120

Figure 3 Class A - SDC Line

CLASS B - SDC LINE



FOR TΔ	T_h A-B	T_c A-B	$\overline{T}_B$
400	550	150	235
350	500	150	222.5
250	400	150	197.5
150	300	150	172.5

Figure 4 Class B - SDC Line

CLASS C - SDC LINE

OD = 14"
ID = 11.5"

Ta = 120oF

FOR TΔ	Th A-D	Tc B-D	$\overline{T}$ @ D
400	550	150	235
350	500	150	222.5
250	400	150	197.5
150	300	150	172.5

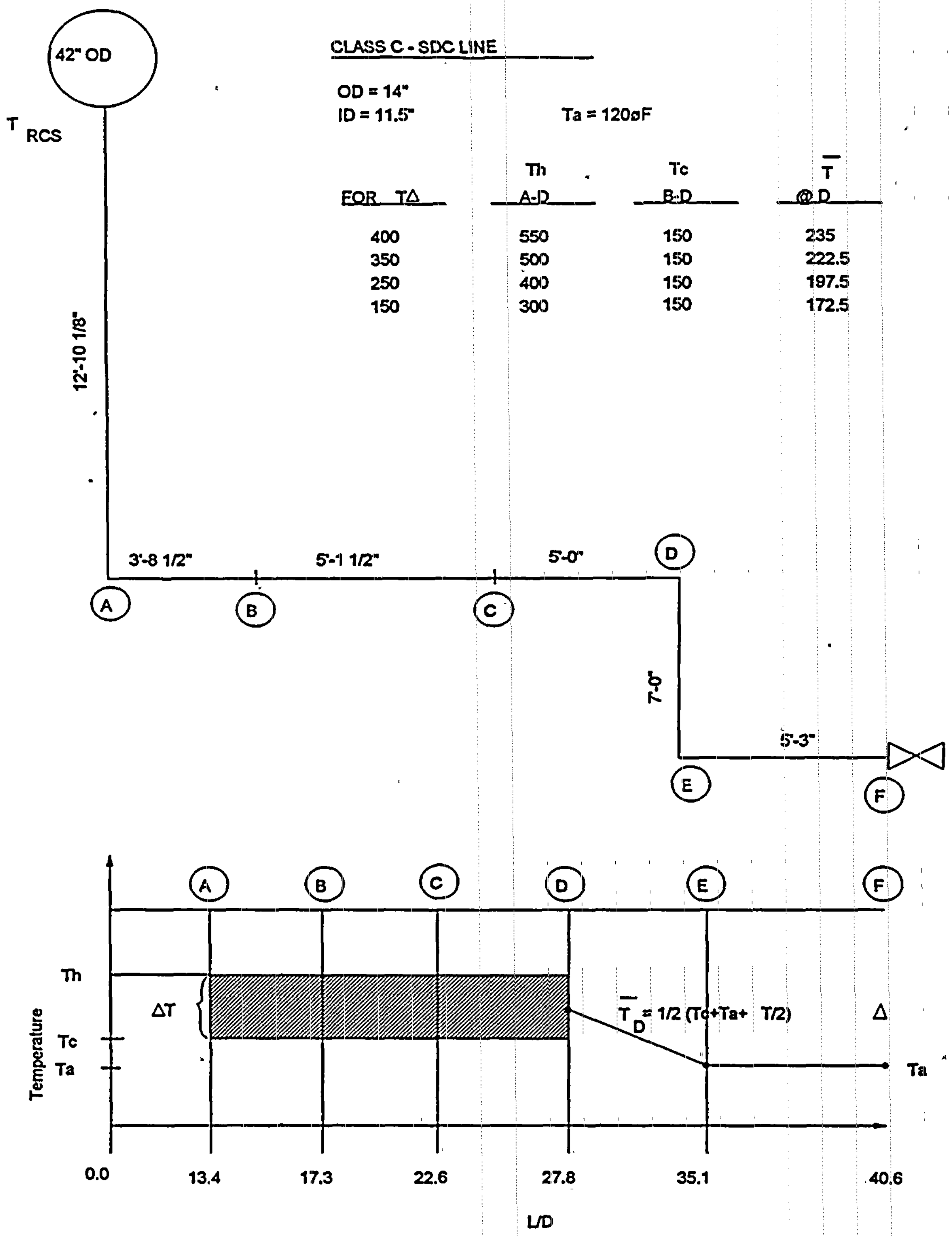


Figure 5 Class C - SDC Line

APPENDIX E

EVALUATION OF THERMAL STRATIFICATION LOADS

CEOG Tasks 818, 827, and 886 determined thermal stratification loads for the Safety Injection, Pressurizer Operated Relief Valve (PORV), and Auxiliary Spray Lines, respectively. Thermal stratification loads, if significant in magnitude, could have a significant impact in the overall stresses and fatigue usage factors. The purpose of this Appendix is to outline a process to determine the overall impact of thermal stratification loads with respect to stress and fatigue levels. This process is described below:

- Screening: Compare loads due to thermal stratification (moments, through wall ΔT) with values that are the major contributors to stress and fatigue levels.
- Usage Factor: Calculate the incremental value of usage factor due to thermal stratification in combination with the design basis value of usage factor at the worst location.
- Design Analysis (If necessary): Perform a complete piping and nozzle stress and fatigue analyses to incorporate the thermal stratification loads

1.0 SCREENING

The purpose of screening process is to identify the location(s) and load cases which have the major contribution to the stress fatigue levels. From this process, it can be qualitatively concluded if additional analysis is required, and if stress and fatigue usage factors need to be calculated.

1. Identify the location(s) with the highest thermal stratification moments

From the current stress report (design basis analysis):

1. Identify the location(s) with the highest Equation 10 values. This Equation includes a ΔT_1 contribution for older year ASME Codes.
2. Identify the location(s) with the highest usage factors. These locations may not necessarily be those with the highest thermal stratified moments above.
3. At each location, identify those load cases which have the greatest impact on the stress and usage factor levels.
4. Compare the thermal stratified loads (typically moments and ΔT_1) to other loads.

5. Determine relative changes in maximum S_n ranges and in usage factors.

If the comparison results indicate that the thermal stratification moments at those selected location(s) are not significantly larger than the design basis moments, and that their impact in the stress and usage factors are not significant because either current stress values are well below allowable limits, and usage factors are also well within allowable limits, it can be concluded that additional analyses are not required. If none of the above, is true, the next step should be followed:

2.0 USAGE FACTORS

In order to determine the significance of the thermal stratification in stress and fatigue levels, satisfaction of the ASME Code allowable limits is required. To better describe the process which need to be followed an actual sample case has been taken from Reference 4.1 and is described below.

2.1 STRESS CONSIDERATIONS

- Elbow, location 10 was found to be the location with highest stratification loads
- Elbow, location 10 was also found to be the location with highest Equation 10 contribution.
- Primary contributors to the fatigue usage factor for the elbow were Load Cases 17 and 14 (Cooldown with Shutdown Cooling initiation and the S.I. Check Valve Test, respectively).

2.2 SAMPLE CASE: CALCULATION OF STRESSES

Load Combination A1: Load Case no. 17 and 400°F thermal stratification:

1) NB-3653.1 PRIMARY PLUS SECONDARY STRESS INTENSITY RANGE S_N

EQUATION 10:

$$S_n = C_1 \frac{P_o D_o}{2\,t} + C_2 \frac{D_o}{2\,I} M_i + C_3\, E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \leq 3\, S_m$$

LOAD CASE NO. 17	M_a	M_b	M_c
Reference 4.3, pg. 1107	-8.0 ft-lb	14207 ft-lb	-27032 ft-lb
for Location 10			
Local Coordinates	=-0.1 in-kips	170 in-kips	-324 in-kips

		M_x	M_y	M_z
Converting Moments to Global Coordinates	=	349 in-kips	0.1 in-kips	-109 in-kips
400°F Thermal Stratification		-2376 in-kips	304 in-kips	1349 in-kips

Ranges		M_x	M_y	M_z
	=	-2725	304	1458

$$M_i = [\,M_x^2 + M_y^2 + M_z^2\,]^{1/2} = 3105 \text{ in-kips}$$

TABLE 1
Load Combination A - Total Moments Calculation

Load Comb	Load Case No. 17 (in-kips)			Therm . Strat.	Moments (in-kips)			Ranges (in-kips)			M_I (in-kips)
	M_x	M_y	M_z	ΔT (°F)	M_x	M_y	M_z	M_x	M_y	M_z	
A1	349	0.1	-109	400	-2376	304	1349	-2725	304	1458	3105
A2				350	-2113	286	1184	-2462	286	1293	2796
A3				250	-1598	252	863	-1947	252	972	2191
A4				150	-1103	219	555	-1453	219	664	1612

Load Combination nos. A1-A4 are used to designate the load set consisting of Load Case No. 17 - Cooldown with Initiation of Shutdown Cooling and the thermal stratification conditions.

Substituting into Equation 10:

$$S_n = 12.64 + 55.25 + 0 = 67.89 \text{ ksi} > 3\,S_m = 57.9 \text{ ksi}$$

TABLE 2
Load Combination A - S_n Calculation

Load Combination	Thermal Strat Δt (°F)	Pressure Term (ksi)	Moment Term (ksi)	S_n (ksi)	3 S_m (ksi)
A1	400	12.64	55.25	67.89	57.9
A2	350	12.64	49.73	62.37	57.9
A3	250	12.64	38.98	51.62	57.9
A4	150	12.64	28.68	41.32	57.9

2) NB-3653.2 PEAK STRESS INTENSITY RANGE S_P

Equation 11:

$$S_p = K_1 C_1 \frac{P_o D_o}{2\,t} + K_2 C_2 \frac{D_o}{2\,I} M_i + \frac{1}{2(1-\nu)} K_3 E\alpha\,|\Delta T_1| + K_3 C_3 E_{ab}\,|\alpha_a T_a - \alpha_b T_b\,| + \frac{1}{(1-\nu)} E\alpha\,|\Delta T_2|$$

Table NB-3681(a)-1 of Reference 4.2: $k_1 = k_2 = k_3 = 1.0$

From Reference 4.3, pg. 1105:

$\nu = 0.3$

ΔT_1 for load case no. 17 = 203 °F

ΔT_2 for load case no. 17 = 120 °F

From Reference 4.2: $E = 28.3 \times 10^6$ psi

$\alpha = 8.42 \times 10^{-6}$ in/in°f

The circumferential temperature gradient stresses for the 400°F thermal stratification condition is accounted for by adding the through-wall stress value of 19.13 ksi (See Assumption 2 of Reference 4.1).

$S_P = 12.64 + 55.25 + 34.55 + 40.85 + 0 + 19.13 = 162.42$ KSI

TABLE 3
Load Combination A - S_P Calculation

Load Comb	Thermal Strat Δt (°F)	Pressure Term (ksi)	Moment Term (ksi)	ΔT_1 Term (ksi)	ΔT_2 Term (ksi)	Circumferential Temperature Gradient (ksi)	S_p (ksi)
A1	400	12.64	55.25	34.55	40.85	19.13	162.4
A2	350	12.64	49.73	34.55	40.85	16.73	154.5
A3	250	12.64	38.98	34.55	40.85	11.95	139.0
A4	150	12.64	28.68	34.55	40.85	7.17	123.9

3) NB-3653.6 SIMPLIFIED ELASTIC-PLASTIC DISCONTINUITY ANALYSIS.

Since the Equation 10 result exceeds the code allowable limit ($S_n > 3\ S_m$) for load combination nos. A1 and A2, the alternative analysis allowed under this section is necessary.

Equation 12:

$$S_e = C_2 \frac{D_o}{2I} M_i^* \leq 3 S_m$$

where M_i^*: same as M_i in Equation 10, except that it includes only moments due to thermal expansion and thermal anchor

$$M_i^* = [\,M_X^2 + M_Y^2 + M_Z^2\,]^{1/2}$$

$$M_i^* = [\,(-2376)^2 + (304)^2 + (1349)^2\,]^{1/2}$$

$$M_i^* = 2749 \text{ in-kips}$$

$S_e = 48.91$ ksi < 3 S_m = 57.9 ksi

4) NB-3653.6 (B) PRIMARY PLUS SECONDARY MEMBRANE PLUS BENDING, EXCLUDING THERMAL BENDING AND EXPANSION STRESSES.

Since Equation 10 is not satisfied for Load Combination Nos. A1 and A2, consideration of this stress is required.

Equation 13:

$$C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o}{2I} M_i + C_3 E_{ab} | \alpha_a T_a - \alpha_b T_b | \leq 3 S_m$$

$$= 12.64 + 0 + 0 = 12.64 < 3 S_M = 57.9 \text{ KSI}$$

5) NB-3653.6 (C) ALTERNATING STRESS

$S_{alt} = K_e S_p / 2$

where: $K_e = 1.0$, for S_n £ 3 S_m

$K_e = 1.0 + [(1-n)/n(m-1)]S_n/3 S_m-1$, for 3 $S_m < S_n <$ 3m S_m and,

$K_e = 1/n$, for S_n ³ 3m S_m

From Table NB-3228.5(B)-1: m = 1.7

n = 0.3

From Assumption 3 of Reference 4.1: $S_m = 19.3$ ksi

Therefore: 3m S_m = 3 (1.7) (19.3) = 98.4

3 $S_m < S_n <$ 3m S_m

For Load Combination A1, $S_n = 67.9$ ksi, hence: 57.9 < 67.9 < 98.4

then:

$K_e = 1.0 + [(1-0.3) / 0.3 (1.7-1)] [67.9 / 3 (19.3) -1]$

$K_e = 1.0 + [(0.7 / 0.21] 0.173$

$K_e = 1.57$

6) NB-3653.7 Thermal Stress Ratchet

Allowable ΔT_1 range = $[y' S_y / 0.7 E \alpha] C_4$

From Reference 4.3: S_y = 23.3 ksi at 300°F for SA-403, WP-316, Table I-2.2

$E = 28.3 \text{ X } 10^6$ psi

$\alpha = 8.42 \text{ X } 10^{-6}$ in/in°F

$C_4 = 1.3$

$x = (PD_o/2t)(1/S_y)$ where P is maximum pressure for the set of conditions under consideration = 2.235 ksi

$x = (2.235)(14)/2(1.25)(1/23.3)$

$x = 0.537$

Interpolating: $y' = 1.85$

Allowable ΔT_1 range = [(1.85)(23.3) / 0.7 (28.3)(8.42)] 1.3 (1000)

Allowable ΔT1 range = 336°F

Translating the Circumferential Temperature Gradient Stresses to a ΔT_1 value for the 400°F Stratified Condition:

Circumferential Temperature Gradient Stresses = $E \alpha (\Delta T_1)/2(1-n)$

$19.13 = E \alpha (\Delta T_1) /2 (1-n)$

Solving for ΔT_1

$\Delta T_1 = [(19.13)\ 2\ (1-0.3)\ 1000] / [28.3\ (8.42)]$

$\Delta T_1 = 112.4$°F

$| \Delta T_1 |$ range = 203 + 112.4°F = 315 °F < 336 °F

Consequently, per NB-3653.5, the Alternating Stress Intensity for Load Combination No. A is calculated as follows:

TABLE 4
Load Combination a - S_{alt} Calculation

Load Combination	K_e	S_P (ksi)	S_{alt} (ksi)
A1	1.57	162.4	127.5
A2	1.26	154.5	97.3
A3	1.0	139.0	69.5
A4	1.0	123.9	62.0

It Is important to note that the same steps of Section 2.2 should be followed for every load case combination. In this case, the same analysis applies for Load Combination B, i.e., Load Case No. 14 and thermal stratification loads:

2.3 FATIGUE CONSIDERATIONS

Consideration of fatigue effects is accomplished by calculating the incremental value of usage factor due to thermal stratification in combination with the design value of usage factor at the same location(s) evaluated for stresses (in the previous section) and also for the design basis worst usage factor location. Emphasis for the fatigue effects should be upon determining the increase in the fatigue usage factor to-date and in estimating a usage factor for the life of the plant. It is noted that, in this particular case, the limiting location does not have the highest usage factor for the entire line. However, the increase in the fatigue usage factor for this location for consideration of thermally stratified conditions should be evaluated such that it effectively bounds all locations in the line.

1) DETERMINATION OF TRANSIENT OCCURRENCES

Determination of transient occurrences should be based on the load cases to be analyzed, and the number of occurrences up to date and for the life of the plant. In the sample case, the number of power reductions up to date, were determined by multiplying the number of power reductions per year by a factor of three (3) and the number of year approximate the number of power reductions for the life of the plant.

Number of power reductions for 20 years = (8 power reductions/year) (3) (20 years)

Number of power reductions for 20 years = 480

Reactor trip and loss of reactor coolant flows:

Actual number = (103 + 1) + 4 = 108 in 13 years

For 20 years = (108/13 year) (20 years) = 166

TOTAL NUMBER OF TRANSIENTS TO DATE = 480+166 = 646

2) TO-DATE FATIGUE USAGE FACTOR CALCULATION (ASME CODE, FIGURE I-9.2.1):

	S_{alt}	N_{all}	N	U
Load Combination No A	127.5 ksi	803	105*	0.131
Load Combination No. B	51.4 ksi	29050	646	0.022
Design Basis Usage Factor (From Ref. 4.3, Pg. 1128)				0.044
	TOTAL USAGE FACTOR			0.197

* To account for fatigue effects of this load combination fro any plant, it is assumed that this load combination has occurred 105 times

3) ESTIMATED USAGE FACTOR FOR FORTY (40) YEARS LIFE

TRANSIENT	20 YRS	40 YRS
Heatup and Cooldown	105	210
Power Reductions (Including trips, etc.)	646	1292

	S_{alt}	N_{all}	N	U
Load Combination No. A	127.5 ksi	803	210	0.262
Load Combination No. B	51.4 ksi	29050	1292	0.044
Design Basis Usage Factor (Ref. 4.3, Pg. 1128)				0.044
	TOTAL USAGE FACTOR			0.350

4) OVERALL USAGE FACTOR

Location with the highest usage factor of 0.398 at point 63; from Reference 4.3, the overall usage factor for the estimated life of the plant.

= 0.398 + 0.350 = 0.748

4.0 REFERENCES

4.1 ABB CE Calculation No. MISC-MECH-CALC-153, Rev. 00, March 1994, "Bounding Evaluation of the Shutdown Cooling Lines subjected to Thermal Stratification as the Basis for Plant Specific Justification for Continued Operation for CEOG Task 772."

4.2. The ASME Boiler and Pressure Vessel Code, Section III, 1986 Edition, no Addenda.

4.3. ANO2 Report No. 85-E-0055-21, Rev 00 (including Class 1 Stress Analysis of the Shutdown Cooling Line).

4.4. Specification No. 6600-M-2200, Rev. 09, "Design Specification for ASME Section III Nuclear Piping for Arkansas Nuclear One - Unit 2."