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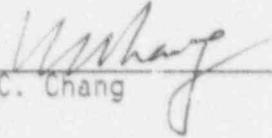
EVALUATION OF THERMAL STRATIFICATION
FOR THE TROJAN NUCLEAR PLANT
PRESSURIZER SURGE LINE

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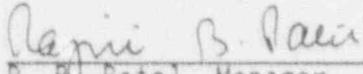
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SUMMARY

This report presents the methods, data, analysis and qualification results for the Trojan pressurizer surge line including thermal stratification.

The report is divided into four sections. Appendix A is a list of computer codes used in this work. Appendix B is a list of references used in this work. The sections are presented in order, reflecting the logical progression of evaluations and analyses:

- 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.
- o Appendix B "References" is a list of applicable references used in this work.

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

- (a) Based on plant monitoring results from several Westinghouse PWR plants (including Trojan) and flow stratification test data, the thermal design transients for the surge line have been updated to incorporate the effects of stratification.
- (b) The structural global and local stresses and loads in the surge line piping and support system meet ASME III Code allowables. The maximum cumulative fatigue usage factor including the effects of striping is []^{a,c,e} for 40 year design life, compared to the Code allowable of 1.0.

In summary, based on the current understanding of the thermal stratification phenomenon, it is concluded that thermal stratification does not affect the integrity of the pressurizer surge line of the Trojan nuclear power plant. 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 Trojan 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) and out of the U-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 must be accounted for.

A common approach for assessing the potential for stratification is to evaluate the Richardson Number^[1] (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.

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

where

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

For a range of surge line flow rates from approximately 700 gpm down to a pressurizer spray line bypass flow of approximately 1 to 5 gpm, and $\Delta T = 320^\circ\text{F}$, 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. General characteristics of flow stratification pattern in the vertical elbow is shown in figure 1-4.

1.1.3 Surge Line Stratification Program

The surge line stratification program for Trojan consists of three major parts:

- (a) Update of design transients
- (b) ASME III stress and fatigue cumulative usage factor (CUF) evaluation
- (c) Temperature and displacement monitoring.

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 Reactor Coolant System, including the pressurizer surge line, are defined in Westinghouse Systems Standard Design Criteria (SSDC) documents SSDC 1.3 [1.3-4].

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 3.9 definition of normal and upset design events and the number of occurrences of the design events remains unchanged.

The total number of current design 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).

SSDC 1.3 was not updated to incorporate surge line data. The monitoring data from four plants was used to create a transient set with stratification for

heatup and cooldown transients. The new heatup and cooldown transients with stratification replaced the SSDC 1.3 heatup and cooldown transients. The balance of the normal and upset transients defined in SSDC 1.3 was used in the surge line evaluation except that the transients were assumed to cause thermal stratification [

]a,c,e

It should be noted that some of the transients defined in SSDC 1.3 assume no insurge or outsurge and are therefore not considered to cause thermal stratification.

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 based on 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 more than a dozen Westinghouse plants. Figures 1-7 through 1-10 show the instrumentation configuration for four of these plants. The data was obtained by continuous monitoring of the piping metal surface 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 1-7 represents the Trojan temperature monitoring configuration.

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 [

which this report addresses.

]^{a,c,e} This is the condition

[

j 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 transient on the Trojan surge line which was caused by the cut-off of the RCP in the same loop as the surge line.

Typical Transient Description: (RCP Cutoff figure 1-11)

[

]a,c,e

[

]a,c,e

One interpretation of the cause and effects of the transient just described is as follows:

[

j 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 between 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. Conservatism has been incorporated throughout the process in the definition of transients (cycles, ΔT) and in the analysis, as described in the report.

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 ($Ri \gg 1$) (figures 1-14^[1] and 1-15^[5]).

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 summarizes 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 1-16 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 1-17 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 temperature 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 1-18.

All normal and upset transients that were postulated to cause insurge or outsurge were []^{a,c,e}. The maximum system delta T was calculated regardless of simultaneity between the RCS temperature and the PZR temperature. In addition certain high cycle normal condition transients such as steady state fluctuations were []^{a,c,e}

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).

[

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 Trojan is 320°F during formation or collapse of the steam bubble. No limitations on this temperature difference exist for other operating conditions. Historical data provided by PGE shows two occurrences where this temperature difference exceeded 320°F; one occurrence at 355°F and one at 332°F. Experiences from available monitoring data indicate that the piping top-to-bottom metal temperature difference (pipe ΔT) will be less than 0.9 of the pressurizer-to-hot leg temperature difference (system ΔT). Evaluation of the Trojan surge line considered the effect of past exceedance of the 320°F system ΔT value.

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 1-20 and 1-21).

To this end, a review of procedures, operational data, operator experience, and historical records was conducted for []^{a,c,e} Westinghouse PWR plants including Trojan (table 1-8).

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 temperatures.

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 1-30 and 1-31 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 1-30 and 1-31 that for the observed heatups, the Trojan plant (figure 1-30) had significant thermal transient activity].^{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 1-32, [

] ^{a,c,e} Figure 1-34 illustrates the difference between the design transients and the transients observed at the Trojan plant (figure 1-33 superimposed on figure 1-30).

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".

[

j^{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

[

]a,c,e

For Heatup: $i = 1$ to 24, $j = 1$ to 6, $k = 1$ to 4

The 24 transients produced are conservatively summed, based on ΔT_i range, into 9 transients (H1 to H9).

For cooldown $i = 1$ to 30, $j = 1$ to 6, $k = 1$ to 5

The 30 transients produced are conservatively summed, based on ΔT_i range, into 7 transients (C1 to C7).]a,c,e

Example:

[

]a,c,e

G) Cooldown Transients

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 1-32 were not used in the development of the striping design transients. [

] ^{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 1-35 shows the relative magnitude and frequency of the striping transients for one heatup or cooldown with respect to the system ΔT (PRZT - RCSIT). 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 Summary

Modification of the pressurizer surge line transients to account for thermal stratification was accomplished by replacing the existing heatup and cooldown transients with a new set of transients that were based on actual monitoring data from several plants. The new heatup and cooldown transients are provided in table 1-3. Analysis of the monitoring data resulted in the conclusion that

[

] ^{a,c,e} In order to assure conservative design it was necessary to not only replace the existing heatup and cooldown transients but to modify the existing normal and upset transients to account for the effects of stratification.

Modification of the existing normal and upset transients (table 1-4) was accomplished by first interpreting these previously defined transients in terms of the type of stratification phenomena they are expected to produce

[

] ^{a,c,e} This is considered to be a conservative representation of what the transients would actually impose on the pipe.

In summary, the existing heatup and cooldown transients were replaced by a set of transients that were developed entirely from several plants monitoring data (including that from Trojan). The existing normal and upset transients were modified to consider the effects of thermal stratification. [

j a . c . e

TABLE 1-1
 IMPORTANT DIMENSIONLESS GROUPS FOR SIMILITUDE
 IN HYDRODYNAMIC TESTING

Parameter	Symbol	Definition	Significance
1. Weibach friction factor	f	$C \Delta P / \rho v^2 L$	Pressure force/inertia force
2. Cavitation number	σ	$(P_s - P_v) / \rho v^2$	Pressure difference/inertia force
3. Reynolds number	Re	$\rho v D / \mu$	inertia force/viscous force
4. Strouhal number	St	$\omega D / v$	vortex shedding frequency/inertia force
5. Weber number	We	$\rho v^2 r / \sigma$	inertia force/surface-tension force
6. Froude number	Fr	$v^2 / g D$	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	μ / k	Momentum diffusivity/thermal diffusivity
10. Peclet number	Pe	$\rho v D C_p / k$ ($Pe = Re Pr$)	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	$L^3 \rho^2 C_p g \beta \Delta T / \mu k$ ($Gr = Re^2 Pr$)	-----

NOMENCLATURE

- | | |
|--|------------------------------------|
| C = specific heat | g = acceleration of gravity |
| ρ = density | P = pressure |
| r = surface tension | P_s = static fluid pressure |
| k = thermal conductivity | P_v = fluid vapor pressure |
| β = volumetric expansion coefficient | L, D = characteristic dimensions |
| ΔT = fluid temperature change | v = fluid velocity |
| ω = vortex shedding frequency | μ = viscosity |

TABLE 1-2
STRATIFICATION POTENTIAL BASED ON
RICHARDSON NUMBER

◀ Stratification potential exists if $R_i > 1$



a, c, e

TABLE 1-3
SURGELINE TRANSIENTS WITH STRATIFICATION
HEATUP (H) AND COOLDOWN (C) - 200 PLANT CYCLES TOTAL

a. c. e

* Input for maximizing moment range only

**These values reduced by 10% due to observed pipe ΔT /system ΔT ratios

I/O = Insurge - Outsurge

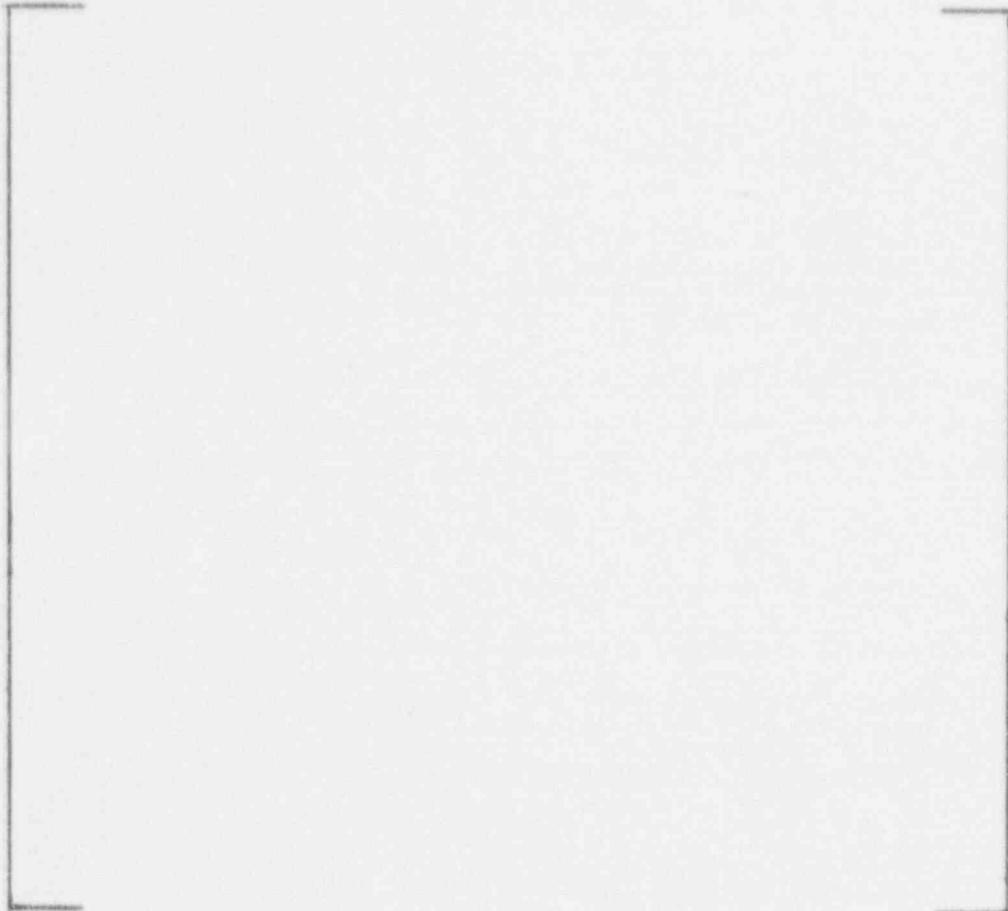
F = Fluctuation

For Trojan plant, one occurrence at $\Delta T = 355^{\circ}\text{F}$ and one occurrence at $\Delta T = 332^{\circ}\text{F}$ were included.

TABLE 1-4
SURGE LINE TRANSIENTS WITH STRATIFICATION
NORMAL AND UPSET TRANSIENT LIST

R.C.E

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



a.c.e

Note: 1) The following additional transients were considered for pressure effects.

- o Primary Side Leak Test 200 cycles
- o Secondary Side Leak Test 80 cycles
- o Tube Leak Test 900 cycles

2) Only one or the other should be used.

TABLE 1-5
STRATIFICATION PROFILES

[

j 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

[o

o

o

o

o]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)
-------	-----------------	---------------------------------

[

J^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



R.C.B.

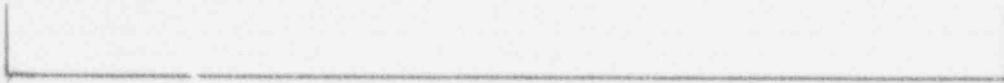


TABLE 1-10
COOLDOWN DATA SUMMARY
(PZR - HOT LEG) TEMP. DIFFERENCE AND TIME DURATION FOR EACH PHASE



a,c,e

TABLE 1-11
TRANSIENT TYPES

[

j 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} Observed Cycles	RSS (1)	[] ^{a,c,e} Observed Cycles	RSS (1)	[] ^{a,c,e} 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 $.70 \leq x < .8$ and $.60 \leq x < .70$ % of total = 3.2% for the interval $.60 \leq x < .80$

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

RSS	J	% of Transients
RELATIVE NUMBER OF CYCLES OF STRENGTH OF STRATIFICATION (RNSSj) AFTER GROUPING		
RNSSj	j	RSSj
% Transients (2)		Strength of Stratification (1)

a,c,e

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: 15.0

Selected No. of Design Cycles: 36.0 (adjusted to observed maximum number of cycles, Trojan)

DESIGN DISTRIBUTION APPLIED TO MAX NUMBER OF
 TRANSIENTS EXPECTED MULTIPLIED BY 200
 HEATUP OR COOLDOWN CYCLES

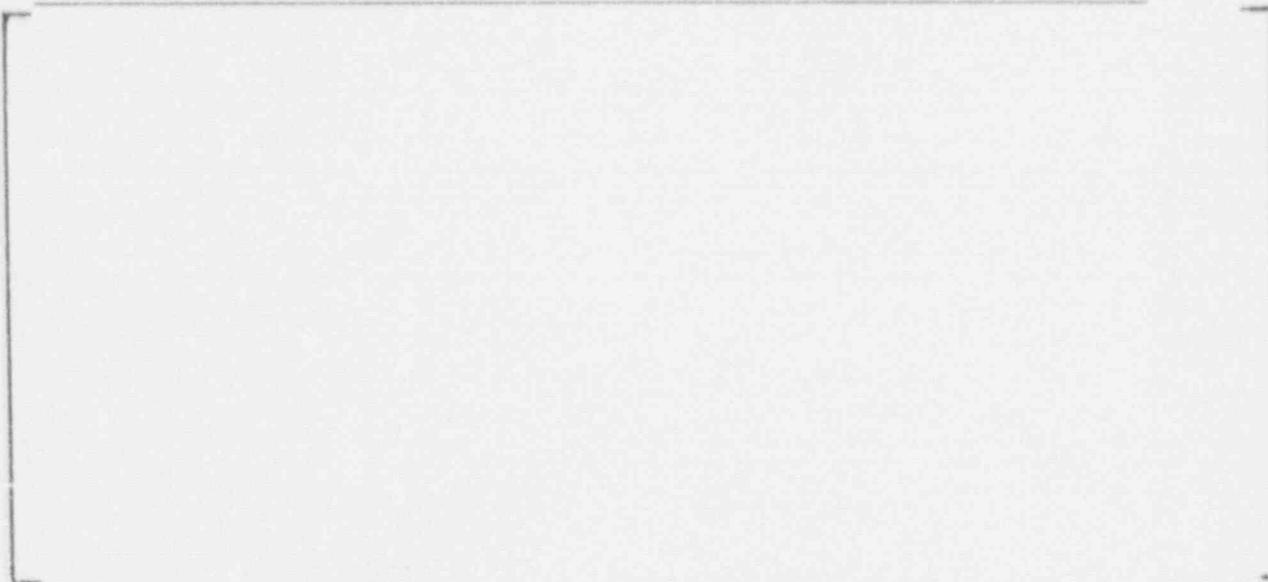
No. of Transients	RSS
[]	

a,c,e

TABLE 1-15
SUMMARY OF % TIMES AT
MAXIMUM TEMPERATURE POTENTIAL

RTMP_K

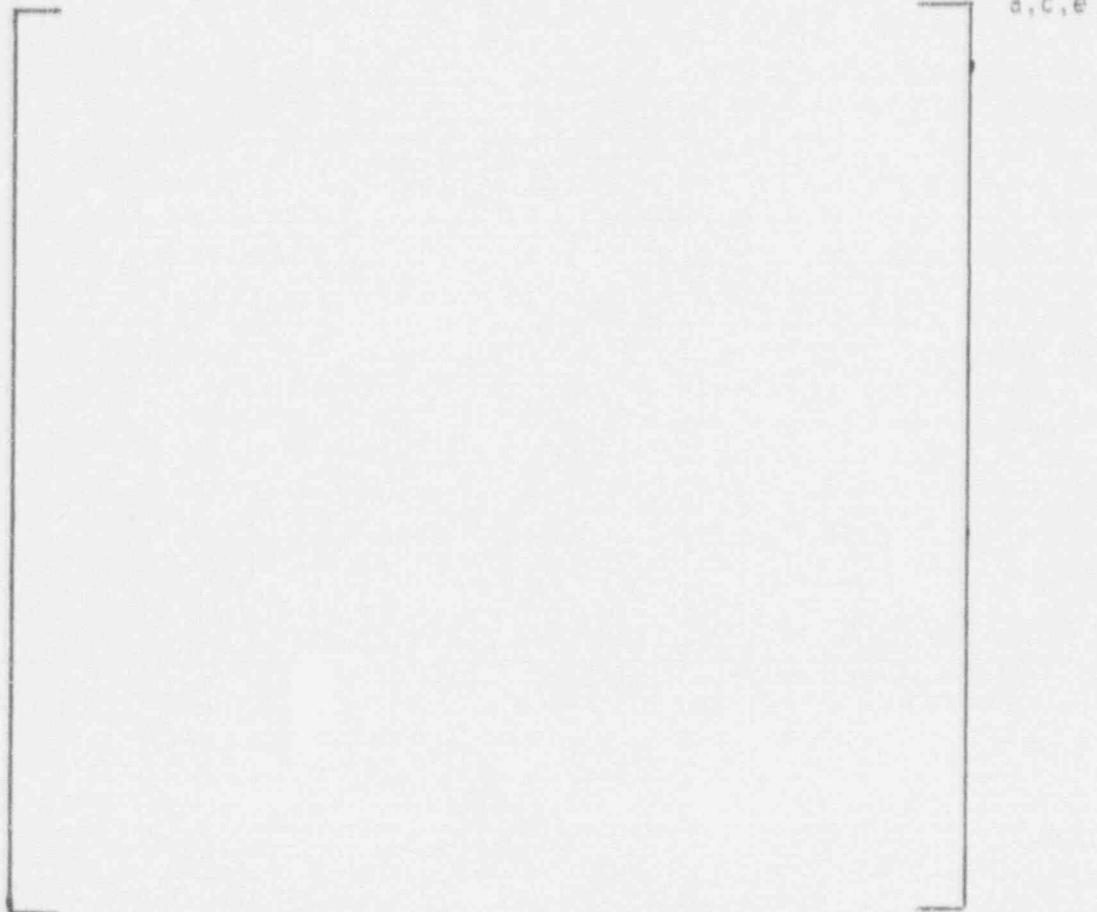
HEATUP



a, c, e

Note: Recorded Range of Systems ΔT and RTMP_K from
Trojan (9 heatups, 7 cooldowns)
Plant B (8 heatups, 7 cooldowns)

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



a, c, e

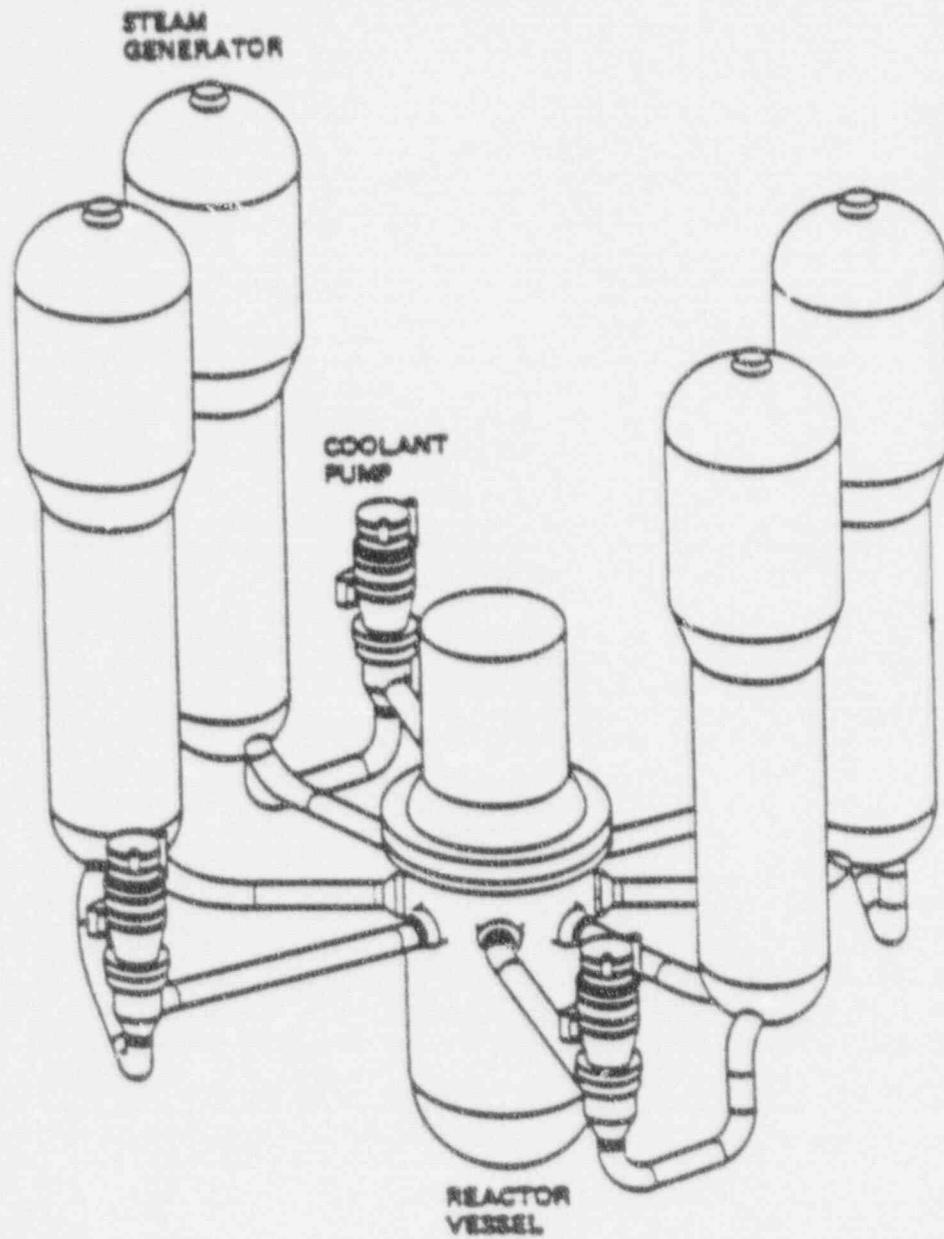


Figure 1-1. Simplified Diagram of the RCS

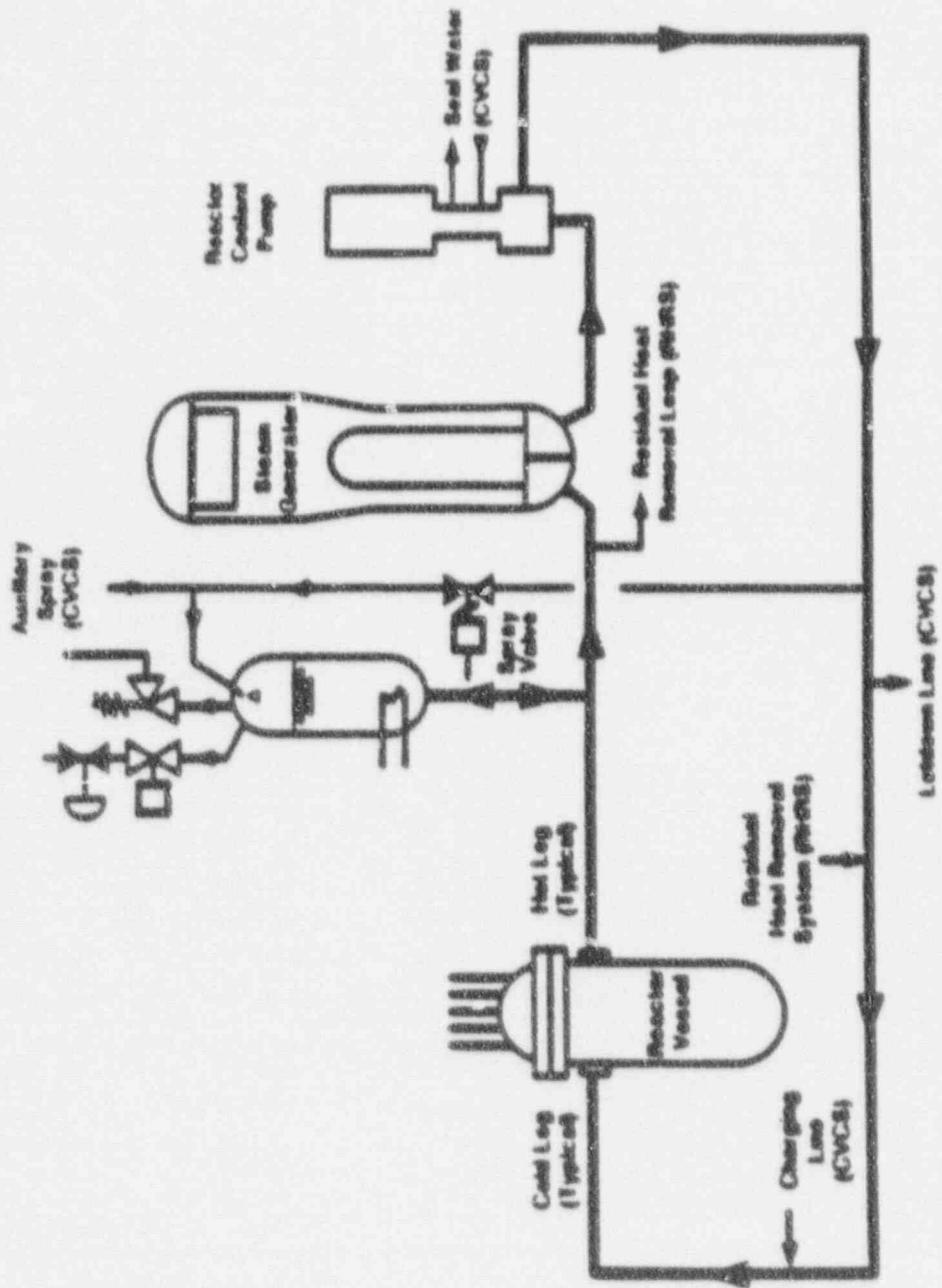


Figure 1-2. Reactor Coolant System Flow Diagram (Typical Loop)

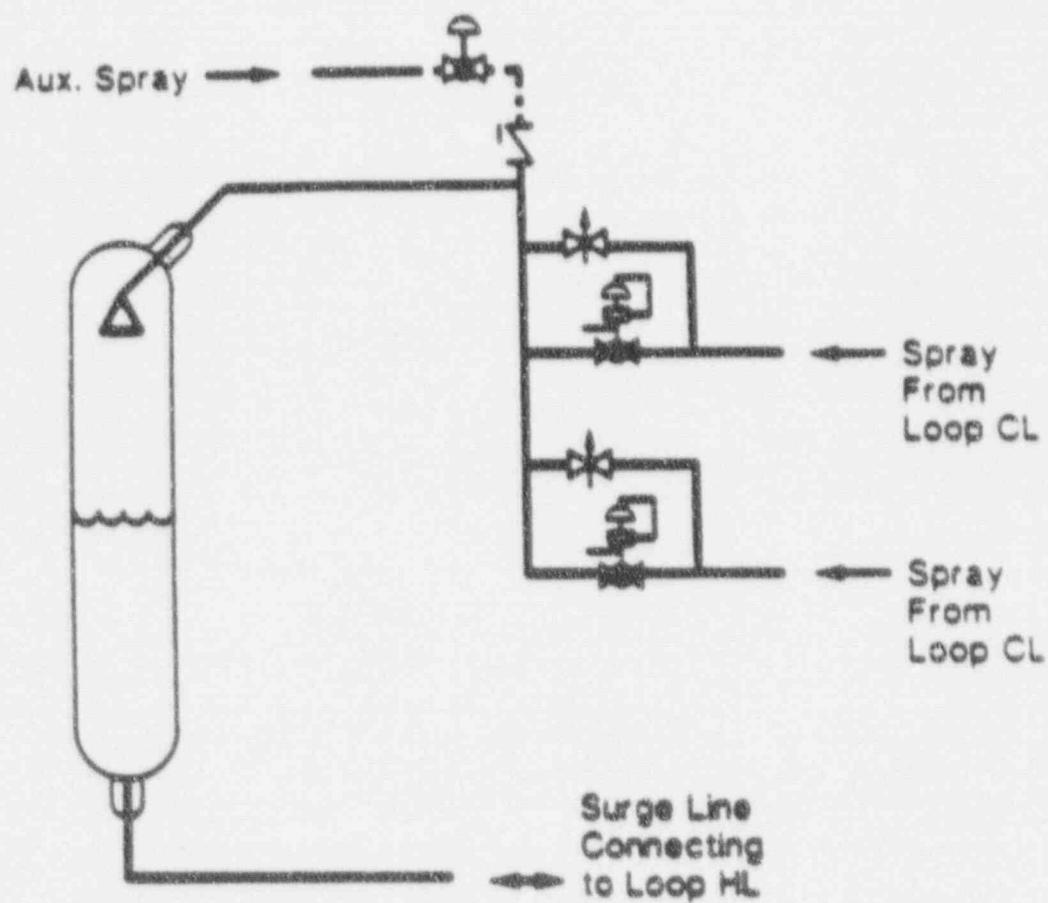


Figure 1-3. RCS Pressurizer

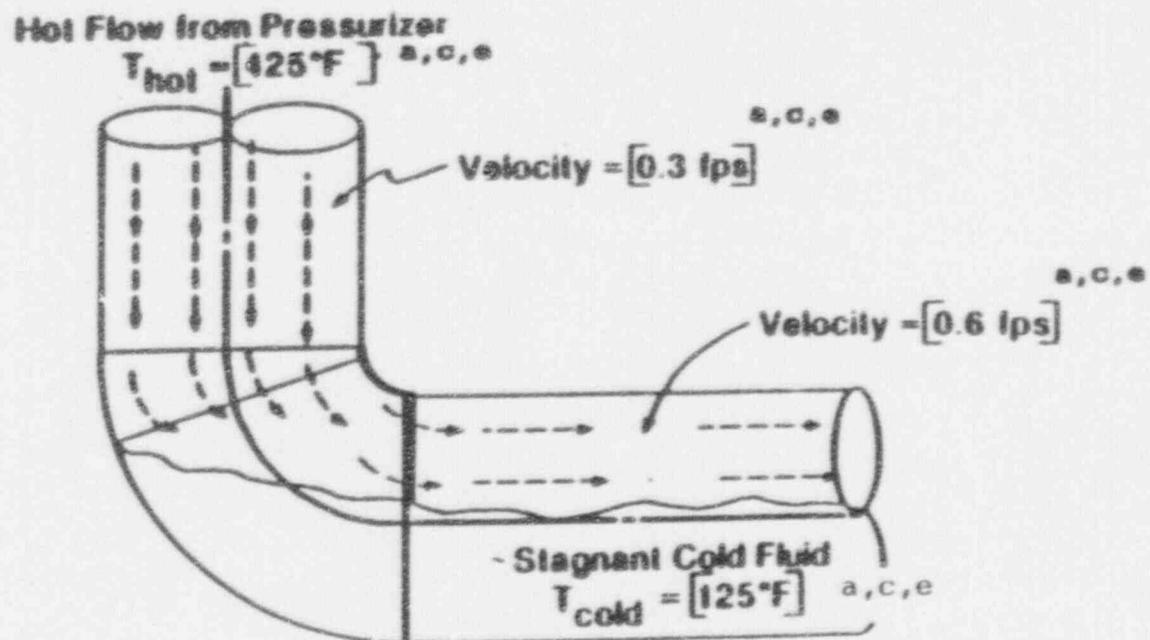
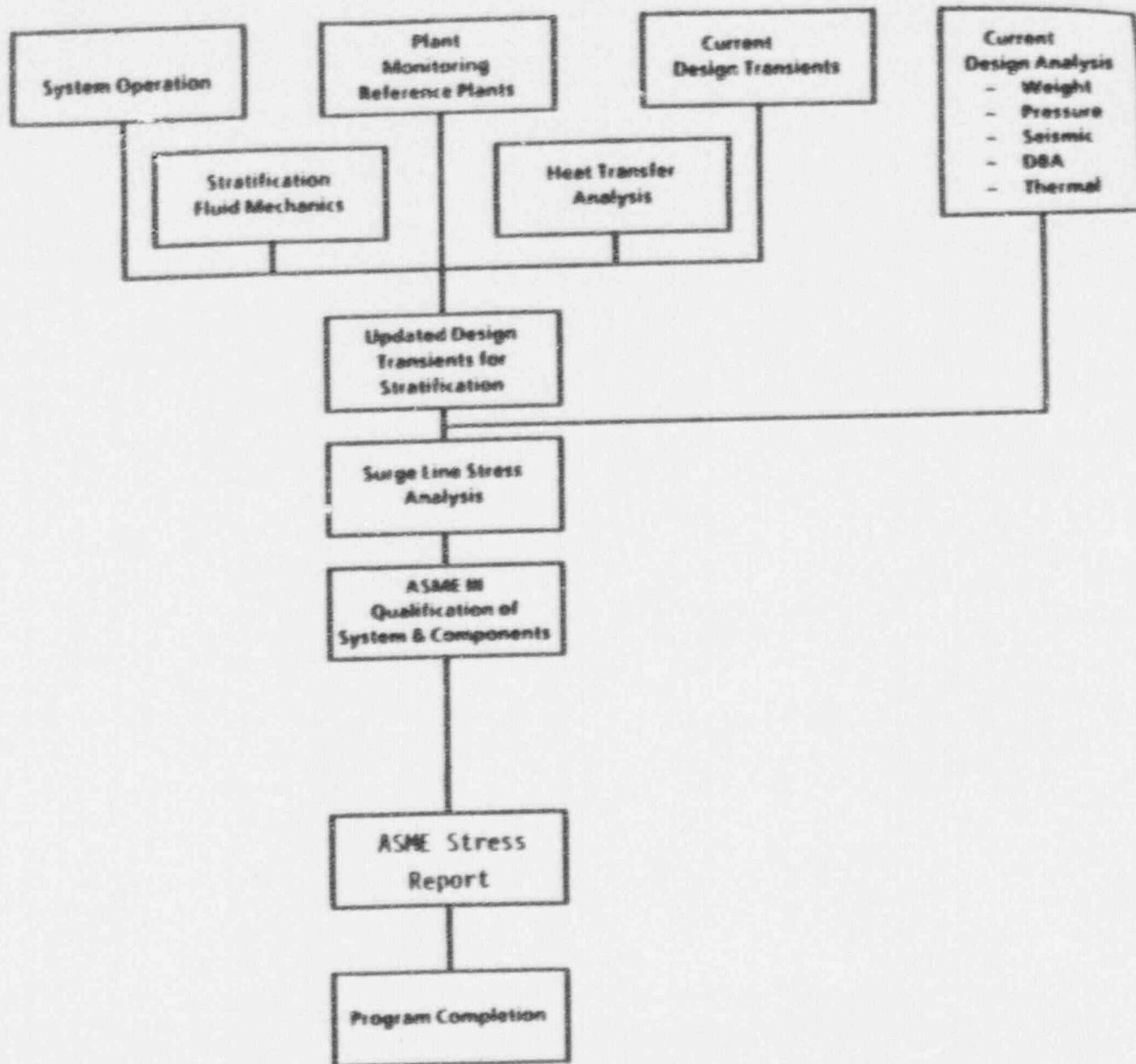


Figure 1-4. Estimate of Flow Stratification Pattern in Elbow Under Pressurizer



1-44

Figure 1-5. Trojan Pressurizer Surge Line Stratification ASME III and Qualification Program

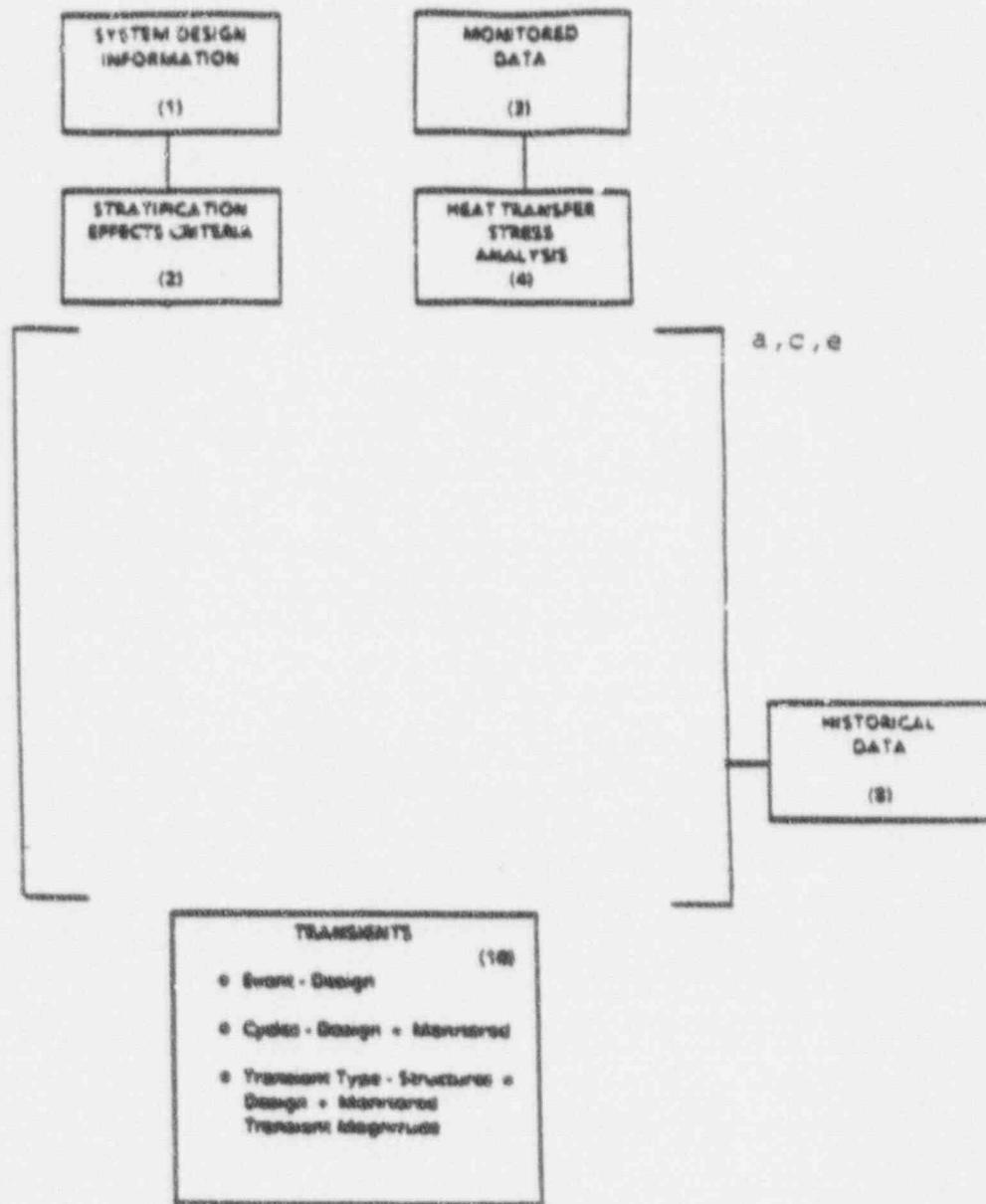


Figure 1-6. Transient Development Flow Chart

a, c, e

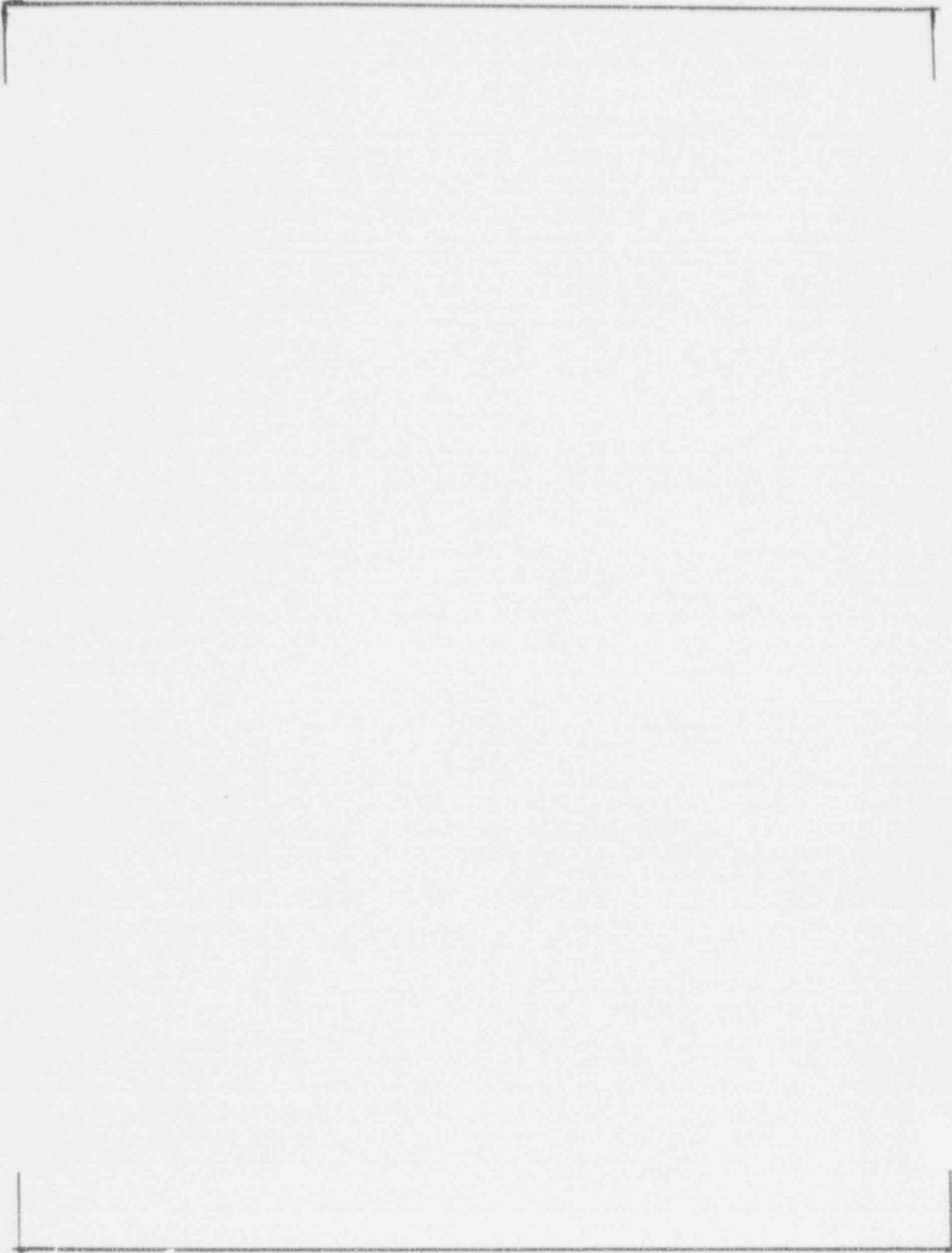


Figure 1-7. Trojan Pressurizer Surge Line Monitoring Locations

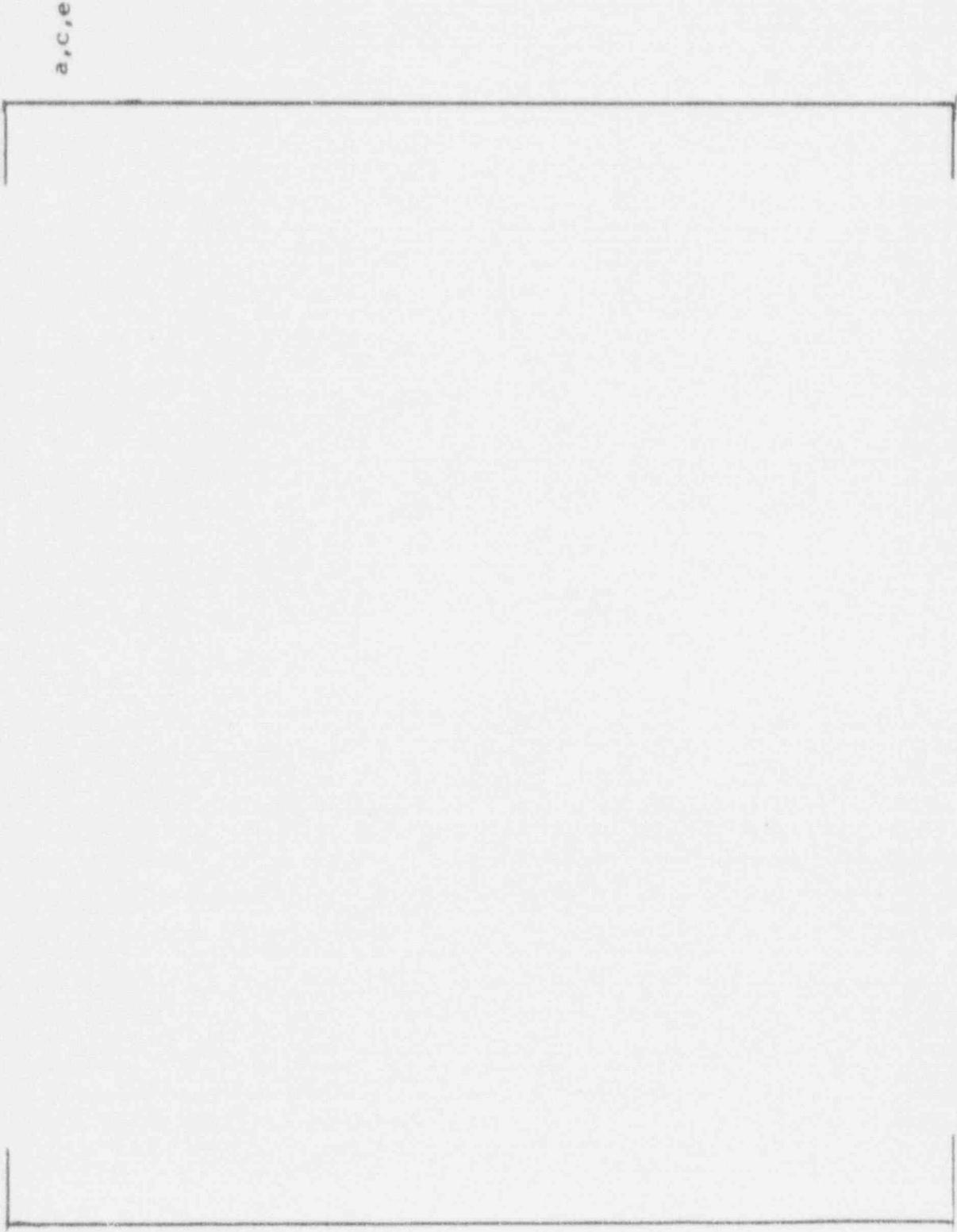


Figure 1-8. []^{a, c, e} Pressurizer Surge Line Monitoring Locations

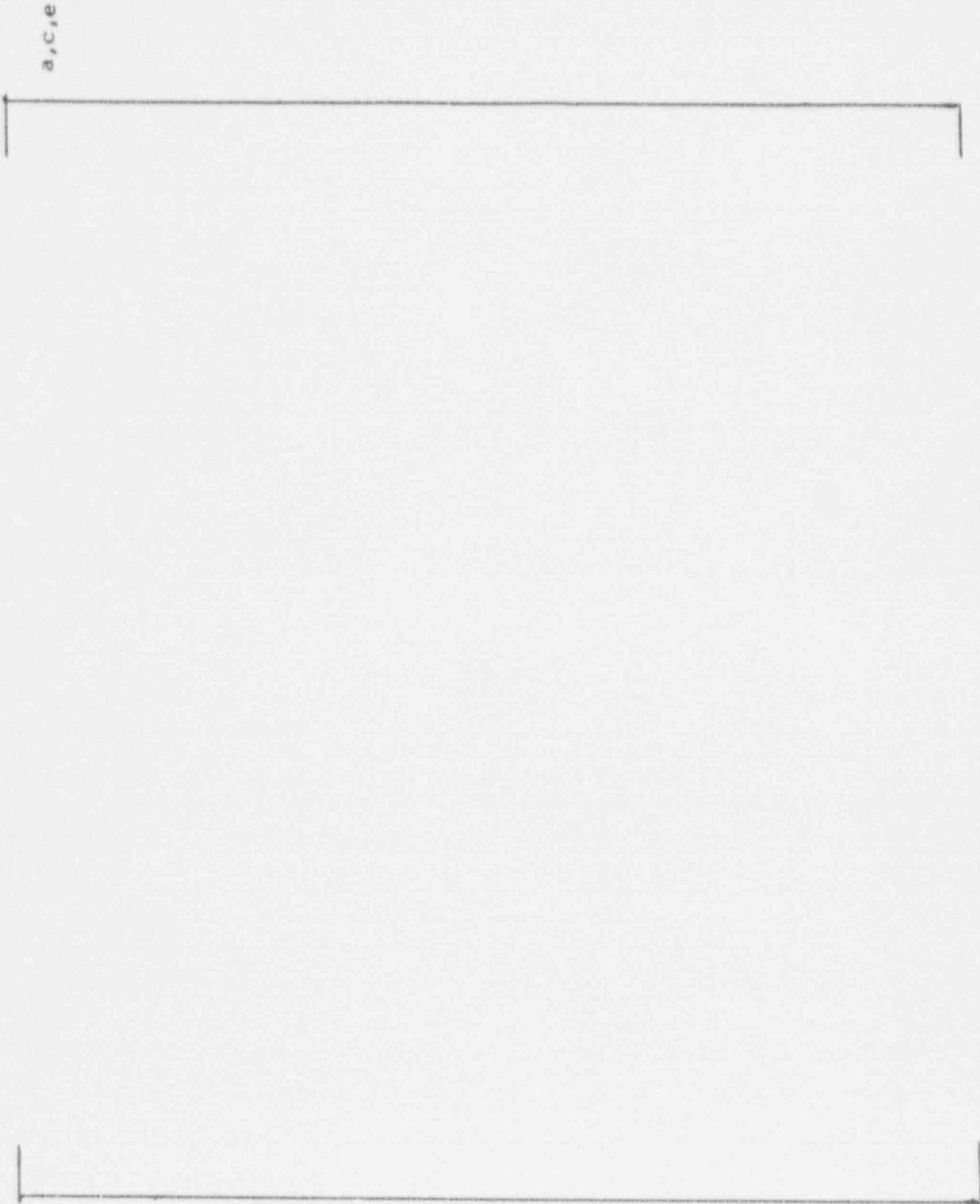


Figure 1-9. [J^{a,c,e} Pressurizer Surge Line Monitoring Locations

41205-011790 10

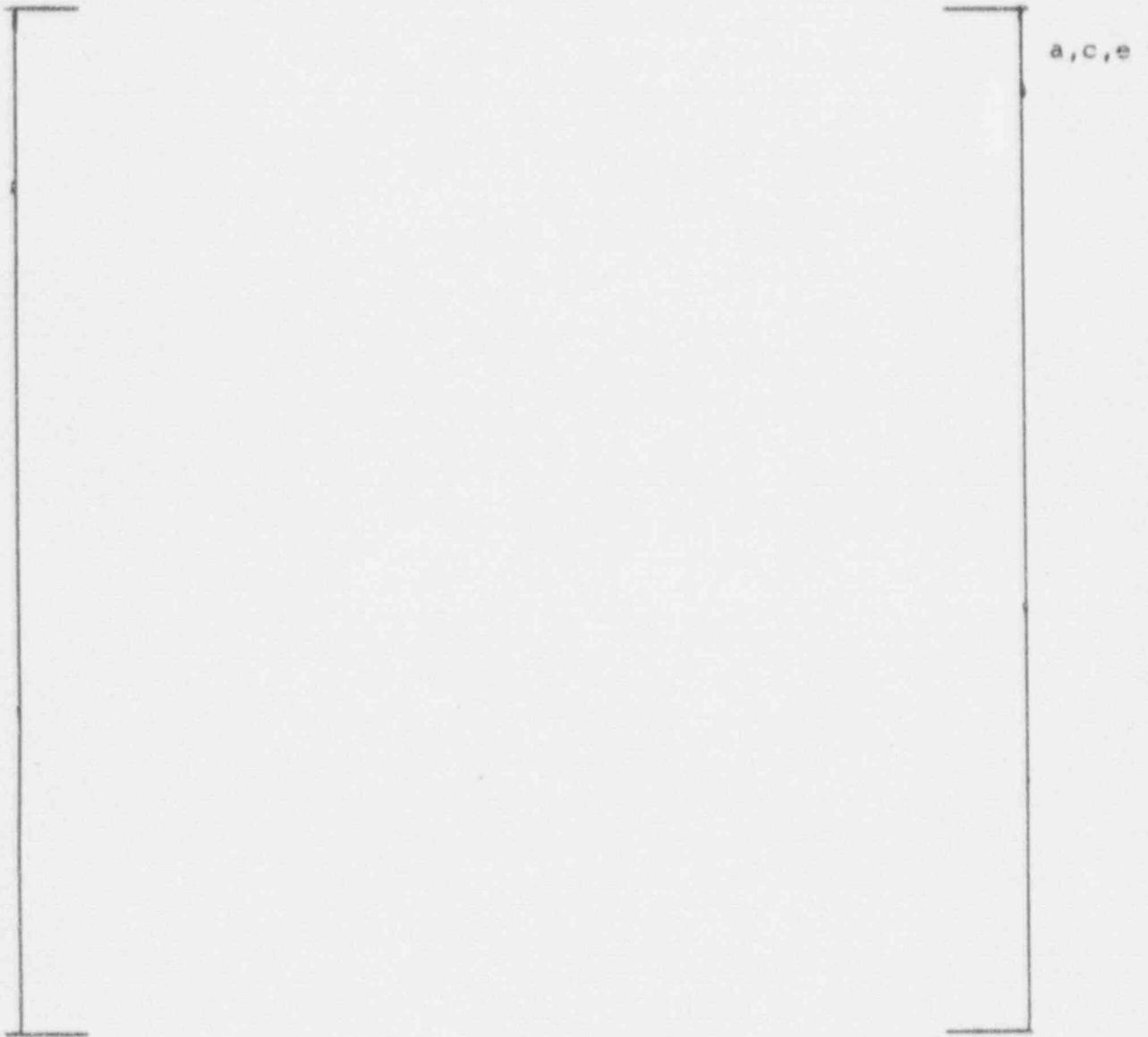


Figure 1-10. []^{a,c,e} Pressurizer Surge Line Monitoring Locations

a,c,e

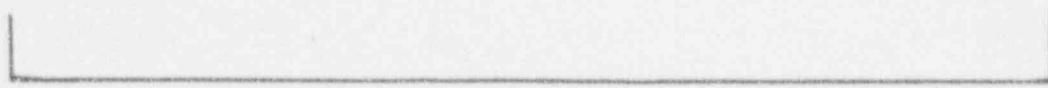


Figure I-11. Reactor Coolant Pump Cut-off Transient
Location Approximately 10' From RCL Nozzle Safe-End

41206-011796 10

a,c,e



Figure 1-12. Reactor Coolant Pump Cut-off Transient RCL_{HL} Nozzle Safe-End

a,c,e

Figure 1-13. Transient Typical of RC Pump Cut-off

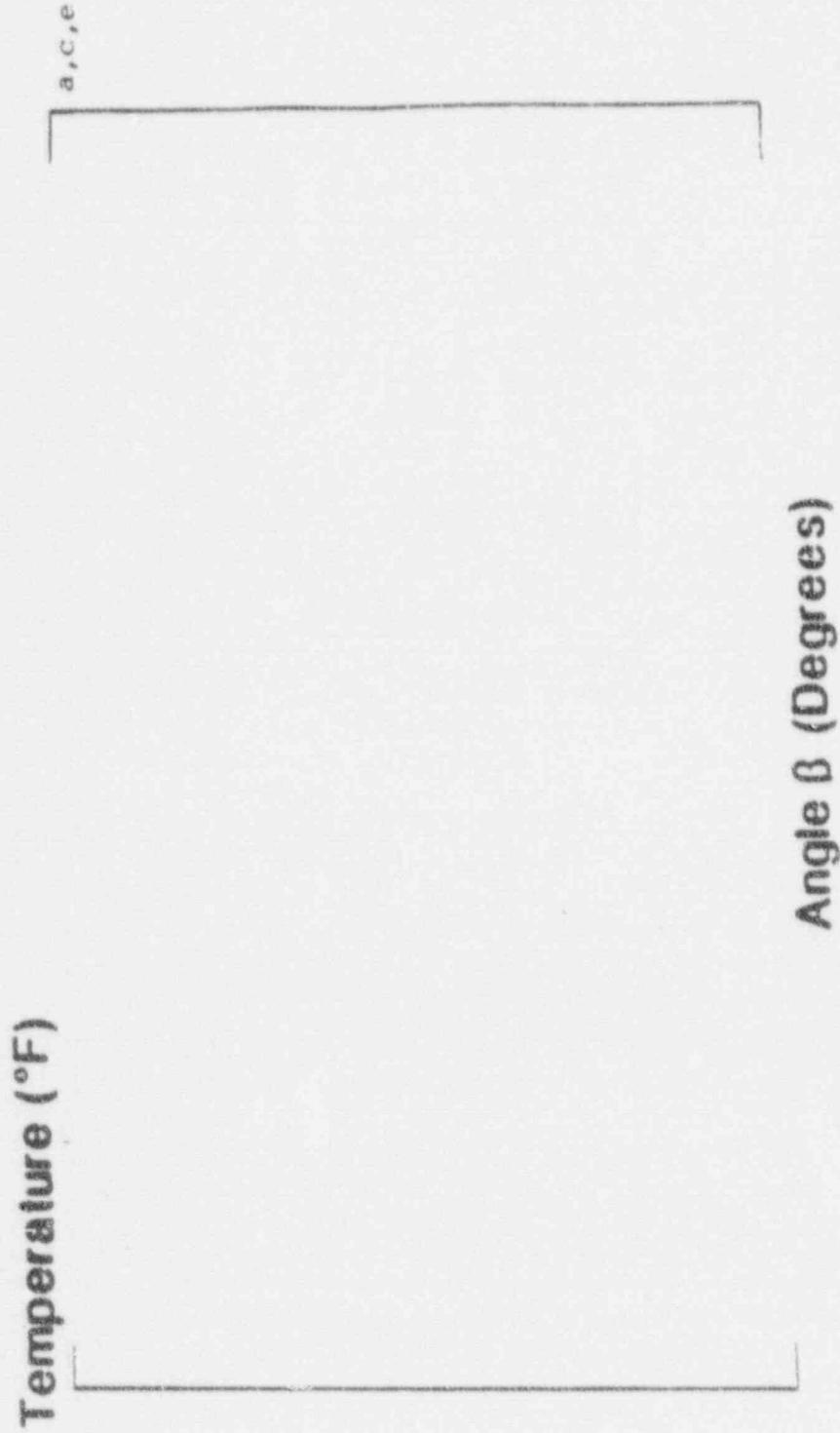
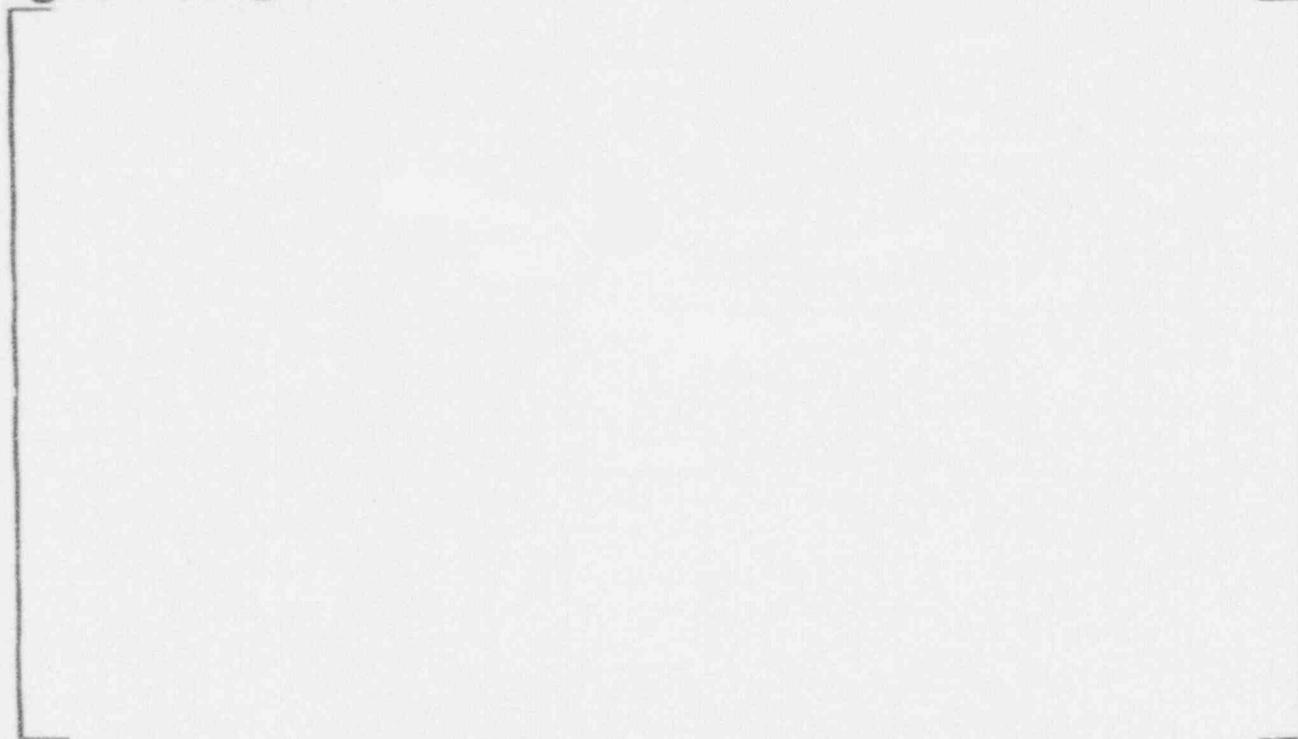


Figure 1-14. Temperature Profile (6.5-inch ID Pipe)

1-54

Angle, (degrees)



a, c, e

Dimensionless Temperature, θ

WESTINGHOUSE PROPRIETARY CLASS 2

Figure 1-15. Dimensionless Temperature Profile (14.3-inch ID Pipe)

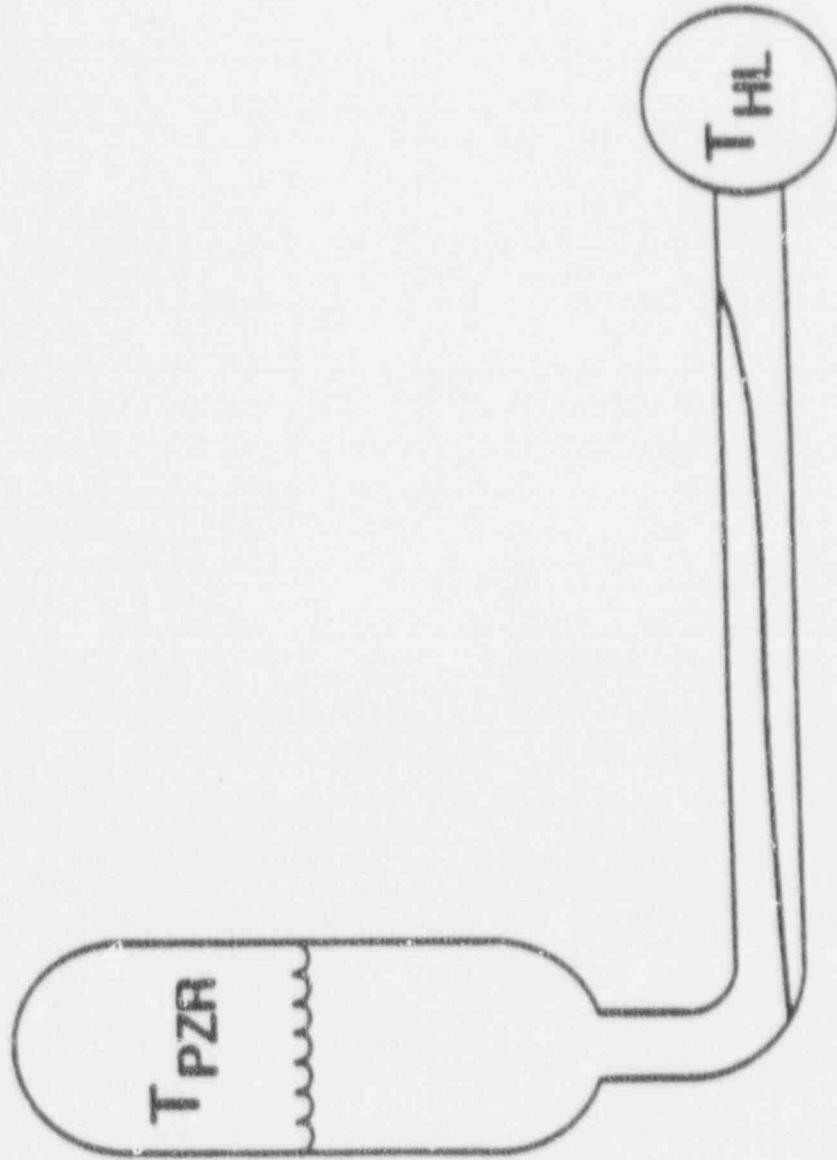


Figure 1-16. Surge Line Stratification

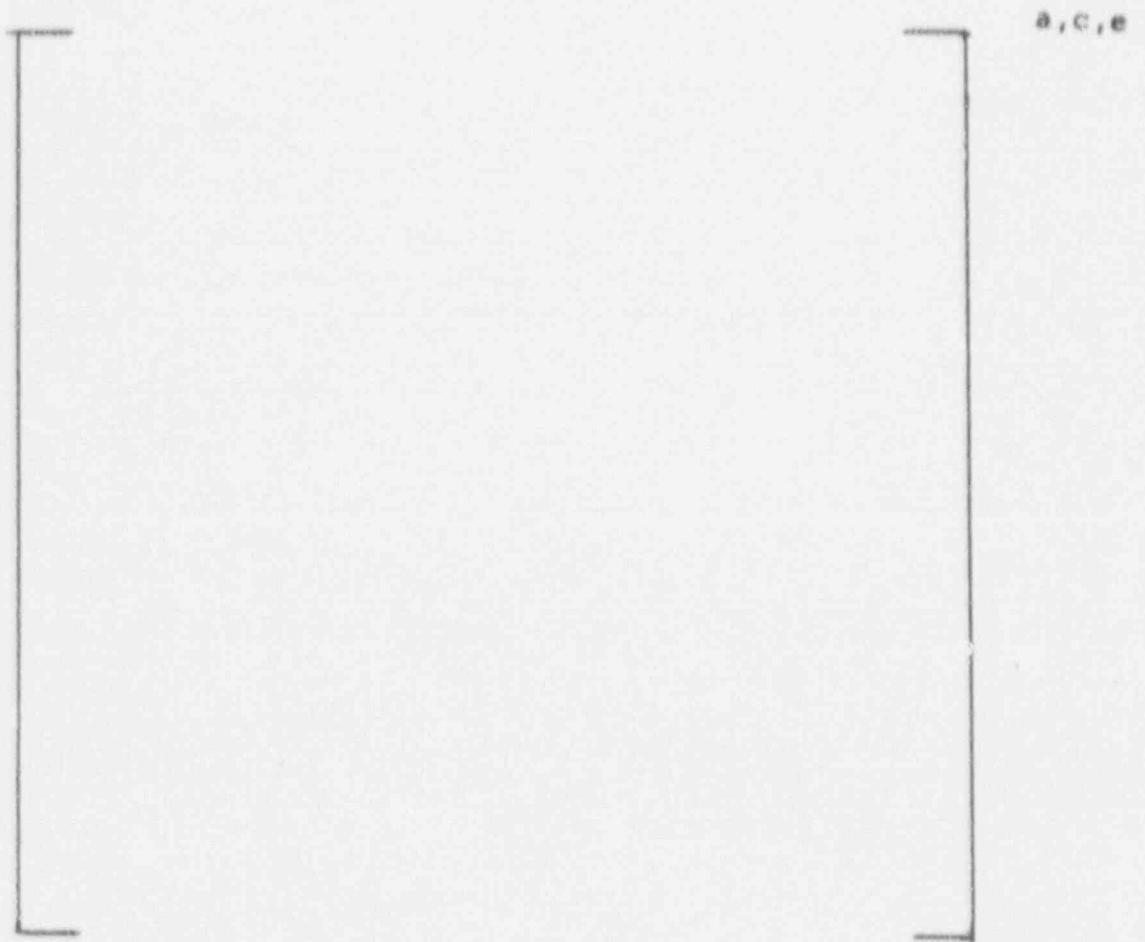


Figure 1-17. Surge Line Hot-Cold Interface Locations

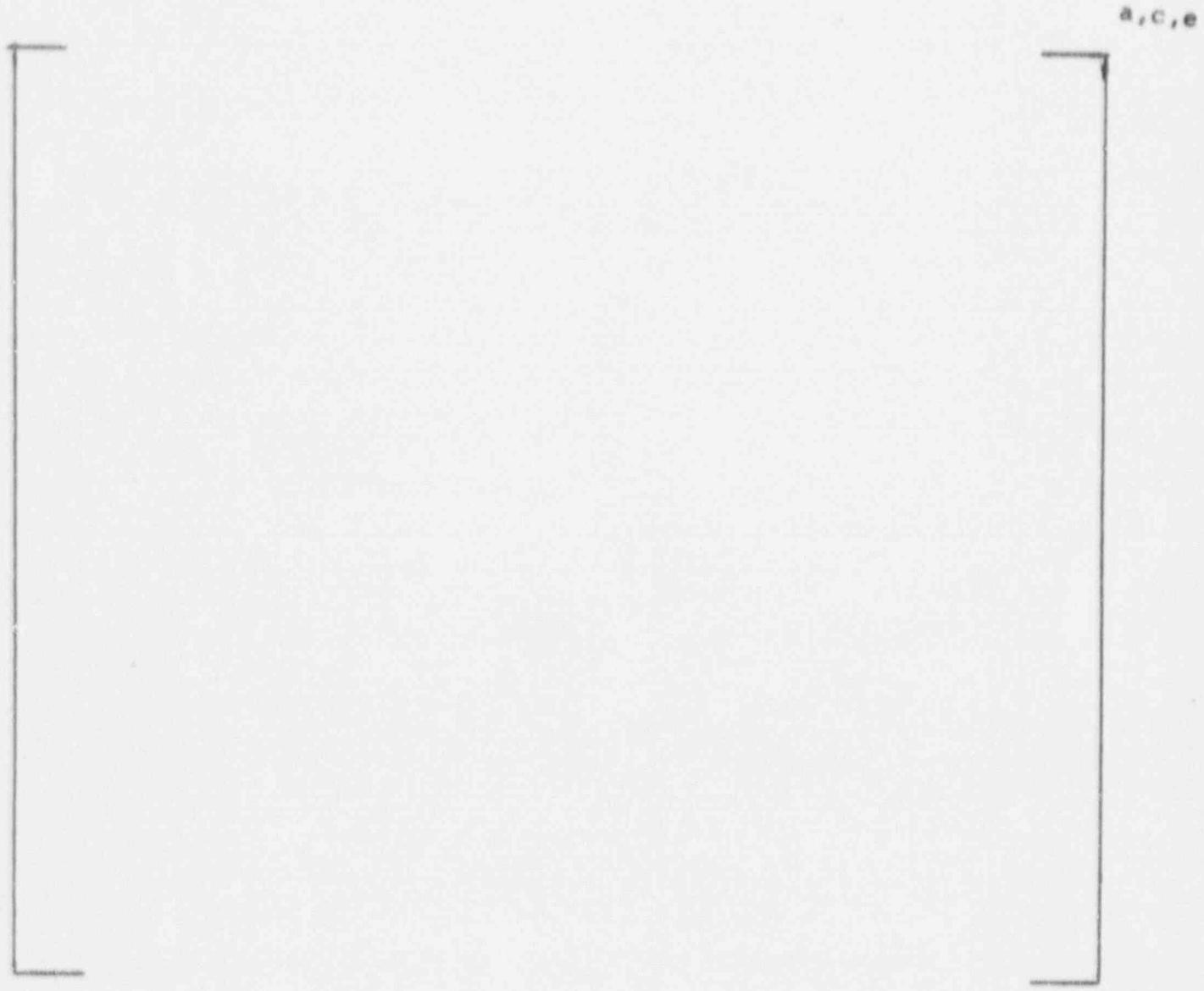


Figure 1-18. Typical []^{a,c,e} Temperature Profiles

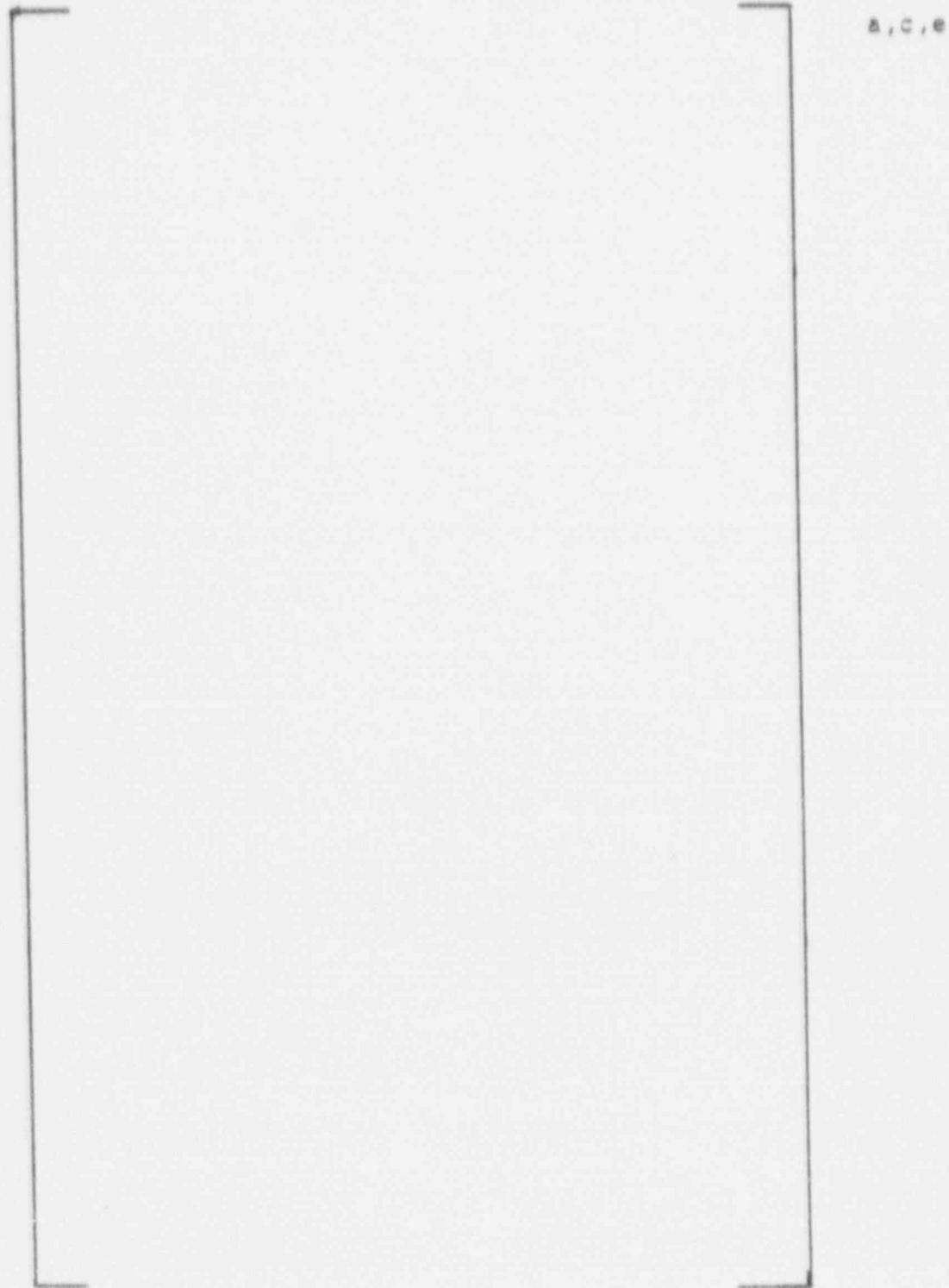


Figure 1-19. Inadvertent RCS Depressurization ($\Delta T = 260^{\circ}\text{F}$ in Surge Line)

Temperature (°F)

Time (Hours)

100, 120, 140

Figure 1-20. Steam Bubble Mode Heatup

Temperature (°F)

a, C, e

Time (Hours)

Figure 1-21. Steam Bubble Mode Cooldown

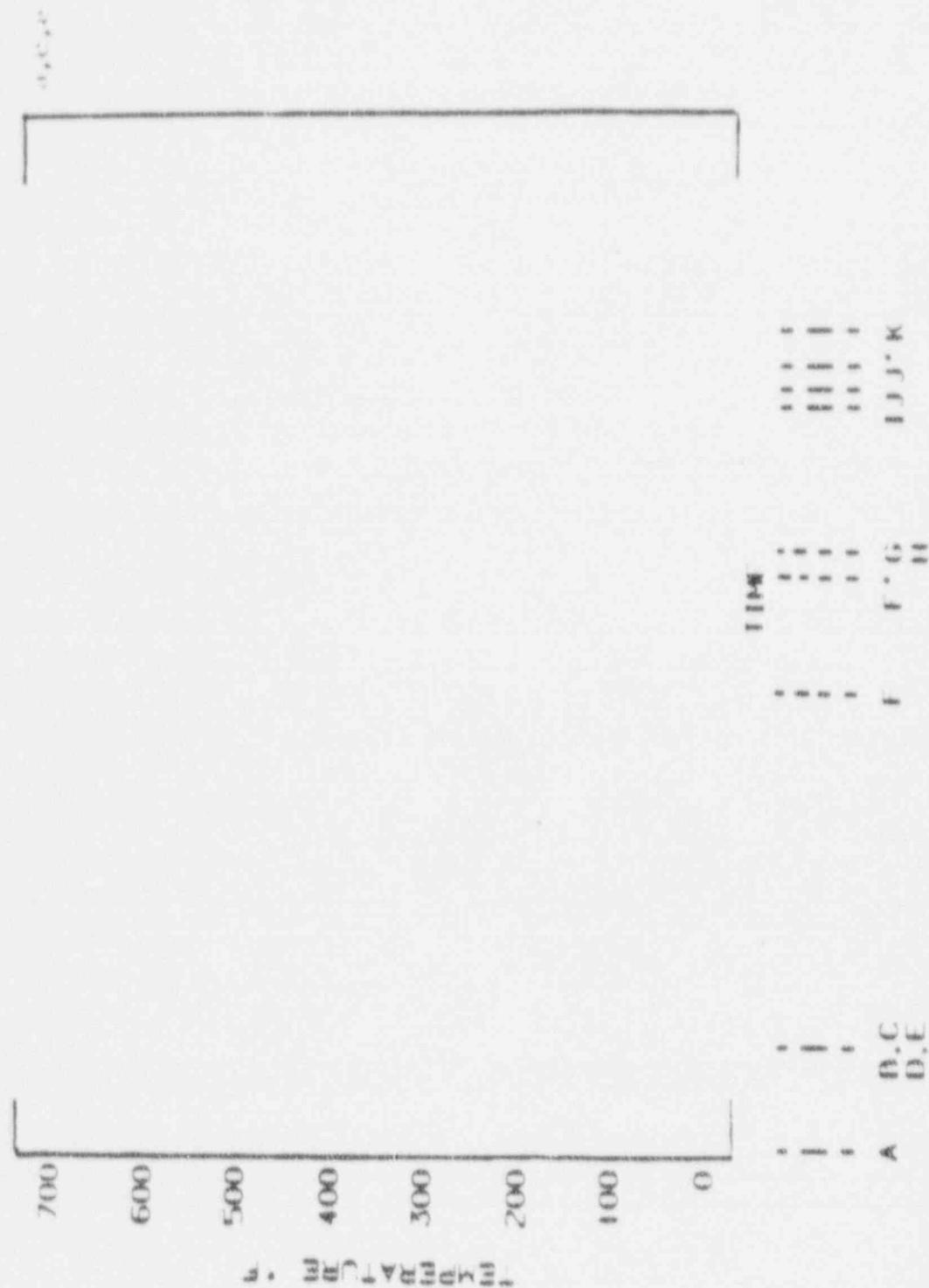


Figure 1-27. Heatup - Trojan



Figure 1-23. Cooldown - Trojan

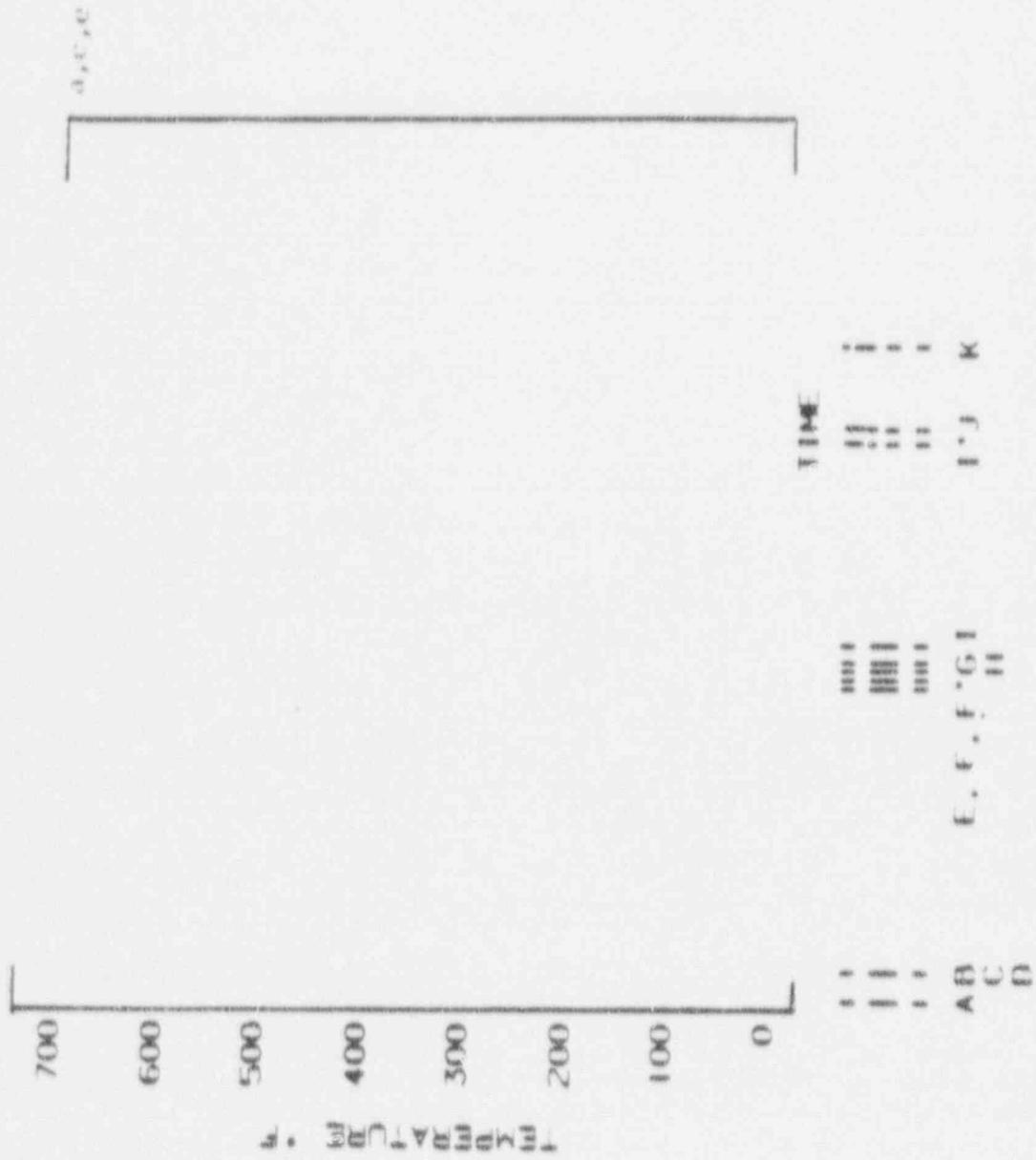


Figure 1-24. Heatup I a, c, e

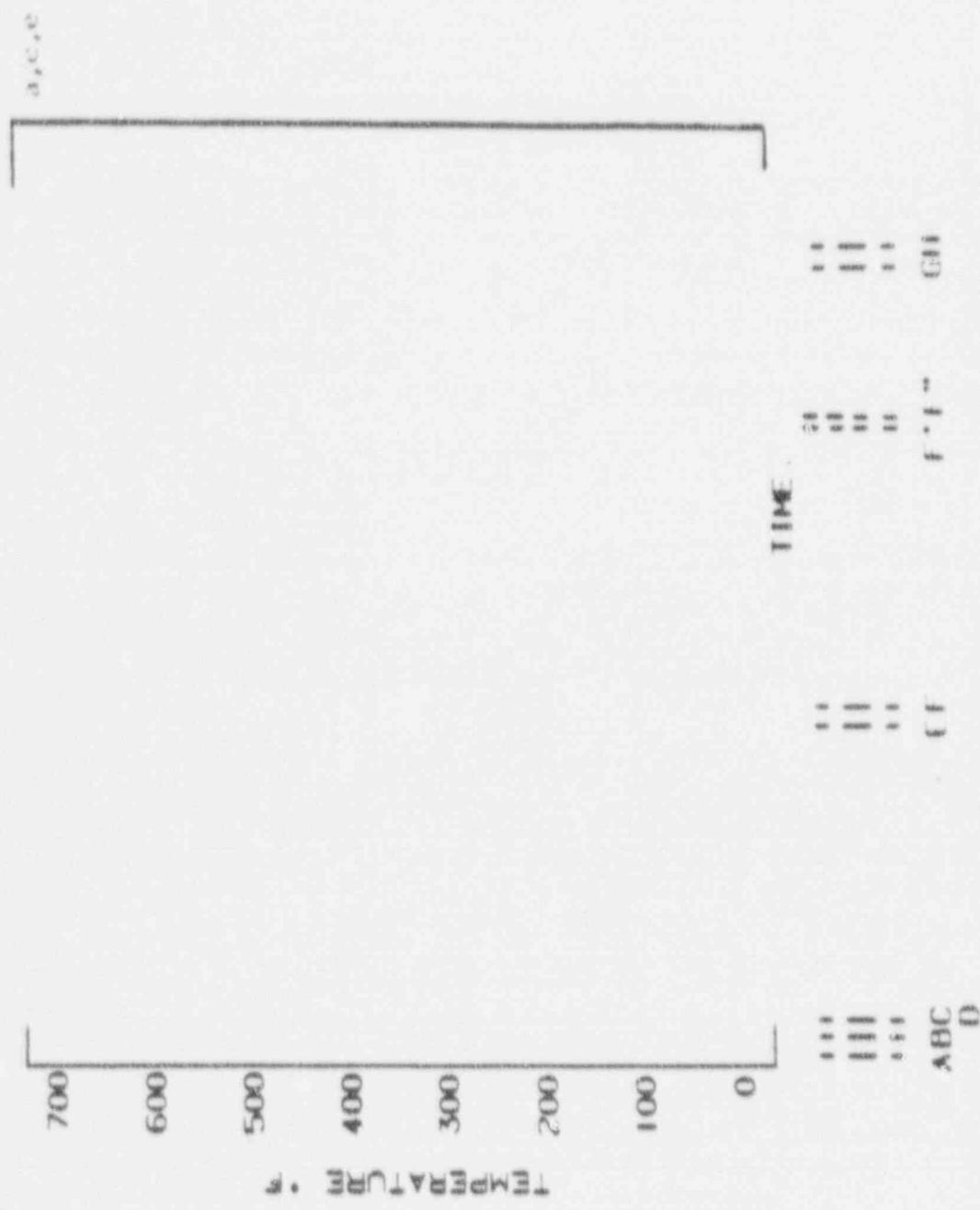


Figure 1-25. Cooldown | a, c, e

7865110000 10

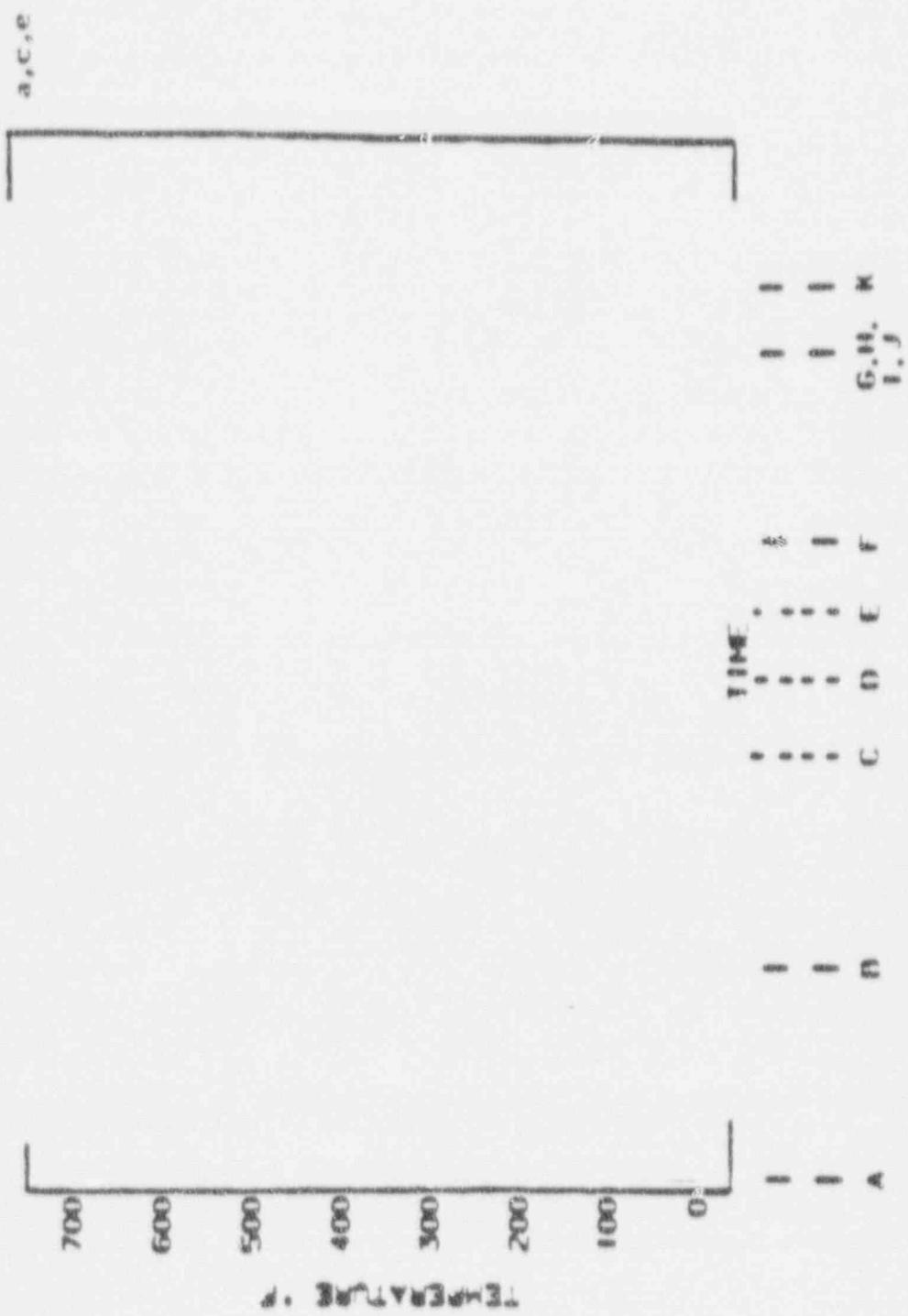


Figure 1-26. Heatup I j^{a, c, e}

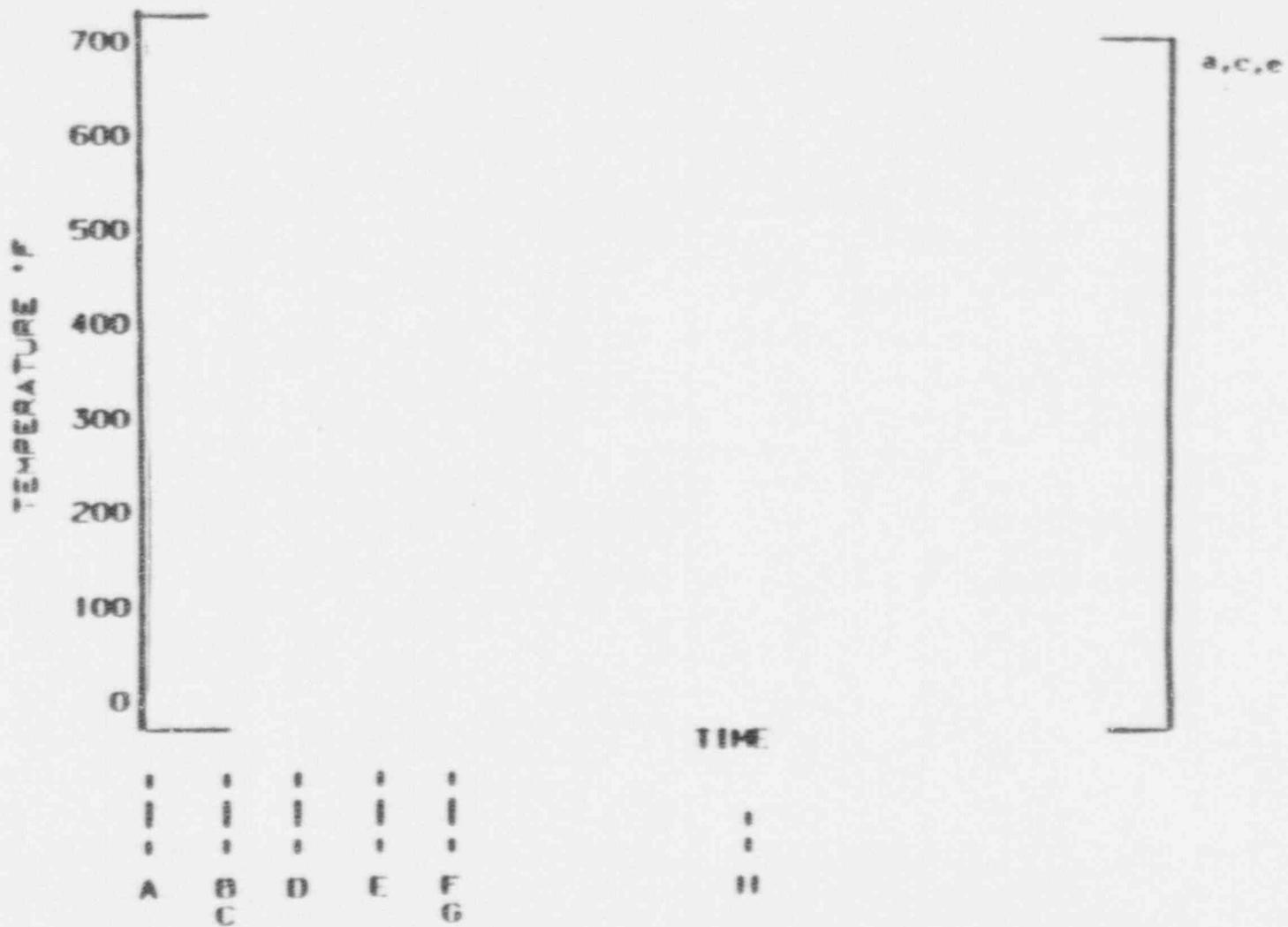


Figure 1-27. Cooldown [}^{a,c,e}

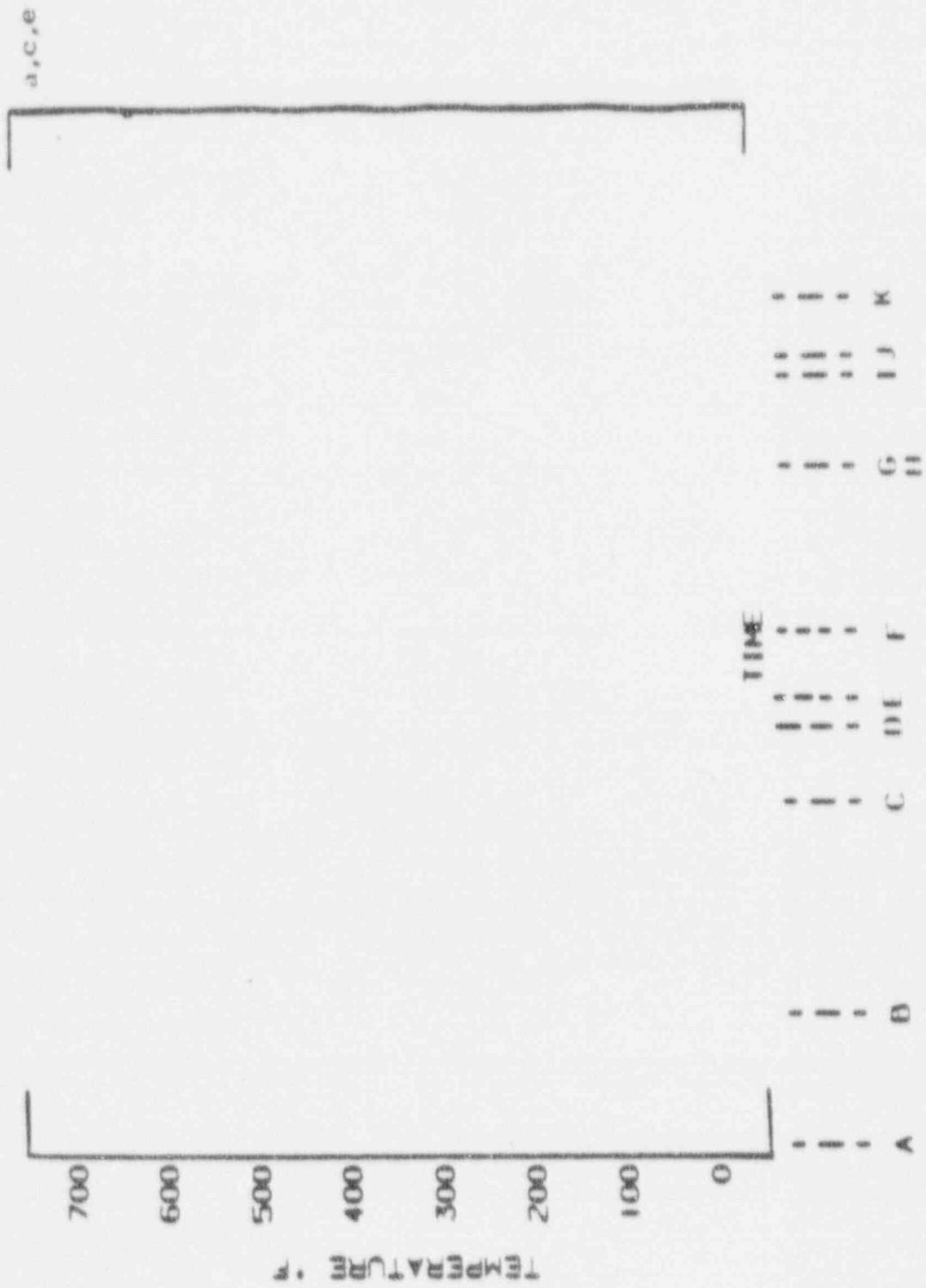


Figure 1-28. Heatup []^{a, c, e}

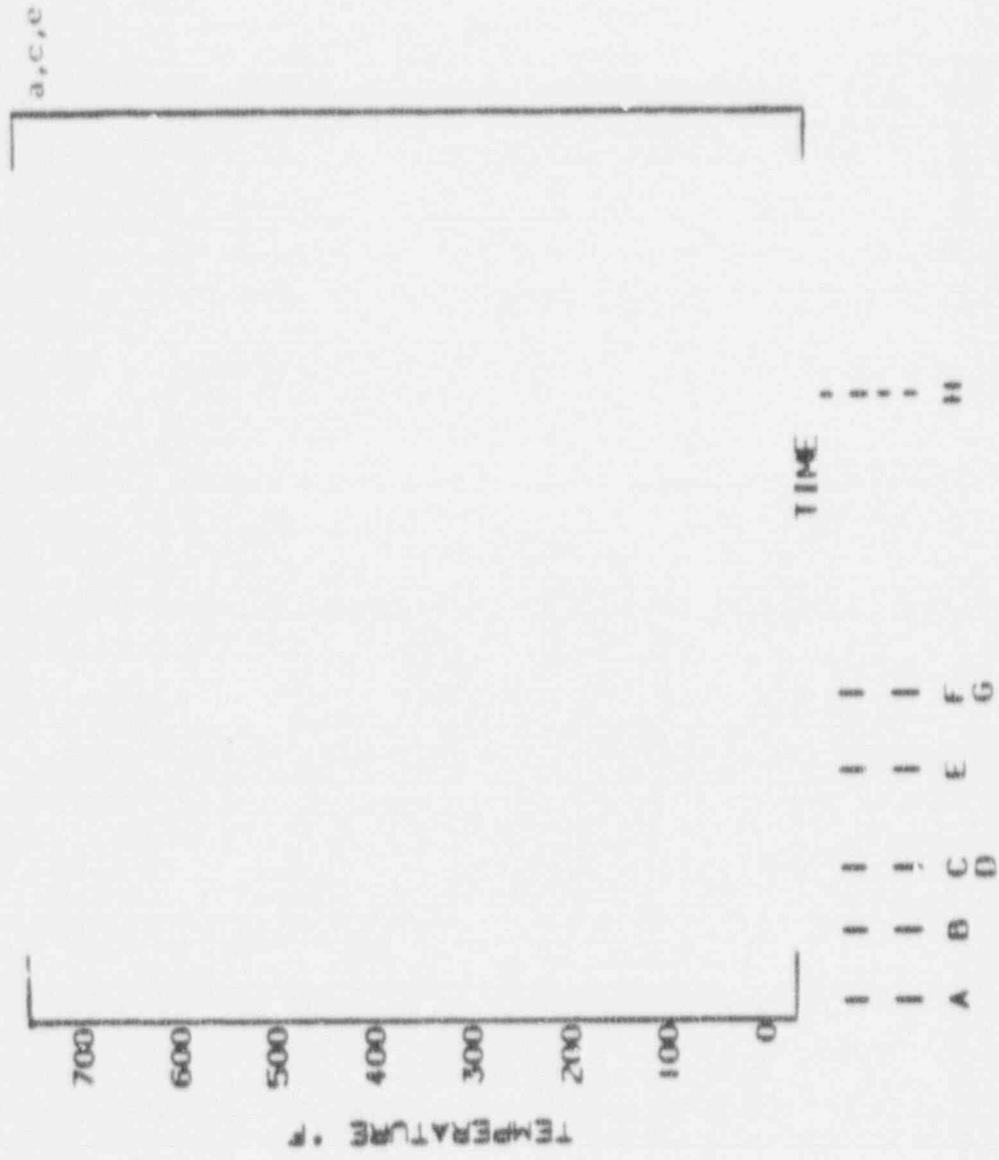


Figure 1-29. Cooldown []^{a, c, e}



Figure 1-30. Trojan Location 1 - Heatup (7 Days)

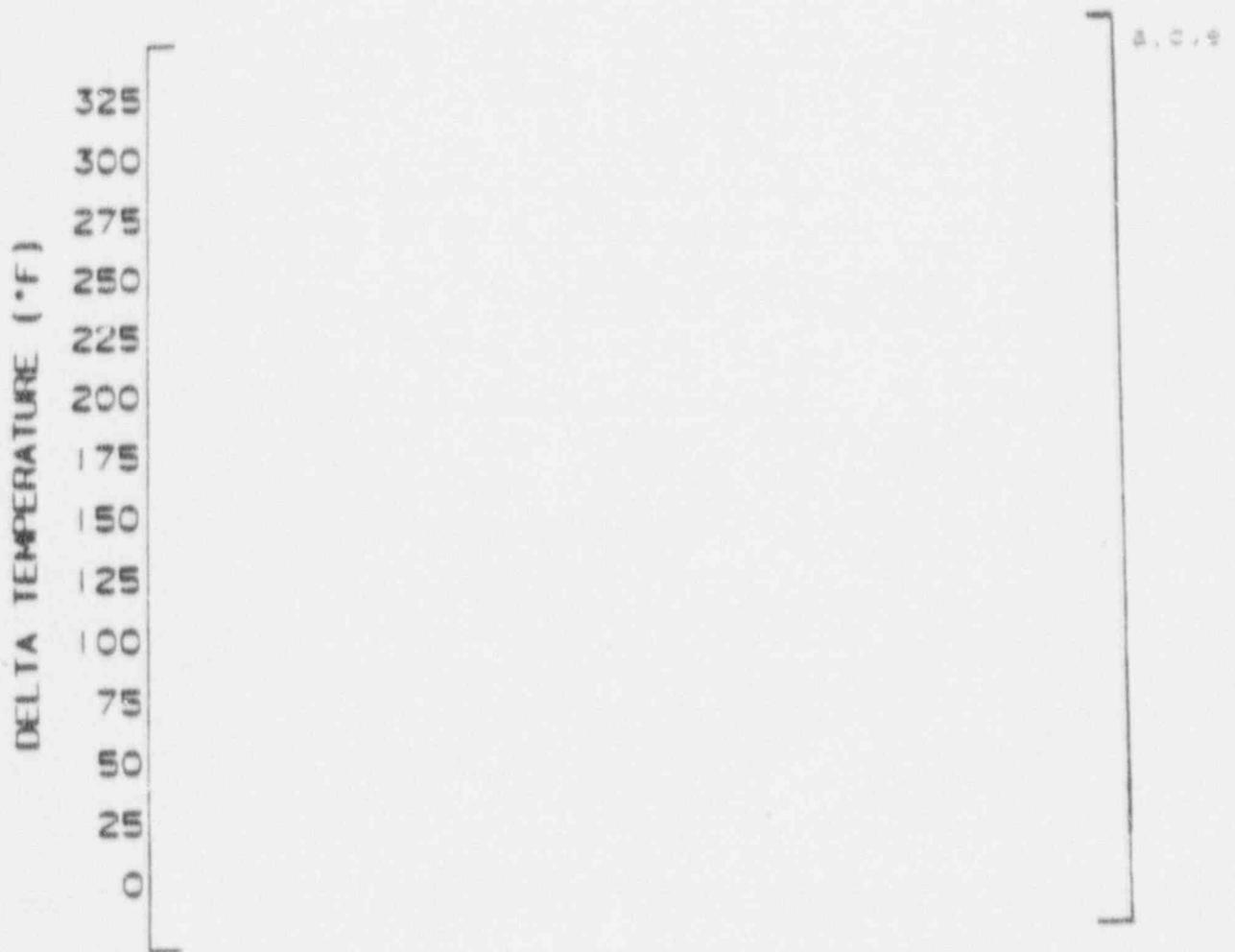


Figure 1-31. []^{a, c, e} Location 1 - Heatup (4 Days)

1-71

DELTA TEMPERATURE (°F)



a,c,e

Figure 1-32. []^{a,c,e} Location 1 Fatigue Cycles - Heatup (11 Days)

1-72

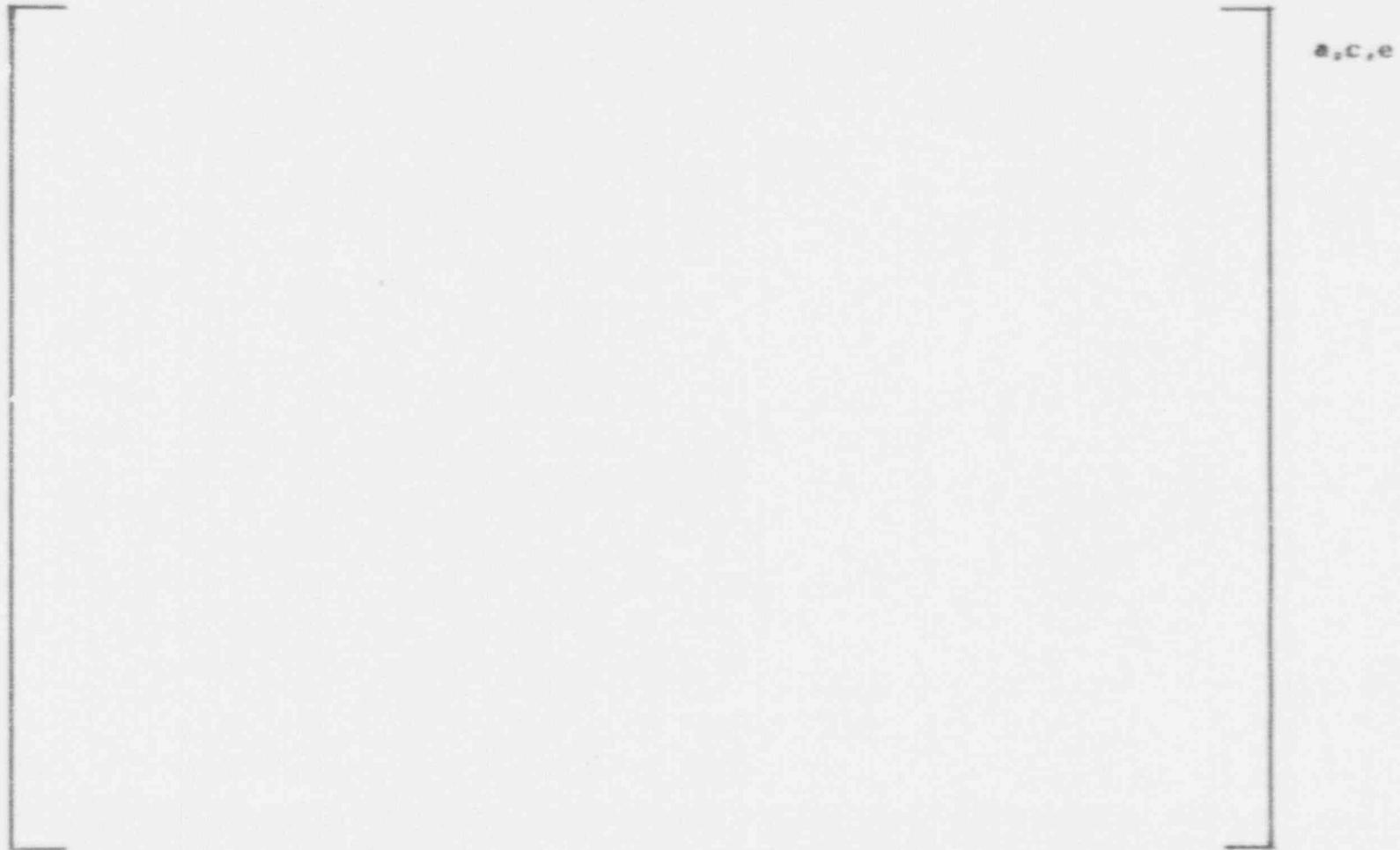


Figure 1-33. Thermal Cycle Distribution Assumed for One Heatup Cycle



Figure 1-34. I

a.c.e

41755-011790-10



Figure 1-35. Initiations of Striping Thermal Cycle Assumed for One Heatup

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. [

j^{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

A structural model of the surge line is created for the ANSYS (Appendix A.4) computer code to predict piping loads, displacements, and restraint loads. The model comprises straight pipe and elbow elements for piping, 3-D interface elements for whip restraints, and displacement boundary conditions for equipment nozzles. The piping elements are loaded with an equivalent linear diametric temperature distribution. [

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

}a,c,e

2.1.2 Discussion On A Typical Surge Line Analysis

The piping layout for a typical surge line is shown in figure 2-3. Rigid support R11, originally installed to reduce deadweight and seismic loads, provides resistance to the displacements caused by thermal stratification.

[

}a,c,e

[

]a,c,e

[

J^{a,c,e}

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

J^{a,c,e}

2.1.3 Additional Information on Linear Equivalent Techniques

2.1.3.1 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

non-linear cross-sectional temperature profiles, such as step change of temperatures at mid-plane. This study was performed using a model developed for WECAN. In order to achieve a less costly analytical solution, an alternative model using pipe and elbow elements was developed for ANSYS. 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 the thermal stratification global analysis. The theoretical basis for the equivalent linear temperature profile is based on a cantilever beam model and is summarized below.

2.1.3.2 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:

[

$\int_{a,c,e}$

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,

$$F = \int_A \sigma dA = 0 \quad (2.1-5)$$

$$M = \int_A \sigma y dA = 0 \quad (2.1-6)$$

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

where

[

] ^{a,c,e}

2.1.3.3 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_{jk} coefficients with $Y_0 = 0$. 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.

2.1.3.4 Discussion

The suitability of ANSYS for the thermal stratification global analysis is demonstrated by the comparisons between case 3 and case 3L. WECAN and ANSYS pipe displacements in 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.

2.1.4 Results For Trojan Surge Line

[

] ^{a,c,e} The 11 cases provide sufficient data to evaluate all the transients defined in tables 1-3 and 1-4.

The pressurizer and RCL temperatures defined in table 2-3 reflect the approximate system delta T and not [] ^{a,c,e} System delta T was only used to define the boundary conditions (thermal anchor movements at both ends of surge line). [

] ^{a,c,e}

The calculated piping stress due to thermal stratification for Trojan surge line is reviewed to ensure that the system will not collapse in a "hinge-moment" mechanism. The 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 [

] ^{a,c,e} A summary of maximum ASME code calculated stresses is presented in table 2-5.

It should be noted that ASME III code C₂ stress indices were used at all locations except [] ^{a,c,e} evaluation used the results of finite element analyses for secondary stresses in lieu of code stress indices to reduce conservatism. C₂ was defined [

However, ASME III code K stress indices were applied at all points.

2.1.4.1 Displacements

Thermal stratification in a surge line causes vertical displacements which are typically much larger than those predicted by past axial thermal expansion analysis. In the original design, pipe whip restraint gaps were determined from the normal thermal expansion analysis. Therefore, the larger vertical displacements from stratification resulted in unintentional restraint of the pipe. The effects of such restraint have been included in the stratification analysis. A summary of maximum thermal displacements at support and pipe whip restraints, based on the existing restraint configuration (as measured in June, 1988) and maximum system ΔT of 320°F, is presented in table 2-6.

A chronology of whip restraint gaps was provided to Westinghouse by Portland General Electric.^[6] This chronology shows variations in gaps throughout past operation of the plant. Some possible reasons for these variations include (1) inconsistent measurements of gaps, (2) cold pulling of the pipe after removal of the loop nozzle thermal sleeve, (3) re-adjustments of shims, and (4) possible minor plastic yielding of the pipe. Because gaps changed throughout past operation of the plant, a conservative approach was taken in the stratification analysis to include enveloping conditions of past restraint configurations. For the fatigue evaluation of future operation, the existing restraint configuration (as measured in June 1988) was used in the stratification analysis.

2.1.4.2 Reactions

The maximum reaction loads at both ends (nozzles) of the Trojan surge line were calculated. It should be noted that these actual loads and loads from all individual transient cases are used to calculate ASME stresses and fatigue

cumulative usage factors at both the hot leg and the pressurizer nozzles. Stresses are provided in table 2-5 and usage factors provided in section 3.0.

2.1.5 Conclusions

Analytical studies with the ANSYS and WECAN computer codes have confirmed the validity of using an equivalent linear diametric temperature profile to represent the thermal stratification for displacement and loads. Comparison between the analysis results and the plant measured displacement was performed and showed good agreement. Eleven cases of thermal stratification were analyzed using the ANSYS code for the Trojan surge line. Results for all other cases of stratification were obtained by interpolation. The resulting loads on the hot leg nozzle are acceptable. From our evaluation^[7], the pressurizer nozzle met the ASME Code stress and fatigue requirements for the loads including thermal stratification. 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 [

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 sample color contour plots of stress intensity distributions in the surge line RCL nozzle due to stratification and moment loading. A summary of local stresses in the RCL nozzle due to thermal stratification is given in table 2-8. A summary of pressure and bending induced stresses for unit loading applied is shown in table 2-9.

2.2.7 Additional Clarification On Superposition Of Stresses

In order to further clarify the process used to obtain total stress at any point in the pipe wall, the following step-by-step procedure is listed.

[

a,c,e

This method of superposition makes it possible to accurately evaluate a large number of stress conditions (fatigue transients) with a minimal amount of finite element analysis. The process of scaling and summation is handled by the program WECEVAL during the fatigue analysis.

2.2.8 Conservatism in Local Stress

Conservatism 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 per reference 6. 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 2-10 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^[8] 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 2-11.

A total of []^{a,c,e} tests were 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}

The flow model test results are used to obtain frequency and duration parameters which are used in the striping evaluation. The frequency and duration parameters are considered to be functions of the flow rate and buoyancy forces between the hot and cold water interface, and not pipe diameter and wall thickness. []

] ^{a,c,e}

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 Trojan Pressurizer surge line, the frequency of [.3 hz]^{a,c,e} was used in the []^{a,c,e}

As shown in table 2-10, the amplitude of ΔT varies from []^{a,c,e} of the full ΔT between the hot and cold fluid temperatures. For the Trojan 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 Trojan 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

[

2.

]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

[

J^{a,c,e}

2.3.6 Conservatism in Striping

The conservatisms in the striping analysis are: 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 [

J^{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 []^{a,c,e} AND
 ANSYS []^{a,c,e} RESULTS FOR CASE 3

Location	Direction	WECAN Case 3	ANSYS Case 3L	Case 3L/Case 3 (Percentage)
a,c,e				

Case 3L ANSYS: DC1SKXY, 11/12/88

TABLE 2-3
TEMPERATURE DISTRIBUTIONS IN TROJAN PRESSURIZER SURGE LINE



a, c, e

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

Y_o	J_{hh}	J_{hc}	J_{ch}	J_{cc}	a, c, e

TABLE 2-5
ASME CODE STRESS SUMMARY



a,c,e

* ASME B&PV Code, Section III, 1977 Edition through 1979 Summer Addenda.

TABLE 2-6
 MAXIMUM THERMAL DISPLACEMENT FOR STRATIFIED CONDITION*
 AT SUPPORT AND PIPE WHIP RESTRAINT LOCATIONS

<u>Support or PWR Locations</u>	<u>ANSYS Analysis Nodes</u>	<u>Displacement (in.)**</u>			a,c,e
		<u>X</u>	<u>Y</u>	<u>Z</u>	
[]

* For system ΔT of 320°F
 ** where x is along North,
 y is vertically upward, and
 z is along East.

TABLE 2-7
 TROJAN SURGE LINE
 MAXIMUM LOCAL AXIAL STRESSES AT [] a,c,e

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

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

TABLE 2-8
 SUMMARY OF LOCAL STRATIFICATION STRESSES
 IN THE TROJAN SURGE LINE AT THE RCL NOZZLE

Location	Diametral Location	All Stress in psi			
		Linearized Stress Intensity Range		Peak Stress Intensity Range	
		Inside	Outside	Inside	Outside
a.c,e					
Empty table body content					

TABLE 2-9
 SUMMARY OF PRESSURE AND BENDING INDUCED STRESSES
 IN THE TROJAN UNIT 1 SURGE LINE RCL NOZZLE FOR UNIT LOAD CASES

Location	Diametral Location	Unit Loading Condition	All Stress in psi			
			<u>Linearized Stress Intensity Range</u>		<u>Peak Stress Intensity Range</u>	
			Inside	Outside	Inside	Outside
<div style="border: 1px solid black; width: 100%; height: 100%;"></div>						

a, c, e

TABLE 2-10
RESULTS FROM TWO HIGHEST THERMOCOUPLE LOCATIONS

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

a.c.e

2-32

*Thermocouple readings taken from tests run at Location #2 (see figure 2-56).

**Thermocouple readings taken from tests run at Location #5 (see figure 2-56).

TABLE 2-11
FLOW RATES AND RICHARDSON NUMBER
FOR WATER MODEL FLOW TESTS

<u>Pipe Section</u>	<u>Cold Water Flow Rate (GPM)</u>	<u>Ri</u>	a,c,e

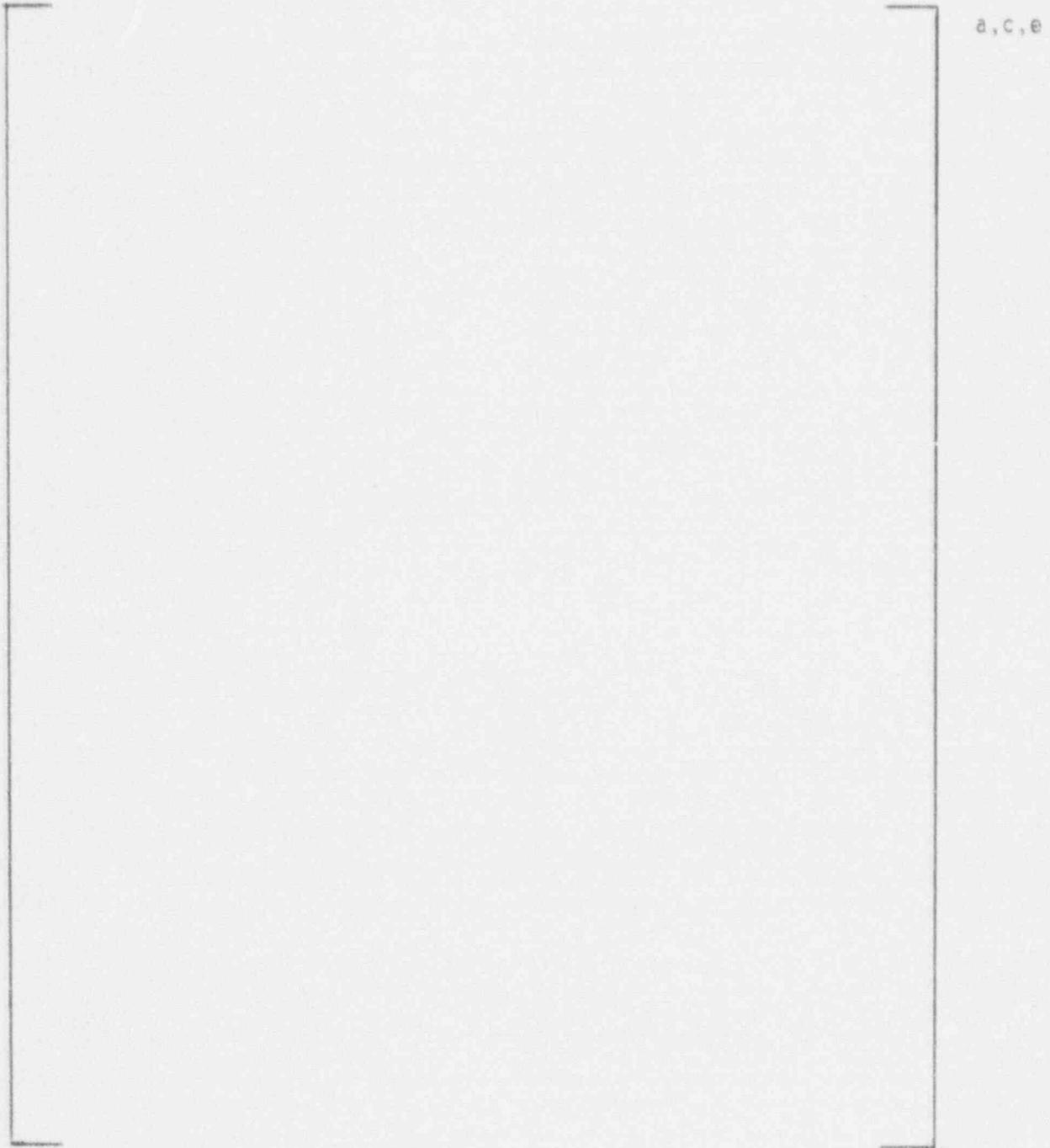
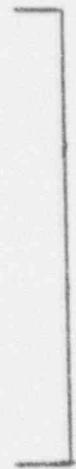


Figure 2-1. Determination of the Effects of Thermal Stratification



a, c, e

Figure 2-2. Stress Analysis

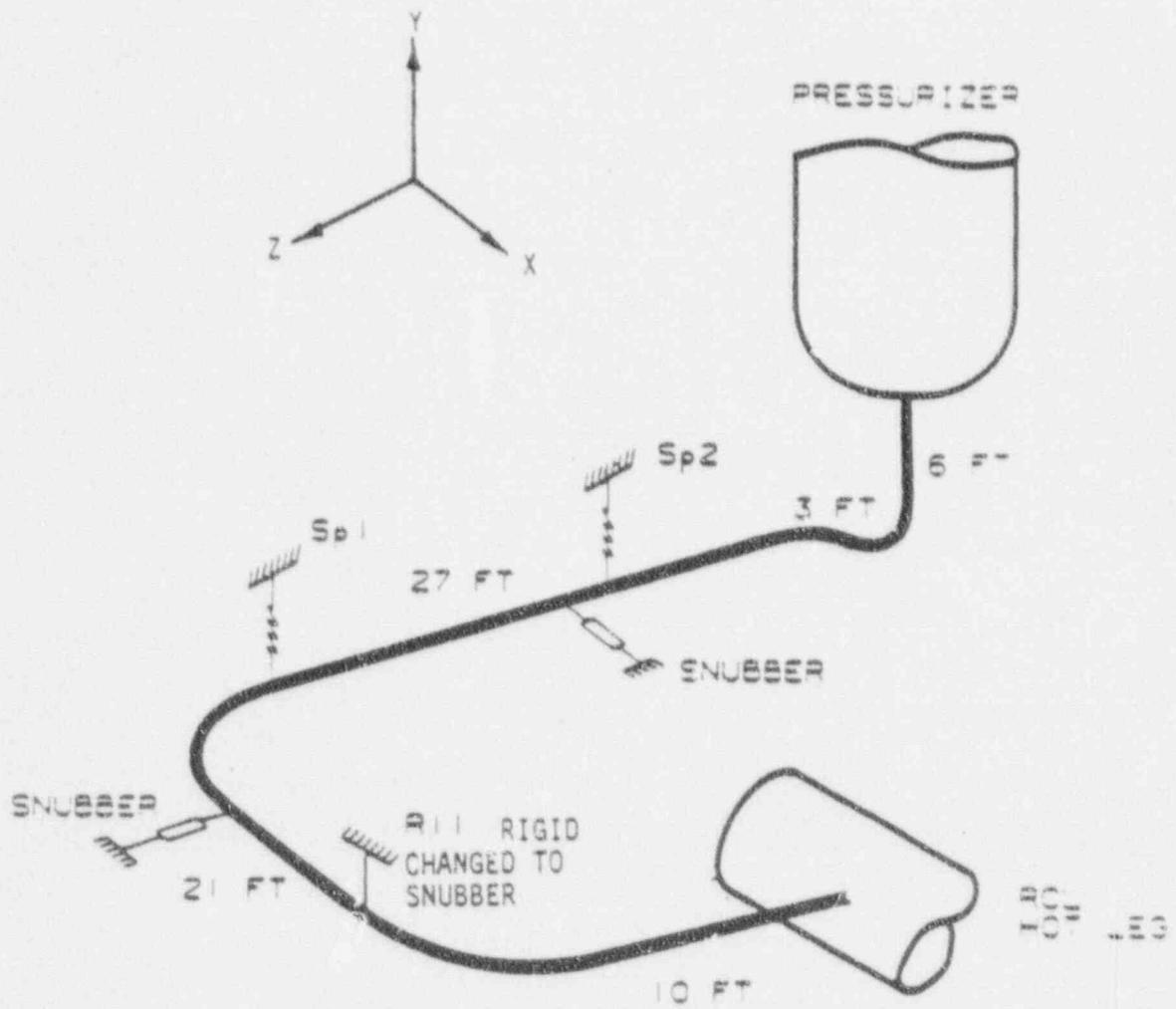


Figure 2-3. Typical Pressurizer Surge Line Layout

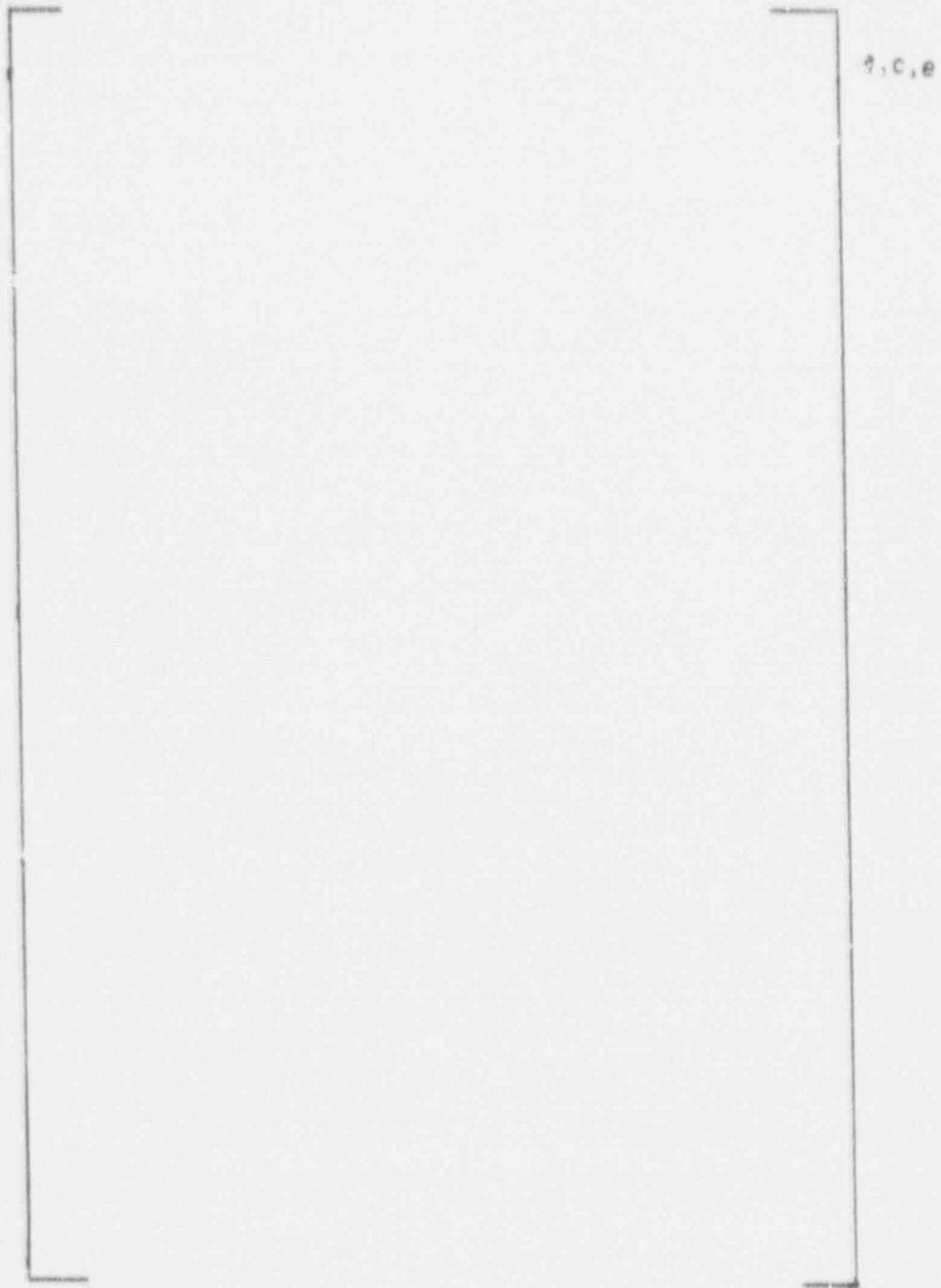


Figure 2-4. Cases 1 to 4: Diametrical Temperature Profiles

a,c,e

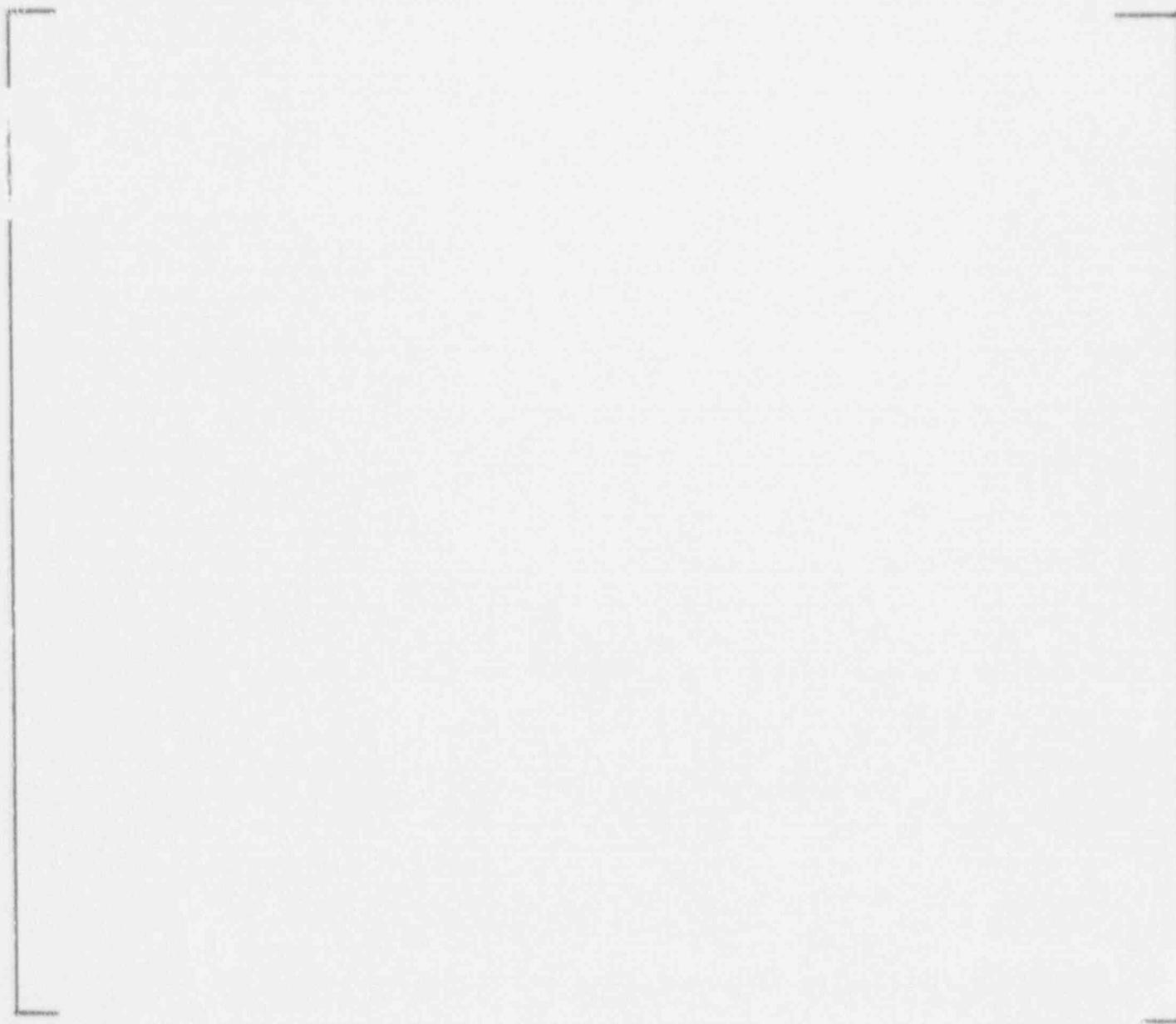


Figure 2-5. Case 5: Diametrical and Axial Temperature Profile



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

a, c, e

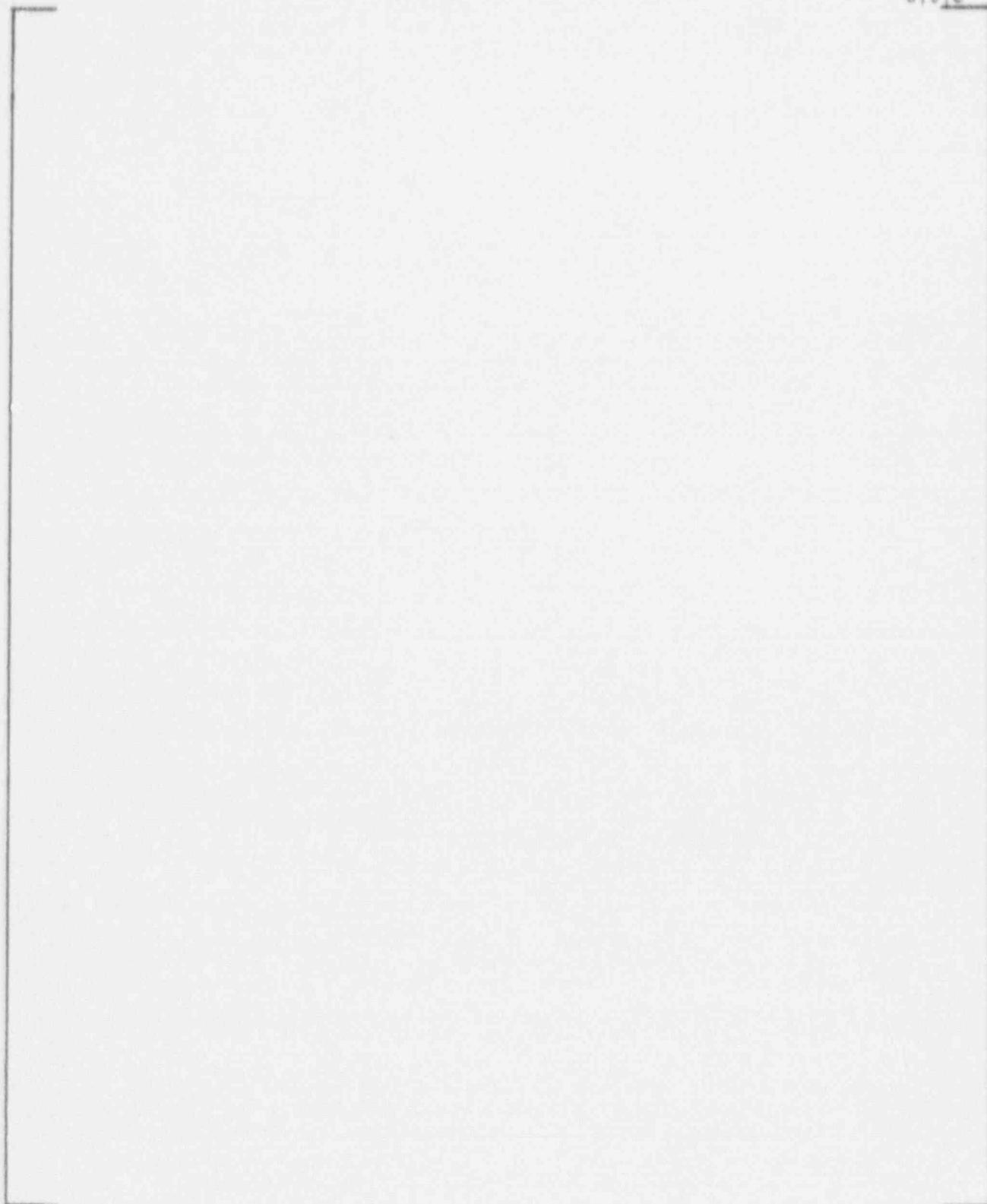


Figure 2-7. Finite Element Model of the Pressurizer Surge Line Piping Hot Leg Nozzle Detail

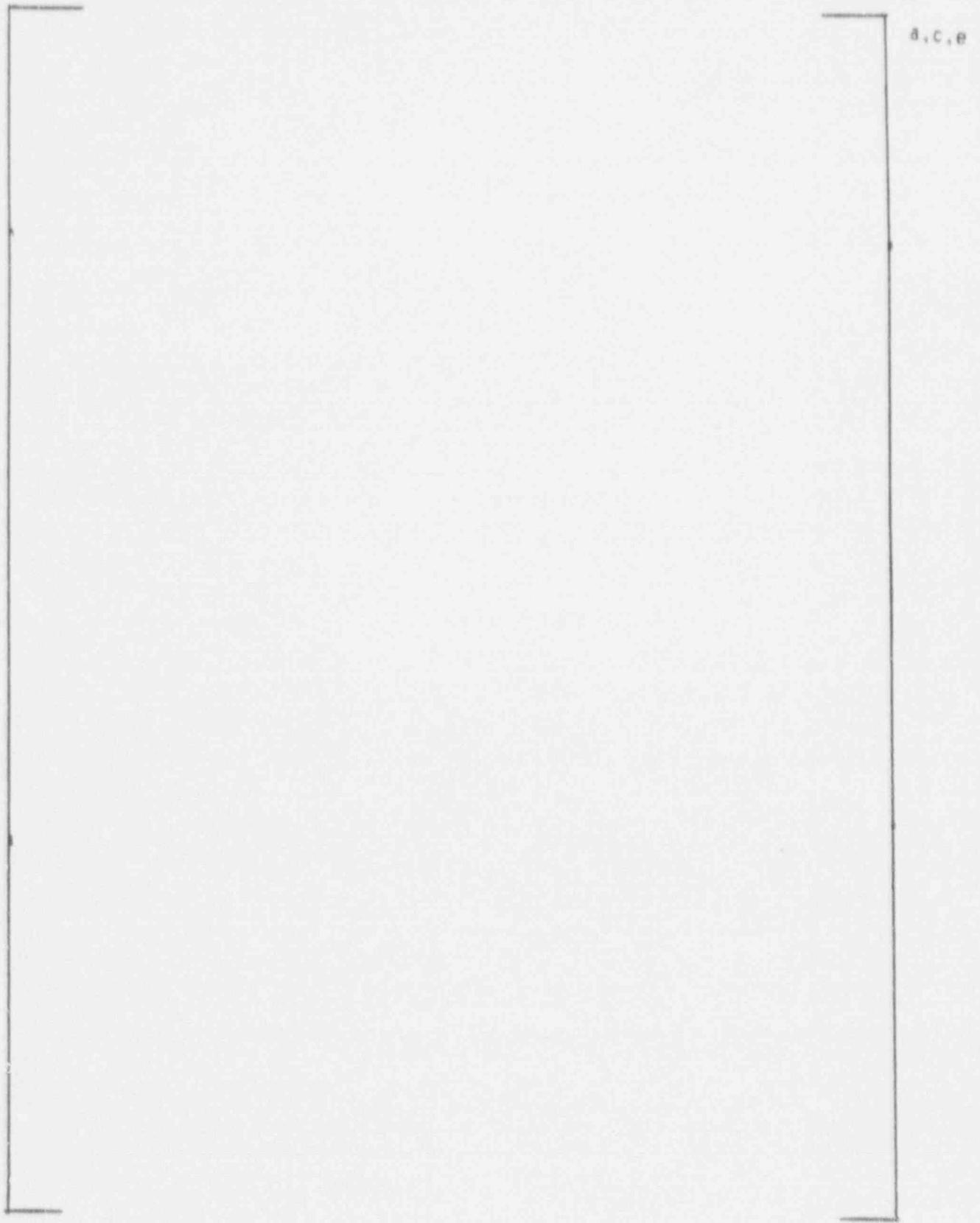


Figure 2-8. Thermal Expansion of the Pressurizer Surge Line Under Uniform Temperature

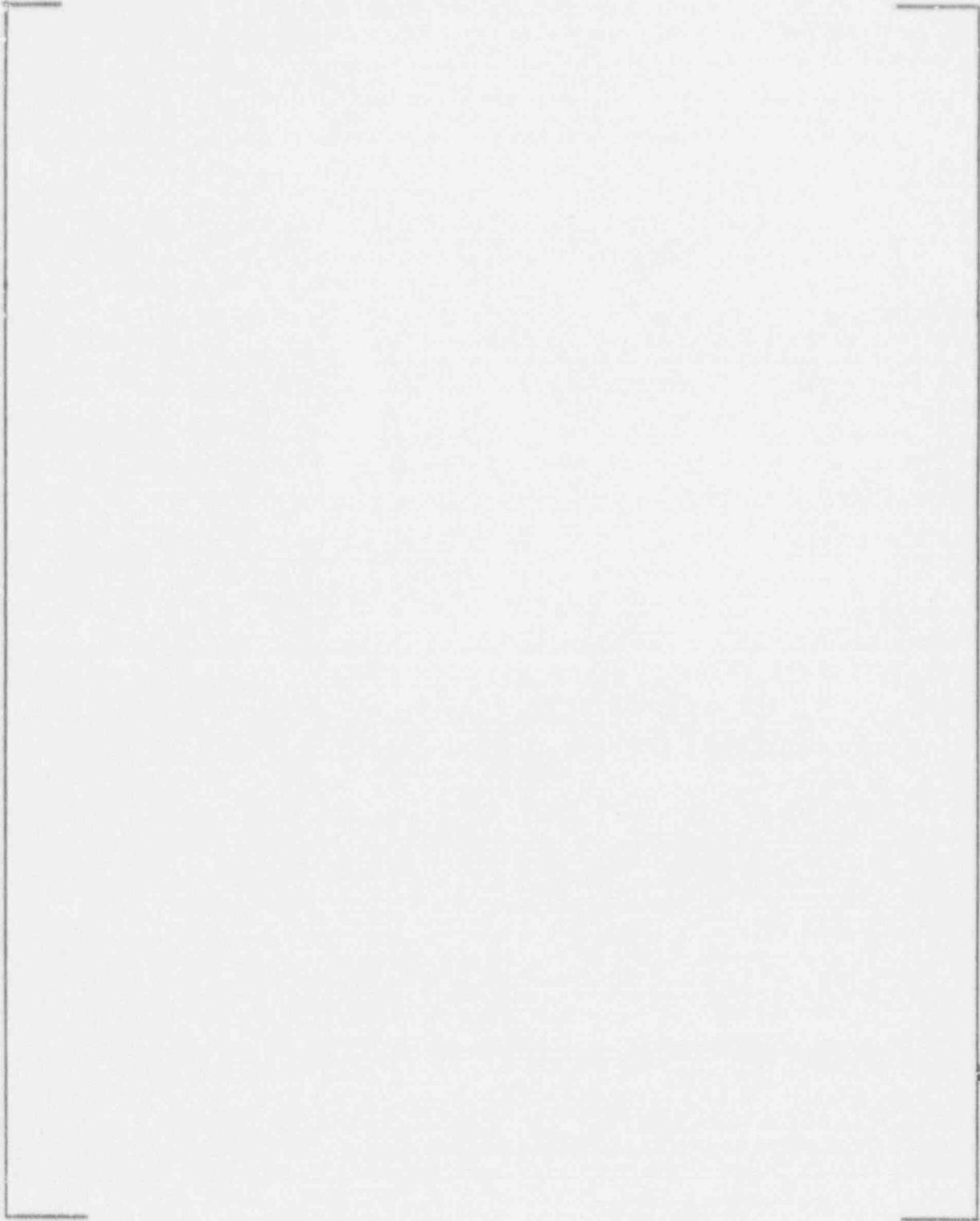


Figure 2-9. Case 2 (linear) Temperature Profile at Hot Leg Nozzle

a,c,e

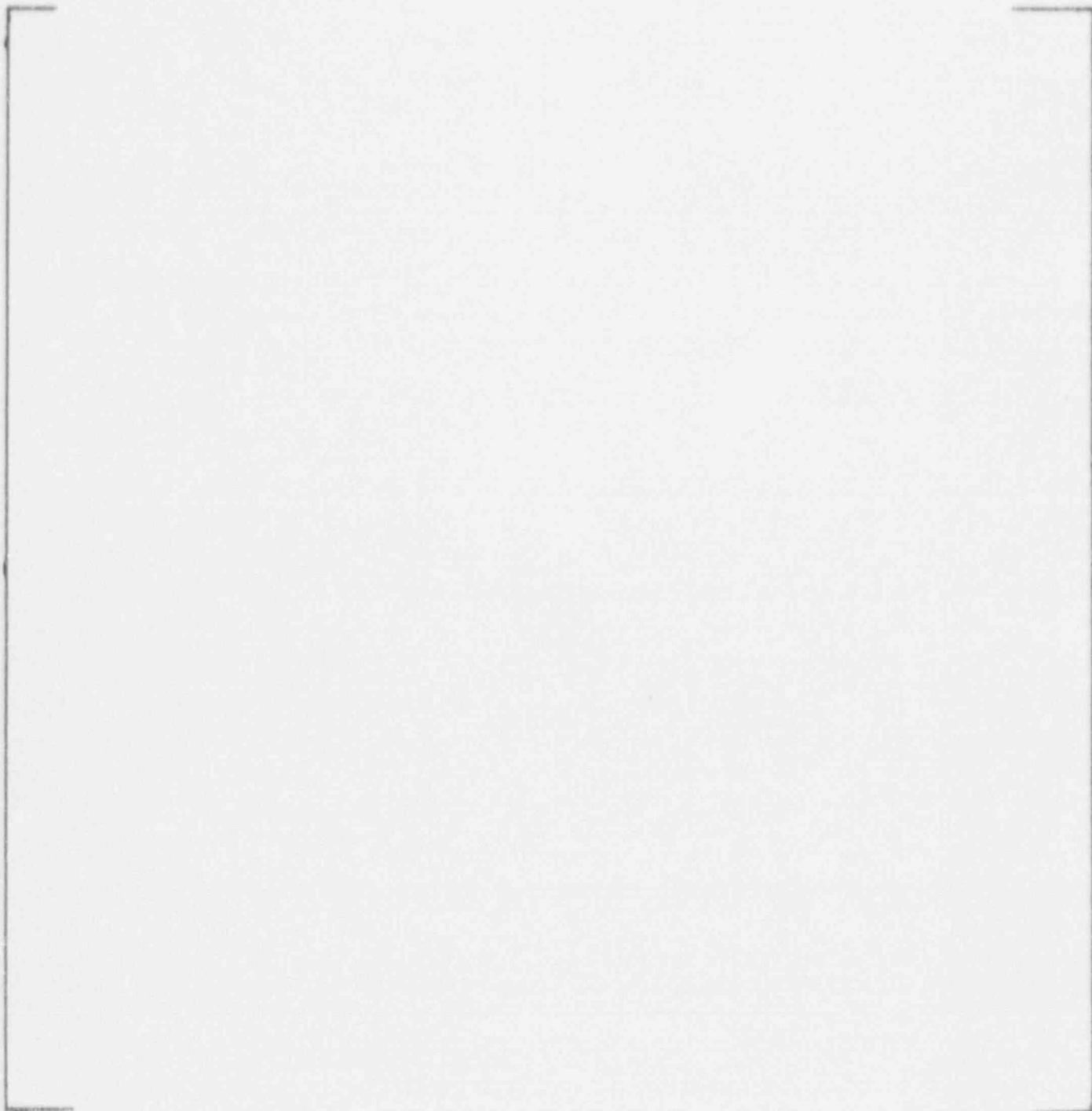


Figure 2-10. Case 2 (linear) Temperature Profile at Pressurizer Elbow

a,c,e

Figure 2-11. Thermal Expansion of Pressurizer Surge Line Under Linear Temperature Gradient



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

4-275-911790 10

a,c,e

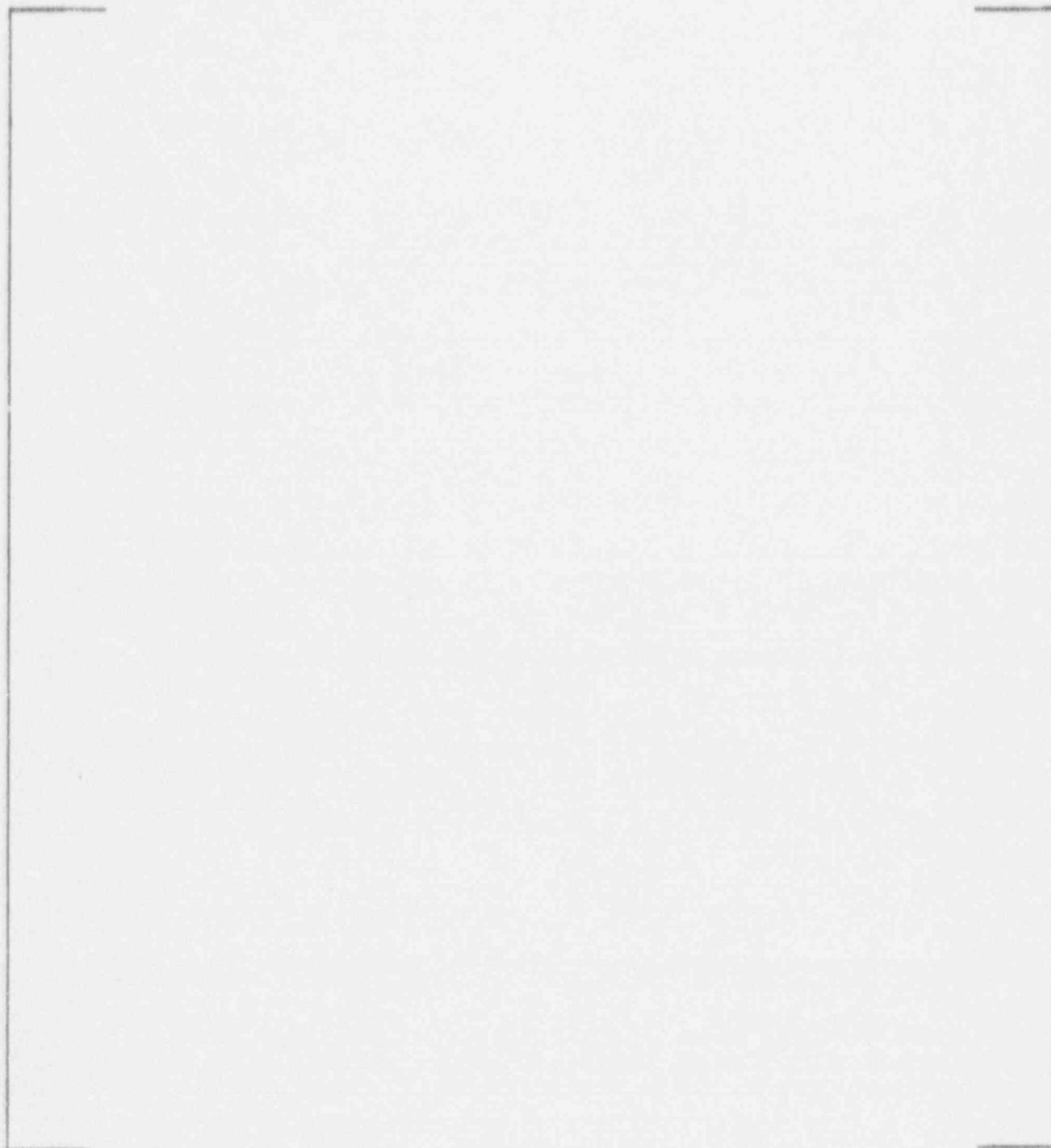


Figure 2-14. Case 3 (Mid-Plane Step): Temperature Profile at Pressurizer Nozzle

a, c, e

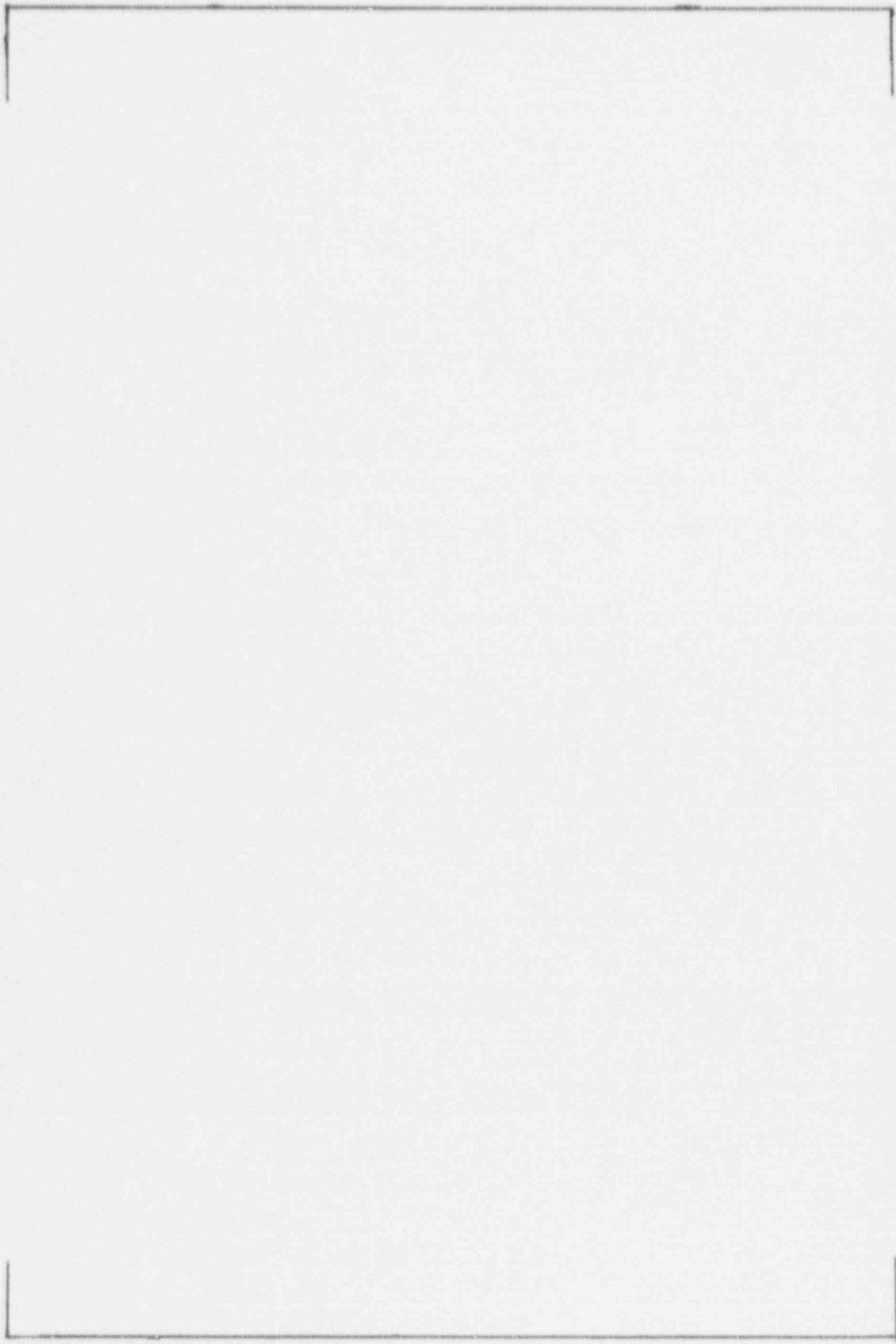


Figure 2-15. Case 4 (Top Half Step): Temperature Profile at Hot Leg Nozzle

41215-011790 16

a, c, e

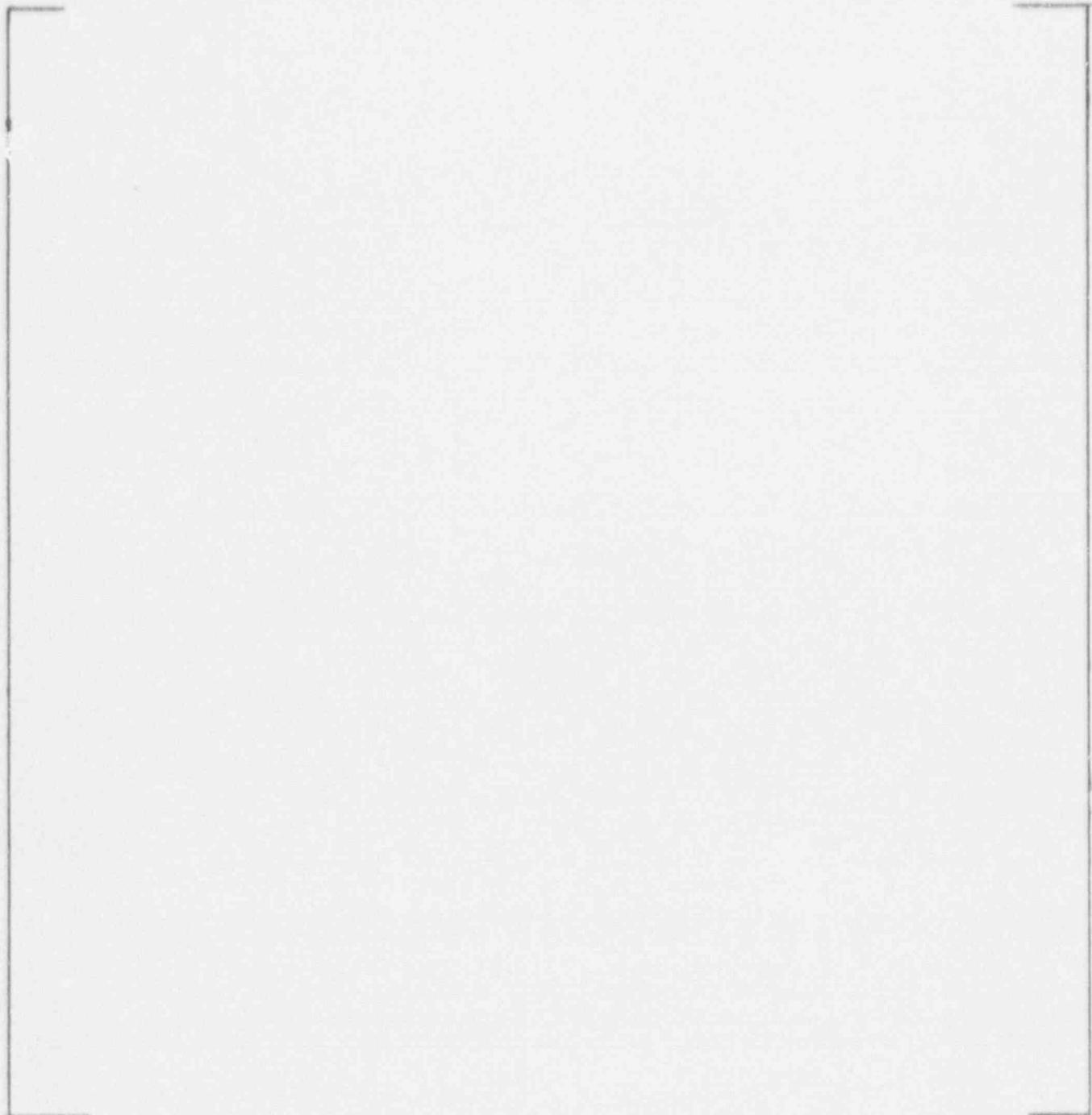


Figure 2-16. Case 4 (Top Half Step): Temperature Profile at Pressurizer Elbow



Figure 2-17. Case 5: Axial and Diametric Temperature Profile

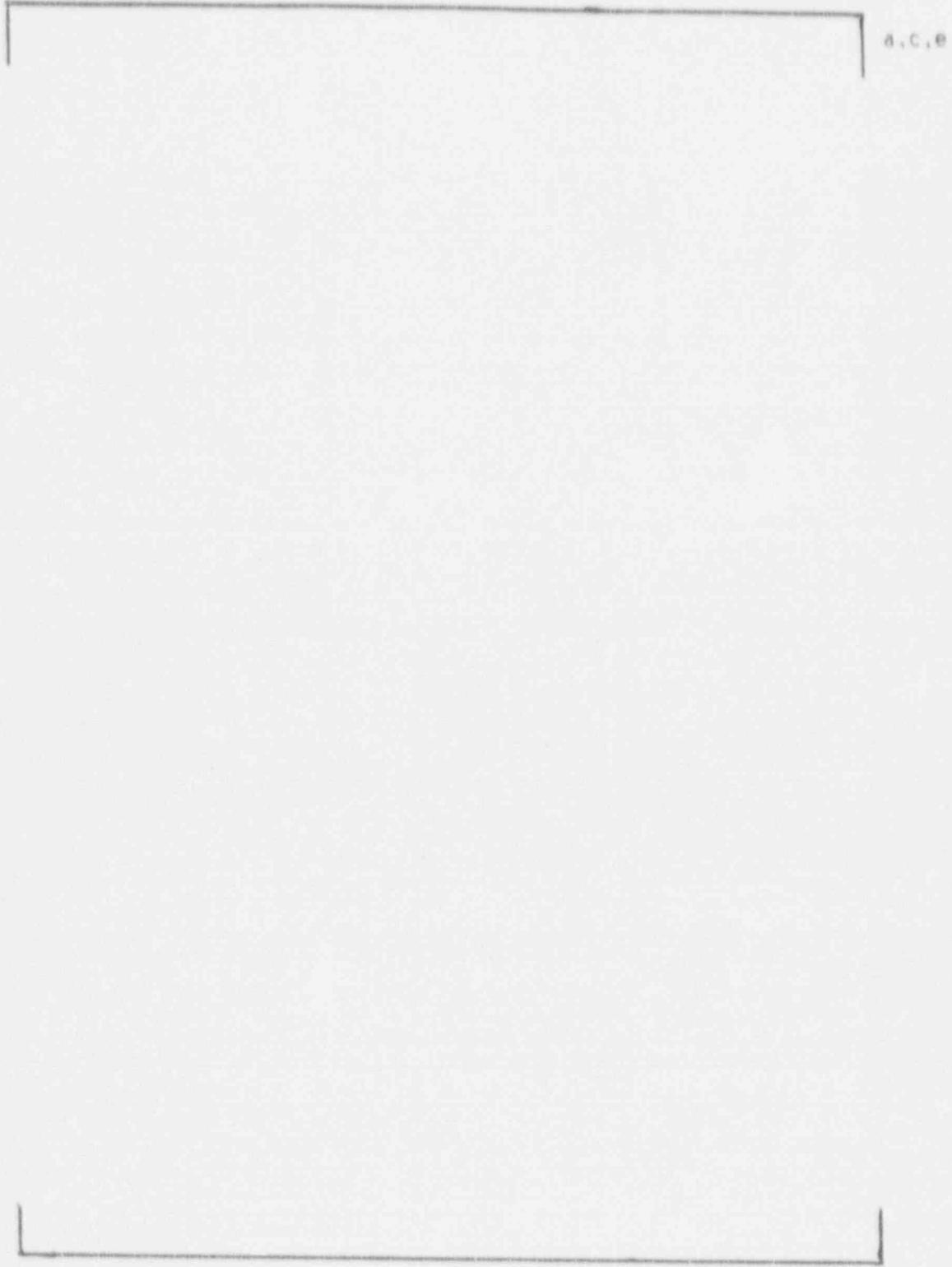


Figure 2-18. Case 5: Axial and Diametric Temperature Profile at Hot Leg Nozzle

#1216-011790 10

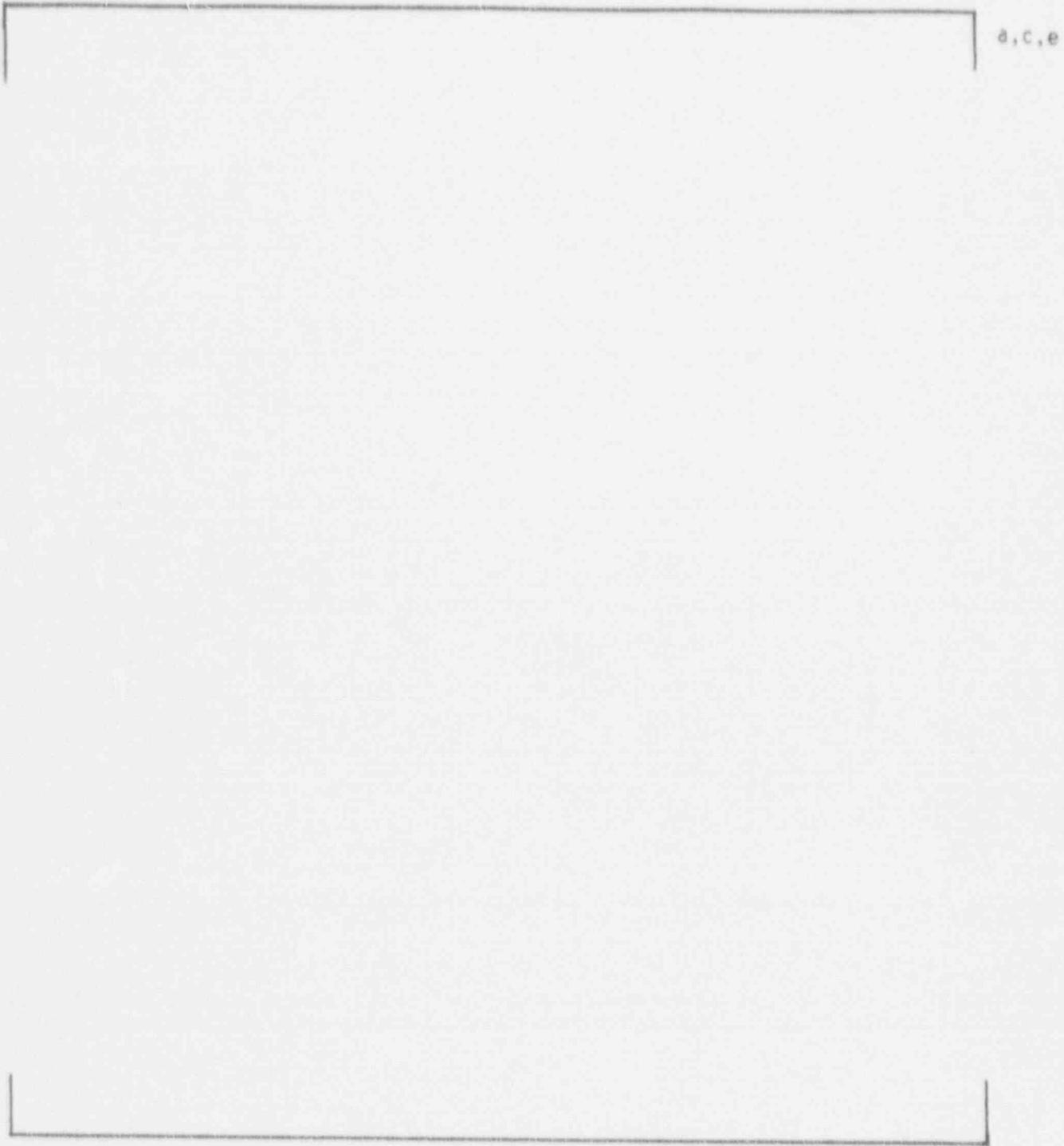


Figure 2-19. Case 5: Axial and Diametric Temperature Profile at Pipe Bend

a, c, e

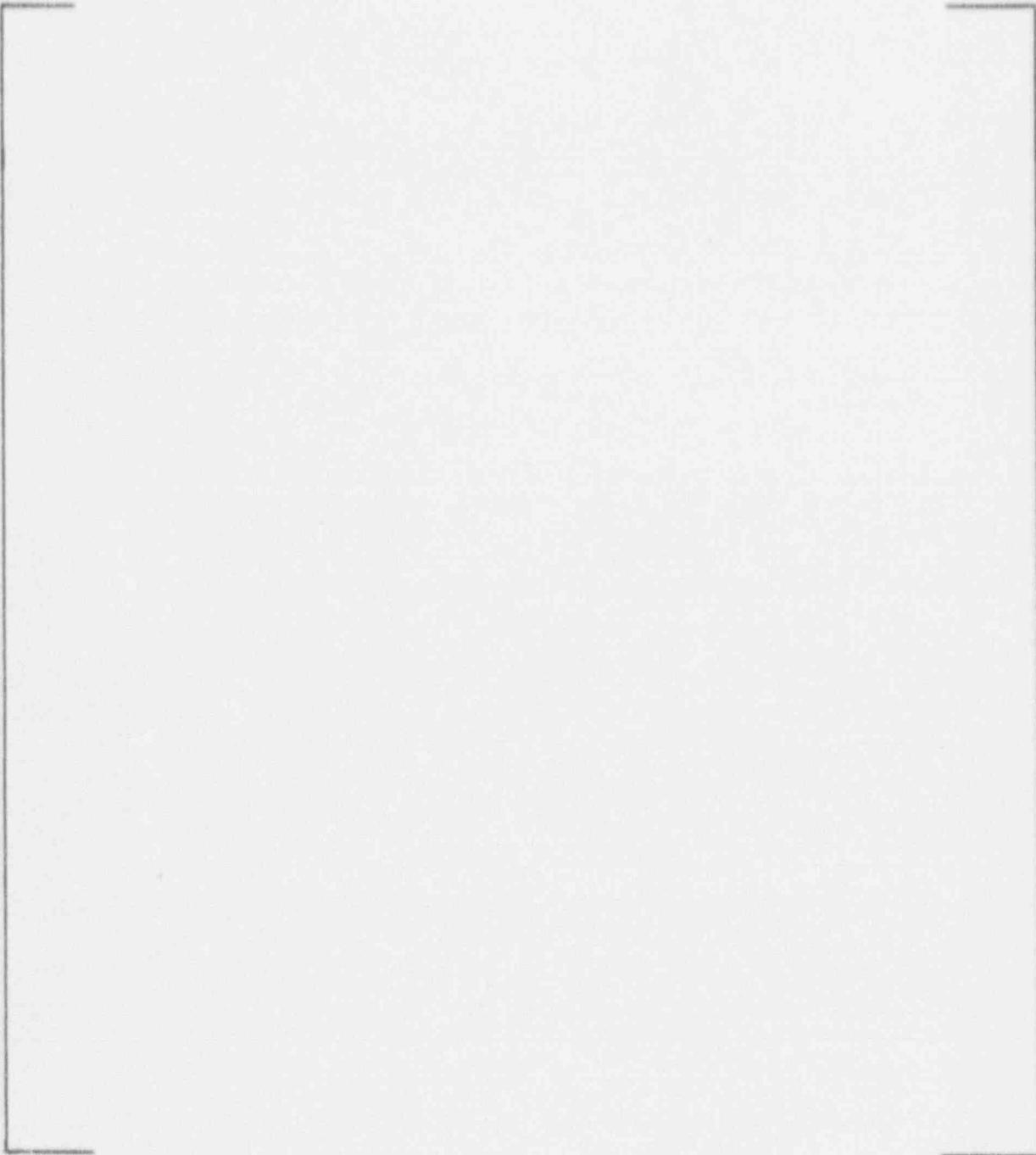


Figure 2-20. Case 5: Axial and Diametric Temperature Profile at Pressurizer Elbow

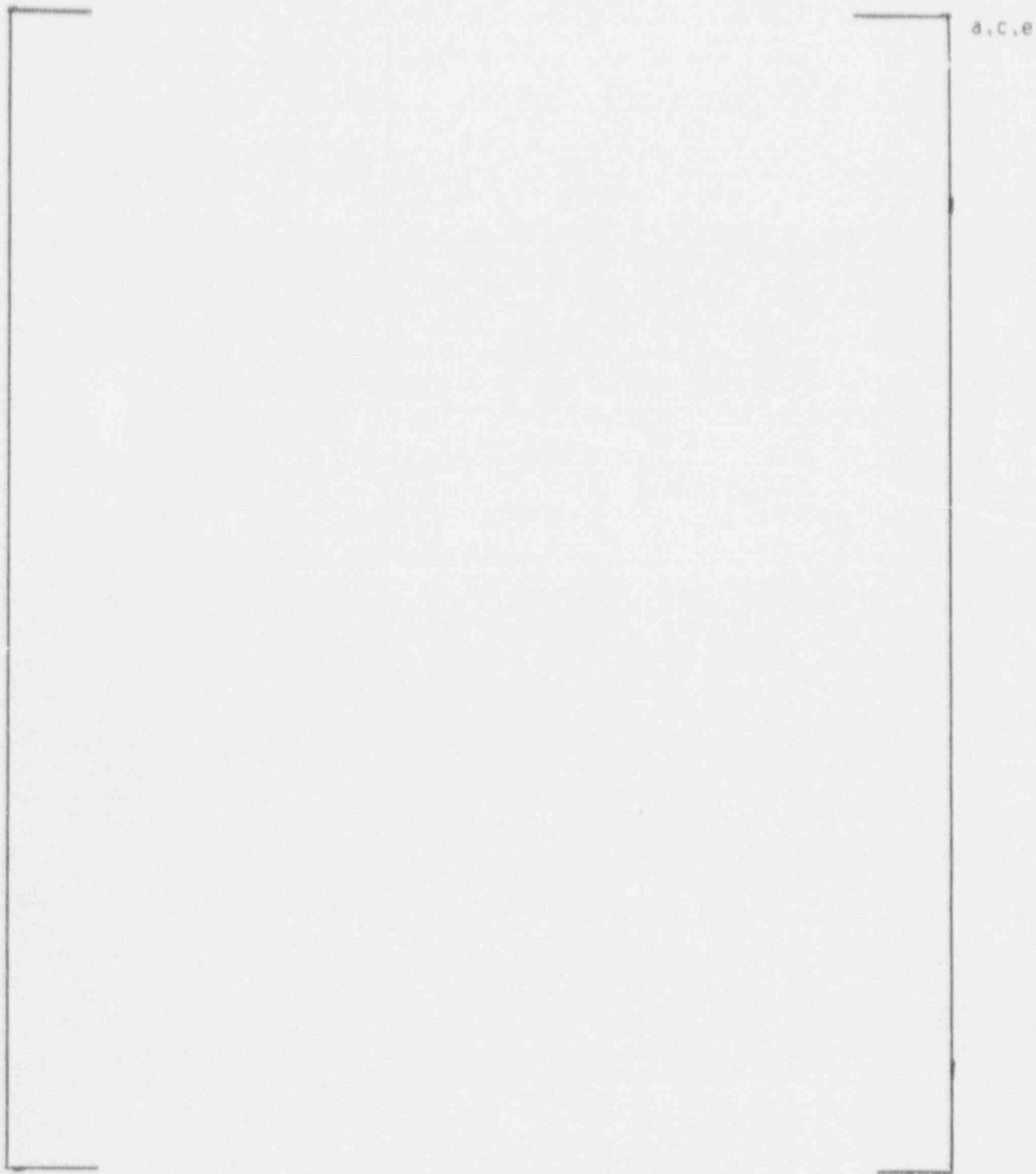


Figure 2-21. [

]a.c.e Profile

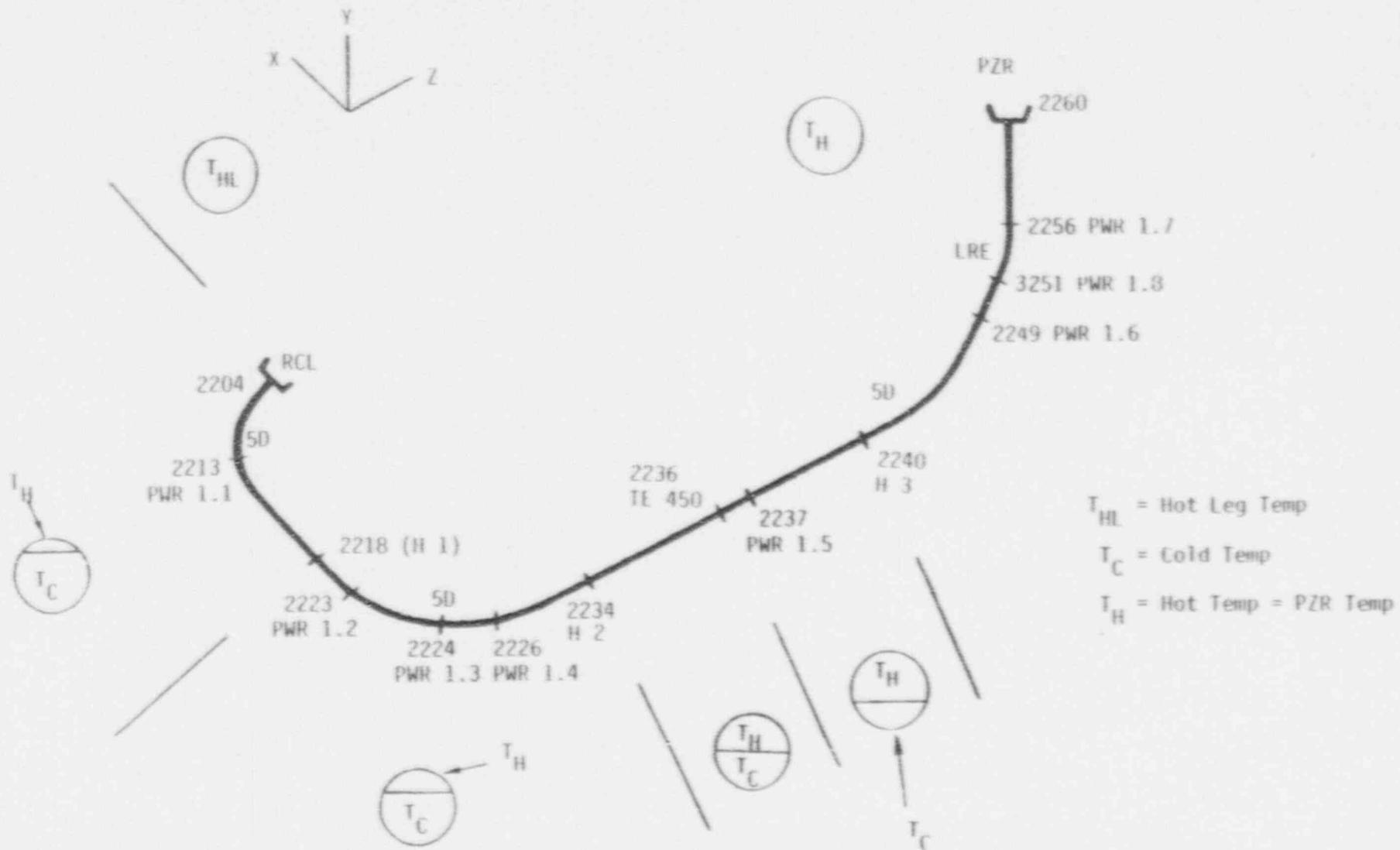


Figure 2 22. Trojan Surge Line Model and Temperature Profile

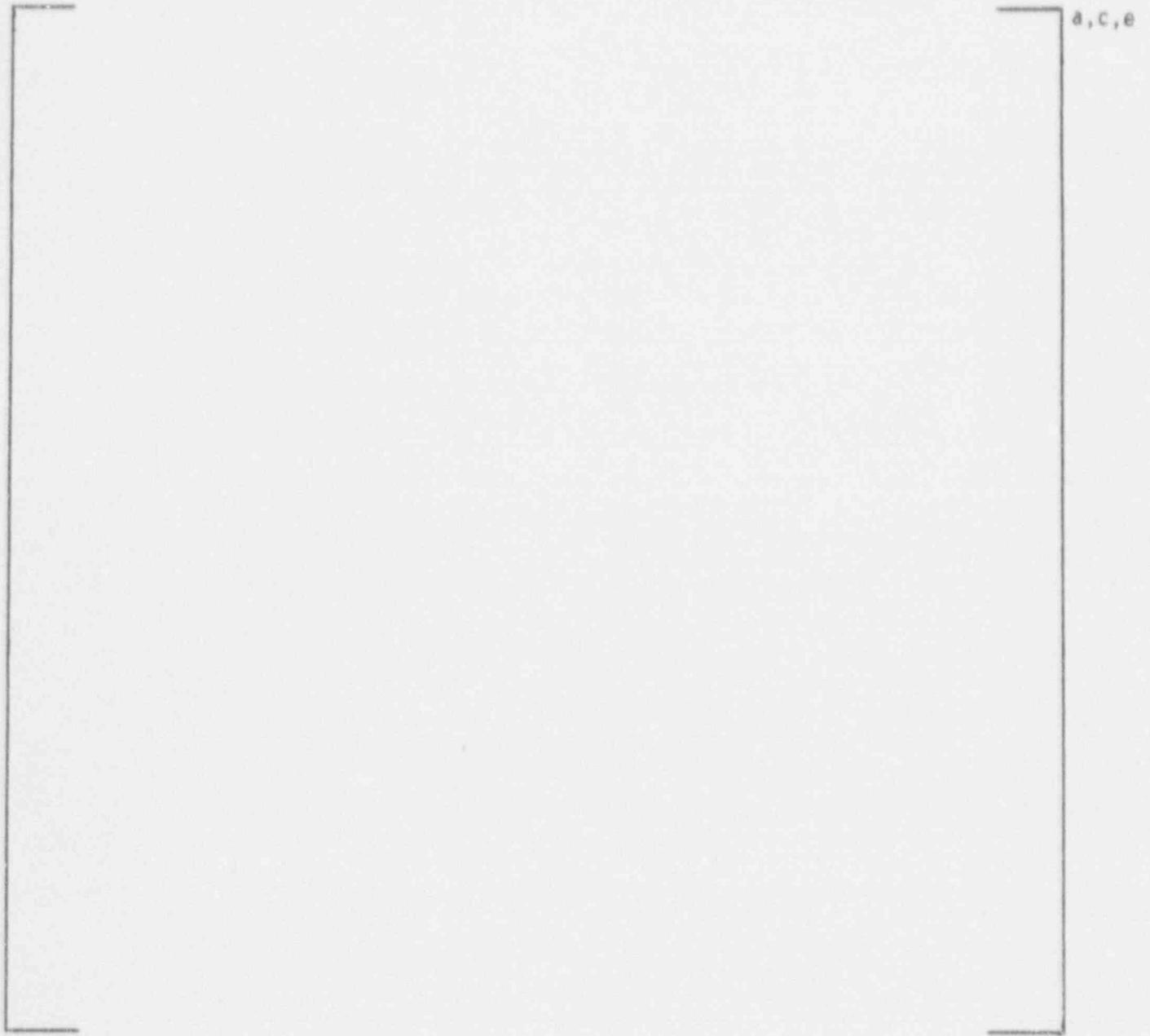


Figure 2-23: Equivalent Linear Temperature

2-57



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

a, c, e

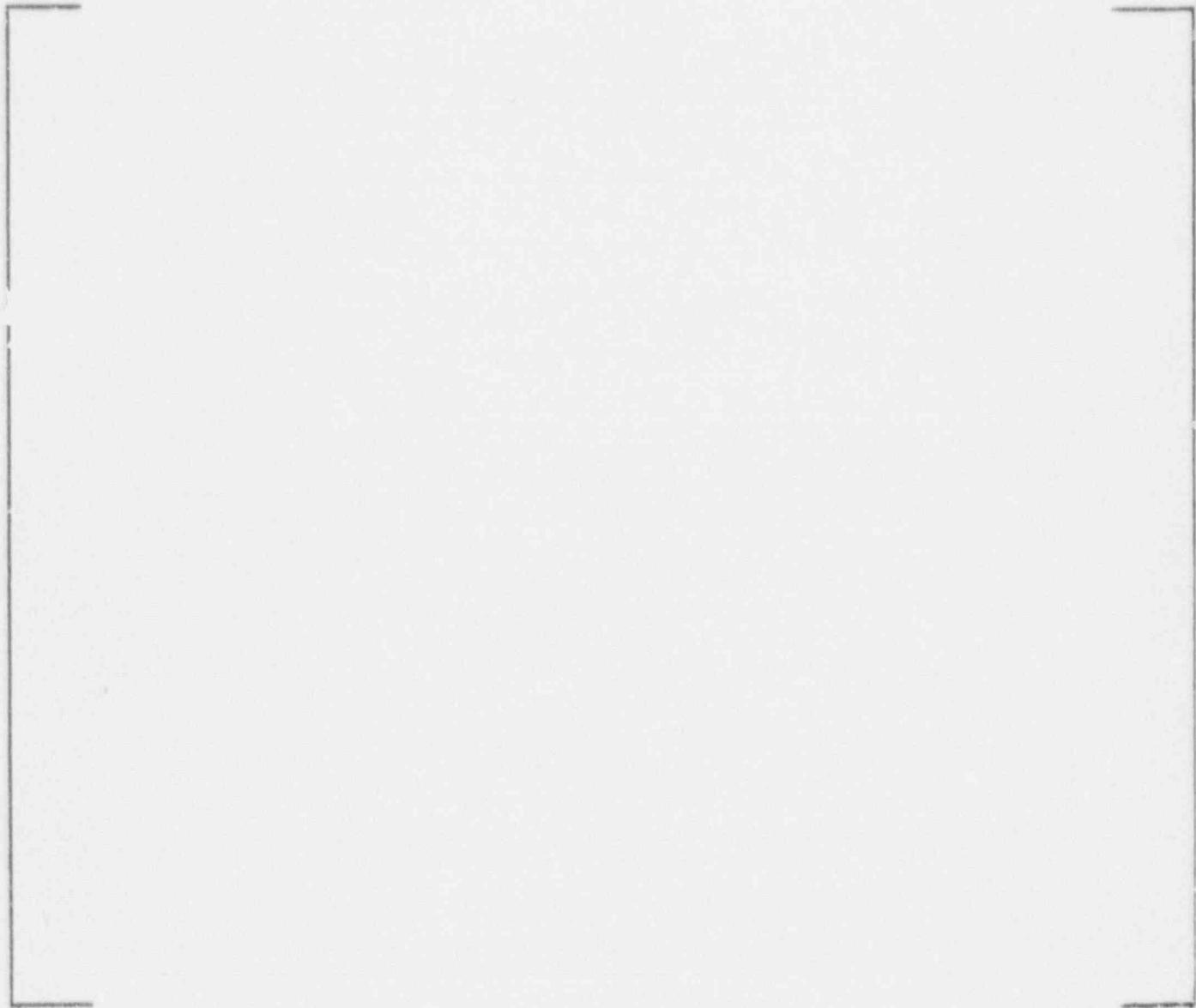


Figure 2-25. Independence of Local and Structural Thermal Stratification Stresses Permitting Combination by Superposition

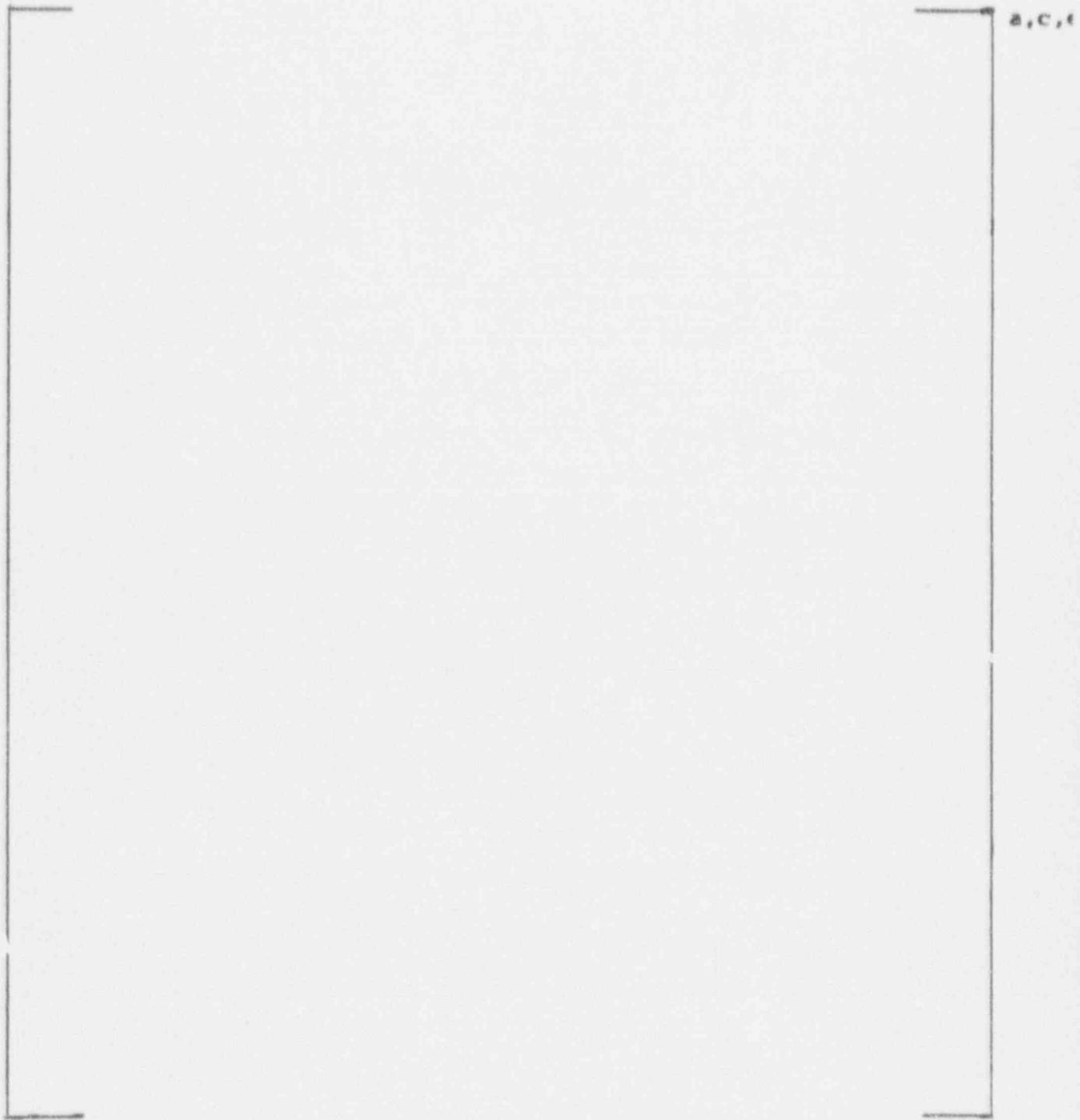


Figure 2-26. Test Case for Superposition of Local and Structural Stresses

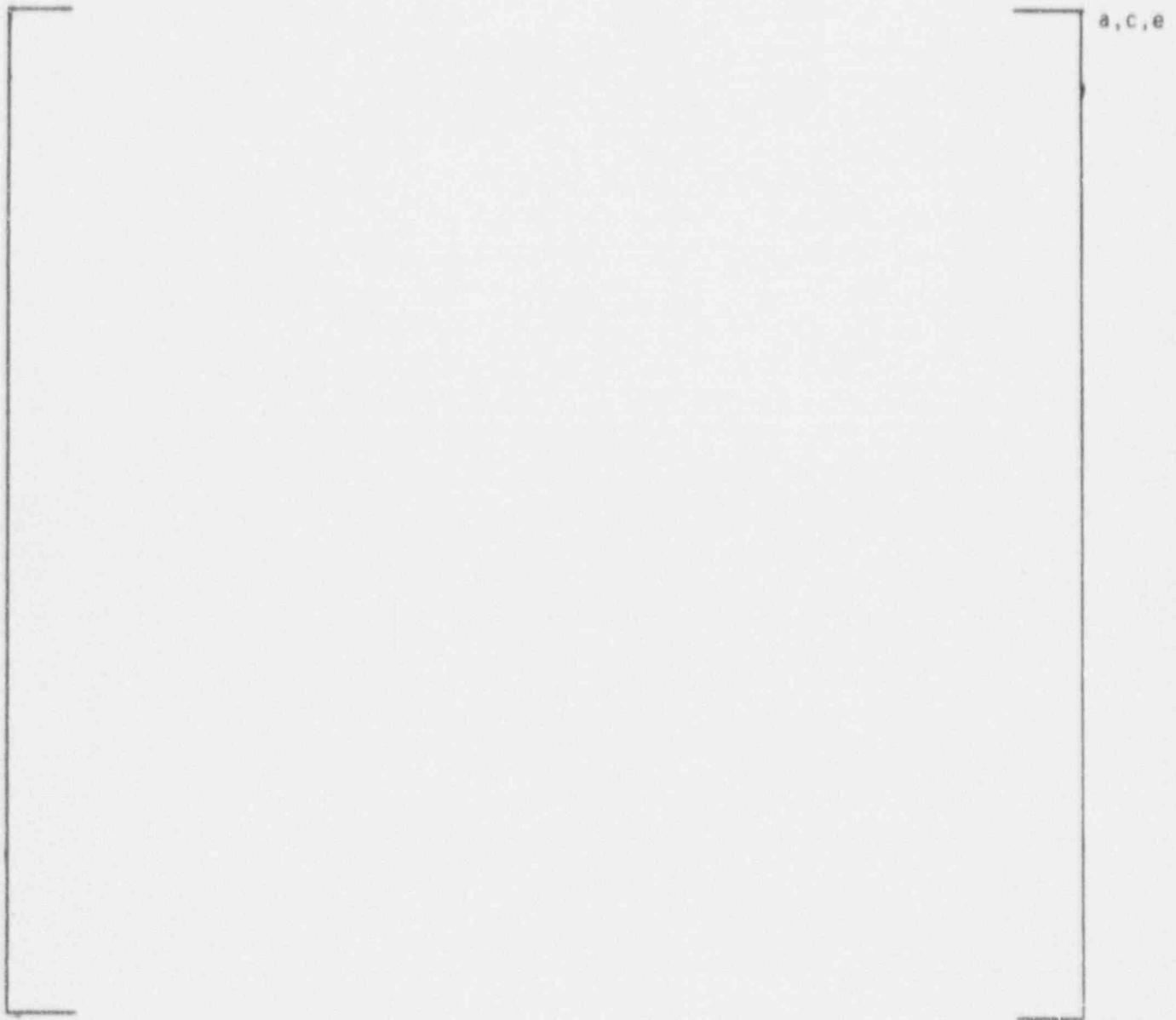


Figure 2-27. Local Stress - Finite Element Models/Loading

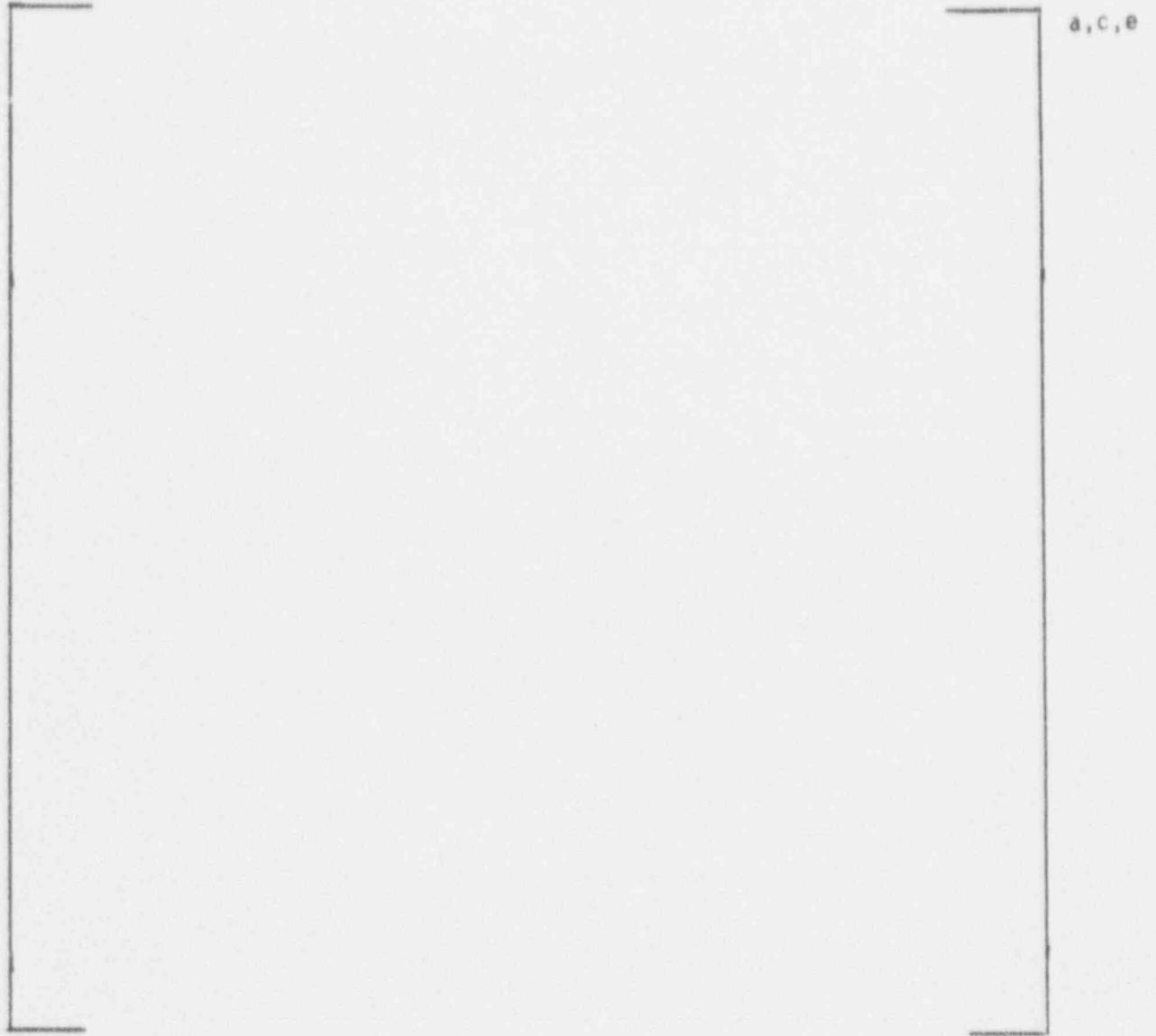


Figure 2-28. Piping Local Stress Model and Thermal Boundary Conditions

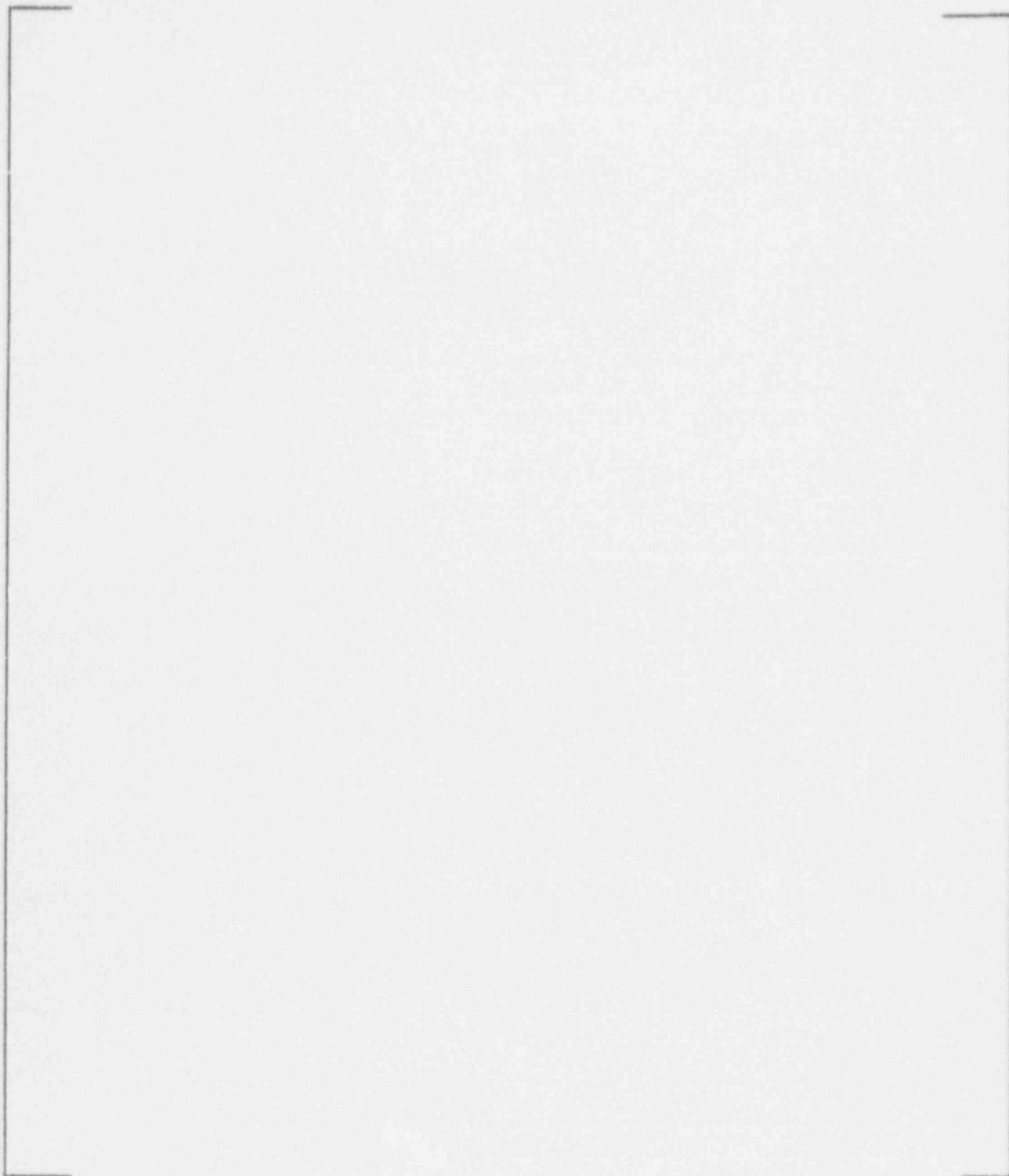


Figure 2-29. Surge Line Temperature Distribution at []^{a,c,e} Axial Locations

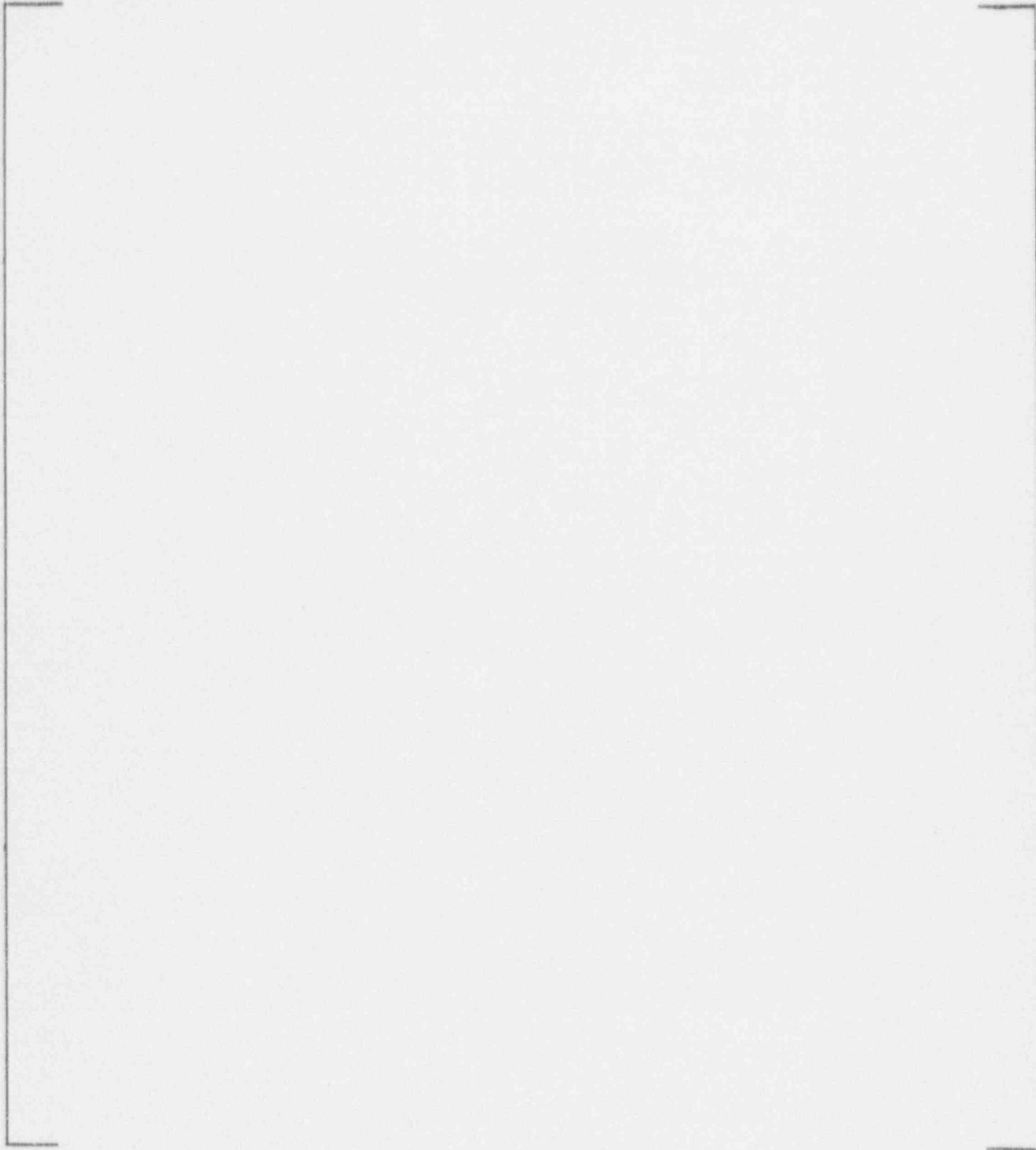


Figure 2-30. Surge Line Local Axial Stress Distribution at []^{a,c,e}
Axial Locations

a.c.e

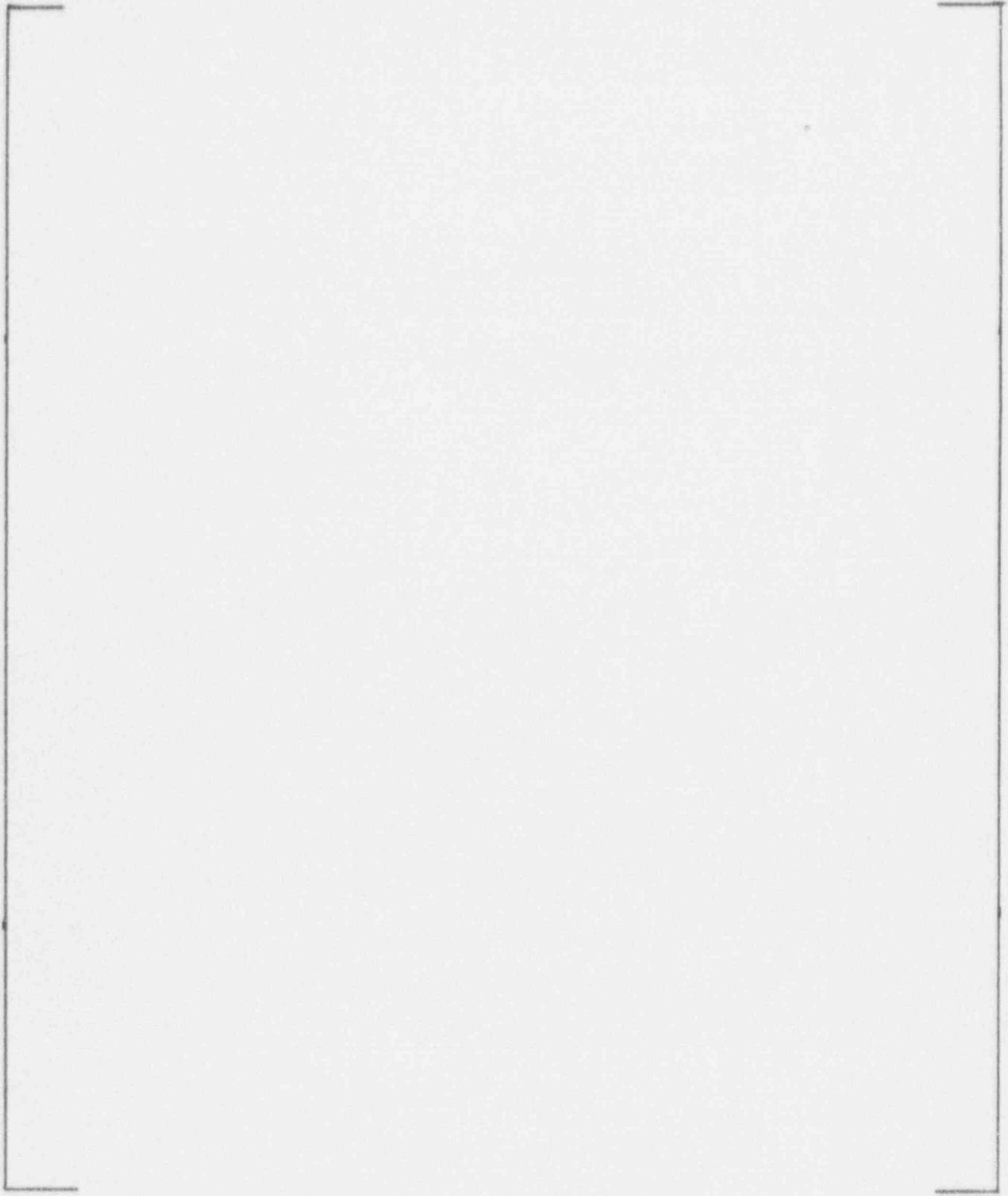


Figure 2-31. Surge Line Local Axial Stress on Inside Surface at []^{a.c.e} Axial Locations

a, c, e

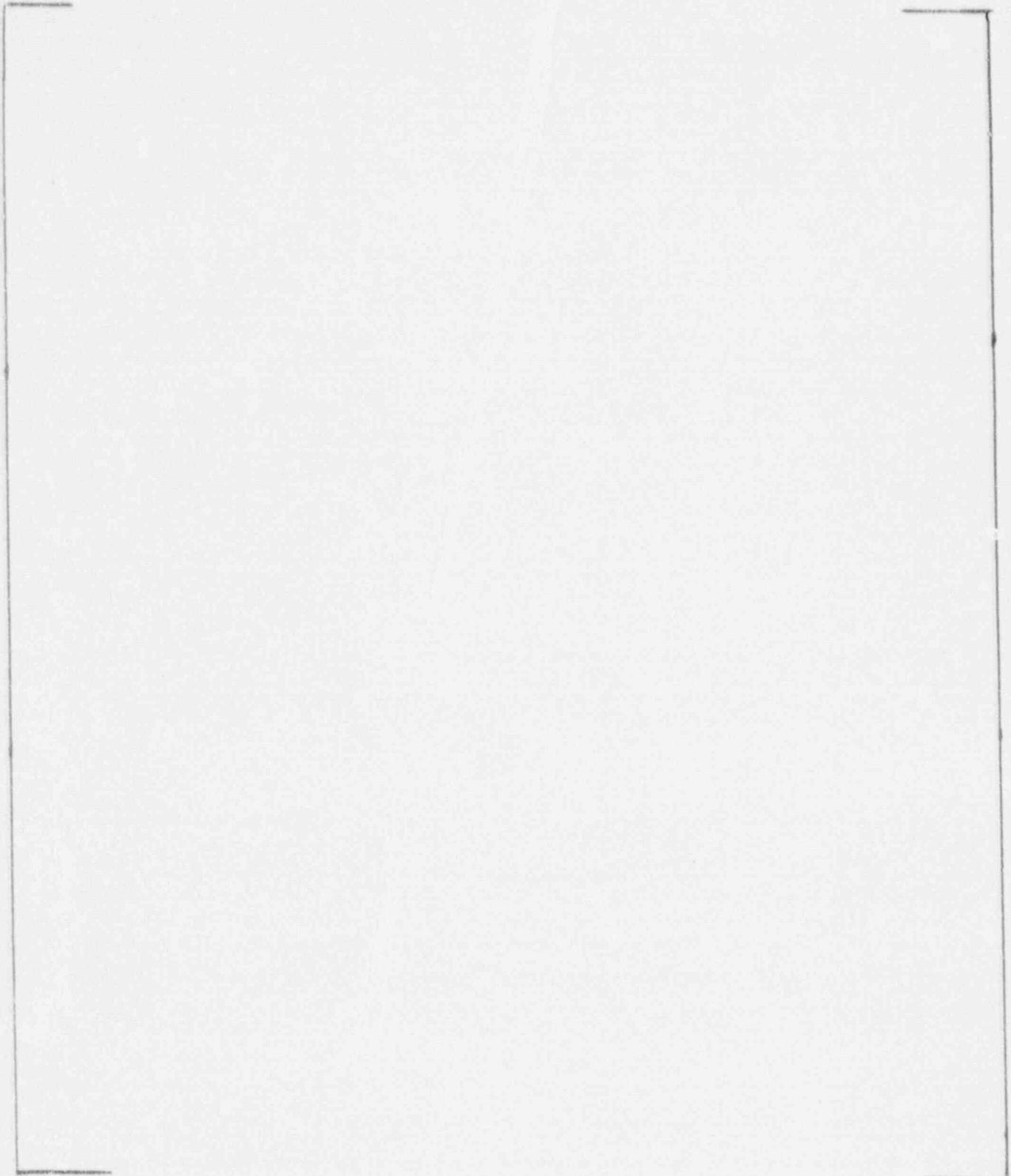


Figure 2-32. Surge Line Local Axial Stress on Outside Surface at []^{a, c, e} Axial Locations



a, c, e

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

41215-011790 10

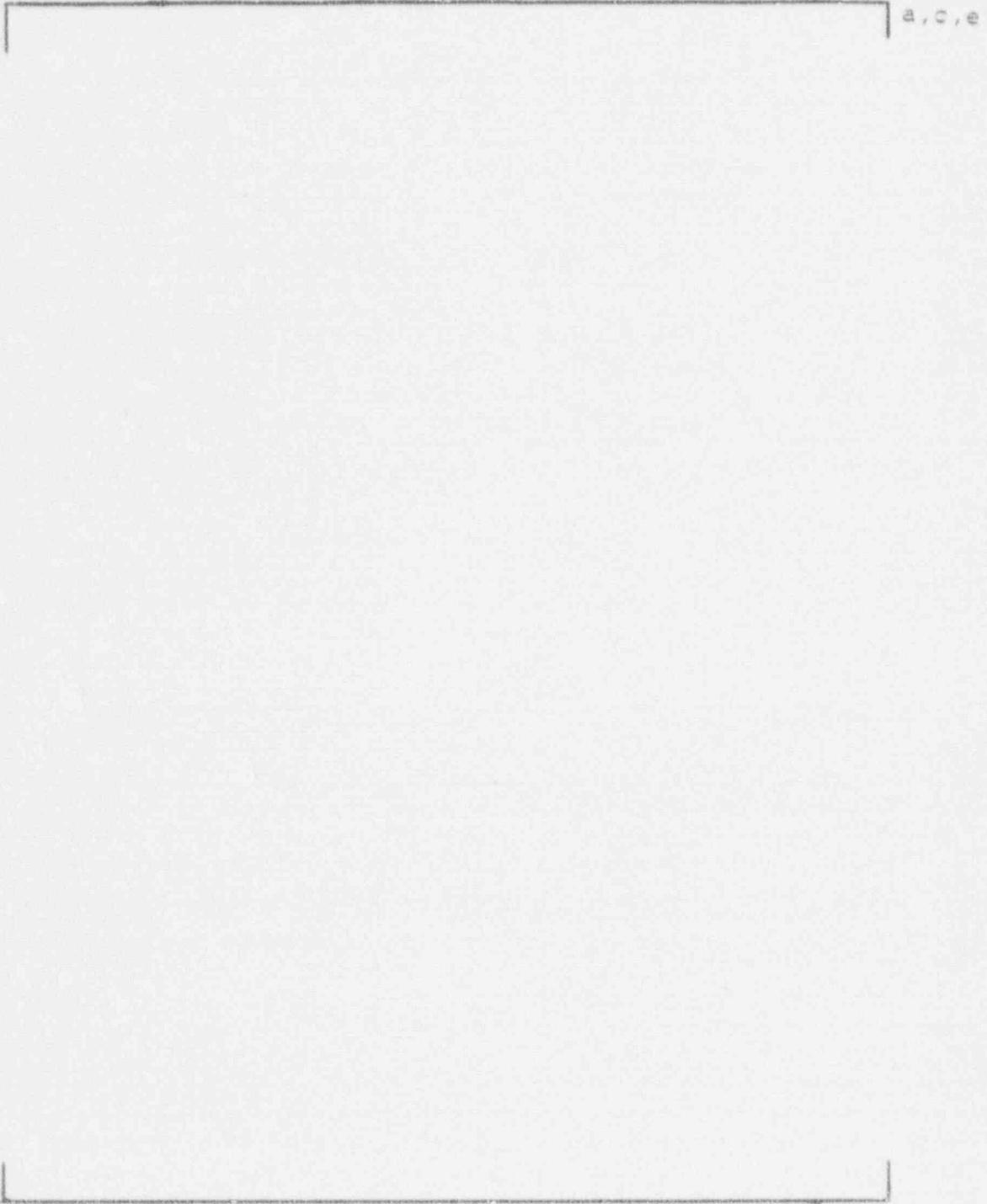


Figure 2-34. Surge Line Local Axial Stress Distribution at Location [J^{a.c.e}

2-68

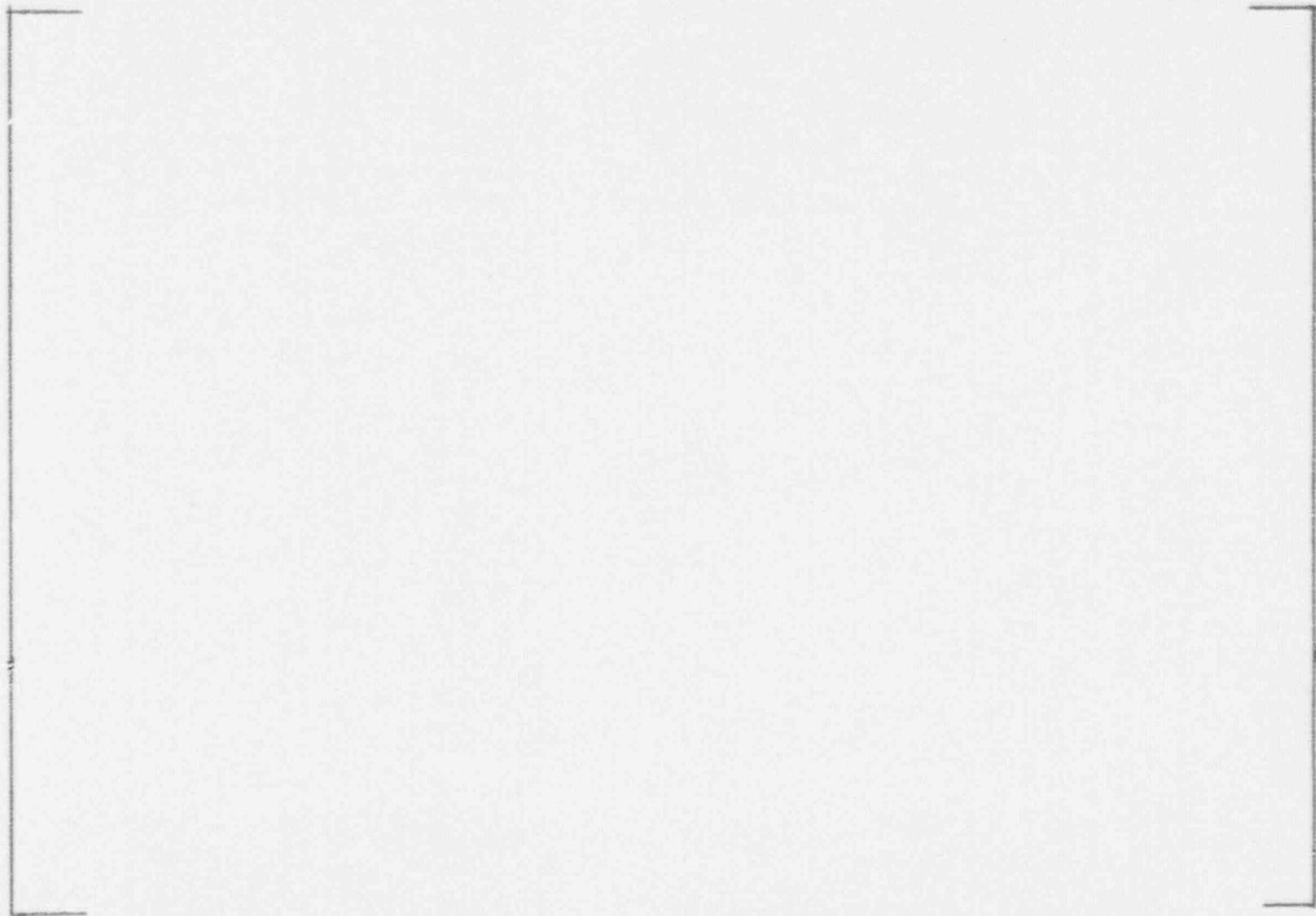


Figure 2-35. Surge Line Temperature Distribution at Location []^{a,c,e}

a,c,e

69-2

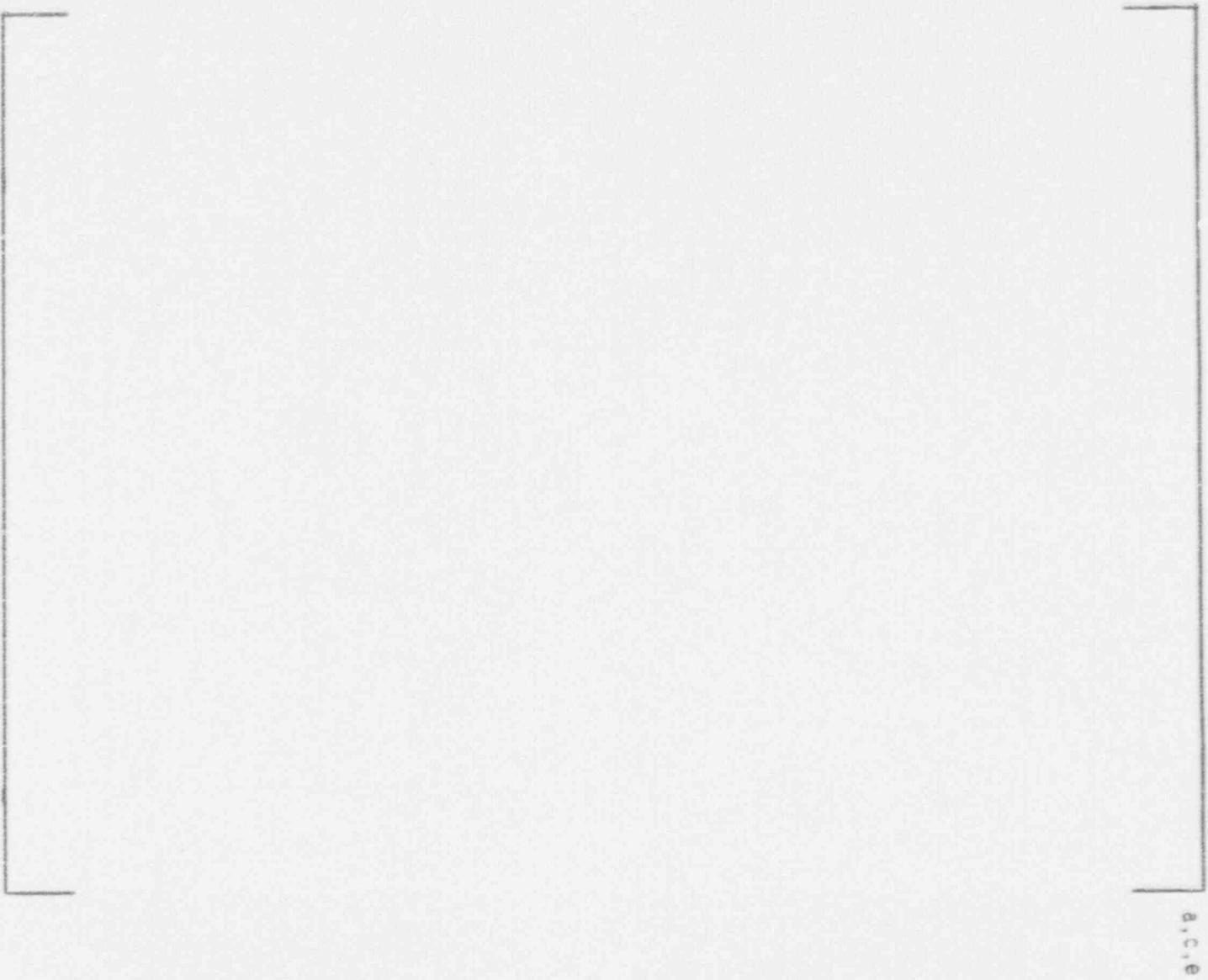


Figure 2-36. Surge Line Local Axial Stress Distribution at Location []^{a,c,e}



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

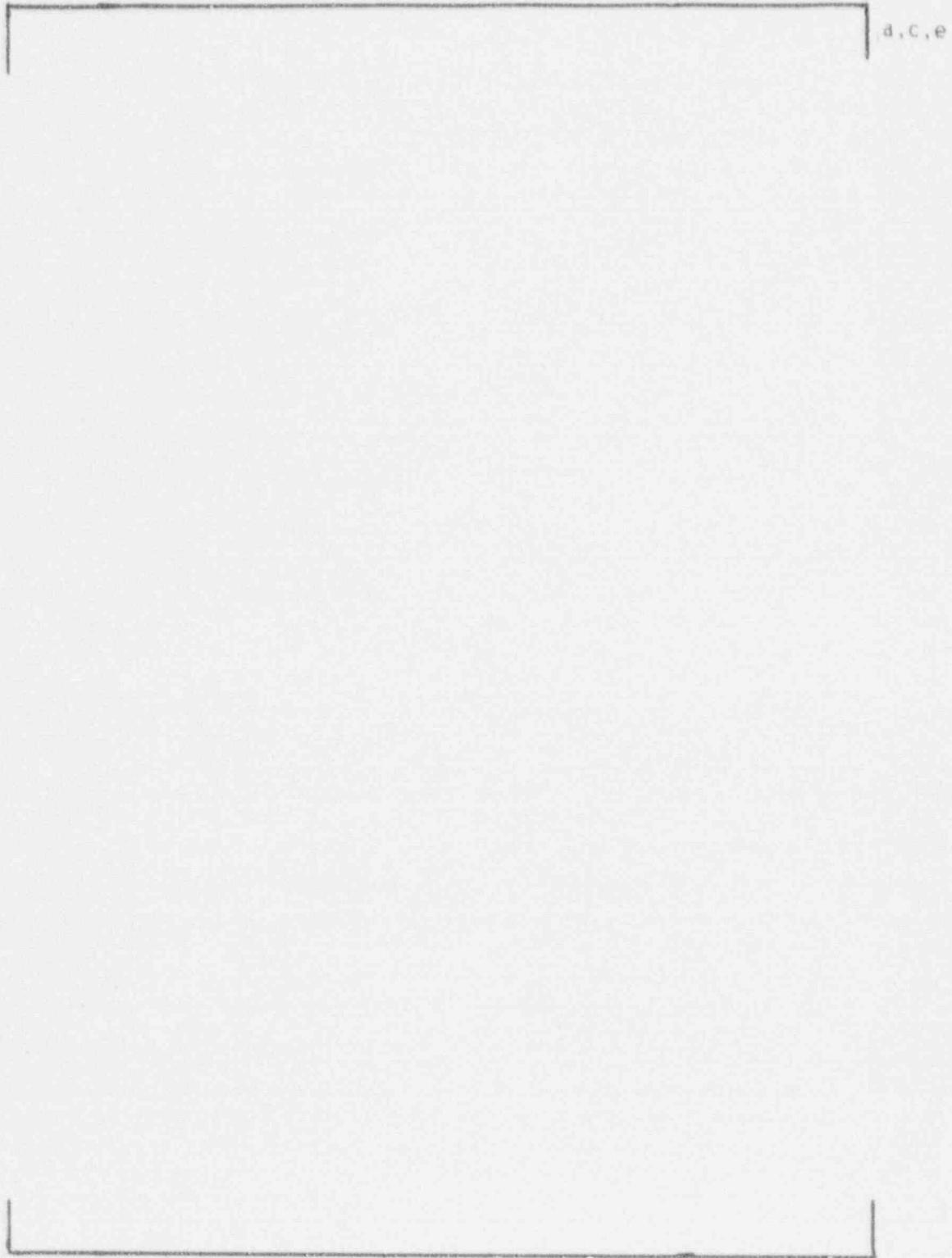


Figure 2-38. Surge Line Local Axial Stress Distribution at Location [$J^{a,c,e}$]

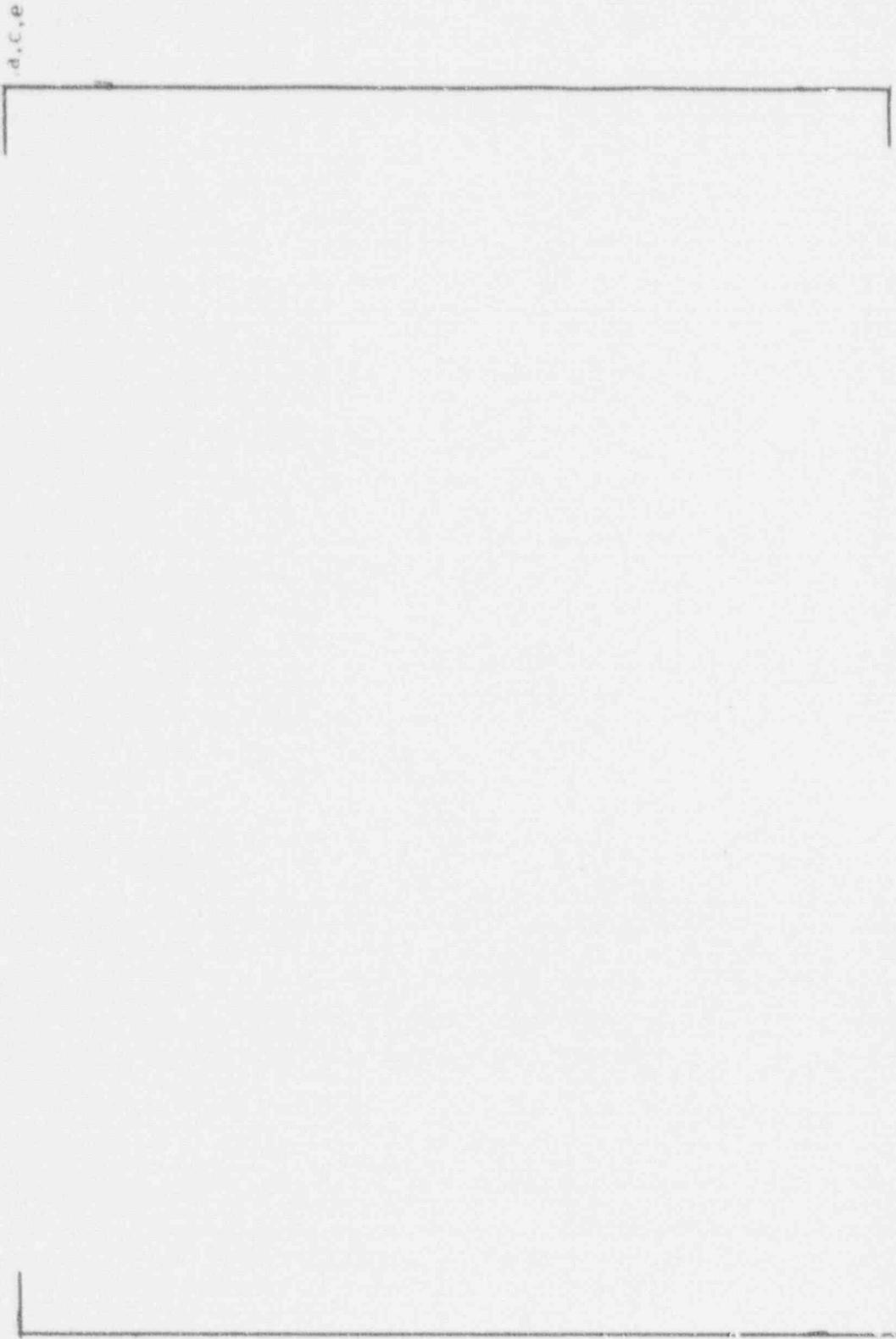


Figure 2-39. Surge Line Temperature Distribution at Location [$J^{a,c,e}$]

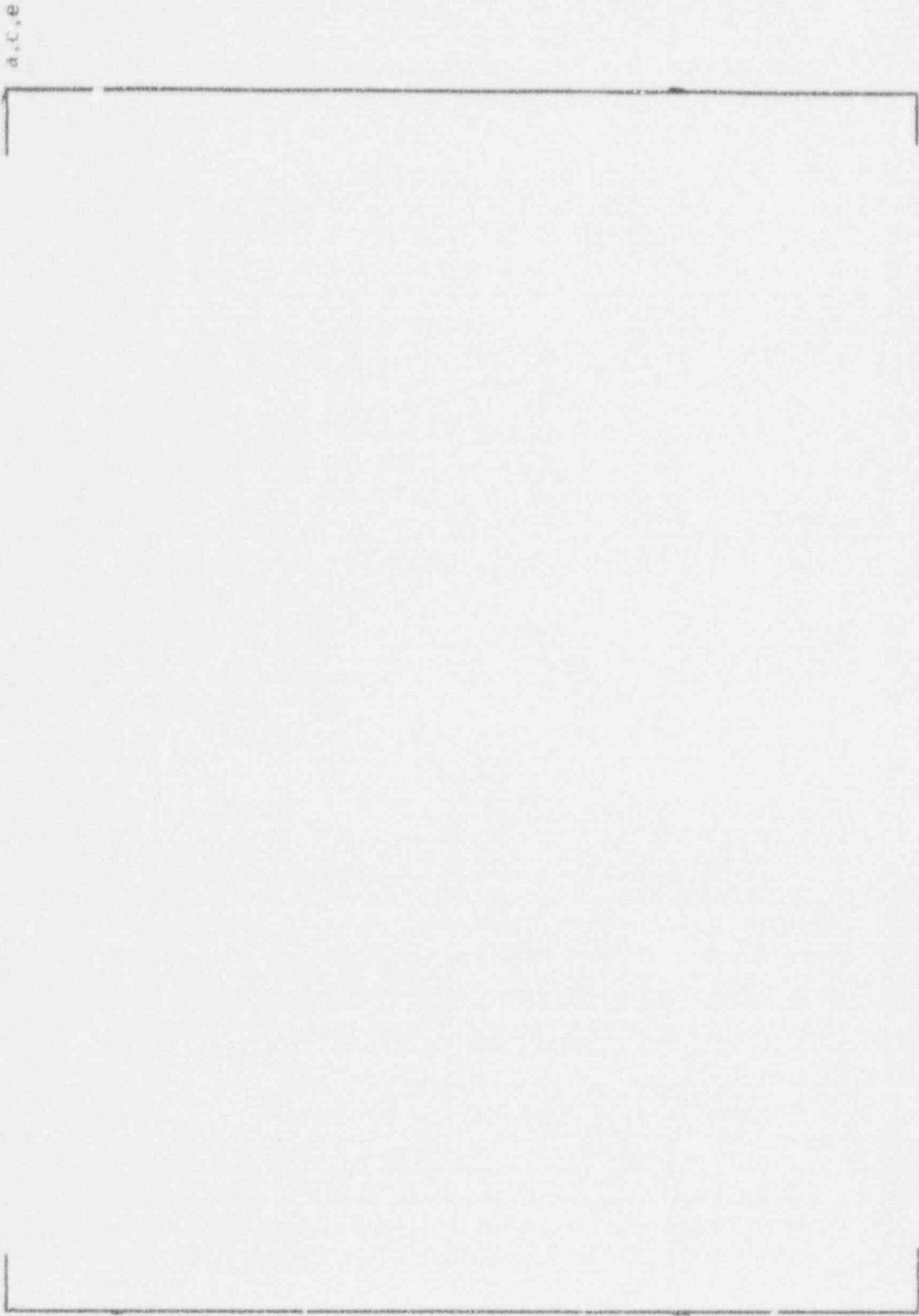


Figure 2-40. Surge Line Local Axial Stress Distribution at Location []^{a, c, e}



a, c, e

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

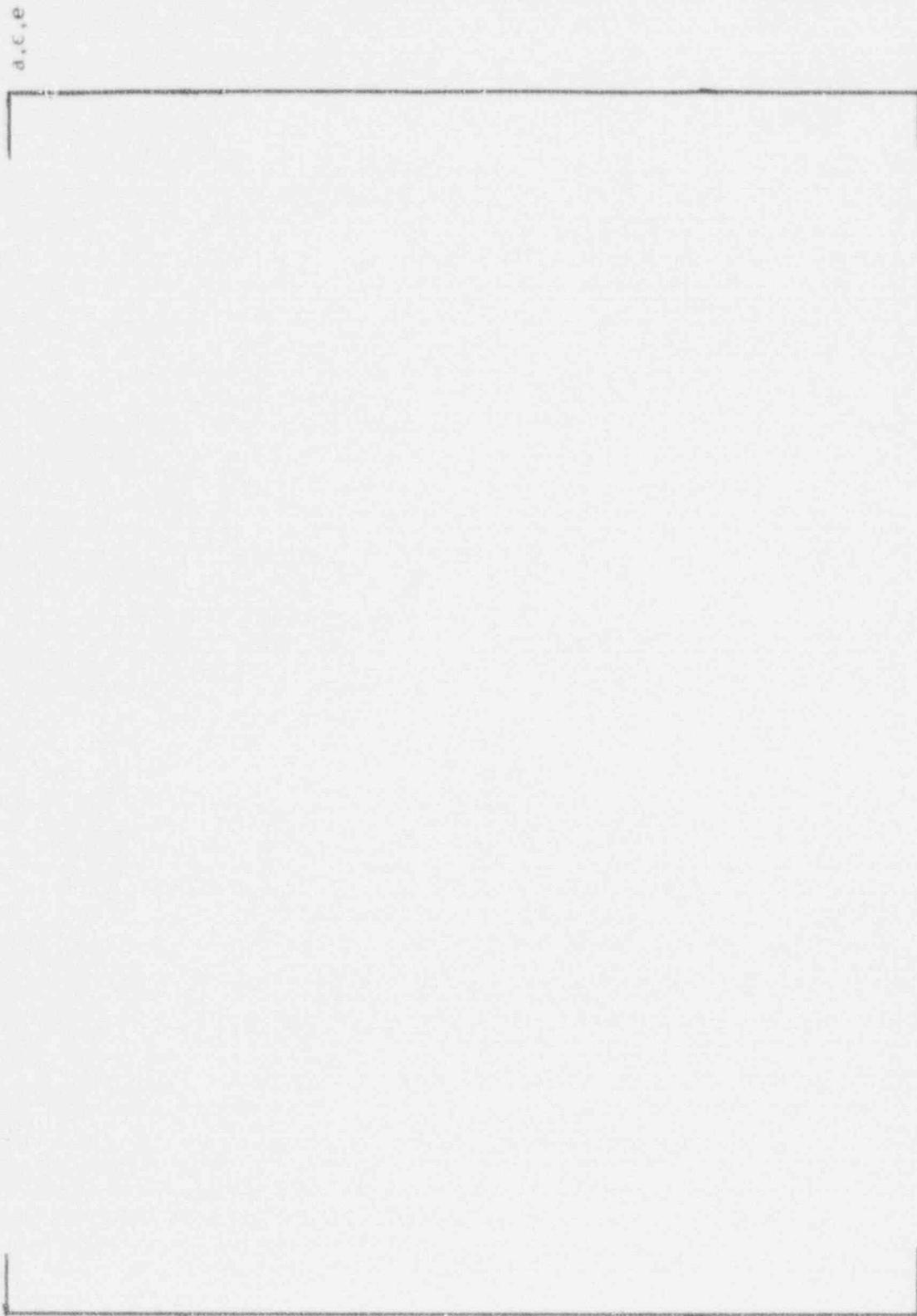


Figure 2-42. Surge Line Local Axial Stress Distribution at Location [$j^{a, c, e}$

2-76

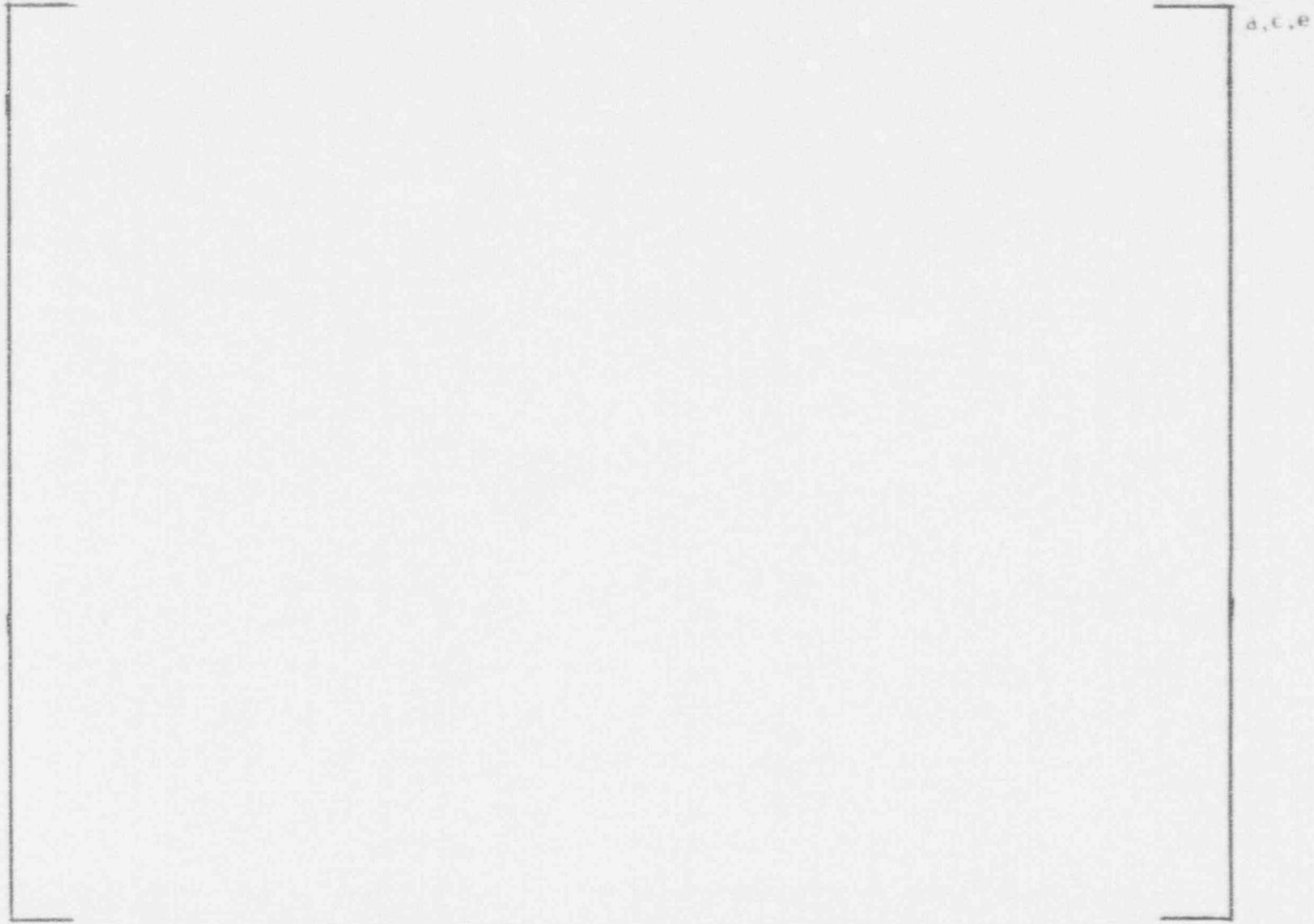


Figure 2-43. Surge Line RCL Nozzle 3-D WECAN Model #1

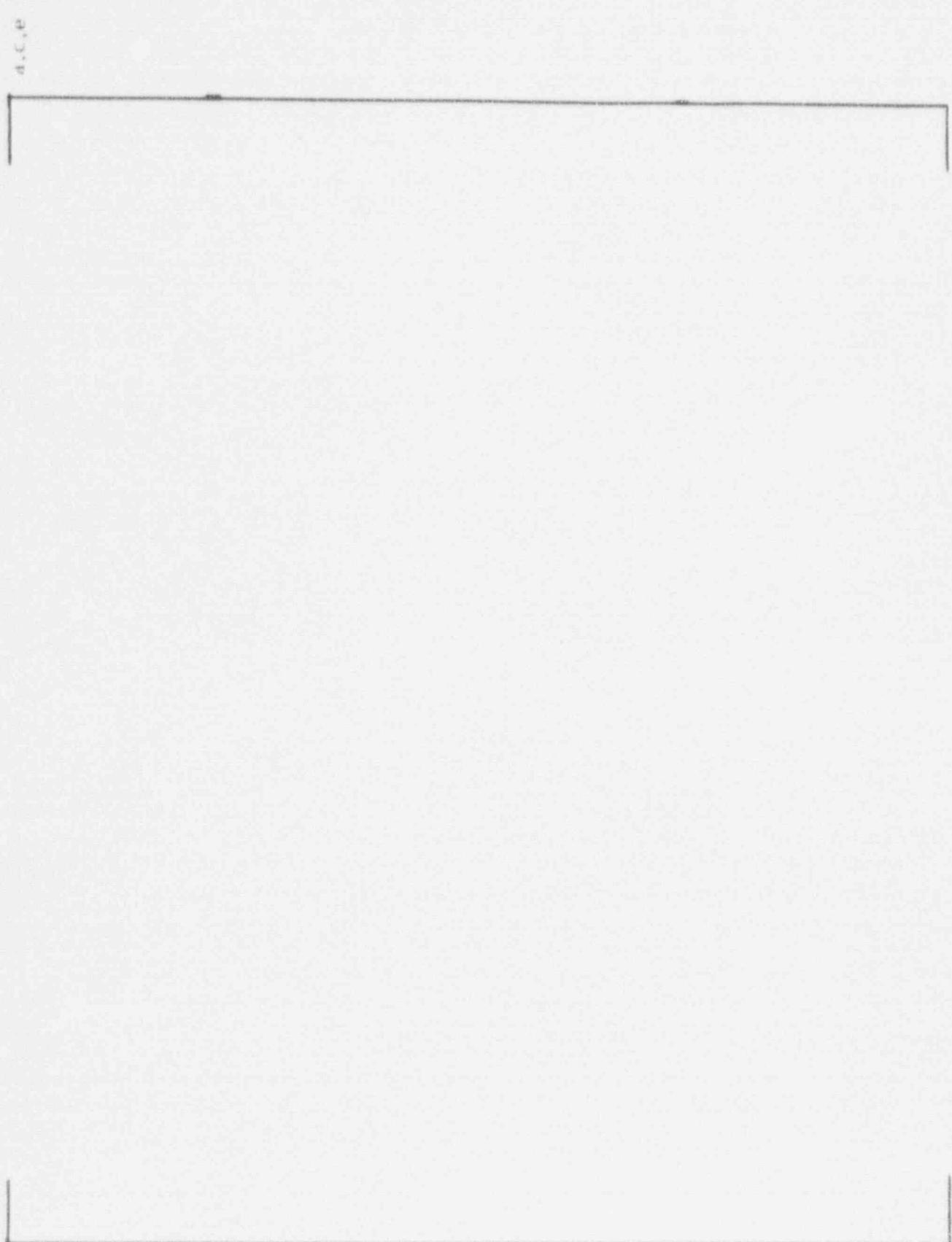
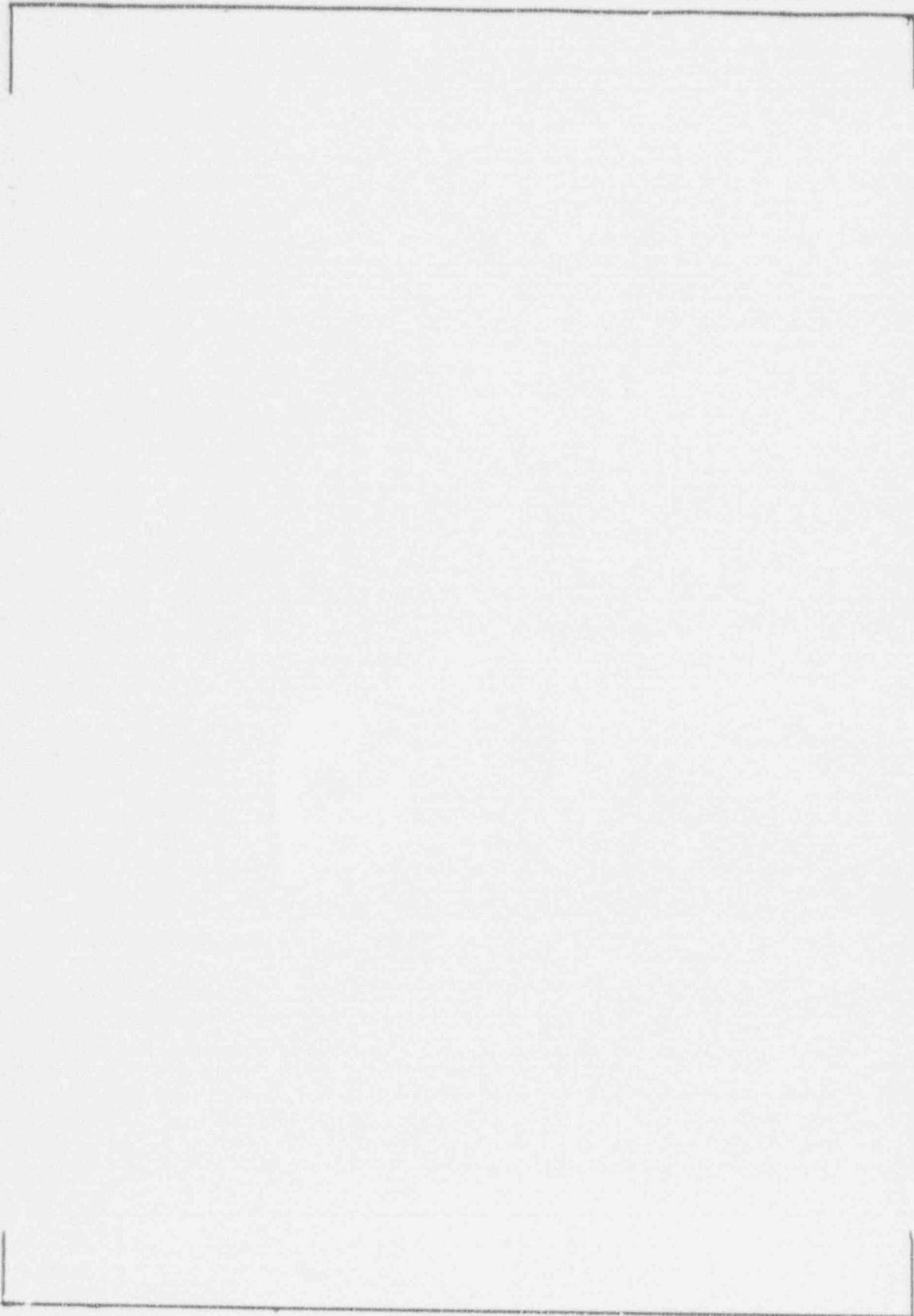


Figure 2-44. Surge Line RCL Nozzle 3-D WECAN Model #2

2-78

a.c.c.e

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



d.c.e

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

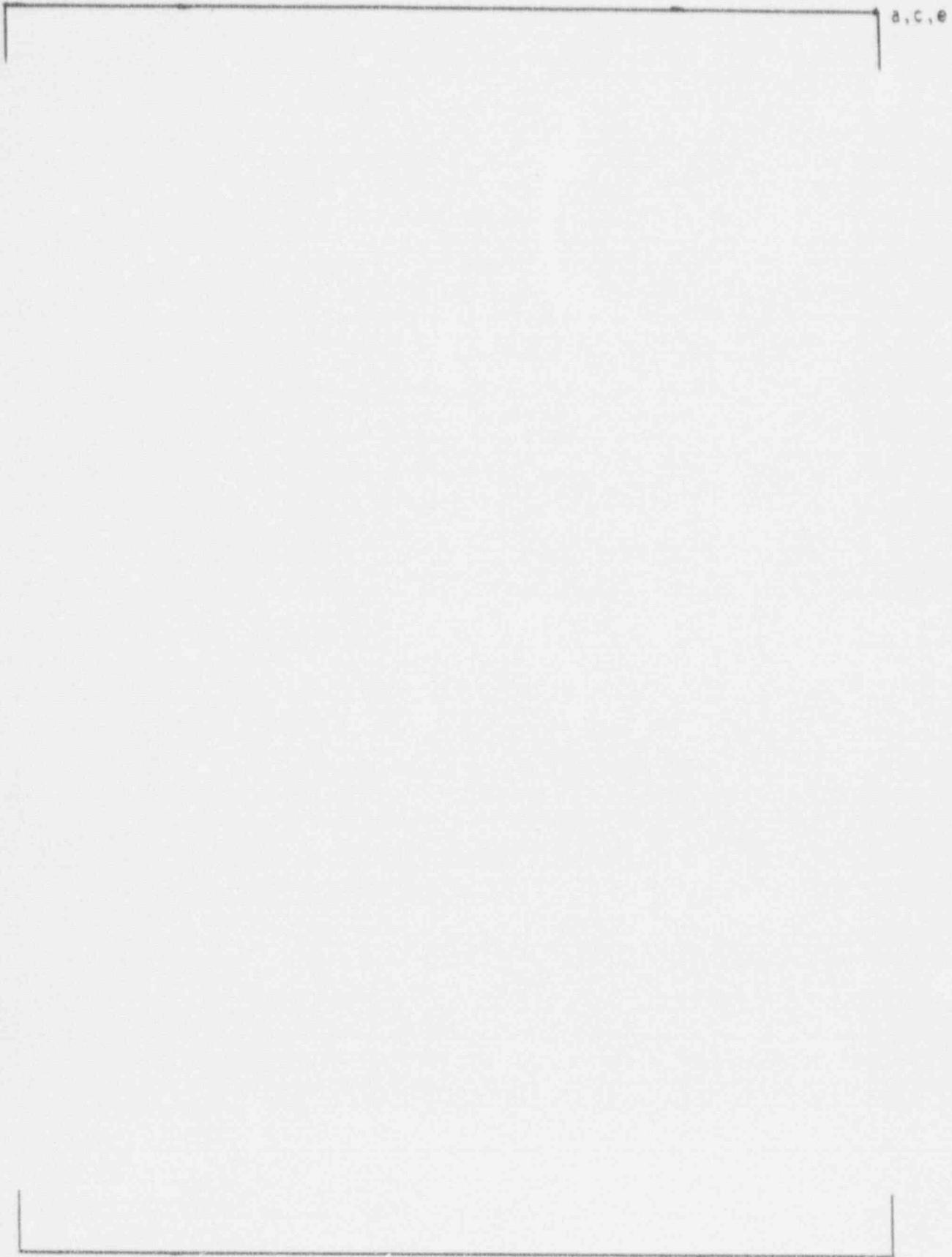


Figure 2-47. Surge Line Nozzle Stress in Direction Axial to Surge Line Due to Thermal Stratification

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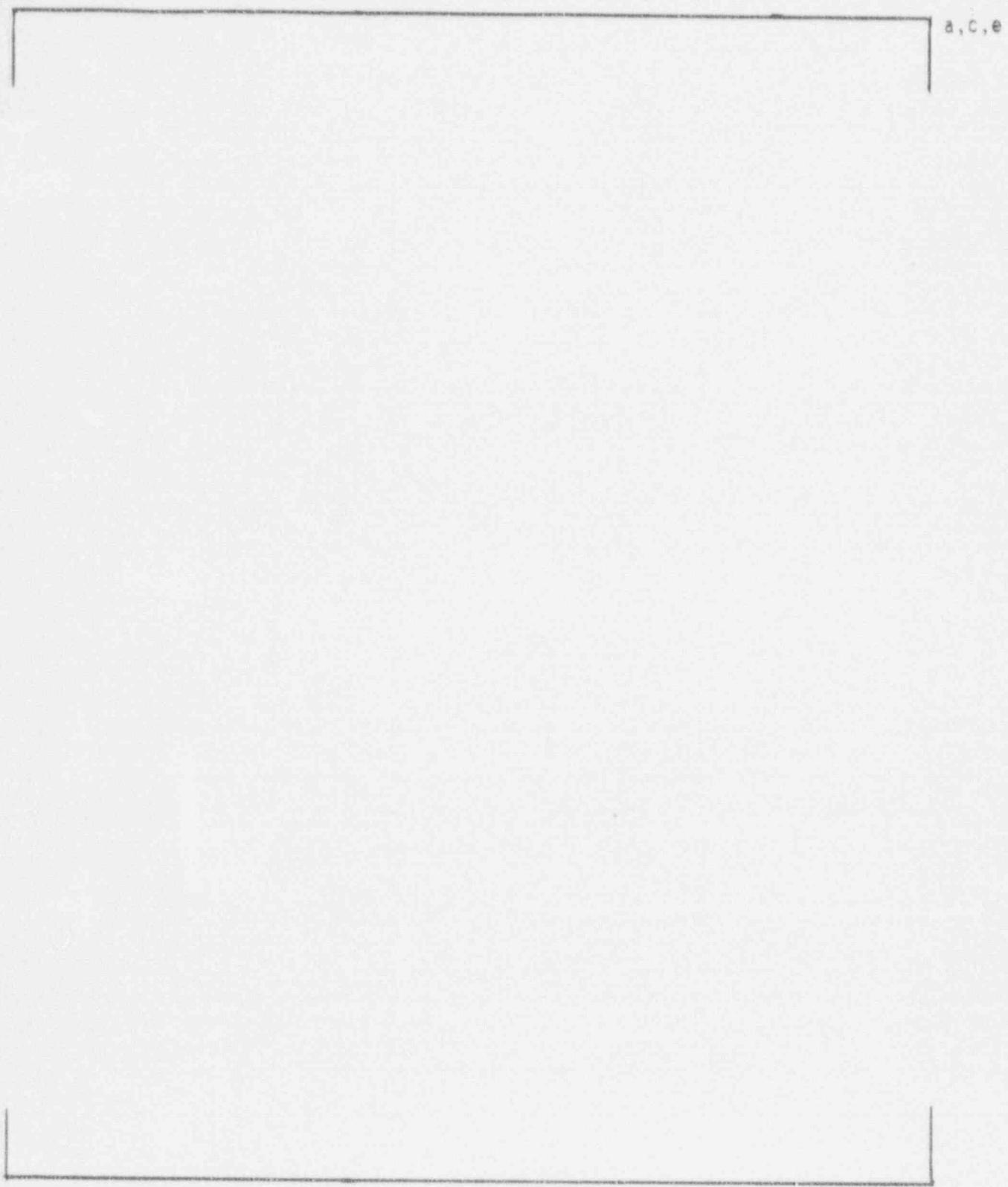
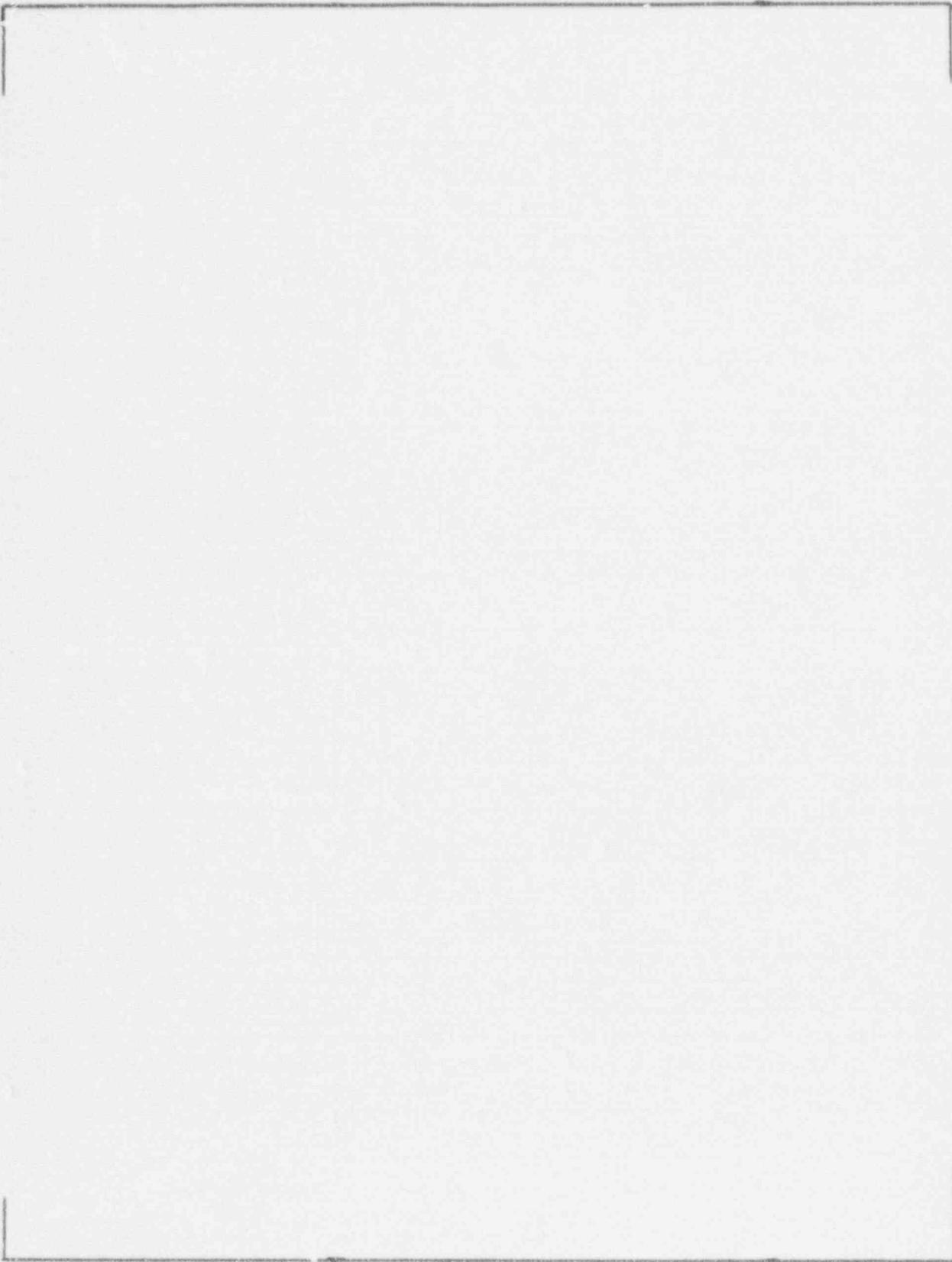


Figure 2-48. Surge Line Nozzle Stress Intensity Due to Pressure



a, c, e

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

41774-011/550 10

a, c, e

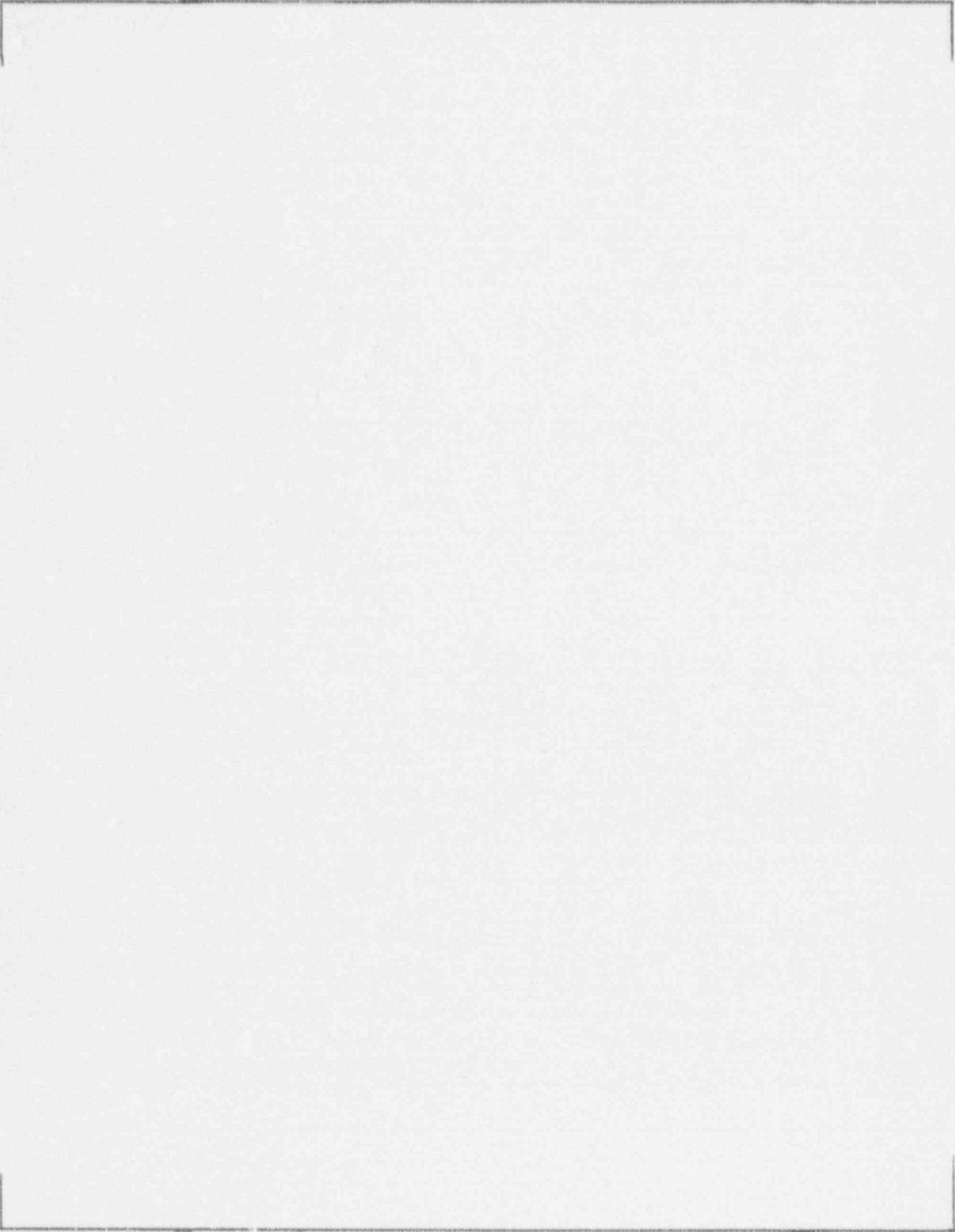
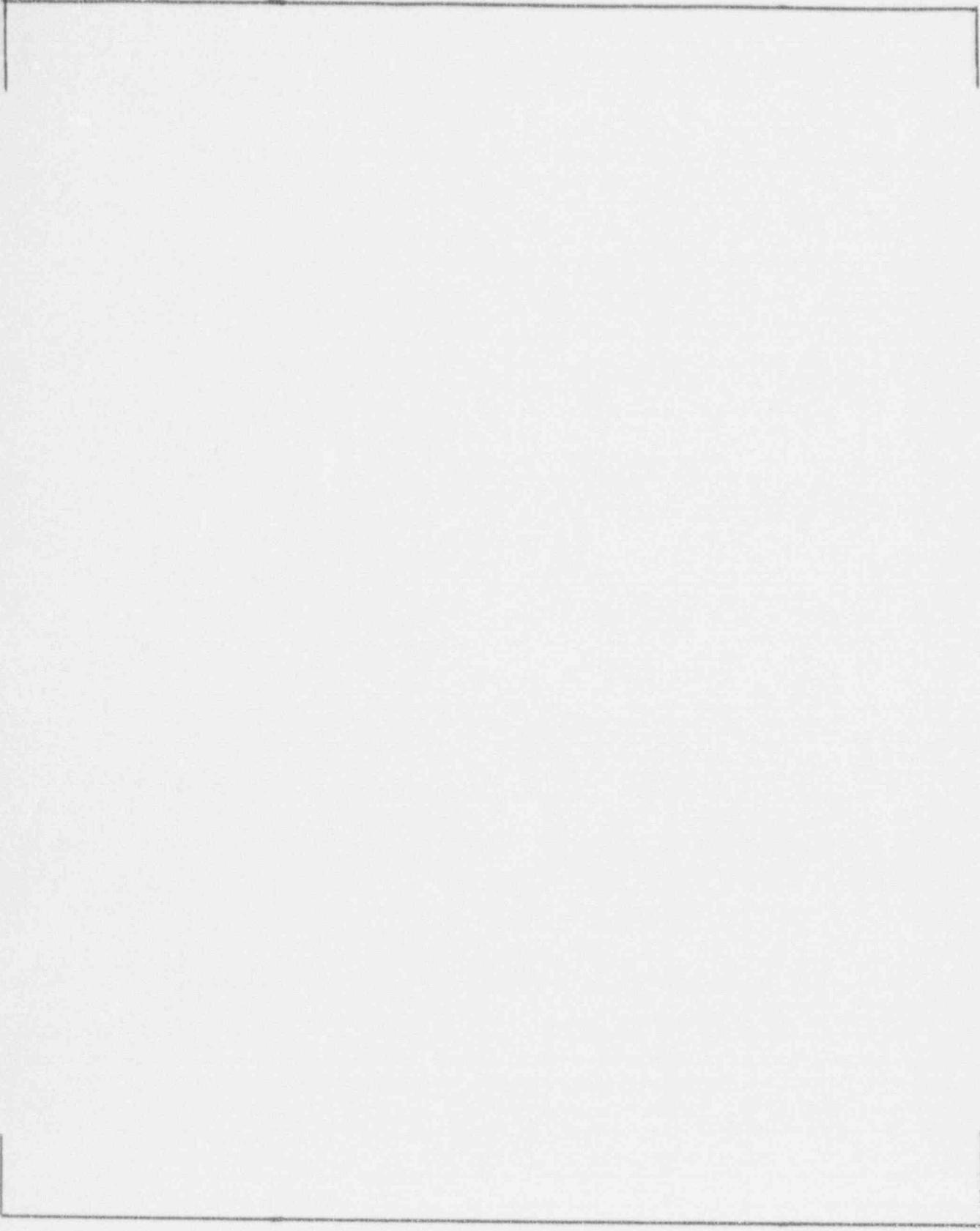


Figure 2-50. Surge Line Nozzle Stress Intensity Due to Bending



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

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a, c, e

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

4127x-011790 16

a, c, e

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

a, c, e



Figure 2-54. Thermal Striping Fluctuation



Figure 2-55. Stratification and Striping Test Models

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



Figure 2-58. Thermal Striping Temperature Distribution



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 Trojan surge line were evaluated based on the requirements of the ASME B & PV Code, Section III, Subsection NB-3600,^[9] 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 the surge line piping using program WECEVAL.^[10] The cases selected in the fatigue analysis are the in-line component in each profile region with the highest C and K stress indices defined by the ASME Code. At 5D bends, K indices for butt welds were conservatively applied to add conservatism.

3.2 Prior Design Methods

The prior design method of surge line piping, before the issuance of NRCB-88-11,^[11] used the NB-3653 techniques but with thermal transients defined by W/SSDC 1.3 Rev. 1,^[2] 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 and schedule 140 pipes. For a given load condition, the total stress in the pipe is determined by superposition of stresses due to pressure, moment and local stratification effects. The stresses in the finite element model due to each of these types of loading were first determined for nominal values of load and stored on computer tapes. [

]a,c,e

Scale factors were then developed for each load condition based on actual pressure, moment and stratification loading for each condition and stress indices for the component being evaluated. [

$J^{a,c,e}$ C_1 and C_2 are determined from ASME Code Subsection NB-3681 for the component being evaluated.

The total stress at each node point in the finite element model is then determined by superposition of the individual contributions as follows:

[

$J^{a,c,e}$

The finite element model stresses on tape are the six stress components at each node point in the model.

After determining the total stress components for each load condition defined in tables 1-3 and 1-4, program WECEVAL proceeds with the fatigue evaluation according to NB-3222.4. In the evaluation, stress concentration effects are conservatively considered by applying the maximum peak stress index from NB-3681 (K_1 , K_2 , K_3) for the component being evaluated to the total stress.

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 stress were calculated - S_n (Eq 10), to determine elastic-plastic penalty factors, K_e , and S_p (Eq 11) - peak stress. For most components in the surge line (girth butt welds, elbows, bends) no gross structural discontinuities are present. As a result, $C_3 E (\alpha_a T_a - \alpha_b T_b)$ in Eq (10) of NB-3600 is zero. Therefore, for these components, the Eq. (10) stresses are due to pressure and moment.

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 the Eq. (10) stresses 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}

3.3.3 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.

The mesh of the finite element model is such that [^{a,c,e}] are defined by the element boundaries and node points in the circumferential direction (see figure 3-1). Thus, [^{a,c,e}] virtually comprise the entire model. The values of stress at each section for each loading are contained on computer tapes used in the evaluation.

Usage factors were calculated at selected node points in the finite element model on the pipe wall surface, corresponding to the analysis sections. These node points were selected based on review of the local stress profiles and previous analysis results where maximum usage factors were calculated. [

] ^{a,c,e} The maximum usage factor was then reported for the global location.

The usage factor calculations include:

- 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, $N_1, N_2 \dots N_n$, 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, \dots, n_n , calculate the usage factors $U_1, U_2 \dots U_n$ 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 $U_{cum} = U_1 + U_2 + \dots + U_n$. The code allowable value is 1.0.

3.3.4 Simplified Elastic-Plastic Analysis

When code Eq. (10), S_n , exceeded the $3S_m$ 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, K_e , 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 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 2.0).

It should be noted that ASME equation 10 is calculated by WECEVAL for every combination at each cross section evaluated at each global location to determine the elastic-plastic penalty factors, K_e . The values of K_e are stored on tape to be used in the subsequent usage factor calculation.

The various locations for which Eq. 10 was exceeded can be obtained by detailed review of the computer runs. In the whole of the analysis, [

$]^{a,c,e}$ Due to the nature of the thermal stratification loading,
[$]^{a,c,e}$ is the more critical for qualification.

3.3.5 Fatigue Usage Results

The maximum Usage factors were [$]^{a,c,e}$ at the RCL nozzle safe-end and [$]^{a,c,e}$ at the long radius elbow underneath the pressurizer. These are less than the code allowable of 1.0.

ASME Code Section III stress indices were used for all components except [$]^{a,c,e}$ [$]^{a,c,e}$ evaluation used the results of finite element analyses for secondary stresses in lieu of Code stress indices.

The above usage factor included the effects of striping. The nature of striping damage is at a much higher frequency, varies in location due to fluid level changes and is maximized at a different location than the ASME usage factor caused by the global bending and local transient effects of thermal stratification.

3.4 Conservatism in Fatigue Usage Calculation

The above calculated ASME usage factors contain the inherent conservatism 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 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.

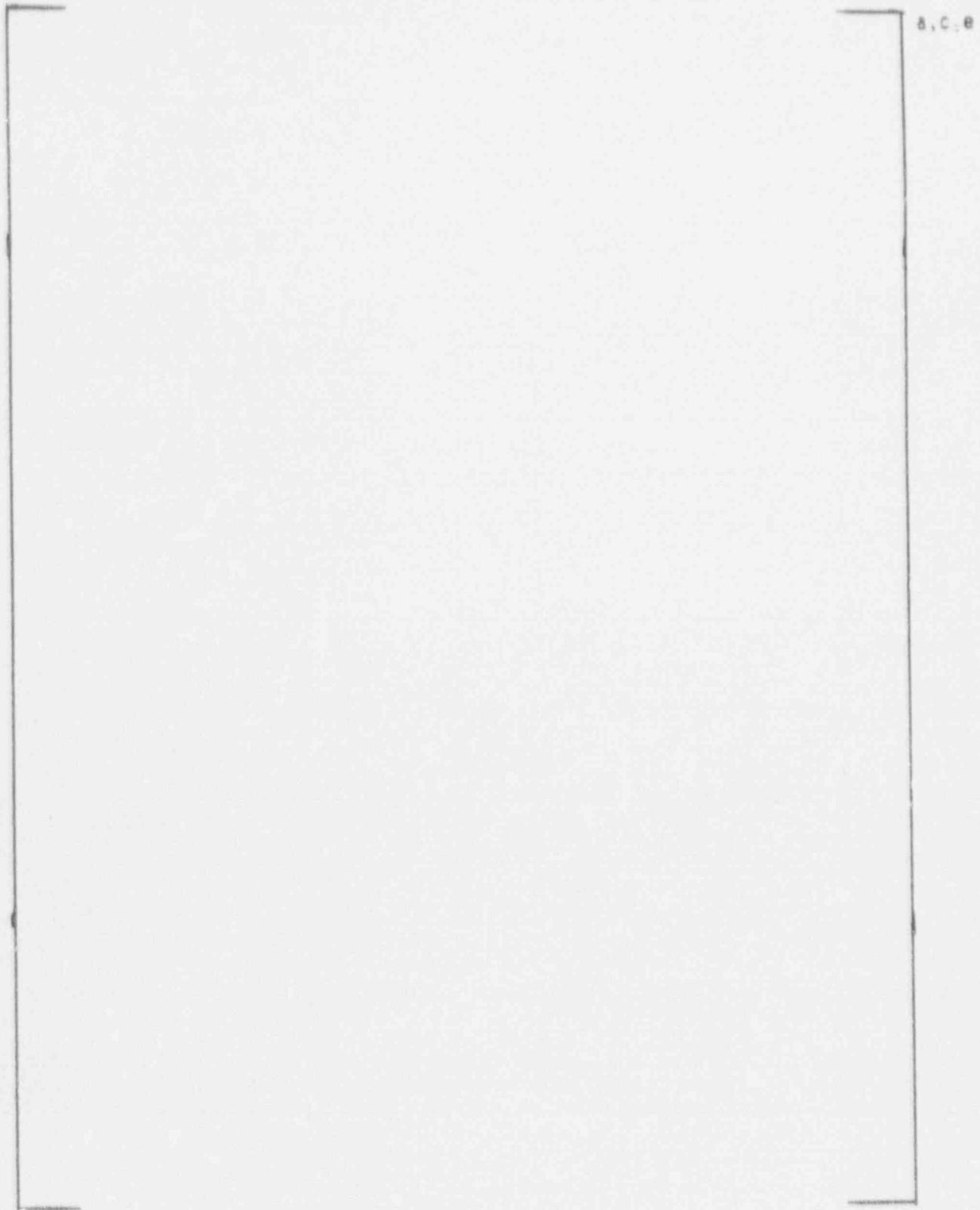


Figure 3-1. Fatigue Calculation Locations

SECTION 4.0
CONCLUSIONS

Based on the monitoring and analysis results presented in the report the following conclusion is reached:

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

In summary, based on the current piping and support configuration and the understanding of the thermal stratification phenomenon, it is concluded that thermal stratification does not affect the integrity of the pressurizer surge line of the Trojan nuclear power plant. The design life (forty years) and ASME III Code compliance are not affected.

APPENDIX A LIST OF COMPUTER PROGRAMS

This appendix lists and summarizes the computer codes used in the analysis of stratification in the Trojan 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 include in the WECAN structural analysis. Such coupled thermal-stress analyses are a standard application used extensively on an industry wide basis.

A.1.3 Program Verification

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

A.2 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 K_e 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 Program Verification

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

A.3 STRFAT2

A.3.1 Description

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

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

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

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

A.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 WESTDYN (Westinghouse piping] analysis code) and WECAN (finite element code, section 8.1). The results from ANSYS are also verified against closed form solutions for simple beam configurations.

APPENDIX B
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