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EVALUATION OF THERMAL STRATIFICATION FOR THE COMANCHE PEAK UNIT 2 PRESSURIZER SURGE LINE

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SUMMARY

This report presents the methods, data, analysis and qualification results for the Comanche Peak Unit 2 pressurizer surge line including thermal stratification.

The report is divided into four sections with one appendix.

- o Section 1.0 - "Introduction and Update of Design Transients" presents the methods and data used to update the design thermal transients to incorporate the effects of flow stratification in the surge line.
- o Section 2.0 - "Stress Analysis" describes the global and local stress effects of stratification, including striping.
- o Section 3.0 - "ASME III Fatigue Usage Factor Evaluation" provides the evaluation results of the ASME III fatigue life of the surge line subject to all design transients plus the effects of stratification.
- o Section 4.0 - "Conclusions" summarizes the results of the evaluations of the effects of stratification in the surge line.
- o Appendix A - "Computer Codes" is a list and description of computer codes used in this work.

The work presented in this report leads to the following conclusions:

(a) Based on plant monitoring results from [ ]^{a,c,e} Westinghouse PWR's (including Comanche Peak Unit 1) and flow stratification test data, the thermal design transients for the surge line have been updated to incorporate the effects of stratification.

(b) The global structural and local stresses and loads in the surge line piping and support system meet ASME III Code allowables. The maximum cumulative fatigue usage factor is [ ]^{a,c,e} for a 40 year design life, compared to the Code allowable of 1.0.

In summary, it is concluded that thermal stratification does not affect the integrity of the pressurizer surge line of the Comanche Peak Unit 2 nuclear power plant and that NRC Bulletin 88-11 requirements are satisfied. The design life (forty years) and ASME III Code compliance are not affected.

SECTION 1.0

INTRODUCTION AND UPDATE OF DESIGN TRANSIENTS

1.1 Introduction

1.1.1 System Description

The primary function of the reactor coolant system (RCS) is to transport heat from the reactor core to the steam generators for the production of steam. The Comanche Peak Unit 2 RCS consists of four similar heat transfer loops connected to the reactor vessel (Figure 1-1). Each loop contains a reactor coolant pump (RCP) and a steam generator. The system also includes a pressurizer, connecting piping, pressurizer safety and relief valves, and a relief tank.

The flow path for a typical reactor coolant loop is from the reactor vessel to the inlet plenum of the steam generator (Figure 1-2). High temperature reactor coolant flows through the U-tubes in the steam generator, transferring heat to the secondary water, out of the tubes into the outlet plenum to the suction of the reactor coolant pump. The reactor coolant pump increases the pressure head of the reactor coolant which flows back to the reactor vessel.

The pressurizer vessel (Figure 1-3) contains steam and water at saturated conditions with the steam-water interface level between 25 and 60% of the volume depending on the plant operating conditions. From the time the steam bubble is initially drawn during the heatup operation to hot standby conditions, the level is maintained at approximately 25%. During power ascension, the level is increased to approximately 60%.

As illustrated in Figure 1-2, the bottom of the pressurizer vessel is connected to the hot leg of one of the coolant loops by the surge line, a 14 inch schedule 160 stainless steel pipe.

The simplified diagram shown in Figure 1-2 indicates the auxiliary systems that interface with the RCS. Of particular significance to surge line stratification are the normal charging and letdown function provided by the Chemical and Volume Control System (CVCS), and the suction and return lines associated with the Residual Heat Removal System (RHRS). The former directly controls the RCS mass inventory and therefore affects flow in the surge line. The RHRS is used to remove heat from the RCS and thereby influences coolant temperature and consequently coolant volume through thermal expansion and contraction.

Other systems which affect surge line flow conditions are main spray flow supplied to the pressurizer from one or two cold legs and the pressurizer electric heaters. Spray operation does not significantly alter the total RCS mass inventory, but does reduce system pressure by condensing some of the steam in the pressurizer. The pressurizer heaters when energized generate steam and as a result increase RCS pressure.

1.1.2 Thermal Stratification In the Surge Line

Thermal stratification in the pressurizer surge line is the direct result of the difference in densities between the pressurizer water and the generally cooler hot leg water. The lighter pressurizer water tends to float on the cooler heavier hot leg water. The potential for stratification is increased as the difference in temperature between the pressurizer and the hot leg increases and as the insurge or outsurge flow rates decrease.

At power, when the difference in temperature between pressurizer and hot leg is relatively small (less than 50°F) the extent and effects of stratification have been observed to be small. However, during certain modes of plant heatup and cooldown, this difference in system temperature could be as large as 320°F, in which case the effects of stratification could be significant.

A common approach for assessing the potential for stratification is to evaluate the Richardson Number (Tables 1-1 and 1-2) which is the ratio of the thermal density head diametrically across the pipe to the fluid flow dynamic head, or

$$Ri = \frac{g\beta D\Delta T}{U^2}$$

where

- Ri = Richardson number
- g = gravitation constant
- U = hot fluid velocity
- ΔT = hot-to-cold fluid temperature difference
- D = pipe inside diameter
- β = coefficient of thermal expansion of water

For a range of surge line flow rates from approximately 700 gpm down to a bypass flow of approximately 1 to 5 gpm and ΔT = 320°F, the Richardson number is greater than the value of 1 which is required to initiate stratification. Thus under this range of conditions, the flow has the potential to be stratified due to the relatively large hot-to-cold fluid temperature difference combined with the low hot fluid velocity. To eliminate stratification (i.e., Ri smaller than 1) a flow velocity of over 2.4 fps (approximately 700 gpm) is needed (Figure 1-4).

1.1.3 Surge Line Stratification Program

The surge line stratification program discussed in this report for Comanche Peak Unit 2 consists of two major parts:

(a) Update of design transients

(b) ASME III stress and fatigue cumulative usage factor (CUF) analyses.

Figure 1-5 shows the steps required to complete this program.

1.2 Update of Design Transients

The method used to update the design transients for stratification is illustrated in Figure 1-6 and is discussed in this section.

1.2.1 System Design Information

The thermal design transients for the Comanche Peak Unit 2 Reactor Coolant System, including the pressurizer surge line, are defined in Westinghouse Systems Standard Design Criteria (SSDC) documents SSDC 1.3.

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

(a) Heatup and Cooldown transients

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

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

The total number of current heatup-cooldown cycles (200) remains unchanged. However, sub-events and the associated number of occurrences ("Label", "Type" and "Cycle" columns of Tables 1-3 and 1-4) are defined to reflect monitoring data, as described later.

In all cases, the surge line fluid temperature distribution is modified from the original uniform temperature to a stratified distribution with the maximum temperature differentials and the associated nominal temperatures ("MAX ΔT_{strat}" and "Nominal" columns on Tables 1-3 and 1-4).

1.2.2 Stratification Effects Criteria

To determine the normal and upset pipe top-to-bottom temperature difference, "ΔT_{strat}" (Tables 1-3 and 1-4), the following conservatism is introduced.

For a given event, the ΔT_{strat} in the pipe will be the difference between the maximum pressurizer temperature and the minimum hot leg temperature, even though they do not occur simultaneously.

[

]^{a,c,e}

1.2.3 Plant Monitoring

Surge line stratification data have been obtained from [ ]^{a,c,e} Westinghouse plants. Figures 1-7 through 1-10 show the instrumentation configuration for four of these plants. The data were obtained by continuous monitoring of the piping OD temperature, displacements and plant parameters. The pipe temperatures were obtained from RTD's located on the outside of surge line. Plant parameters were obtained from the plant computer. Figure 1-11 represents the Comanche Peak Unit 1 monitoring configuration.

Temperature data from the other reference plant surge lines were reviewed. The data, in all cases, show the presence of stratification in the surge lines. The stratification observed is assumed to behave under the influence of gravity and consequently will have an axial profile defined by the slope of

the pipe. The data interpretation herein is an attempt to classify and characterize observed thermal conditions.

There are two basic causes of thermal stratification. Thermal stratification can be initiated either by [ ]a,c,e or the [

a,c,e This is the condition which this report addresses.

]a,c,e

[

]a,c,e

The establishment of a highly stratified condition is best described by considering the following typical transient example. This transient is based on an observed reference plant transient which was caused by the cut-off of the RCP in the same loop as the surge line.

Typical Transient Description: (RCP Cutoff Figure 1-12)

[

]a,c,e

[

]a,c,e

O... inter retation of the cause and effects of the transient just described is as follows:

[

]a,c,e

[

]a,c,e

The data are sufficient to characterize stratification temperatures in the pipe during critical operating transients and heatup-cooldown operation. Also, the data are sufficient to verify that the pipe movements are consistent with analytical predictions, within an accuracy normally expected from hot functional and/or power ascension tests, as discussed in section 2.1.

The monitoring of plant parameters is sufficient to correlate measured temperature fluctuations to changes in operation. In particular, it is apparent that temperature fluctuations are due to flow insurge (into the pressurizer) and outsurge (out of the pressurizer) which in turn are due to differential pressure in the system. While a simple quantitative mechanistic relationship betw. plant operation and insurge and outsurge has not been found, the data indicate that a steady state stratified condition can be altered by any of the following events:

a) Expansion of the pressurizer bubble
b) RCP trip in the surge line loop
c) Safety injection
d) Large charging - letdown mismatch
e) Large spray rates

In light of these observations, the update of design transients is based on plant monitoring results, operational experience and plant operational procedures. Conservatisms have been incorporated throughout the process in the definition of transients (cycles, ΔT) and in the analysis, as described in the report. The design transients used in this report have been shown to be quite conservative based on comparison to monitored data for Comanche Peak Unit 1.

1.2.4 Heat Transfer and Stress Analyses

The correlation of measured pipe OD temperature to ID temperature distribution is achieved by heat transfer analysis as well as previous experience with flow at large Richardson numbers (Ri>>1) (Figures 1-15 and 1-16).

These analyses and test data available to date show that a stratified flow condition, [ ]^{a,c,e} is a proper and conservative depiction of the flow condition inside the pipe at large ΔT and low flow rates (Ri>1).

An additional conclusion from the heat transfer and stress analyses is that [

]^{a,c,e}

1.2.5 Stratification Profiles

Table 1-5 summaries the major stratification profile characteristics. The monitored data shows a consistent axial temperature profile along the horizontal portions of the [ ]^{a,c,e} surge lines monitored.

The axial temperature profile is a function of the geometric characteristics of each line. Each line monitored showed a definite relationship between axial length of stratification and slope of the line. Figure 1-17 depicts a typical axial stratification profile. Note that the actual length of stratification is dependent on the volume of the insurge. Low volume insurges tend to stratify a shorter distance along the line. Similarly large volume insurges stratify longer distances provided the slope of the line is low enough. As the slope increases, smaller sections of the line will be affected by stratification. The slope also affects the type of stratification interface. As the slope is increased the flow characteristics of the interface are affected. There are two basic interface types; one which is narrow and highly defined is characteristic of laminar flow. The other is characteristically wide and a product of turbulent flow. The flow becomes turbulent at the interface when forced to a higher level than gravity would normally dictate. Flow velocity is also an integral part of this relationship.

Figure 1-18 shows a cross section of the pipe with the various hot and cold fluid interface levels created by a laminar flow or static steady state conditions.

1.2.6 Development of Conservative Normal and Upset Transients

Transients in the surge line were characterized as either due to insurges or outsurges (I/O) from the pressurizer or fluctuations. Insurges and outsurges are the more severe transients and result in the greatest change in tempera-ture in the top or bottom of the pipe. An insurge may cool the bottom of the pipe significantly, to very close to the temperature of the RCS hot leg. Conversely, an outsurge can sweep the line and heat the pipe to close to the temperature of the pressurizer. The thermal transients are shown in Figure 1-19.

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

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

Several conservatisms were introduced in the redefined normal and upset thermal transients (Tables 1-3, 1-4, 1-6 and 1-7).

[

]a,c,e

(b) Full stratification cycles are assumed for all transients, except for steady state fluctuations, unit loading and unloading, and reduced temperature return to power, where level fluctuations are sufficiently conservative based on flow rate and observations.

(c) The temperature of stratification was based on the minimum hot leg temperature at any time during the transient (for bottom of pipe) and the maximum pressurizer temperature (for top of pipe). Figure 1-20 shows a case where this resulted in a very conservative 260°F stratification transient although the maximum temperature difference at any point in time was about 50°F.

(d) The current number of design cycles of each event is unchanged.

The normal and upset transients modified to account for the stratification phenomena are listed in Tables 1-3 and 1-4.

1.2.7 Temperature Limitations During Heatup and Cooldown

The maximum permitted temperature difference between the pressurizer and the hot leg for Comanche Peak Unit 2 is 320°F. This maximum ΔT is defined in and controlled by the station operating procedures. Therefore the maximum possible top-to-bottom temperature stratification is 320°F.

With the RCL cold, the pressurizer pressure (and therefore temperature) is limited by the cold overpressure mitigation system (COMS).

Practically, plants operate to minimize downtime and heatup-cooldown time, when power is not being generated. The times at large ΔT are therefore reasonably limited, as discussed later.

1.2.8 Historical Data

Since not all heatup and cooldown parameters affecting stratification are formally limited by Technical Specification or Administrative controls, it is necessary to reconsider plant operational procedures and heatup-cooldown practices to update the original heatup and cooldown design transient curves of SSDC 1.3 (Figures 1-21 and 1-22).

To this end, a review of procedures, operational data, operator experience, and historical records was conducted for [ ]^{a,c,e} Westinghouse PWR plants (Table 1-8). Similarly, operations procedures for Comanche Peak Unit 1 and 2 were reviewed and heatup cooldown curves developed (shown in Figures 1-23 and 1-24).

The heatup and cooldown operations information acquired from this review is summarized in Tables 1-9 and 1-10, [

]^{a,c,e}

The information is divided into heatup and cooldown tables and diagrams. The diagram presents the pressurizer water and hot leg temperature profiles versus time. The various phases of the process are identified by letters along the diagrams' abscissa and in Tables 1-9 and 1-10.

1.2.9 Development of Heatup and Cooldown Design Transients With Stratification

As described above, the database of information used to update the heatup and cooldown transients included the following:

a) Typical heatup and cooldown curves, as developed from review of procedures, operational data and operators experience.

b) Transients as monitored at [ ]a,c,e plants

c) Historical records of critical heatup and cooldown temperature.

The heatup and cooldown transients are presented in the following sections as [ ]a,c,e and in similar fashion to the normal and upset transients. Table 1-11 gives the general characteristics of the two types of transients observed.

The heatup cooldown transient labels have the following logic:

1. Transients H1 through H12 correspond to insurge or outsurge transients postulated during heatups (H).

2. Transients HF1A through HF3 correspond to fluctuation transients postulated during heatups (HF).

3. Transients C1 through C9 correspond to insurge or outsurge transients postulated during cooldown (C).

4. Transient CF1 represents the fluctuation transients postulated for cooldowns (CF).

1.2.9.1 [ ]a,c,e Transients

A) Monitoring Transient Summary

For a given monitored location, plots of temperature difference versus time were generated (Figures 1-33 and 1-34 are examples of relatively high transient activity). Two parameters were plotted, the pipe top to bottom temperature difference (labeled "surge line") and the pressurizer to hot leg temperature difference (labeled "system").

It is clear from Figures 1-33 and 1-34 that for the observed heatups, [ ]a,c,e

For conservatism, the envelope from measured transients in all plants is applied to define the transients.

B) Fatigue Cycles

The fatigue cycles were obtained using the technique illustrated on Figure 1-35, [

]^{a,c,e} Figure 1-37 illustrates the difference between the design transients and the transients observed at plant A.

C) Strength of Stratification

Plant monitoring data indicate that for the various transients observed the ΔT in the pipe (top to bottom) is not as large as the ΔT in the system (pressurizer to hot leg). The ratio of ΔT in the pipe to ΔT in the system will be referred to as "strength of stratification".

[

]^{a,c,e}

D) Number of Stratification Cycles (Table 1-14)

Plant monitoring data indicated the significant events which could occur during a given heatup.

[

]a,c,e

E) Maximum Temperature Potential

The key factor in thermal stratification of the surge line is the temperature difference between the pressurizer and hot leg (section 1.2). This temperature difference is clearly maximized during the heatup and cooldown, when the plant is in mode 5 cold shutdown (hot leg less than 200°F) and the pressurizer bubble has been drawn with the reactor coolant pump running (pressurizer temperature larger than 425°F). [

]a,c,e

F) Final Cycles and Stratification Ranges

[

]a,c,e

Example:

[

]a,c,e

G) <u>Cooldown Transients</u>

The procedure used in heatup is applied to develop transients for plant cooldown. [

]a,c,e

1.2.9.2 [ ]a,c,e Transients

[

]a,c,e

1.2.10 Striping Transients

Mean stress effects are included in determining the usage factor contributed by thermal striping. Fatigue cycles like those shown in Figure 1-35 were not used in the development of the striping design transients. [ ]a,c,e

[ ]a,c,e It should be noted that each striping transient cycle is assumed to initiate a discrete hot to cold fluid interface that will be attenuated with time (see section 2.3 for discussion). Figure 1-38 shows the relative magnitude and frequency of the striping transients for one heatup or cooldown with respect to the system ΔT (PRZT - RCST). The highest pipe ΔT (pipe T_{Top} - pipe T_{bot}) observed during heatup never exceeded [ ].a,c,e However, the design striping transients consider [ ]a,c,e transients at pipe ΔT's greater than [ ]a,c,e

Striping transients use the labels HST and CST denoting striping transients (ST). [

]a,c,e

1.3 Conclusions

Design transients were updated to incorporate stratification. The transients were developed to conservatively represent the cyclic effects of stratification. To illustrate the margin included in the development of heatup transients, a simplified fatigue factor calculation is provided in Figures 1-39 and 1-40. This comparison indicates that the design transients have a factor of conservatism of approximately [

]a,c,e

Also, the temperature monitoring data collected from the Comanche Peak Unit 1 surge line was reviewed, a set of transients specific to Comanche Peak was developed, and this set of transients was compared to the set used in the stress analysis of the Comanche Peak surge lines. This comparison showed that approximately seven times as many transients were used in the analysis. Additionally, the axial stratification profile observed in the monitoring data was determined to be less severe than the profile used in the analysis.

TABLE 1-1

IMPORTANT DIMENSIONLESS GROUPS FOR SIMILITUDE IN HYDRODYNAMIC TESTING

	Parameter	Symbol	Definition	Significance
1	Weisbach friction factor	f	$D\Delta P/2\rho V^2 L$	Pressure force/inertia force
2	Cavitation number	σ	$(P_1 - P_v)/\rho V^2$	Pressure difference/inertia force
3	Reynolds number	Re	$\rho V D/\mu$	Inertia force/viscous force
4	Strouhal number	Sr	nD/V	Vortex shedding frequency/inertia force
5	Weber number	We	$\rho D V^2/\sigma$	Inertia force/surface-tension force
6	Froude number	Fr	V^2/gD	Inertia force/gravity force
7	Richardson number (Modified Froude number)	Ri	$\Delta\rho g D/\rho V^2$	Buoyancy force/inertia force
8	Euler number	Eu	$\Delta P/\rho V^2$	Pressure force/inertia force
9	Prandtl number	Pr	$\mu C/k$	Momentum diffusivity/thermal diffusivity
10	Peclet number	Pe	$\rho V D C/k$ (Re × Pr)	Convective heat transfer/conductive heat transfer
11	Grashof number	Gr	$L^3\rho^2 g\beta\Delta T/\mu^2$	Buoyancy force/viscous force
12	Rayleigh number	Ra	$L^3\rho^2 C g\beta\Delta T/\mu k$ (Gr × Pr)	——

NOMENCLATURE:

C = specific heat
ρ = density
σ = surface tension
k = thermal conductivity
β = volumetric expansion coefficient
ΔT = fluid temperature change
n = vortex shedding frequency
g = acceleration of gravity
P = pressure
P_1 = static fluid pressure
P_v = fluid vapor pressure
L, D = characteristic dimensions
V = fluid velocity
μ = viscosity

TABLE 1-2

STRATIFICATION POTENTIAL BASED ON RICHARDSON NUMBER

- Stratification potential exists if $Ri > 1$

[ ] a,c,e

3488s-121688 10

TABLE 1-3

SURGELINE TRANSIENTS WITH STRATIFICATION

HEATUP (H) AND COOLDOWN (C) - 200 PLANT CYCLES TOTAL

[ ] a,c,e

TABLE 1-4

SURGE LINE TRANSIENTS WITH STRATIFICATION

NORMAL AND UPSET TRANSIENT LIST

a,c,e

[ ]

TABLE 1-4 (Cont'd.)
SURGE LINE TRANSIENTS WITH STRATIFICATION
NORMAL AND UPSET TRANSIENT LIST

a,c,e

TABLE 1-5

STRATIFICATION PROFILES

[

]a,c,e

TABLE 1-6

HEATUP - COOLDOWN TRANSIENTS

o Transients Were Developed Based On:

- Typical Heatup Cooldown Curves
- Envelope (Plus Margin) of Events (Transients) Monitored
- Historical Data on Temperature Plateaus

[

]a,c,e

TABLE 1-7

DESIGN TRANSIENTS WITH STRATIFICATION

o Heatup and Cooldown Combined With Other Events

o Design Transient Criteria

[

]a,c,e

o Input for Local and Structural Analysis Defined - Plus Nozzle

o Striping Transients Defined to Consider Maximum Stratification Cycles Regardless of Range

TABLE 1-8

OPERATIONS SURVEY

o Summary of Plants Surveyed

PLANT	NO. OF LOOPS	YEARS OF OPERATION (MAXIMUM)
[		
		]a,c,e

o Reviewed Typical Heatup Cooldown Process

o Reviewed Administrative/Tech Spec Limitations

o Reviewed Historical Events and Time Durations

o Developed Heatup - Cooldown Profiles

TABLE 1-9

HEATUP DATA SUMMARY

(PZR - HOT LEG) TEMP. DIFFERENCE AND TIME DURATION FOR EACH PHASE

a,c,e

3693s/041389:10

TABLE 1-10

COOLDOWN DATA SUMMARY

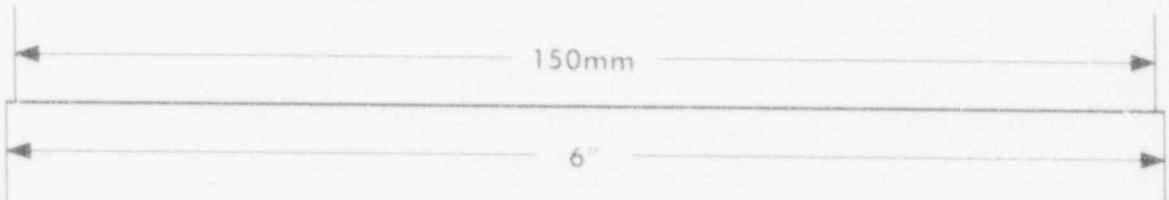
(PZR - HOT LEG) TEMP. DIFFERENCE AND TIME DURATION FOR EACH PHASE

[ ] a,c,e

3693s/041389 10

2

IMAGE EVALUATION TEST TARGET (MT-3)



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2

IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

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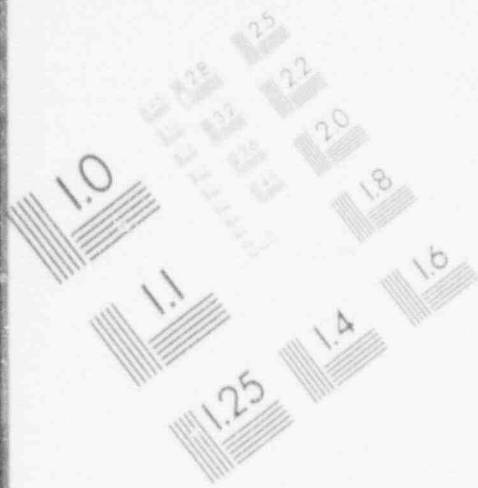
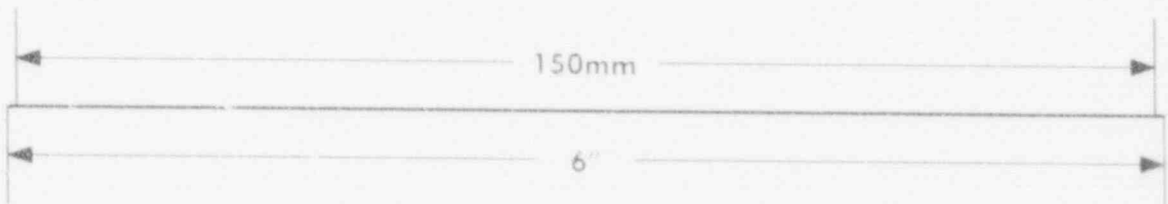
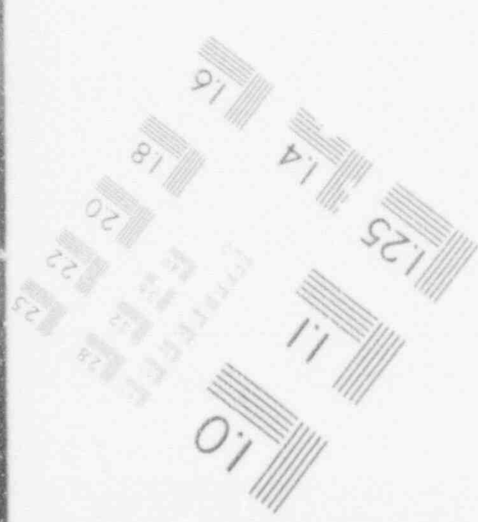
WEBSTER, NEW YORK 14580
(716) 265-1600



2

IMAGE EVALUATION TEST TARGET (MT-3)





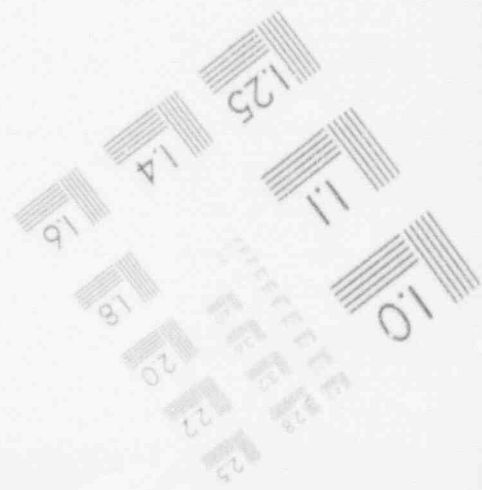


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TABLE 1-11

TRANSIENT TYPES

[

]a,c,e

TABLE 1-12

SUMMARY OF FATIGUE CYCLES FROM [ ]a,c,e

Cycle	Delta Range (°F)	Cycle	Delta Range (°F)

[ ]a,c,e

NOTE: The delta range represents the relative severity (ΔT) of each transient following the fatigue cycle approach.

TABLE 1-13
SUMMARY OF PLANT MONITORING HEATUP/COOLDOWN TRANSIENTS
WITH STRENGTH OF STRATIFICATION (RSS)

[ ]a,c,e		[ ]a,c,e		[ ]a,c,e	
Observed Cycles	RSS (1)	Observed Cycles	RSS (1)	Observed Cycles	RSS (1)
[ ]a,c,e					

OBSERVED TRANSIENTS GROUPED
BY STRENGTH OF STRATIFICATION
(RSS) INTERVALS

RSS	No. Observed Cycles	% of Total
[ ]a,c,e		

Note: The No. of groups is reduced by combining the intervals .70 ≤ x < .8 and .60 ≤ x < .70 % of total = 3.4% for the interval .60 ≤ x < .80

TABLE 1-13 (cont.)
SUMMARY OF PLANT MONITORING HEATUP/COOLDOWN TRANSIENTS
WITH STRENGTH OF STRATIFICATION (RSS)

RSS	J	% of Transients

a,c,e

RELATIVE NUMBER OF CYCLES OF
STRENGTH OF STRATIFICATION (RNSSj)
AFTER GROUPING

RNSSj % Transients (2)	j	RSSj Strength of Stratification (1)

a,c,e

Nomenclature:

(1) Strength of Stratification (RSS)
(2) Relative Number of Cycles of Strength of Stratification (RNSS)

TABLE 1-14

SUMMARY OF MONITORED TRANSIENT CYCLES (ONE HEATUP)

Plant	No. of Cycles
[	] a,c,e

Avg. Monitored Cycles: 15.75 * x;

Selected No. of Design Cycles: 36.5 (added 30% to observed maximum number of cycles, plant A)

DESIGN DISTRIBUTION APPLIED TO MAX NUMBER OF TRANSIENTS EXCEPTED MULTIPLIED BY 200 HEATUP OR COOLDOWN CYCLES	
No. of Transients	RSS
[	] a,c,e
Total	

TABLE 1-15

SUMMARY OF % TIMES AT

MAXIMUM TEMPERATURE POTENTIAL

$RMTP_K$

a,c,e

TABLE 1-16
SURGE LINE TRANSIENTS - STRIPING
FOR HEATUP (H) and COOLDOWN (C)

a,c,e

[ ]

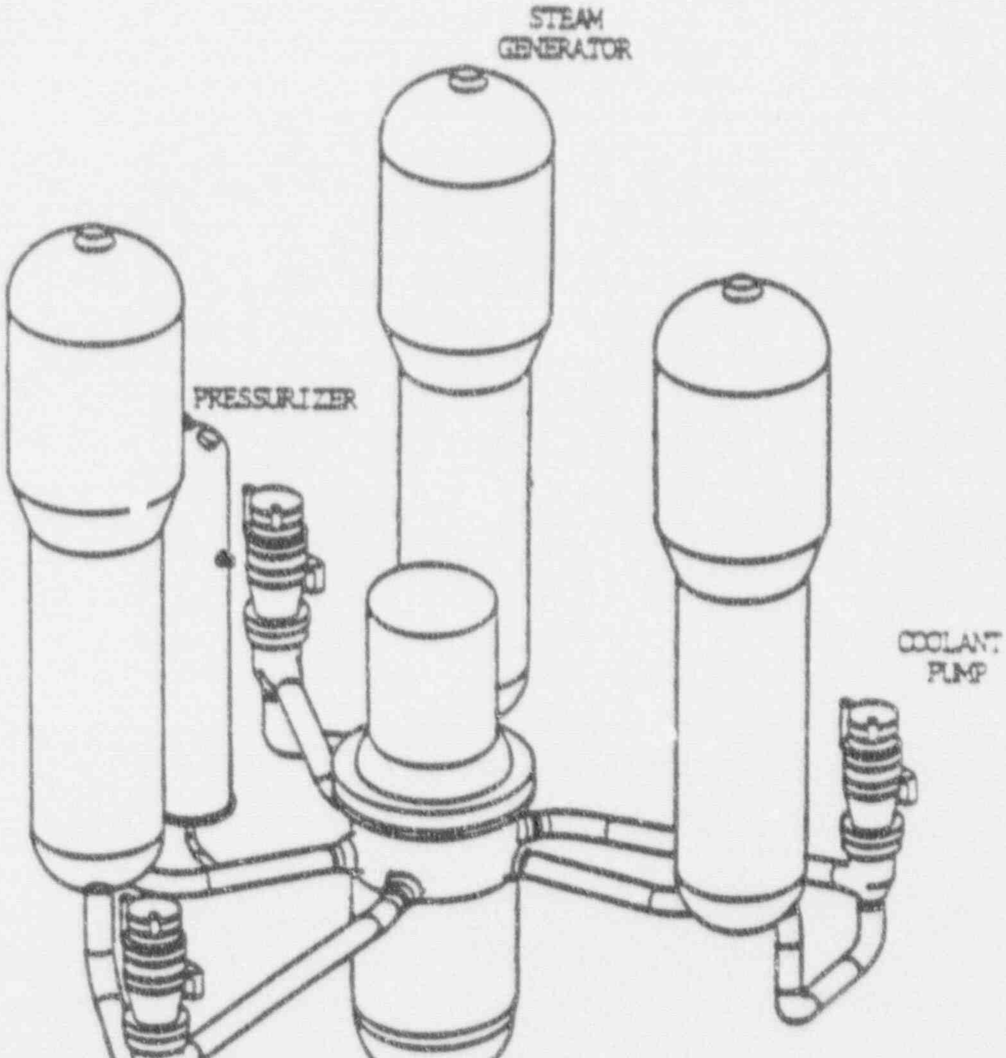

Figure 1-1. Simplified Diagram of the NSSS

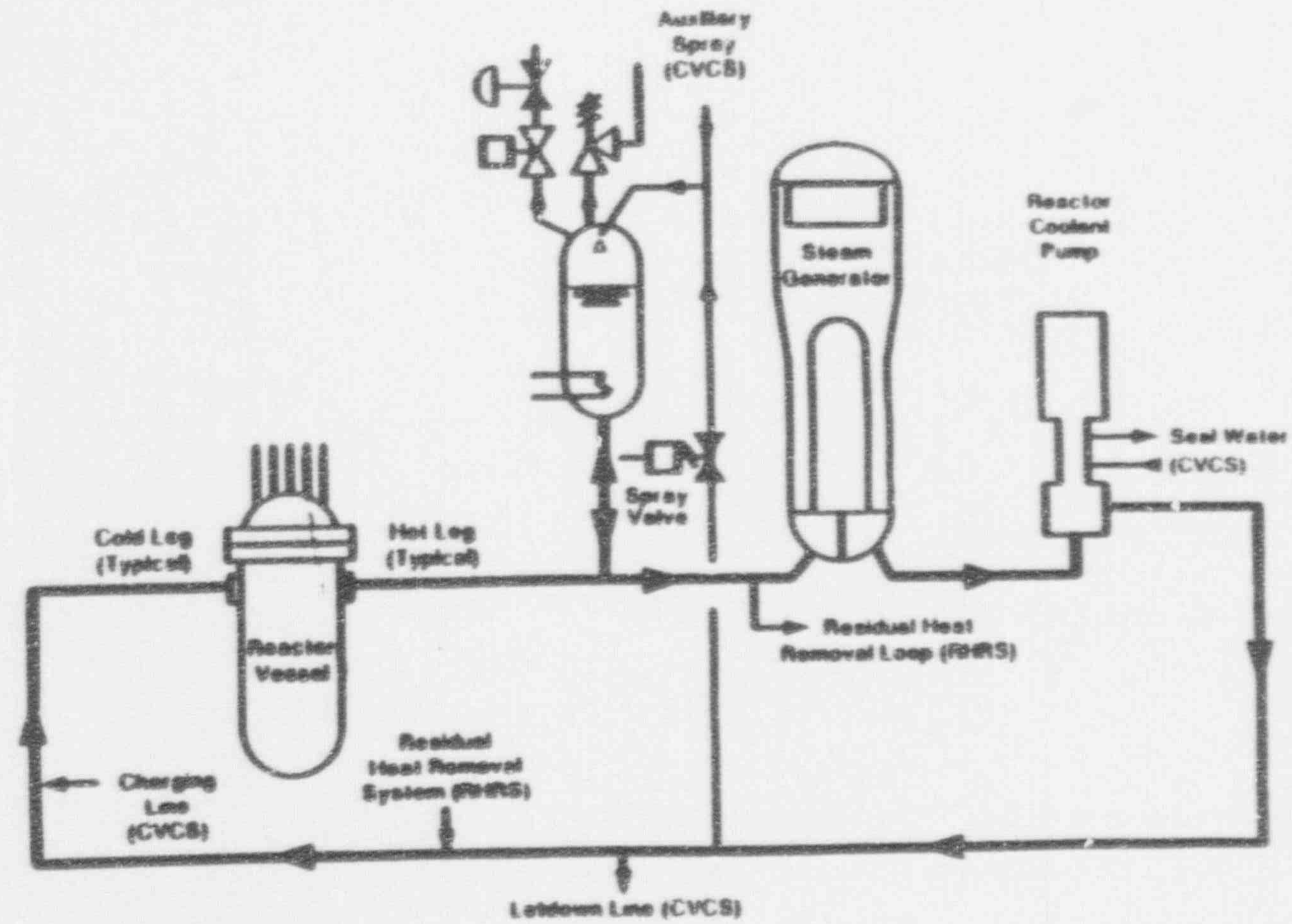

Figure 1 2. Reactor Coolant System Flow Diagram (Typical Loop)

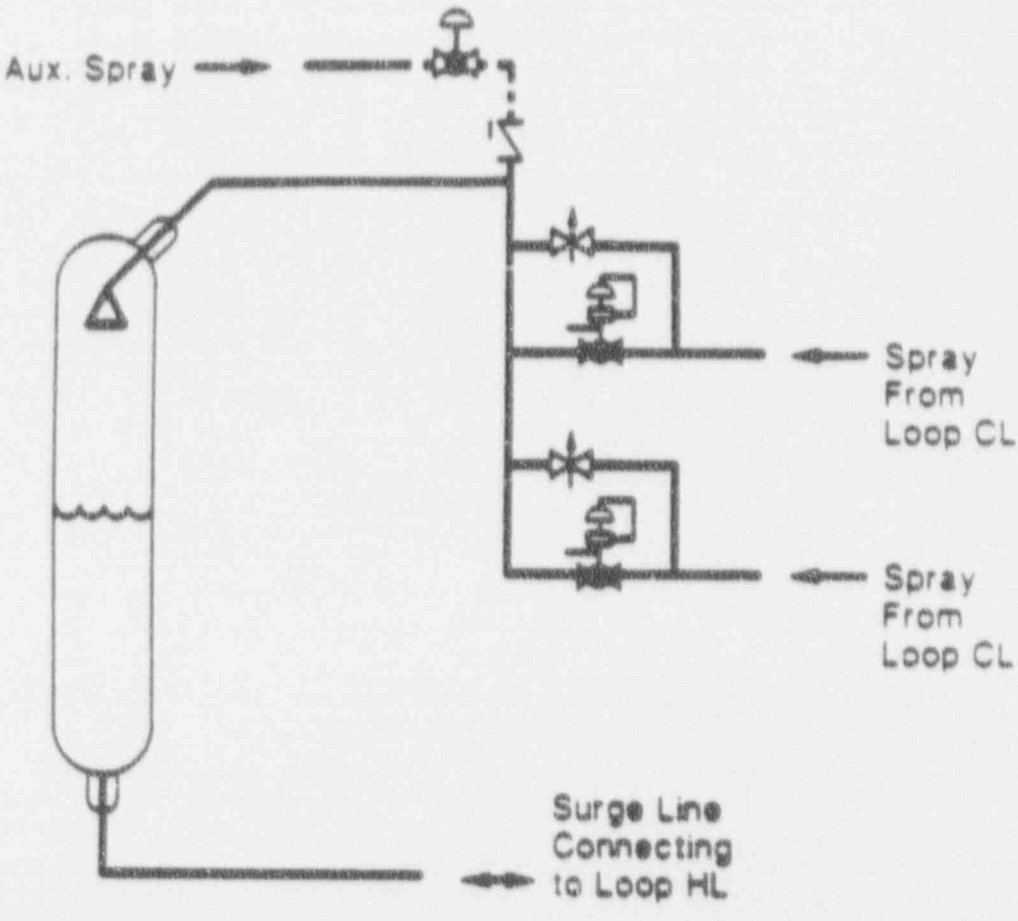

Figure 1-3. RCS Pressurizer

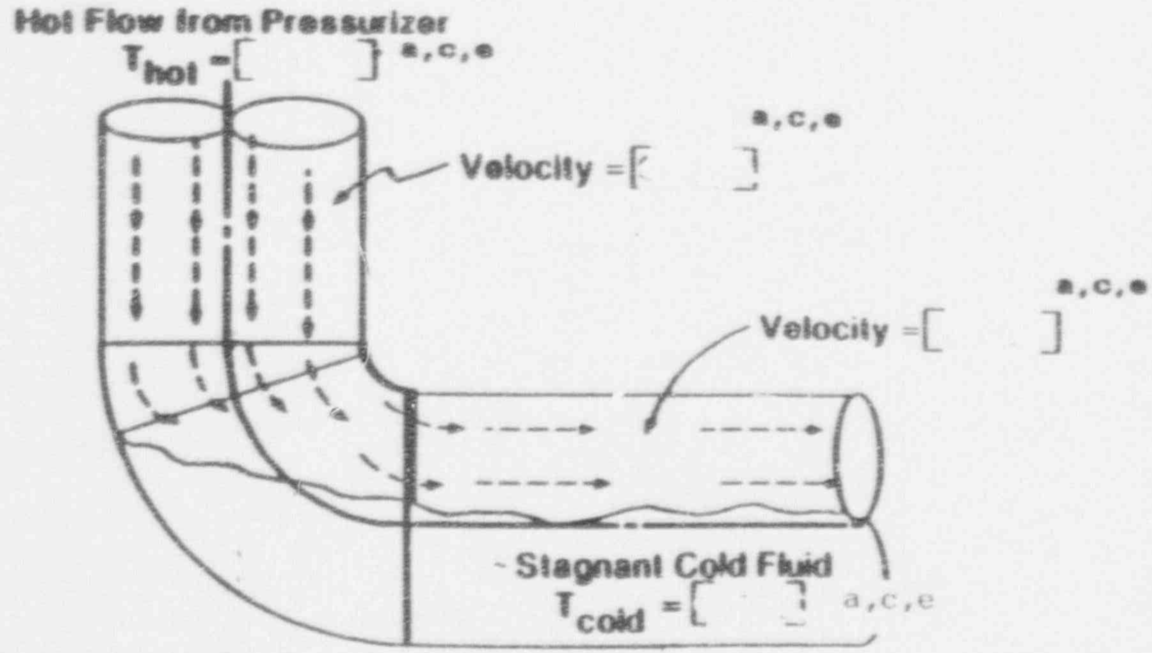

Figure 1-4. Estimate of Flow Stratification Pattern in Elbow Under Pressurizer

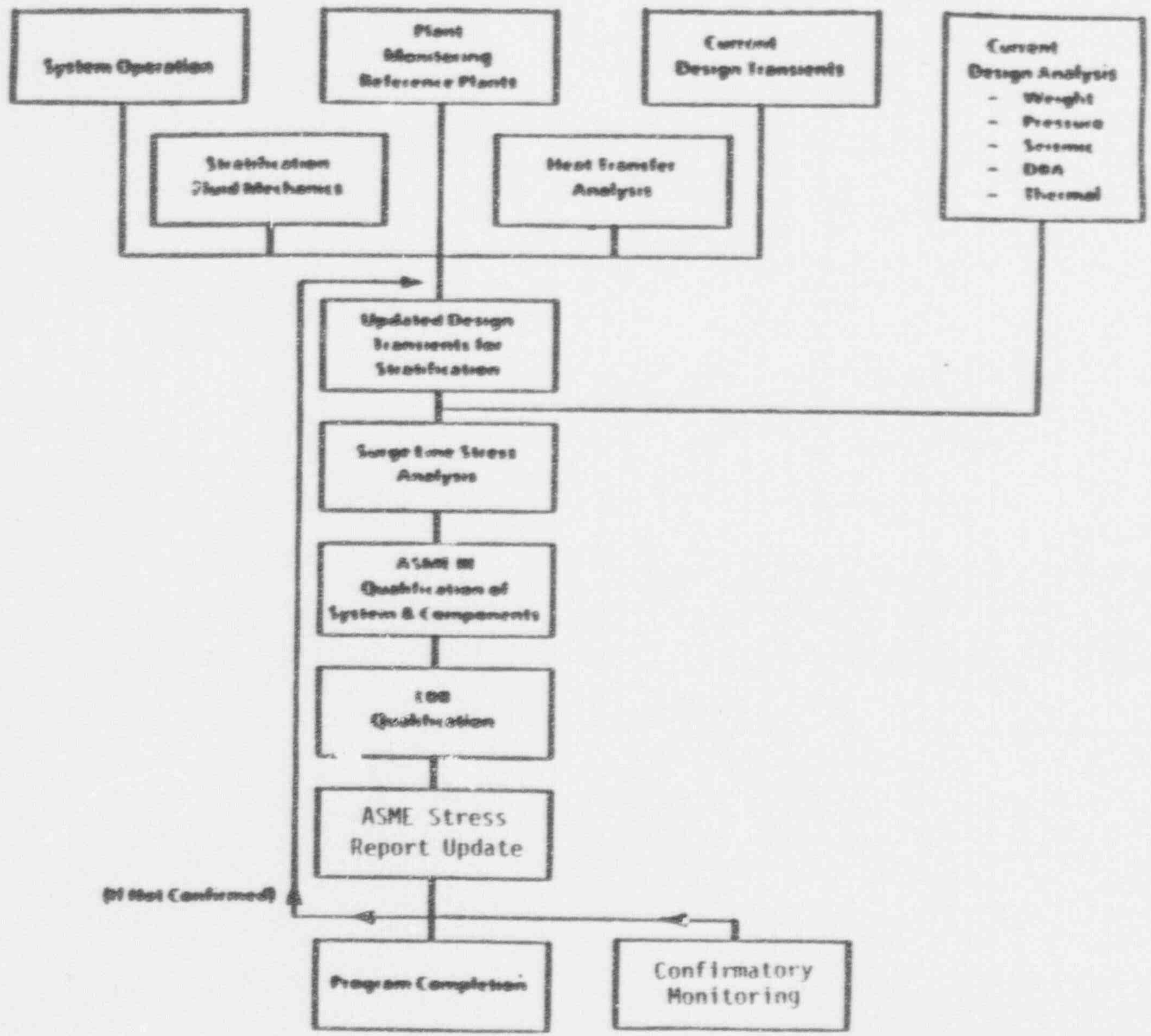

Figure 1-5. Comanche Peak Unit 1 Pressurizer Surge Line Stratification ASME III and Qualification Program

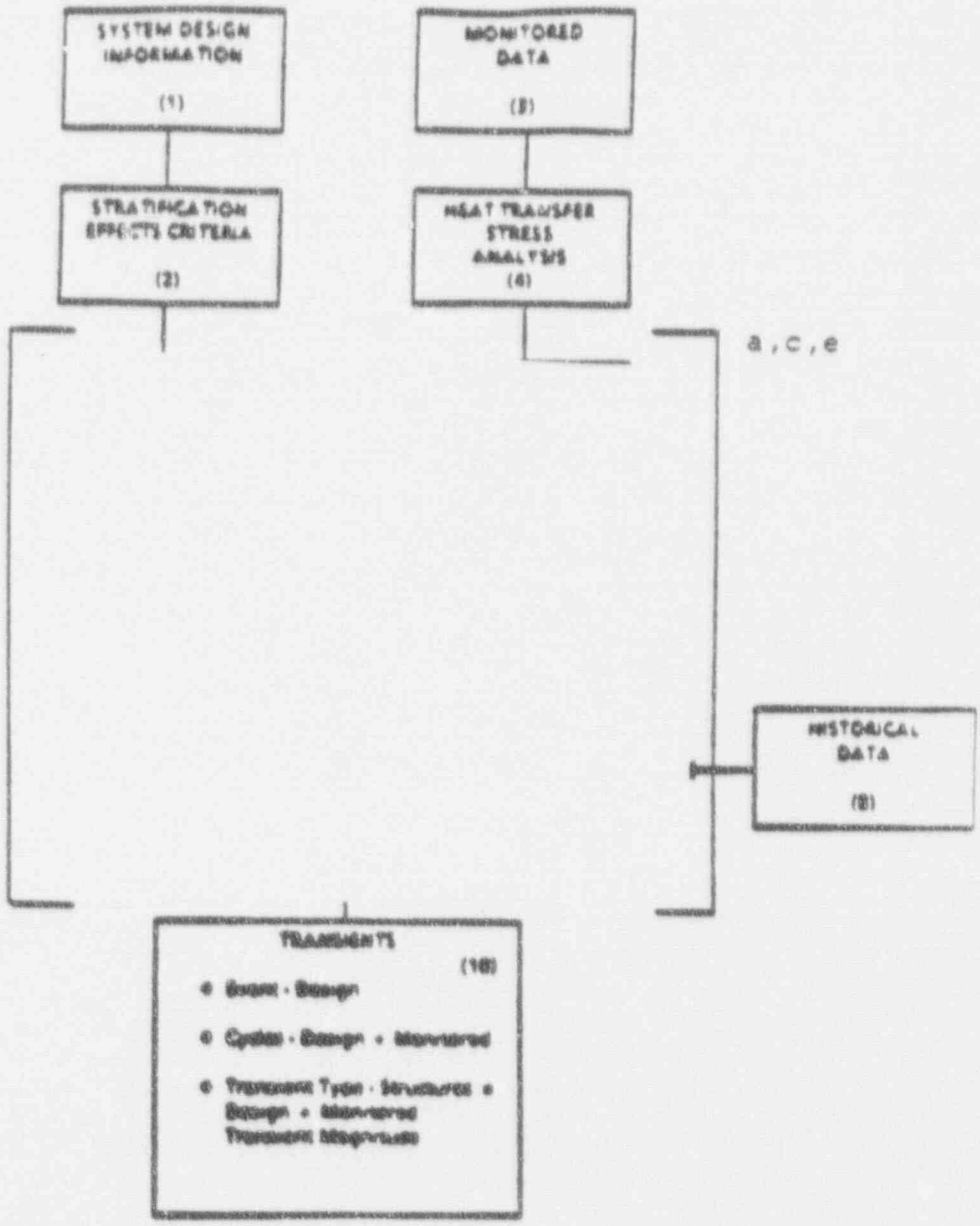

Figure 1-6. Transient Development Flow Chart

a,c,e

Figure 1-7. [Plant A][a,c,e] Pressurizer Surge Line Monitoring Locations

3693s/041089:10

a,c,e

Figure 1-8. [Plant B]^{a,c,e} Pressurizer Surge Line Monitoring Locations

3083s/041089:10

a,c,e

Figure 1-9. [Plant C]^{a,c,e} Pressurizer Surge Line Monitoring Locations

1891s-041089 10

a,c,e

Figure 1-10. [Plant D][a,c,e] Pressurizer Surge Line Monitoring Locations

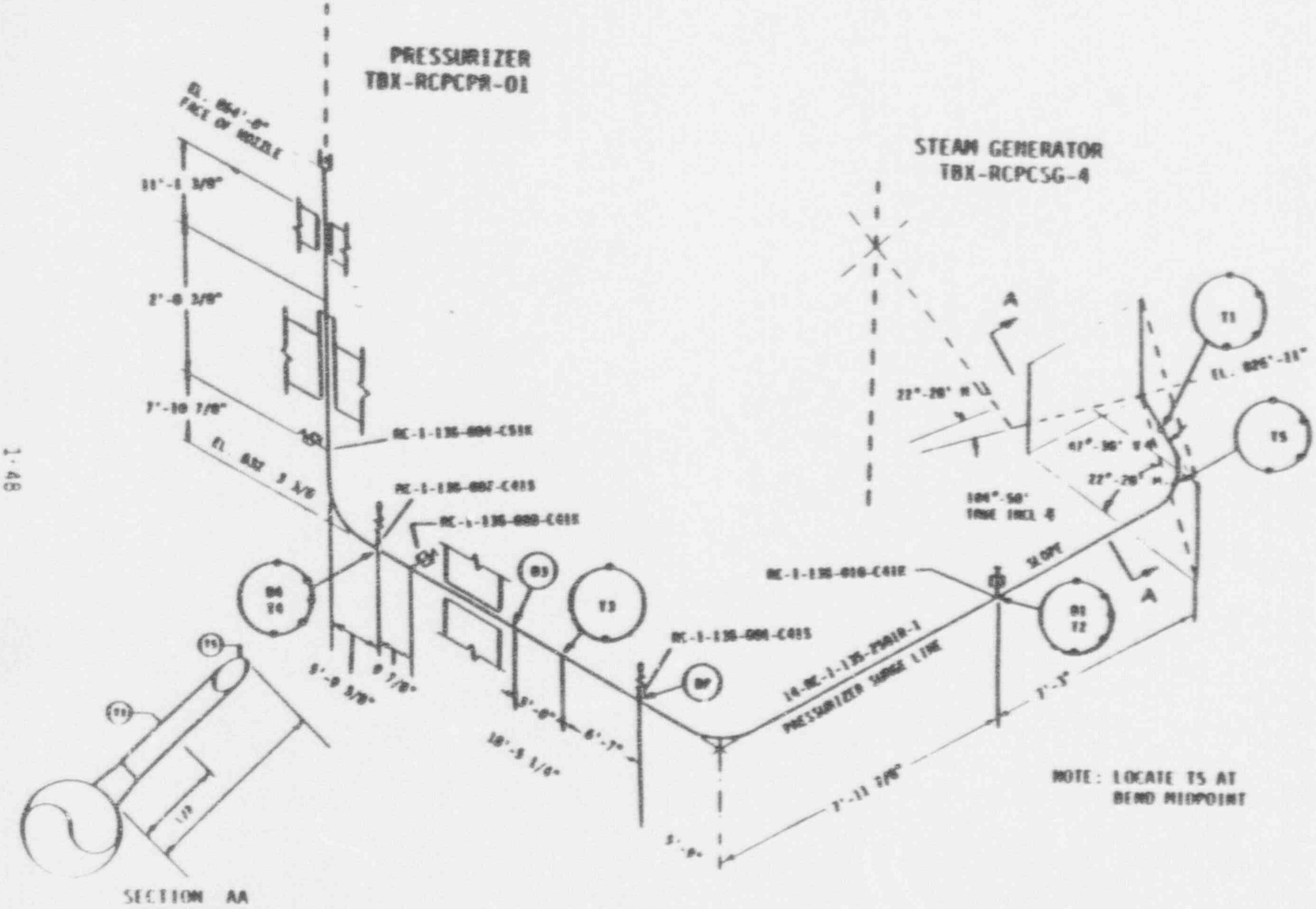

Figure 1-11. Comanche Peak Pressurizer Surge Line Monitoring Locations

a,c,e

Figure 1-12. Reactor Coolant Pump Cut-off Transient
Location Approximately 10' From RCL Nozzle Safe-End

a,c,e

Figure 1-13. Reactor Coolant Pump Cut-off Transient RCL_{HL} Nozzle Safe-End

3091s/041389 10

a,c,e

Figure 1-14. Transient Typical of RC Pump Cut-off

Temperature (°F)

a,c,e

Angle β (Degrees)

Figure 1-15. Temperature Profile (6.5 inch ID Pipe)

Angle, (degrees)

a,c,e

Dimensionless Temperature, 0

Figure 1-16. Dimensionless Temperature Profile (14.3 inch ID Pipe)

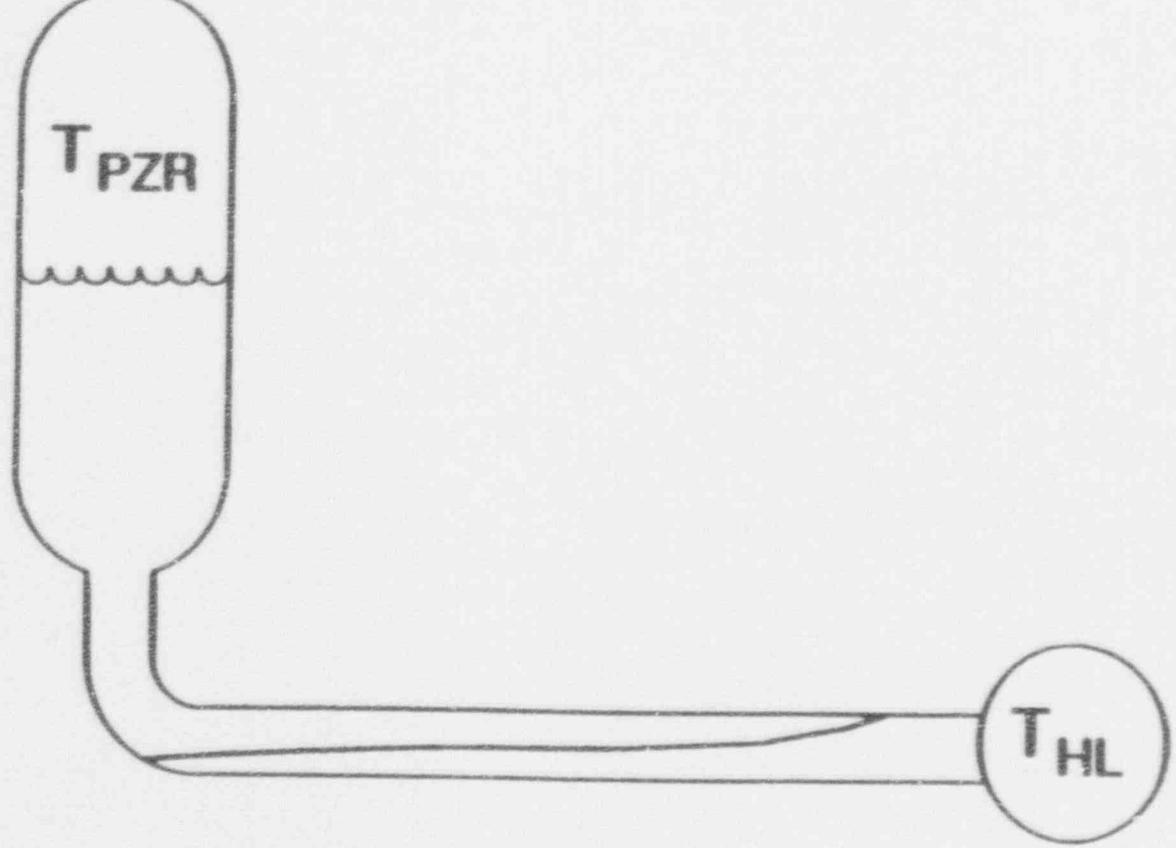

Figure 1-17. Surge Line Stratification

a,c,e

Figure 1-18. Surge Line Hot-Cold Interface Locations

a,c,e

Figure 1-19. Typical [Insurge-Outsurge ( ]^{a,c,e} Temperature Profiles

a,c,e

Figure 1-20. Inadvertent RCS Depressurization (ΔT = 260°F in Surge Line)

Temperature (°F)

a,c,e

Time (Hours)

Figure 1-21. Steam Bubble Mode Heatup

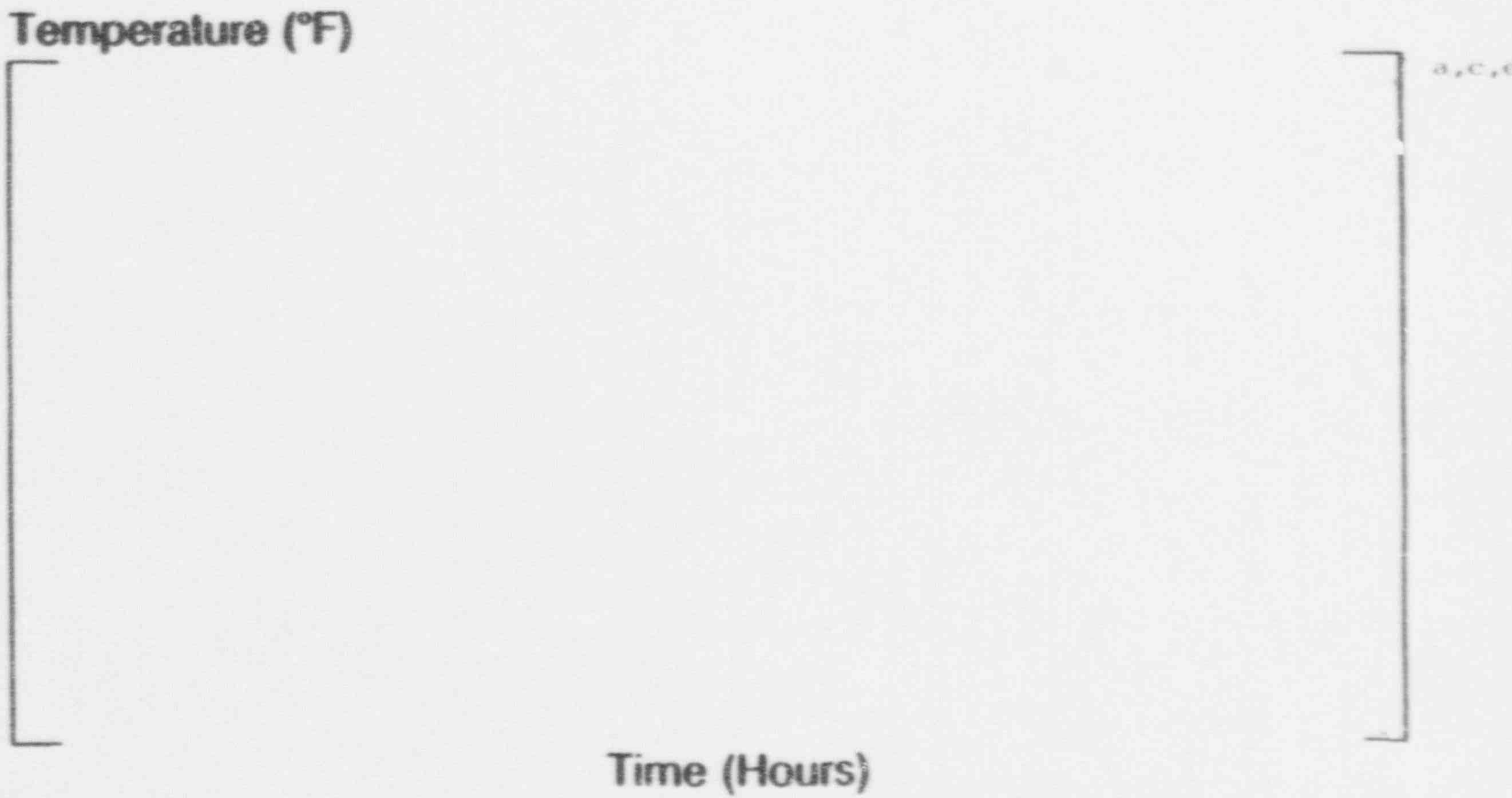

Figure 1-22. Steam Bubble Mode Cooldown

a,c,e

Figure 1-23. Heatup Comanche Peak

a,c,e

Figure 1 74. Cooldown - Comanche Peak

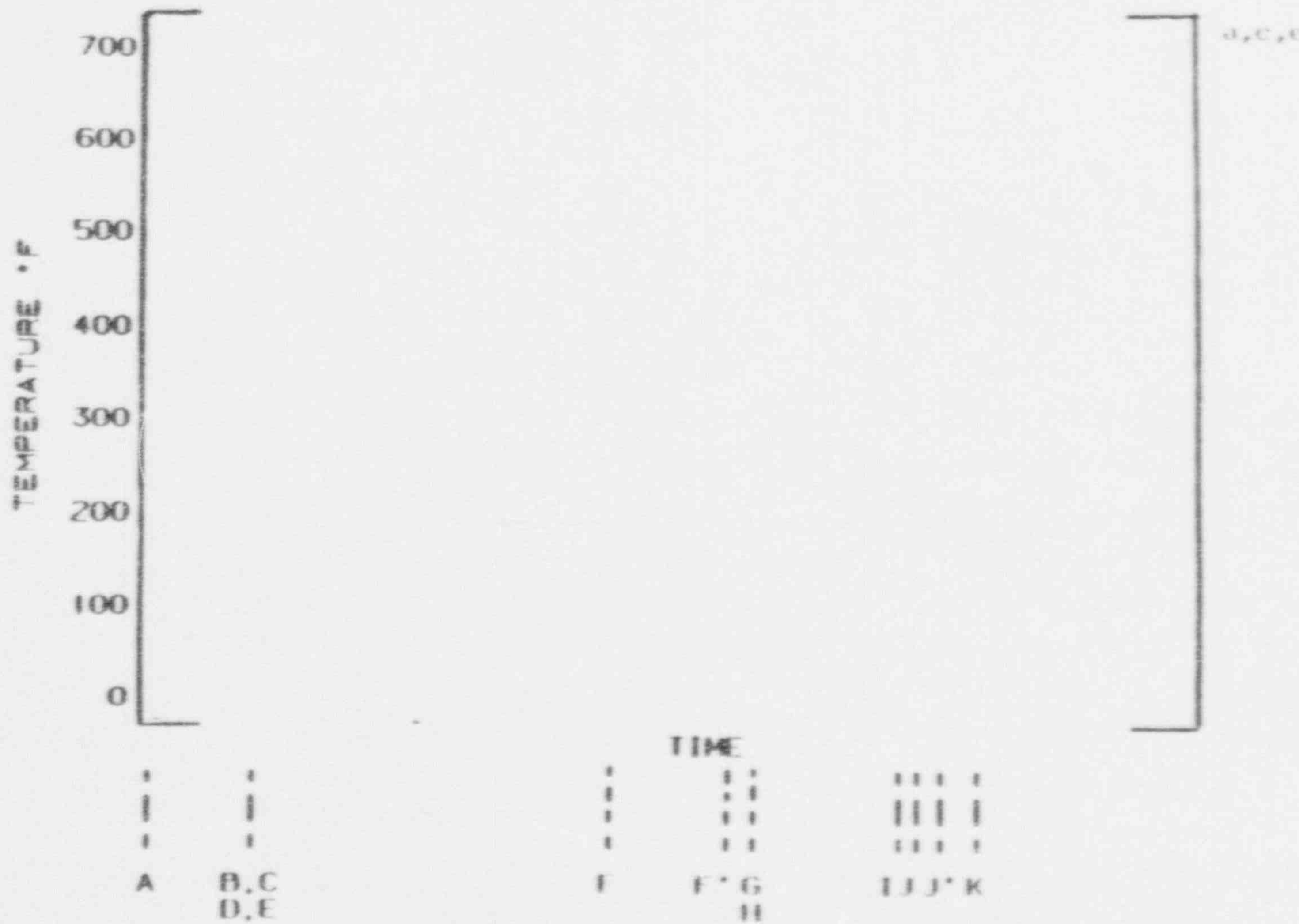

Figure 1.25. Heatup [ ]a,c,e

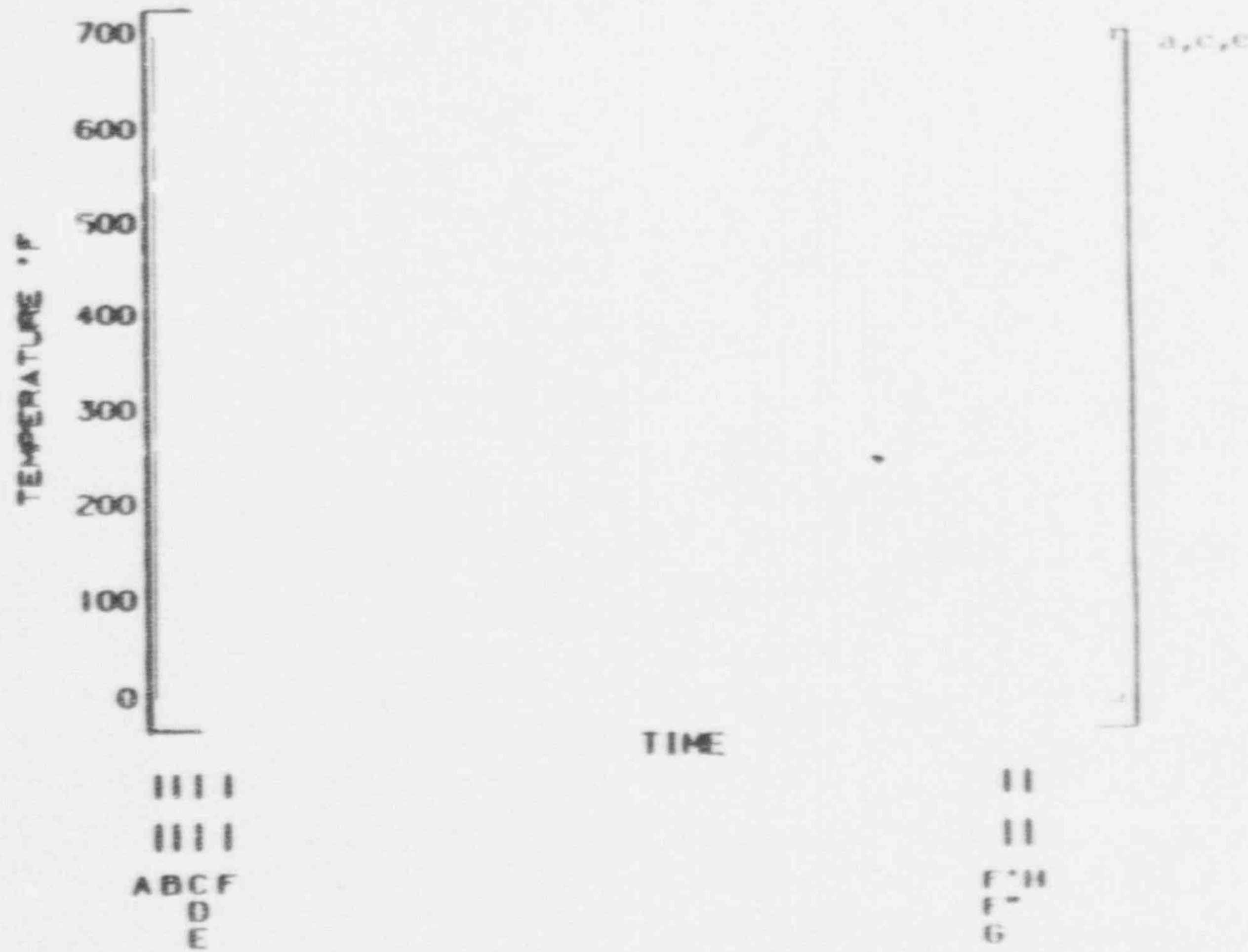

Figure 1-7b. Cooldown [ ]^{a,c,e}

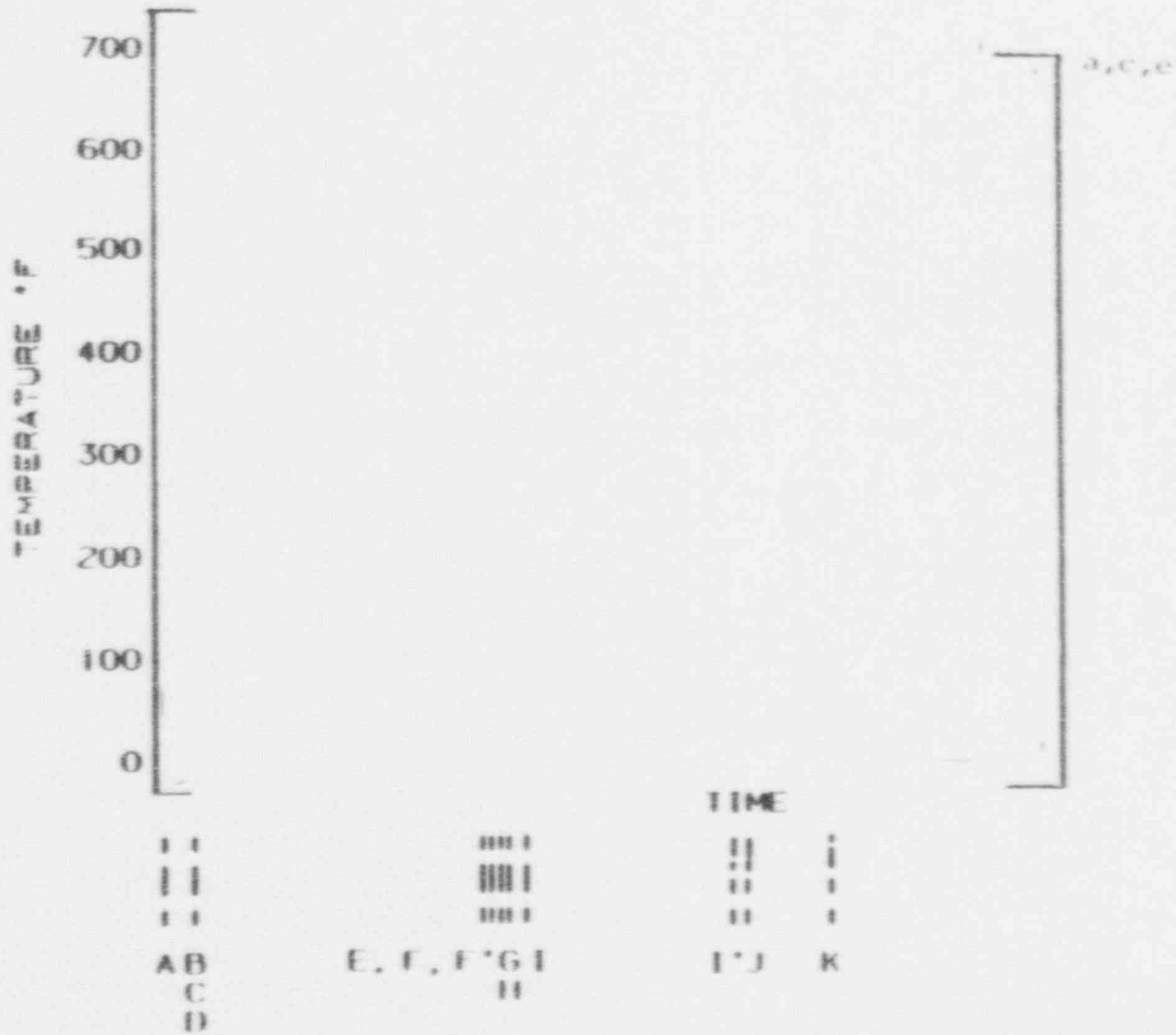

Figure 1 27. Heatup [ ]a,c,e

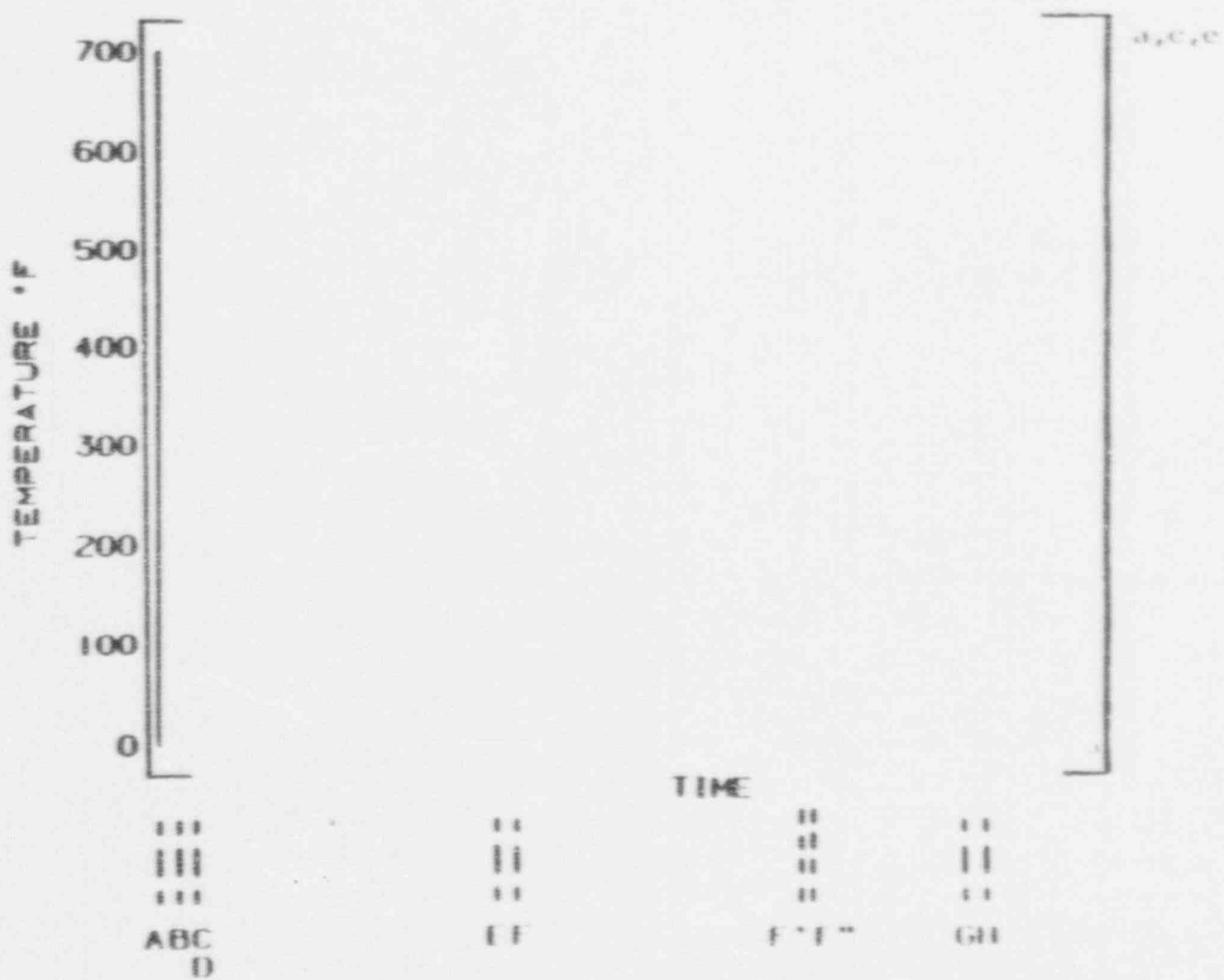

Figure 1-28. Cooldown]a,c,e

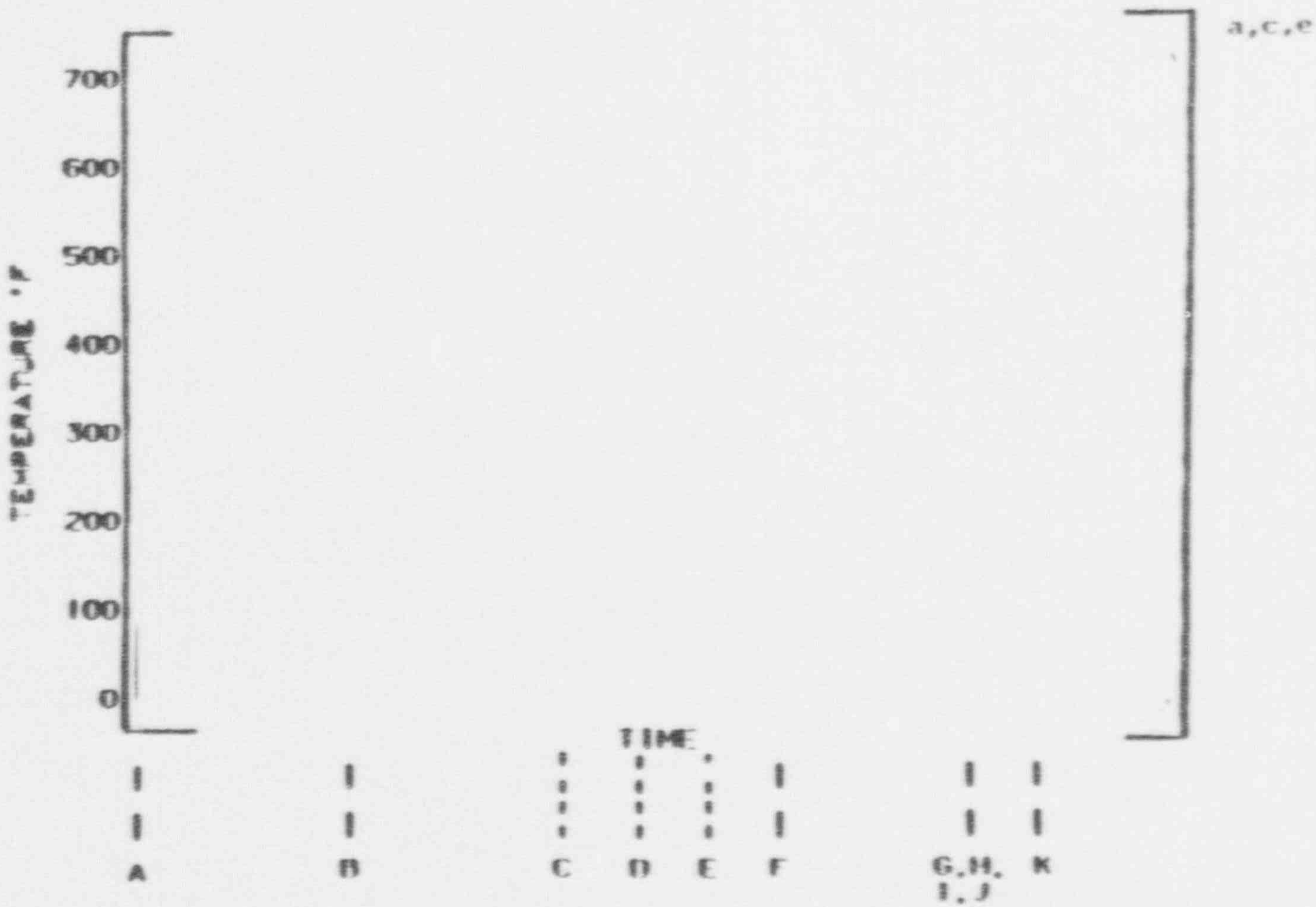

Figure 1-29. Heatup [ ]^{a,c,e}

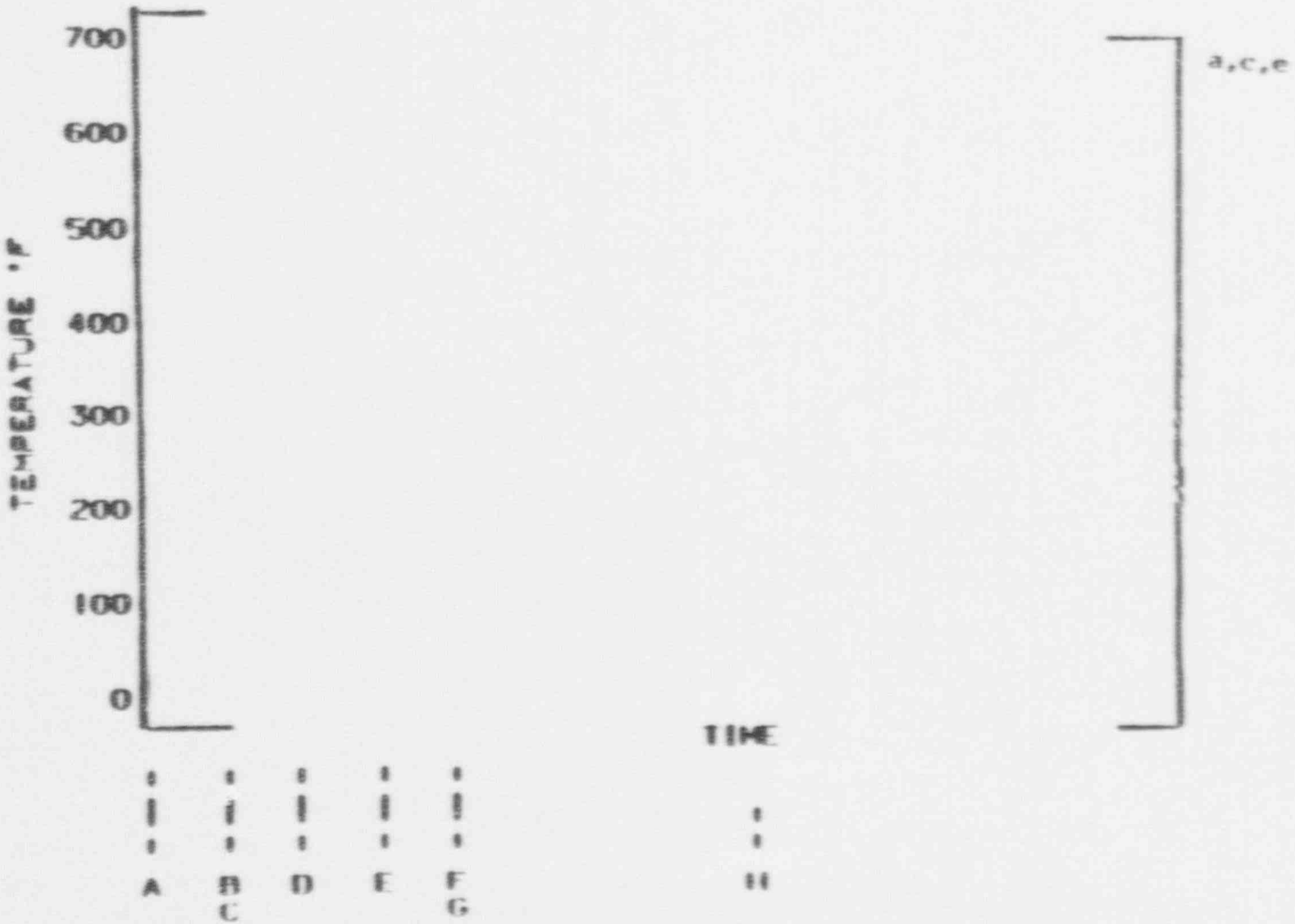

Figure 1-30. Cooldown [ ]a,c,e

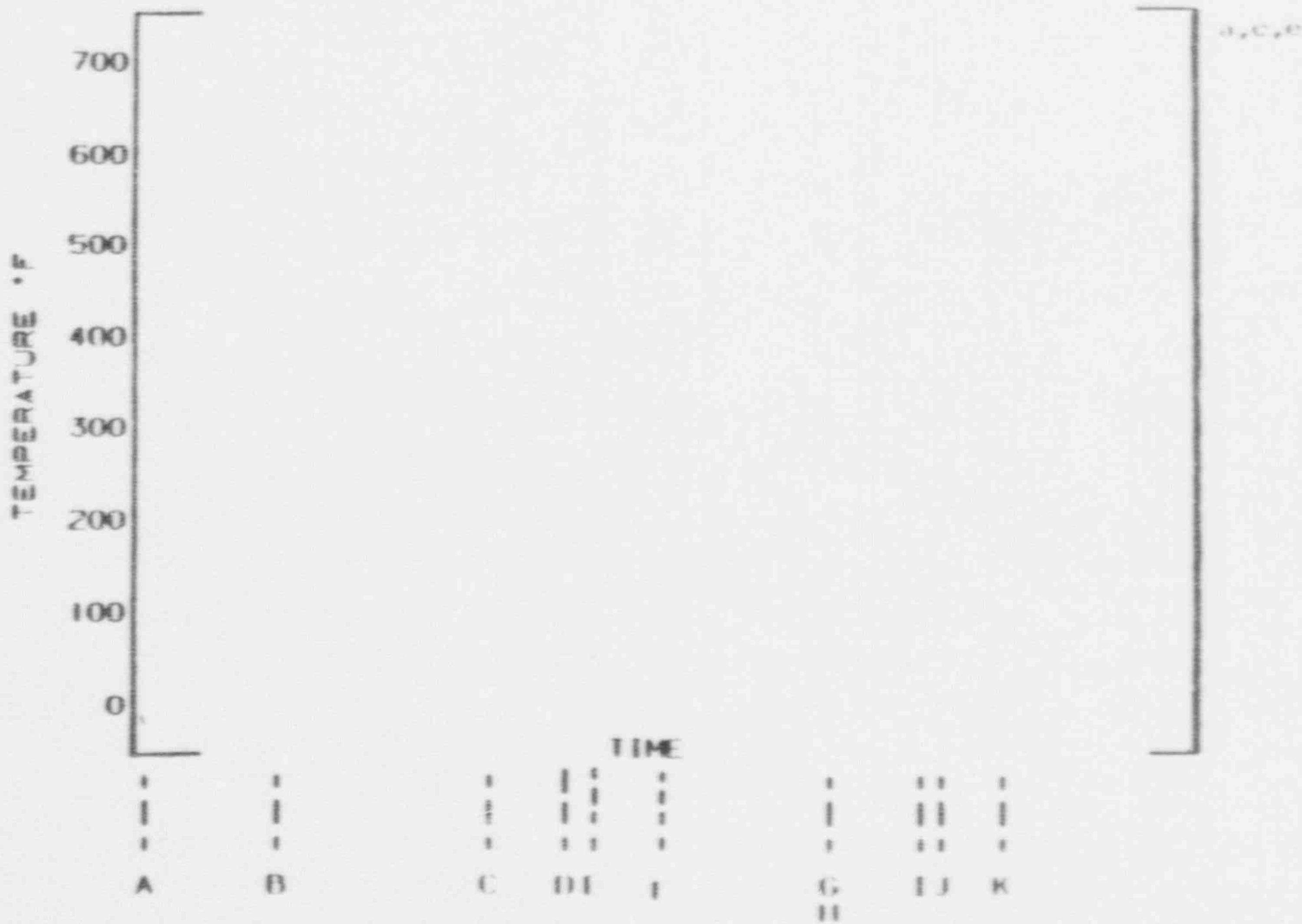

Figure 1.11. Heatup [ ]a,c,e

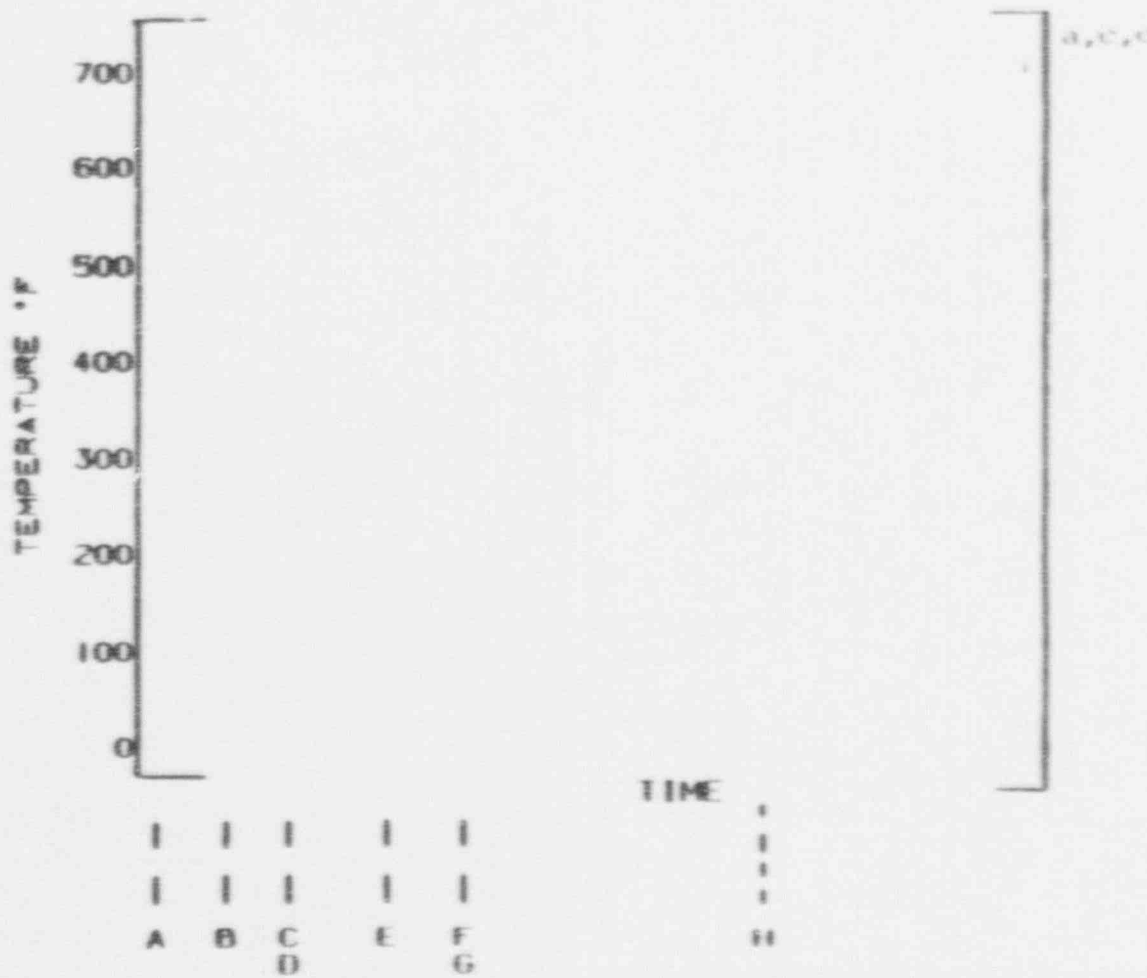

Figure 1.32. Cooldown [ ]a,c,e

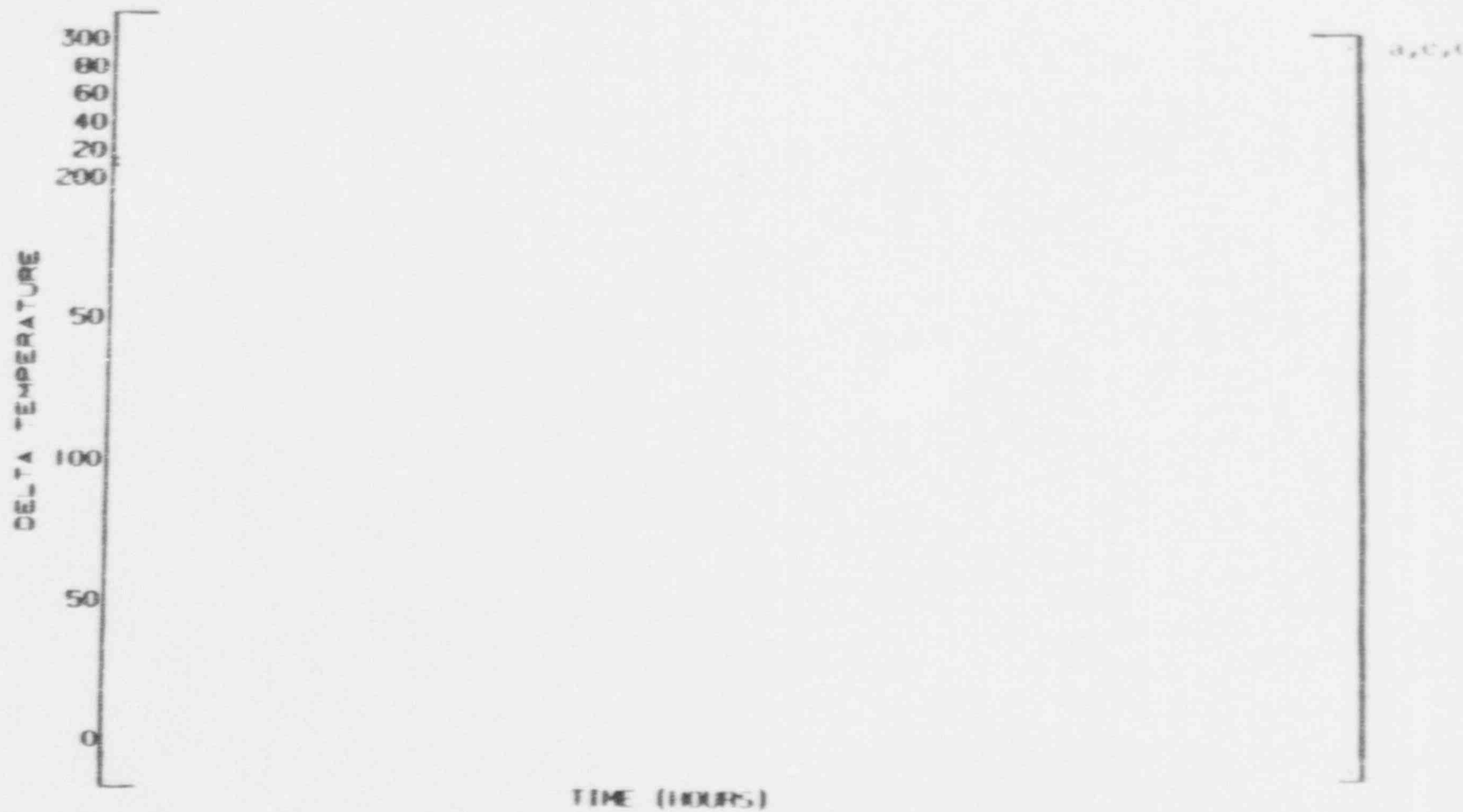

Figure 1-33. [ ]^{a,c,e} Location 1 - Heatup (7 Days)

3801s/041088 10

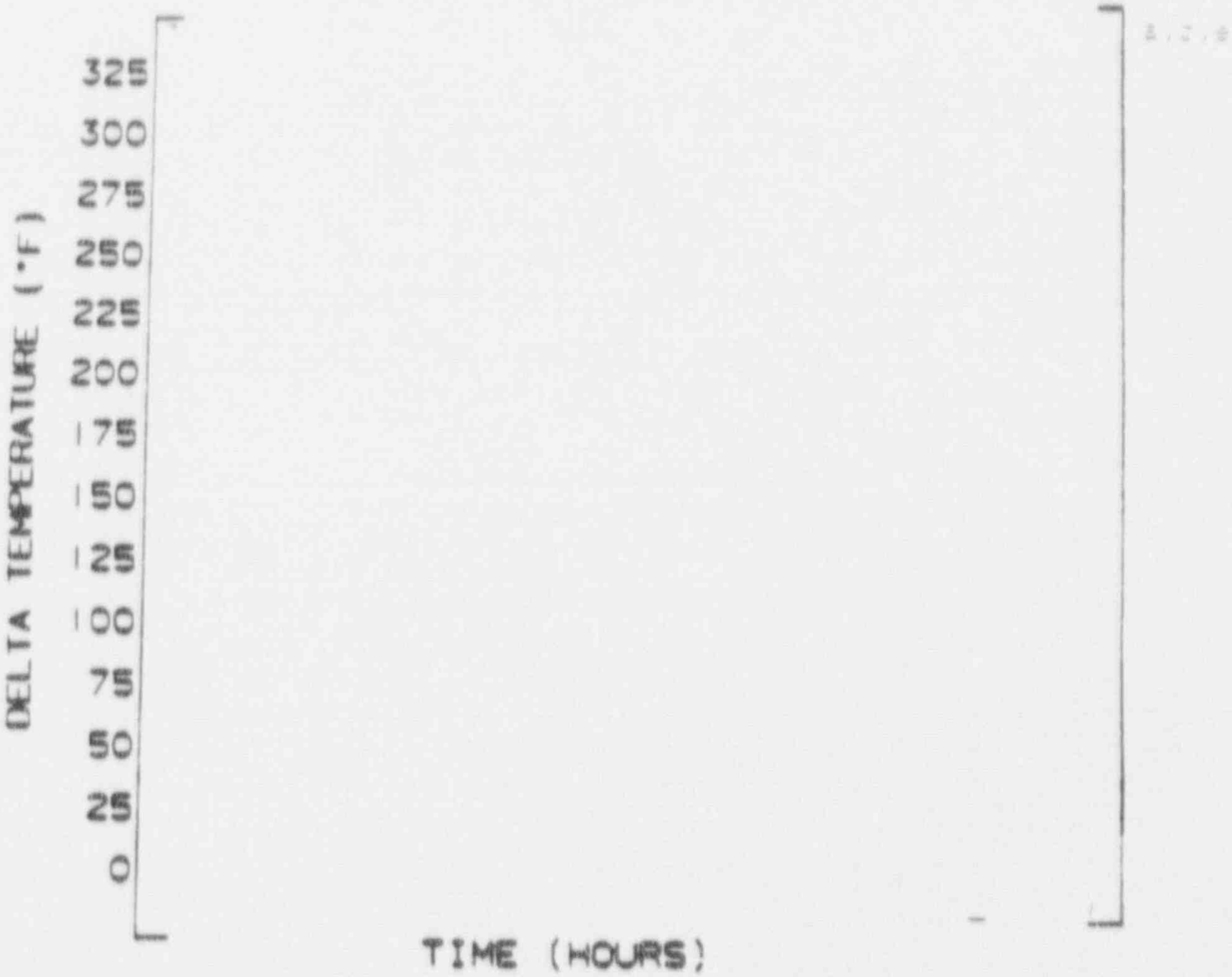

Figure 1-34. [ ]^{a,c,e} Location 1 - Heatup (4 Days)

[ ]a,c,e

DELTA TEMPERATURE (°F)

EVENT NUMBER

Figure 1-35. [ ]a,c,e Location 1 Fatigue Cycles Heatup (11 Days)

a,c,e

Figure 1-36. Thermal Cycle Distribution Assumed for One Heatup Cycle

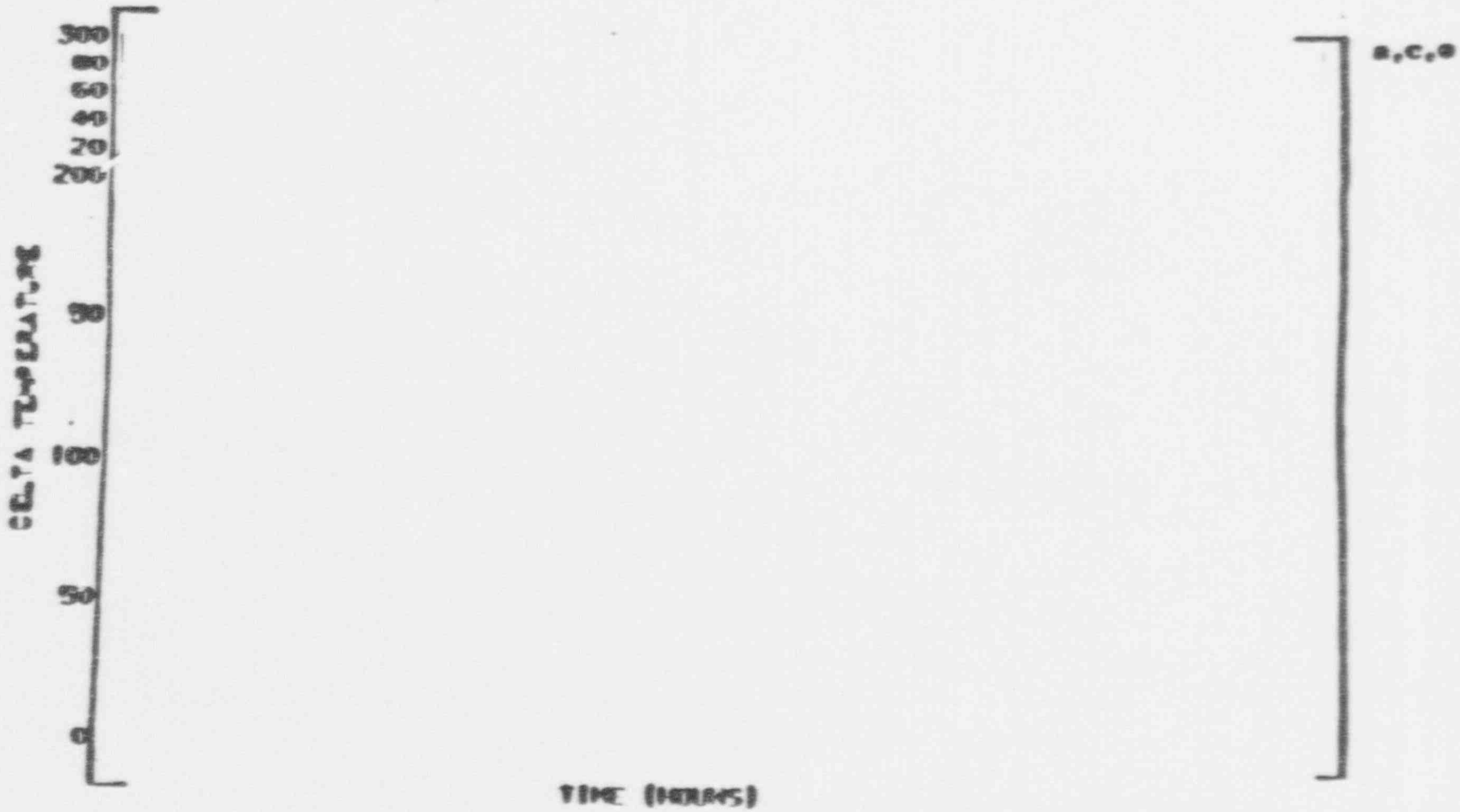

Figure 1-37. [ ]^{a,c,e}

a,c,e

Figure 1-38. Indications of Striping Thermal Cycle Assumed for One Heatup

Figure 1-39. Comparison of Design to Monitored Transients

a,c,e

Figure 1-40. Comparison of Design to Monitored Transients

SECTION 2.0
STRESS ANALYSES

Figure 2-1 describes the procedure to determine the effects of thermal stratification on the pressurizer surge line based on transients developed in section 1.0. [

]^{a,c,e}

Section 2.1 Addresses the structural or global effect of stratification

Section 2.2 Addresses the local stress effects due to the nonlinear portion of the temperature profile

Section 2.3 Addresses the total stress effects due to the oscillation of the hot-to-cold boundary layer (striping) plus the thermal stratification stress

2.1 Piping System Structural Analysis

2.1.1 Introduction

The computer analysis of the surge line to determine the pipe displacements, support loads, and internal pipe loads is referred to as the piping system structural analysis. These loads are used as input to the fatigue evaluations. The thermal stratification condition consists of both axial and diametric variations in the pipe metal temperature, as described in section 1.0. The model consists of straight pipe and elbow elements for the ANSYS computer code. [

]^{a,c,e} These studies verified the suitability of ANSYS for thermal stratification analysis. [

]^{a,c,e}

[

]a,c,e

2.1.2 Discussion On Typical Surge Line Analysis

The piping layout for a typical surgeline is shown in Figure 2-3. The rigid support, Ril, originally installed to reduce deadweight and seismic loads provides resistance to the displacements caused by thermal stratification. This configuration conservatively envelops the Comanche Peak Unit 2 surgeline, which does not contain a vertical rigid support. [

]a,c,e

[

]a,c,e

[

]a,c,e

Based on the above discussion, ANSYS is suitable for thermal stratification analysis. [

]a,c,e

[

]a,c,e

2.1.3 Results Fcr Comanche Peak Unit 2 Surge Line

The calculated piping stress due to thermal stratification for the Comanche Peak Unit 2 surge line is reviewed to ensure that the system will not collapse

in a "hinge-moment" mechanism. The primary plus secondary stress limit for this piping stress is given by ASME III, Section NB 3600, Equation 12 as 3.0 Sm. The maximum stress intensity range, which occurs at the RCL hot leg nozzle, is 52.1 ksi. This is less than the Code allowable value of 57.9 ksi. This corresponds to a bounding thermal stratification case with $\Delta T = 320°F$. It should be noted that the stress index for the hot leg nozzle in equation 12 was developed from finite element analysis of the RCL nozzle. A summary of maximum ASME code calculated stresses is presented in Table 2-11.

2.1.4 Additional Information on Linear Equivalent Techniques

2.1.4.1 Introduction

A review of the pressurizer surge line thermal stratification for several plants indicated that the actual stratification temperature profiles are better described by nonlinear diametric (cross-sectional) temperature distributions. These temperature profiles will have effects on the global structural behavior of the surge lines in terms of loads and displacements. The use of isoparametric solid elements has made possible the study of nonlinear cross-sectional temperature profiles, such as step change of temperatures at mid-plane. This study was performed using a model developed for the WECAN computer code. In order to achieve a less costly analytical solution, an alternative model using pipe and elbow elements was developed for the ANSYS computer code. These elements can only be loaded with a constant cross-section temperature or a linear top-to-bottom cross-section temperature. It, therefore, becomes necessary to establish an equivalent linear temperature profile which will result in the same deflections and loads in the piping system as would a nonlinear temperature profile. It should be noted that there are differences in the WECAN and ANSYS models as described in section 2.1.2. These modeling differences will contribute to minor differences when results obtained from the analyses are compared. The purpose of the study and the comparison with the measured displacements is to verify the suitability of ANSYS for thermal stratification global analysis. The theoretical basis for the equivalent linear temperature profile is based on a cantilever beam model and is summarized below.

2.1.4.2 Theory

The closed form solution is determined for the free-end vertical and axial displacements of a cantilever cylindrical beam subject to two types of stratification temperature profiles:

a) linear equivalent variation from top to bottom;
b) step change at distance Y_0 below the beam centerline.

The axis of the beam (x-axis) lies in a horizontal plane. The solution is based on the following principles:

[

]a,c,e

5. For a cantilever beam subject to thermal stratification, the axial force (F) and bending moment (M) are zero at each cross section (A), thus.

$$F = \int_A \sigma \, dA = 0 \quad (2.1\text{-}5)$$
$$M = \int_A \sigma \, y \, dA = 0 \quad (2.1\text{-}6)$$

The above equations are solved in closed form with the following results:

[

]a,c,e

The solution for the equivalent linear temperature in the form of coefficients J_{ik} is obtained by equating (2.1-7) with (2.1-9) and (2.1-8) with (2.1-10).

[

]^{a,c,e}

2.1.4.3 Application

The deflections and loads in the surge line for case 3 (step at mid-plane) have been calculated by WECAN. The same step change temperature profile is converted to an equivalent linear temperature profile (case 3L) for ANSYS using the J_{ik} coefficients with $Y_o = 0$. Table 2-4 is an example for 14-inch schedule 140 pipe. The case 3 and case 3L temperature profiles used in the analyses are shown in Figure 2-23c and 2-23d. The results are presented in Table 2-2.

2.1.4.4 Discussion

The suitability of ANSYS for thermal stratification global analysis is demonstrated by the comparisons between case 3 and case 3L. WECAN and ANSYS pipe displacements on Table 2-2 also confirm this. In addition, case 3L is representative of the eleven analysis cases which represent various step temperature profiles along the pipe axis.

2.1.5 Conclusions

Analytical studies with ANSYS and WECAN have confirmed the validity of using an equivalent linear diametric temperature profile to represent thermal stratification. Eleven cases of thermal stratification were analyzed using ANSYS for the Comanche Peak Unit 2 surgeline. Results for all other cases of stratification were obtained by interpolation. The resulting loads on the pressurizer and hot leg nozzles are acceptable. The surge line pipe stress satisfies the ASME III NB-3600 Code Equation 12 limits.

2.2 Local Stress Due to Non-Linear Thermal Gradient

2.2.1 Explanation of Local Stress

Figure 2-24 depicts the local axial stress components in a beam with a sharply nonlinear metal temperature gradient. Local axial stresses develop due to the restraint of axial expansion or contraction. This restraint is provided by the material in the adjacent beam cross section. For a linear top-to-bottom temperature gradient, the local axial stress would not exist. [

]^{a,c,e}

2.2.2 Superposition of Local and Structural Stresses

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

]^{a,c,e} Local and structural stresses may be superimposed to obtain the total stress. This is true because linear elastic analyses are performed and the two stresses are independent of each other as summarized in Figure 2-25.

Figure 2-26 presents the results of a test case that was performed to demonstrate the validity of superposition. As shown in the figure, the superposition of local and structural stress is valid. [

]^{a,c,e}

2.2.3 Finite Element Model of Pipe for Local Stress

A short description of the pipe finite element model is shown in Figure 2-27. The model with thermal boundary conditions is shown in Figure 2-28. Due to symmetry of the geometry and thermal loading, only half of the cross section was required for modeling and analysis. [

]^{a,c,e}

2.2.4 Pipe Local Stress Results

Figure 2-29 shows the temperature distributions through the 14 in. schedule 160 pipe wall [

]^{a,c,e}

2.2.5 Unit Structural Load Analyses For Pipe

In order to accurately superimpose local and global structural stresses, several additional stress analyses were performed using the 2-D pipe model. [

]^{a,c,e}

2.2.6 RCL Hot Leg Nozzle Analysis

Two RCL surge line nozzle models were developed to evaluate the effects of thermal stratification. These two models are shown in Figures 2-43 and 2-44.

[

]a,c,e

Figures 2-45 thru 2-53 present color contour plots of temperature and stress distributions in the surge line RCL nozzle. A summary of local stresses in the RCL nozzle due to thermal stratification is given in Table 2-6. A summary of stresses for unit loading applied is shown in Table 2-7.

2.2.7 Conservatisms

Conservatisms in the local stress analysis are listed below:

1. The hot/cold fluid interface is assumed to have zero width. A more gradual change from hot to cold would significantly decrease local stresses.

2. Stresses are based on linear elastic analysis even though stress levels exceed the material yield point.

2.3 Thermal Striping

2.3.1 Background

At the time when the feedwater line cracking problems in PWR's were first discovered, it was postulated that thermal oscillations (striping) may significantly contribute to the fatigue cracking problems. These oscillations were thought to be due to either mixing of hot and cold fluid, or turbulence in the hot-to-cold stratification layer from strong buoyancy forces during low flow rate conditions. (See Figure 2-54 which shows the thermal striping fluctuation in a pipe). Thermal striping was verified to occur during subsequent flow model tests. Results of the flow model tests were used to establish boundary conditions for the stratification analysis and to provide striping oscillation data for evaluating high cycle fatigue.

Thermal striping was also examined during water model flow tests performed for the Liquid Metal Fast Breeder Reactor primary pipe loop. The stratified flow

was observed to have a dynamic interface region which oscillated in a wave pattern. (See Figure 2-55 for test pipe sizes, thermocouple locations, and Table 2-8 for typical frequency of striping oscillations.) These dynamic oscillations were shown to produce significant fatigue damage (primary crack initiation). The same interface oscillations were observed in experimental studies of thermal striping which were performed in Japan by Mitsubishi Heavy Industries.

2.3.2 Additional Background Information

Thermal striping was examined during 1/5 scale water model flow tests performed for the Liquid Metal Fast Breeder Reactor primary pipe loop. These tests were performed by Westinghouse at the Waltz Mills test facility. In order to measure striping, thermocouples were positioned at 5 locations in the hot leg piping system (three in the small diameter pipe and two in the large diameter pipe.) The inside diameters of the large and small pipes were 6-1/2 and 4 inches, respectively. Figure 2-56 shows the test setup and locations of the thermocouples. (Figure 2-55 shows test pipe sizes with circumferential position of thermocouples.) Thermocouple locations were selected [ ]^{a,c,e} The thermocouples extended [ ]^{a,c,e} into the fluid. The flow rates and corresponding Richardson numbers for each pipe size are shown in Table 2-9.

A total of [ ]^{a,c,e} tests was performed and evaluated. Three parameters were measured during the water tests which help define thermal striping: frequency of fluctuations, duration, and amplitude of delta fluid temperature. The [ ]^{a,c,e} were recorded in the discussion of test results and are presented in Table 2-10.

The frequencies of the temperature fluctuations from these test results were reported to be in the range of [ ]^{a,c,e} As shown in Table 2-10, the [

]^{a,c,e}

[

]^{a,c,e}

In order to use the water test data for the surge line striping analysis, the test data with a [
]^{a,c,e} was chosen to be used in the evaluation. From Table 2-9, the [ ]^{a,c,e} inch I.D. pipe with flow rates of [
]^{a,c,e} for the pressurizer surge line.

When all other factors are equal, it has been shown that the thermal striping stress is [ ]^{a,c,e}

A typical value of usage factor was calculated with the [
]^{a,c,e} as follows:

[

]^{a,c,e}

This distribution corresponded to [
]^{a,c,e} considered to occur at a stress level calculated with frequencies of [ ],^{a,c,e} respectively. Calculations revealed that there was [ ]^{a,c,e} in the usage factor when a [
]^{a,c,e} Therefore, [ ]^{a,c,e} was assumed in all usage factor calculations.

For the Comanche Peak Unit 2 Pressurizer surge line, the frequency of [
]^{a,c,e} was used in the [
]^{a,c,e}

As shown in Table 2-1C, the amplitude of ΔT varies from [

]^{a,c,e} of the full ΔT between the hot and cold fluid temperatures. For the Comanche Peak Unit 2 Surge line, the amplitude was assumed to be at [

]^{a,c,e}

as shown by the curve in Figure 2-57. This is conservative since a higher ΔT results in higher stress.

The maximum duration of thermal striping from Table 2-10 shows that thermal striping occurred for [ ]^{a,c,e} For the Comanche Peak Unit 2 pressurizer surge line, thermal striping was considered to occur [

]^{a,c,e}

2.3.3 Thermal Striping Stresses

Thermal striping stresses are a result of differences between the pipe inside surface wall and the average through wall temperatures which occur with time, due to the oscillation of the hot and cold stratified boundary. (See Figure 2-58 which shows the typical temperature distribution through the pipe wall). [

]^{a,c,e}

The peak stress range and stress intensity is calculated from a 2-D finite element analysis. (See Figure 2-59 for a description of the model.) [

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

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

[

]^{a,c,e}

2.3.4 Summary of Striping Stress Considerations

[

]^{a,c,e}

[

]^{a,c,e}

2.3.5 Thermal Striping Total Fluctuations and Usage Factor

Thermal striping transients are shown at a ΔT level and number of cycles. [

]^{a,c,e}

[

]^{a,c,e}

[

$]^{a,c,e}$

2.3.6 Conservatisms

The conservatisms in the striping analysis are that striping occurs at one location, surface film coefficients assume high values with constant flow, and conservative design transients are used. The major conservatism involves the combination of maximum striping usage factor with fatigue usage factor from all other stratification considerations. The [

$]^{a,c,e}$

TABLE 2-1
COMPARISON OF WECAN AND ANSYS RESULTS FOR
LINEAR STRATIFICATION - Case 2
(Displacements in Inches)

(JOBANSF) WECAN	(AGJAQLM) ANSYS	ANSYS/WECAN (PERCENTAGE)

a,c,e

TABLE 2-2

COMPARISON OF WECAN [(Step Change)][a,c,e] AND ANSYS [(Equivalent Linear)][a,c,e] RESULTS FOR CASE 3

Location	Direction	WECAN Case 3	ANSYS Case 3L	Case 3L/Case 3 (Percentage)

a,c,e

TABLE 2-3

TEMPERATURE DISTRIBUTIONS IN COMANCHE PEAK UNIT 2 PRESSURIZER SURGE LINE

a,c,e

TABLE 2-4
THE EQUIVALENT LINEAR COEFFICIENTS J_{ik}
(14 inch - Schedule 140 Pipe)

a.c.e

TABLE 2-5

COMANCHE PEAK UNIT 2 SURGE LINE

MAXIMUM LOCAL AXIAL STRESSES AT [LOCATIONS 1 THRU 5][a,c,e]

		Local Axial Stress (psi)	
Location	Surface	Maximum Tensile	Maximum Compressive

[ ]a,c,e

Note: Local thermal stresses shown are for a $\Delta T = 260°F$.

TABLE 2-6

SUMMARY OF LOCAL STRATIFICATION STRESSES

IN THE COMANCHE PEAK UNIT 2 SURGE LINE AT THE RCL NOZZLE

		All Stress in psi			
		Linearized Stress Intensity Range		Peak Stress Intensity Range	
Location	Diametral Location	Inside	Outside	Inside	Outside

a,c,e

TABLE 2-7

SUMMARY OF PRESSURE AND BENDING INDUCED STRESSES

IN THE COMANCHE PEAK UNIT 2 SURGE LINE RCL NOZZLE FOR UNIT LOAD CASES

			All Stress in psi			
			Linearized Stress Intensity Range		Peak Stress Intensity Range	
Location	Diametral Location	Unit Loading Condition	Inside	Outside	Inside	Outside

a,c,e

TABLE 2-8

STRIPING FREQUENCY AT 2 MAXIMUM LOCATIONS FROM 15 TEST RUNS

[ ]a,c,e

TABLE 2-9
FLOW RATES AND RICHARDSON NUMBER
FOR WATER MODEL FLOW TESTS

Pipe Section	Cold Water Flow Rate (GPM)	Ri
4.0 inch I.D.		
6.5 inch I.D.		

a,c,e

TABLE 2-10

RESULTS FROM TWO HIGHEST THERMOCOUPLE LOCATIONS

FREQUENCY (HZ)						TOTAL DURATION # CYCLES/ LGTH IN TIME (SEC)	AMPLITUDE (% OF POTENTIAL)					
MIN.	% (DURATION)	MAX.	% (DURATION)	AVG.	% (DURATION)		MIN.	% (CYCLES)	MAX.	% (CYCLES)	AVG.	% (CYCLES)

a,c,e

TABLE 2-11

ASME CODE STRESS SUMMARY

a,c,e

[ ]

DETERMINATION OF THE EFFECTS OF THERMAL STRATIFICATION

a,c,e

Figure 2-1. Determination of the Effects of Thermal Stratification

a,c,e

Figure 2-2. Stress Analysis

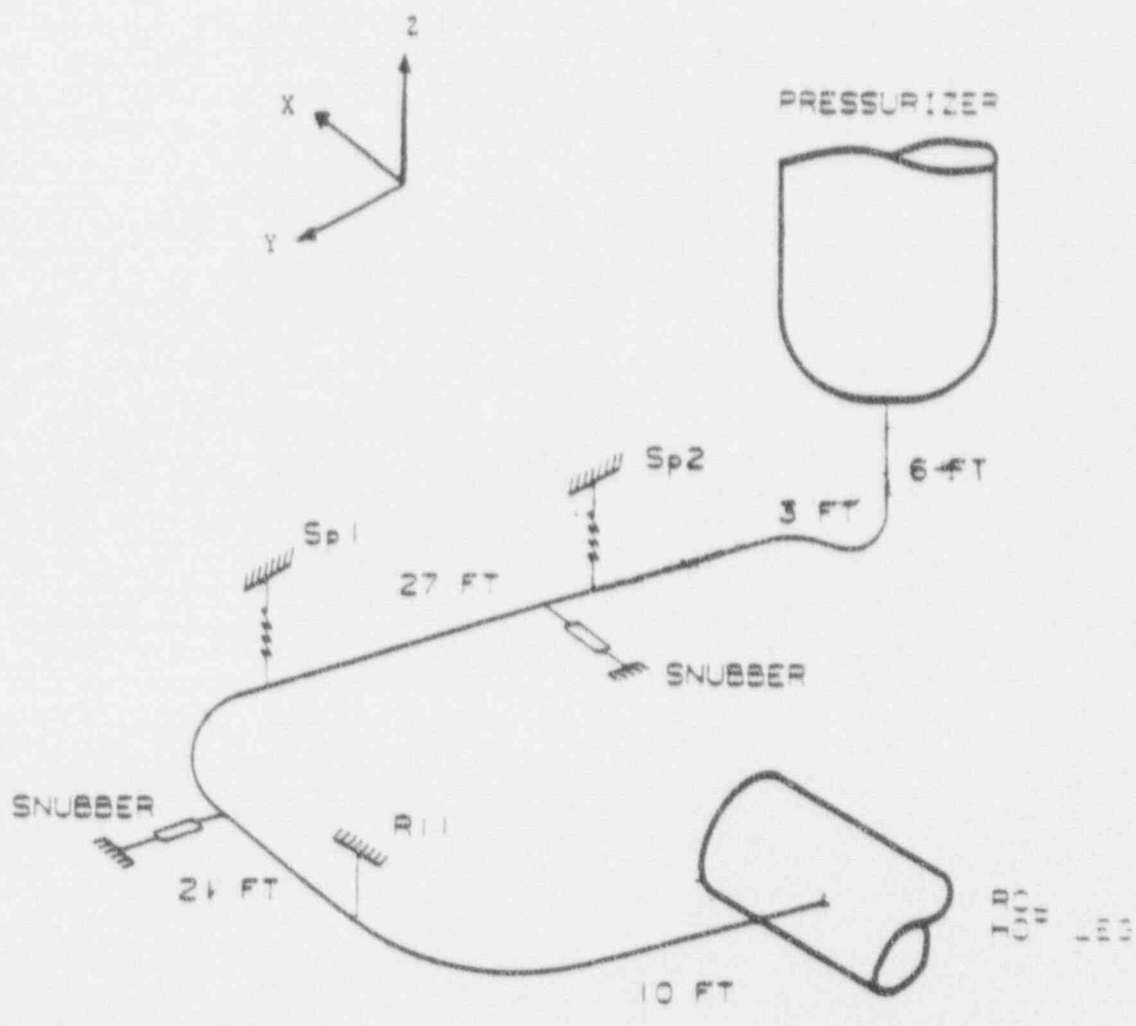

Figure 2-3. Typical Pressurizer Surge Line Layout

a,c,e

Figure 2-4. Cases 1 to 4: Diametric Temperature Profiles

a,c,e

Figure 2-5. Case 5: Diametric and Axial Temperature Profile

a,c,e

[ ]

Figure 2-6. Finite Element Model of the Pressurizer Surge Line Piping General View

a,c,e

Figure 2-7. Finite Element Model of the Pressurizer Surge Line Piping Hot Leg Nozzle Detail

a,c,e

Figure 2-8. Thermal Expansion of the Pressurizer Surge Line Under Uniform Temperature

a,c,e

Figure 2-9. Case 2 (linear) Temperature Profile at Hot Leg Nozzle

a,c,e

Figure 2-10. Case 2 (linear) Temperature Profile at Pressurizer Elbow

a,c,e

Figure 2-11. Thermal Expansion of Pressurizer Surge Line Under Linear Temperature Gradie[illegible]

a,c,e

Figure 2-12. Bowing of Beams Subject to Top-to-Bottom Temperature Gradient

a,c,e

Figure 2-13. Case 3 (Mid Plane Step) Temperature Profile at Hot Leg Nozzle

a,c,e

Figure 2-14. Case 3 (Mid-Plane Step): Temperature Profile at Pressurizer Nozzle

3583s/011400:10

a,c,e

Figure 2-15. Case 4 (Top Half Step) Temperature Profile at Hot Leg Nozzle

3401s-121588:10

a,c,e

Figure 2-16. Case 4 (Top Half Step): Temperature Profile at Pressurizer Elbow

3401s/121588 10

a,c,e

Figure 2-17. Case 5 Axial and Radial Temperature Profile

3481s/121588:10

a,c,e

Figure 2-18. Case 5 Axial and Radial Temperature Profile at Hot Leg Nozzle

a,c,e

Figure 2-19. Case 5 Axial and Radial Temperature Profile at Pipe Bend

3481a/121588:10

a,c,e

Figure 2 20. Case 5. Axial and Radial Temperature Profile at Pressurizer Elbow

3401s/121588:10

a,c,e

Figure 2-21. [ ]^{a,c,e} Profile

a,c,e

Figure 2-22. Comanche Peak Surge Line Model and Temperature Profile

a,c,e

Figure 2-23. Equivalent Linear Temperature

a,c,e

Figure 2-24. Local Stress in Piping Due to Thermal Stratification

a,c,e

Figure 2-25. Independence of Local and Structural Thermal Stratification Stresses Permits Combination by Superposition

a,c,e

Figure 2-26. Test Case for Superposition of Local and Structural Stresses

a,c,e

Figure 2-27. Local Stress - Finite Element Models/Loading

a,c,e

Figure 2-28. Piping Local Stress Model and Thermal Boundary Conditions

a,c,e

Figure 2-29. Surge Line Temperature Distribution at [ ]^{a,c,e} Axial Locations

3411s-121588 10

a,c,e

Figure 2-30. Surge Line Local Axial Stress Distribution at [ ]a,c,e Axial Locations

a,c,e

Figure 2-31. Surge Line Local Axial Stress on Inside Surface at [ ]^{a,c,e} Axial Locations

a,c,e

Figure 2-32. Surge Line Local Axial Stress on Outside Surface at [ ]^{a,c,e} Axial Locations

a,c,e

Figure 2-33. Surge Line Temperature Distribution at Location [ ]]^{a,c,e}

3491s/121588:10

]a,c,e

Figure 2-34. Surge Line Local Axial Stress Distribution at Location [ ]a,c,e

3491s:121588:10

[ ]a,c,e

Figure 2-35. Surge Line Local Axial Stress Distribution at Location [ ]a,c,e

3001s/121588 10

a,c,e

Figure 2-36. Surge Line Local Axial Stress Distribution at Location [ ]^{a,c,e}

3481s-121588 10

[ ]^{a,c,e}

Figure 2-37. Surge Line Temperature Distribution at Location [ ]^{a,c,e}

[ ]a,c,e

Figure 2-38. Surge Line Local Axial Stress Distribution at Location [ ]a,c,e

3563s-012488 10

a,c,e

Figure 2-39. Surge Line Local Axial Stress Distribution at Location [ ]a,c,e

3481s-121588:10

a,c,e

Figure 2-40. Surge Line Local Axial Stress Distribution at Location [ ]a,c,e

[ ][a,c,e]

Figure 2-41. Surge Line Temperature Distribution at Location [ ][a,c,e]

3491s/121588:10

^{a,c,e}

Figure 2-42. Surge Line Local Axial Stress Distribution at Location [ ]^{a,c,e}

1583s/011488 10

a,c,e

Figure 2-41. Surge Line RCL Nozzle 3-D WECAN Model #1

a,c,e

Figure 2-44. Surge Line RCL Nozzle 3-D WECAN Model #2

a,c,e

Figure 2-45 Surge Line Nozzle Temperature Profile Due to Thermal Stratification

3481s/121588 10

Figure 2-46 Surge Line Nozzle Stress Intensity Due to Thermal Stratification

a,c,e

Figure 2-47. Surge Line Nozzle Stress in Direction Axial to Surge Line Due to Thermal Stratification

3481s/121588:10

Figure 2-48 Surge Line Nozzle Stress Intensity Due to Pressure

a,c,e

Figure 2-49. Surge Line Nozzle Stress Intensity Due to Pressure

3481s/121588 10

Figure 2 50. Surge Line Nozzle Stress Intensity Due to Bending

Figure 2-51. Surge Line Nozzle Stress in Direction Axial to Surge Line Due to Bending Showing Magnified Displacement

Figure 2-52. Surge Line Nozzle Stress Intensity Due to Bending Showing Showing Magnified Displacement

3491s-121588:10

a,c,e

Figure 2-53 Surge Line Nozzle Stress Intensity Due to Bending

3481s-121588:10

a,c,e

Figure 2-54. Thermal Striping Fluctuation

a,c,e

Figure 2-55. Stratification and Striping Test Models

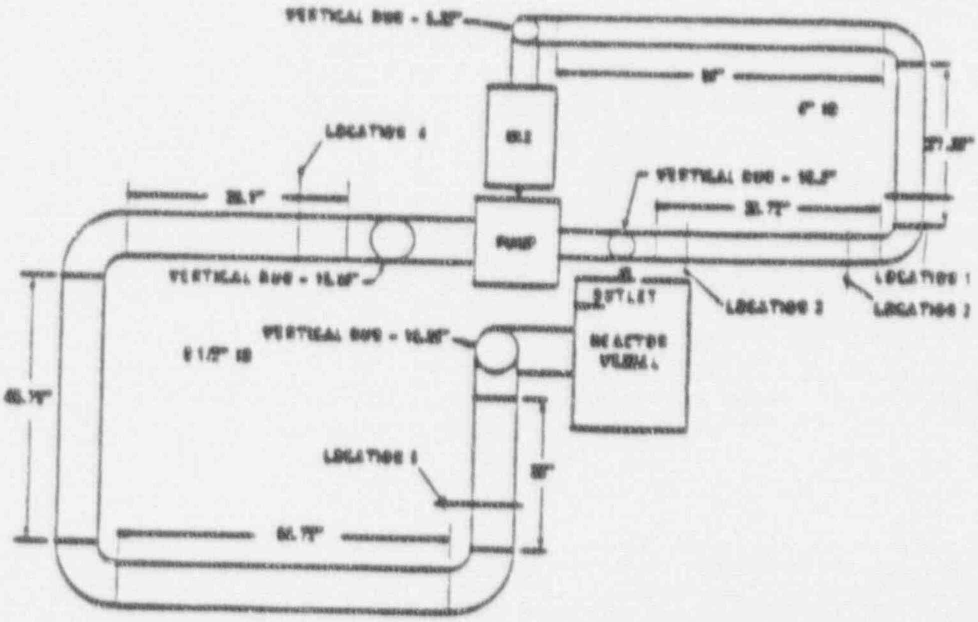

Figure 2-56. Water Model of LMFBR Primary Hot Leg

a,c,e

Figure 2-57. Attenuation of Thermal Striping Potential by Molecular Conduction (Interface Wave Height of [1 inch)][a,c,e]

a,c,e

Figure 2-58. Thermal Striping Temperature Distribution

a,c,e

Figure 2-59. Striping Finite Element Model

SECTION 3.0
ASME SECTION III FATIGUE USAGE FACTOR EVALUATION

3.1 Code and Criteria

Fatigue usage factors for the Comanche Peak Unit 2 surge line were evaluated based on the requirements of the ASME B & PV Code, Section III (reference 3-1), Subsection NB-3600, for piping components. The more detailed techniques of NB-3200 were employed, as allowed by NB-3611.2. ASME III fatigue usage factors were calculated for [ ]^{a,c,e} points in the surge line piping using program WECEVAL (reference 3-2).

3.2 Previous Design Methods

Previous methods of surge line piping fatigue evaluation used the NB-3653 techniques but with thermal transients defined by W SSDC 1.3 F[3-3] and 1.3.X [3-4], assuming the fluid surges to sweep the surge line piping with an axisymmetric temperature loading on the pipe inside wall. These evaluations produced typical usage factors of approximately [ ]^{a,c,e} at girth butt welds, [ ]^{a,c,e} at elbows and bends, and [ ]^{a,c,e} at the RCL hot leg nozzle crotch region. Effects of stratification were not included in previous design analyses.

It must be noted that these usage factors are conservative since, in the design process, calculations are carried to the point where results meet code requirements, and are not further refined to reduce the usage factor.

3.3 Analysis for Thermal Stratification

With thermal transients redefined to account for thermal stratification as described in section 1.0, the stresses in the piping components were established (section 2.0) and new fatigue usage factors were calculated. Due to the non-axisymmetric nature of the stratification loading, stresses due to all loadings were obtained from finite element analysis and then combined on a stress component basis.

3.3.1 Stress Input

Stresses in the pipe wall due to internal pressure, moments and thermal stratification loadings were obtained from the WECAN 2-D analyses of 14 inch, schedule 160 pipe. [

]^{a,c,e}

[

]^{a,c,e}

3.3.2 Classification and Combination of Stresses

As described in 3.3.1 the total stress in the pipe wall was determined for each transient load case. Two types of stresses were calculated: S_n to determine elastic-plastic penalty factors, K_e, and S_p, peak stress. For most components in the surge line (girth butt welds, elbows, bends) no gross structural discontinuities are present. As a result, the code-defined "Q" stress, the $C_3 E_{ab}|\alpha_a T_a - \alpha_b T_b|$ portion of the S_n stress, is zero.

For the RCL hot leg nozzle, the results of the 3-D finite element WECAN analysis of the nozzle were used to determine "Q" stress for transients with stratification in the nozzle. Note also that S_n included appropriate stress intensification using the secondary stress indices from NB-3681.

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

]^{a,c,e}

3.3.4 Simplified Elastic-Plastic Analysis

When code Eq. 10, S_n, exceeded the 3Sm limit, a simplified elastic-plastic analysis was performed per NB-3653.6. This requires separate checks of expansion stress, Eq. 12, and Primary Plus Secondary Excluding Thermal Bending Stress, Eq. 13, and Thermal Stress Ratchet, and calculation of the elastic-plastic penalty factor, Ke, which affects the alternating stress by $S_{alt} = K_e S_p/2$. The K_e values for all combinations were automatically calculated by WECEVAL. Thermal stress ratchet is also checked by WECEVAL. Eq. 13 is not affected by thermal stratification in the pipe where no gross structural discontinuities exist, but is required to be verified at the nozzle. Eq. 12 was evaluated in the Global ANSYS analysis by checking the worst possible range of stress due to the expansion bending moments (section 2).

3.3.5 Fatigue Usage Results

The maximum Usage factors were [ ]^{a,c,e} at the RCL nozzle safe-end (node 1010, Figure 1-7) and [ ]^{a,c,e} at the 5-D bend located underneath the pressurizer, (Figure 1-7) which are less than the code allowable of 1.0.

The above usage factors included the effects of striping. The nature of striping damage is at a much highe- frequency, varies in location due to fluid level changes and is maximized at a different location than the ASME usage factor.

3.4 Conservatisms in Fatigue Usage Calculation

The above calculated ASME usage factors contain the inherent conservatisms known to be in the ASME Code methods. These include the conservatism in the elastic-plastic penalty factor, K_e, the method of combining loadsets based on descending S_{alt}, and the factor of 2 on stress and 20 on cycles in the design fatigue curve.

Also, due to input limitations in program WECEVAL, the maximum value of peak stress intensification for all loading types was used. This was conservative

3.3.3 Cumulative Fatigue Usage Factor Evaluation

Program WECEVAL uses the S_n and S_p stresses calculated for each transient to determine usage factors at selected locations in the pipe cross section. Using a standard ASME method, the cumulative damage calculation is performed according to NB-3222.4(e)(5). The inside and outside pipe wall usage factors were evaluated at [ ]^{a,c,e} through the pipe wall of the 2-D WECAN model.

This includes:

1) Calculating the S_n and S_p ranges, K_e, and S_{alt} for every possible combination of the [ ]^{a,c,e} transient load sets.

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

3) Using the actual cycles of each transient loadset supplied to WECEVAL, $n_1, n_2, \ldots n_n$, calculate the usage factors U_1, $U_2 \ldots U_n$ from $U_i = n_i/N_i$. This is done for all possible combinations. If N_i is greater than 10^{11} cycles, the value of U_i is taken as zero.

   [

   ]^{a,c,e}

4) The cumulative usage factor, U_{cum}, is calculated as $U_{cum} = U_1 + U_2 + \ldots + U_n$. The code allowable value is 1.0.

at girth butt welds, since K_1 = 1.2, K_2 = 1.8, K_3 = 1.7 in NB-3681 and K=1.8 was used in WECEVAL for all stresses.

3.5 References

3-1. ASME Boiler and Pressure Vessel Code, Section III, 1986 Edition.

3-2. WCAP-9376, WECEVAL, A Computer Code to Perform ASME BPVC Evaluations Using Finite Element Model Generated Stress States, April, 1985. [Proprietary]

3-3. W Systems Standard 1.3.F, Rev. 0. (Proprietary)

3-4. W Systems Standard 1.3.X, Rev. 0 (Proprietary)

3-5. WCAP-12248, Evaluation of Thermal Stratification for the Comanche Peak Unit 1 Pressurizer Surge Line, April, 1989.

SECTION 4.0
CONCLUSIONS

Based on the analysis results presented in this report, the global structural and local stresses in the surge line piping meets ASME III Code allowables. The maximum cumulative fatigue usage factor is [ ]^{a,c,e} for a 40 year design life, compared to the Code allowable of 1.0.

In summary, it is concluded that thermal stratification does not affect the integrity of the pressurizer surge line of the Comanche Peak Unit 2 nuclear power plant and that NRC Bulletin 88-11 requirements are satisfied. The design life (forty years) and ASME III Code compliance are not affected. In addition, confirmatory temperature monitoring is not required for Comanche Peak Unit 2 based on conservatisms as described in this report and comparisons of developed design transients to temperature monitoring data collected during the first fuel cycle of Comanche Peak Unit 1.

APPENDIX A
LIST OF COMPUTER PROGRAMS

This appendix lists and summarizes the computer codes used in the analysis of stratification in the Comanche Peak Unit 2 pressurizer surge line. The codes are:

1. WECAN
2. WECEVAL
3. STRFAT2
4. ANSYS

A.1 WECAN

A.1.1 Description

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

A.1.2 Feature Used

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

A.1.3 Program Verification

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

A.2 WECEVAL

A.2.1 Description

WECEVAL is a multi-purpose program which processes stress input to calculate ASME Section III, Subsection NB equations and usage factors. Specifically, the program performs primary stress evaluations, primary plus secondary stress intensity range analysis, and fatigue analysis for finite element models generated and run using the WECAN computer program. Input to WECEVAL consists of card image data and data extracted from the output TAPE12's generated by WECAN's stress elements. The program reads the input data, performs the necessary calculations, and produces summary sheets of the results.

The required stresses are read from the WECAN TAPE12's and placed onto intermediate or restart files. The user may then catalog these files for use in later evaluations. The stress state for a particular loading condition is obtained by a ratio-superposition technique. This optimal stress state is formed by manipulating the signs of the applied loads to generate the largest possible stress magnitude.

A.2.2 Feature Used

WECEVAL has many options and features which enhance its versatility. Among those used for this evaluation were:

1. The ability to perform simplified elastic-plastic analysis per NB-3228.5, including the automatic calculation of Ke factors and removal of thermal bending stresses from the maximum range of stress intensity evaluations.

2. Built-in ASME fatigue curves plus provisions for accepting user-defined fatigue curves.

3. Equivalent moment linearization technique, along with the ability to correct for the radius effects in cylindrical and spherical geometries,

4. The ability to limit the interactions among load conditions during the fatigue analysis,

A.2.3 <u>Program Verification</u>

WECEVAL is verified to Westinghouse procedures by independent calculations of ASME III NB Code equations and comparison to WECEVAL results.

A.3 <u>STRFAT2</u>

A.3.1 <u>Description</u>

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

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

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

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

A.3.2 Feature Used

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

A.3.3 Program Verification

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

A.4 ANSYS

A.4.1 Description

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

A.4.2 Feature Used

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

A.4.3 Program Verification

As described in section 2.1, the application of ANSYS for stratification has been independently verified by comparison to WECAN. The results from ANSYS are also verified against closed form solutions for simple beam configurations.