POTENTIAL REACTOR SYSTEM VOIDING DURING ANTICIPATED TRANSIENTS

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1.0 PROBLEM INTRODUCTION AND SUMMARY

1.1 Introduction

The NRC has expressed concern that steam pockets can and do form in B&W primary systems during some reactor trips and furthermore, this steam could collect in the candy cane and potentially hinder natural circulation after loss of offsite power. The source of this steam is postulated to be from stored heat in metal, stagnant pockets of "hot" water, or pressurizer outsurge water (650°F); any or all causing flashing during low pressure periods after a trip.

The purpose of this report is to show that the formation of a steam pocket in the primary system during most reactor trips is highly improbable and that the production of a volume of steam required to hinder natural circulation is virtually impossible.

1.2 Summary

Based on review of several past B&W reactor trips along with several assumptions and calculations discussed in Section 2, the following statements can be made:

(1) Minimum RC pressure after trips about the same time as the minimum coolant temperature (as expected) and not because of a primary system "Steam Pocket" restricting a further pressure decrease.* These minimum temperatures correlate with secondary side steam pressures.

(2) With the most conservative assumptions steam pockets are virtually impossible during transients where minimum measured pressure is greater than 1740 psig.

*Specific concern per reference 1

(3) Using more realistic assumptions regarding potential steam production, it is unlikely that any net steam production can occur at measured pressures greater than 1500 psig.

2.0 Analysis, Assumptions and Event Descriptions

2.1 Analysis of Steam in the Upper Vessel Plenum

2.1.1 Stagnant "Hot" Water

Typically, the hottest bundle in a 2772 MWT core is a 1.5 relative peaked bundle. This localized power could conservatively result in localized stagnant water temperatures of ∿ 620°F* in the upper control rod guide (column weldment). For this situation to occur, at least 53 in^2 of flow area in the column weldment (see flow path 2 on figure 2.1.1) would have to be blocked. If this blockage could occur, then the following statement can be made: Any B&W reactor trip resulting in minimum RC tap pressures less than 1740 psig (the tap pressure is ∿ 40 psid lower than core plenum pressure) voiding may occur.

Since this blockage is highly unlikely, a somewhat more realistic hot spot assumption would be localized maximum temperatures of 610°F (instead of 620°) in the upper vessel plenum. This assumption is based on (1) water stagnating (or having an extremely low flow rate) in the upper plenum (per Fig. 2.1.2) and acquiring the steady state enviromental temperature of the 59 column weldment flow temperatures and (2) plugged return holes (per figure 2.1.2, Flow Path 3). This condition would not allow flashing until the pressure decreases to 1660 psia, i.e., 1605 psig at the pressure tap.

*Typical outlet temperatures were verified from TMI-2 pre March, 1979 100% power outlets thermocouple data.

The most realistic assumption is the design condition of ∿ 5% core flow through the guide tubes into the upper plenum. Following a reactor trip, the coolant temperature in this region will decrease rapidly to below 600F as core outlet temperature eliminating the potential for "hot" water pockets at any pressures above HPI injection levels.

2.1.2 Residual Heat Stored in Metal

After a trip, the metal in the upper vessel will be conservatively assumed to remain at 610°F until a minimum pressure is reached. The upper plenum coolant temperature at this minimum pressure should be ∿ 550°F (in this region) but 575°F will be conservatively assumed due to hypothetical "slow" mixing. The available stored energy in the metal will be:

Stored Energy = $Cp_m \times Mass_m \times \Delta T$

$Cp_m = .11$ BTU/lb_m °F

$\Delta T = 610° - 575° = 35°F$

$Mass_m \sim 5x10^5$ lbm = total mass of metal above the outlet hot leg piping including reactor vessel

Stored Energy = $1.925x10^6$ BTU's

The amount of water in this region is 1366 $ft.^3$

1366 $ft.^3 \times 44.5^*$ $lbm/ft^3 = 6.08x10^4$ lb of water

Conservatively assuming this energy is instantly released to the water, the water temperature will increase from 575°F to ∿ 601°.** The pressure required for flashing at this temperature is ∿ 1505 psig (at the pressure tap). Therefore, in order to fill this region with

*This is water density at 575°F, 1600 psia.

**$1.925x10^6$ BTU's/$6.08x10^4$ lb = 32 BTU/lb or ∿ 26°F temperature increase.

steam (to cause spillover into the hot legs) from just residual heat, 20 times more mass of hot metal would be required. (~ 10 BTU/lb are needed to reach Tsat and another 533 BTU/lb to vaporize the water. This equals 543 $\frac{BTU}{lb}$ required to convert a pound of water to a pound of steam).

2.1.3 Conclusion

The previous calculations and discussion basically show that it is impossible to produce steam in the upper head above a measured pressure of 1740 psig, highly improbable above 1620 psig, and highly unlikely above 1500 psig. (Very few transients have ever gone below 1600 psig.) This statement assumes no primary system breaks.

2.2 Analysis of Steam in the Candy Cane

2.2.1 Pressurizer outsurge water mixing with hot leg flow

At the time period of minimum pressure after a trip the hot leg coolant temperature is ~ 550°F during 4-pump operation and ~ 570°F during natural circulation. The respective hot leg flow rates are ~ 70×10^6 and 2.5×10^6 lb/hr during this period. The pressurizer is outsurging ~ 650°F water at ~ 40000 lb/hr into the hot leg.

Conservatively assuming only 10% of the hot leg flow mixes with the pressurizer outsurge, the resulting maximum fluid temperature in the candy cane will be ~ 551°F for four pump operation and 581°F for natural circulation.

The saturation pressures for these temperatures is well below 1500 psig.

2.2.2 Residual Heat Stored in Metal

The residual heat stored in the hot leg metal is conservatively calculated to be $\sim 1.89 \times 10^5$ BTU's. This calculation is based on

(1) hot leg piping temperature remains at $\sim 605^{\circ}$F for 60 seconds after the trip and

(2) the residual heat is dumped instantaneously into the hot leg flow volume at the RTD indicated temperature of $\sim 550^{\circ}$F and 1600 psia.

Hot leg metal volume = 70.45 ft^3

Hot leg metal mass = $70.45\ ft^3 \times \frac{490\ lb}{ft^3} = 3.45 \times 10^4$ lbm

The ΔT driving function will be $605^{\circ} - 555^{\circ}$ or $50^{\circ}\ \Delta T$.

Therefore stored energy released is

$$.11\ \frac{BTU}{lb^{\circ}F} \times 50^{\circ}F \times 3.45 \times 10^4 = 1.89 \times 10^5 \text{ BTU's}$$

The volume of water in the hot leg is $\sim 1.97 \times 10^4$ lb

Therefore:

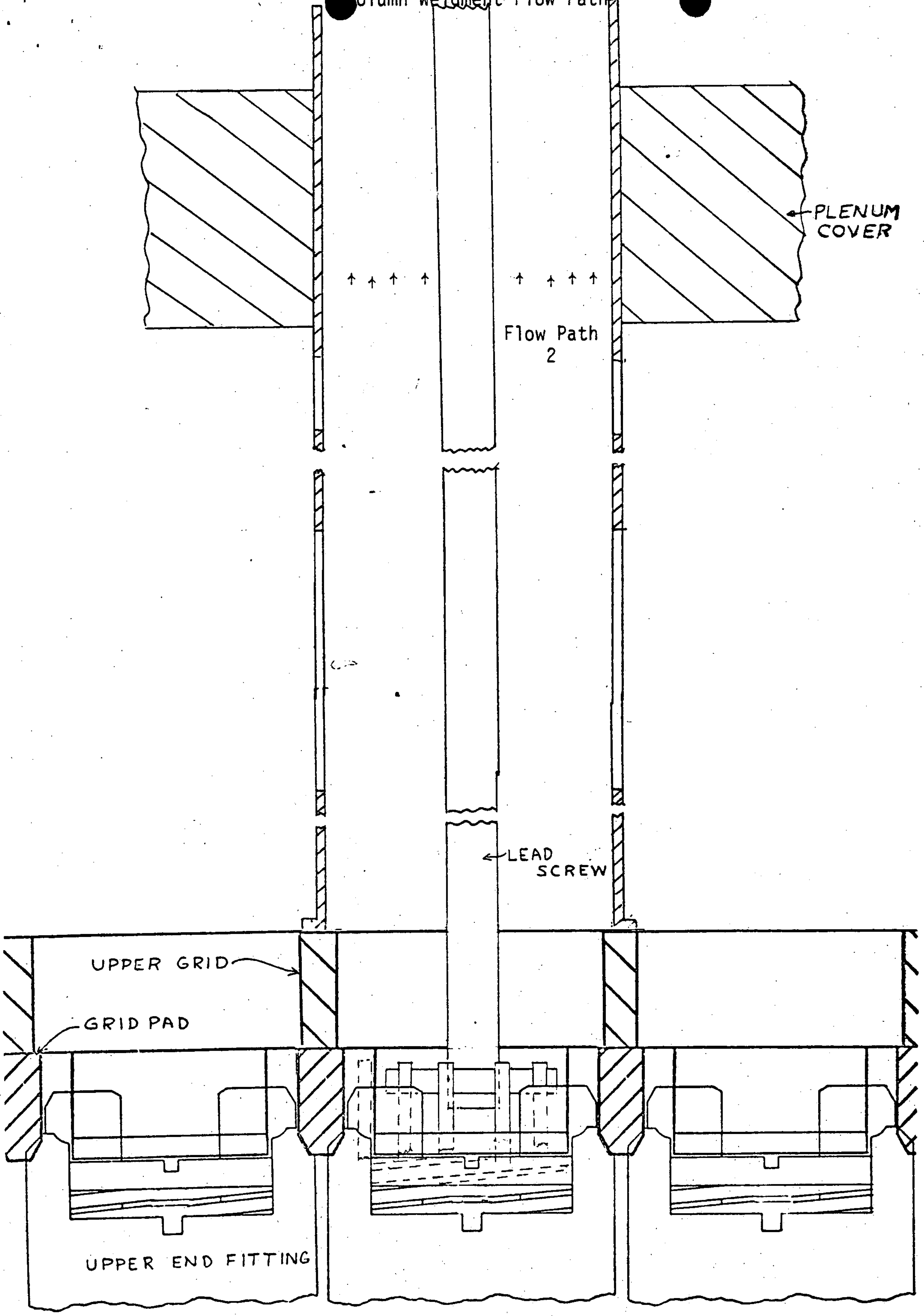
$$\frac{1.89 \times 10^5\ BTU}{197 \times 10^4\ lb} \sim 10\ BTU/lb$$

This is equivalent to $\sim 8^{\circ}$F in temperature addition.

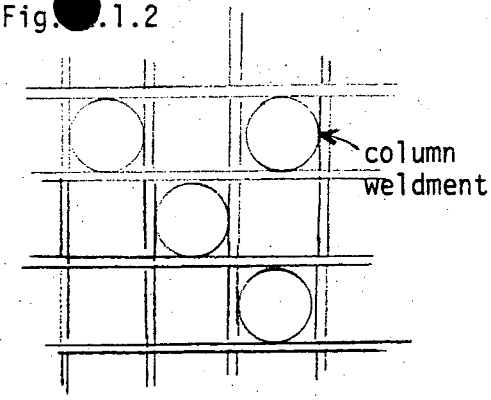
Therefore, the saturation pressures for $551^{\circ}F^* + 8^{\circ}F = 559^{\circ}F$ and $581^{\circ}F + 8^{\circ}F = 589^{\circ}F$ are below 1500 psig.

*Per previous calculation

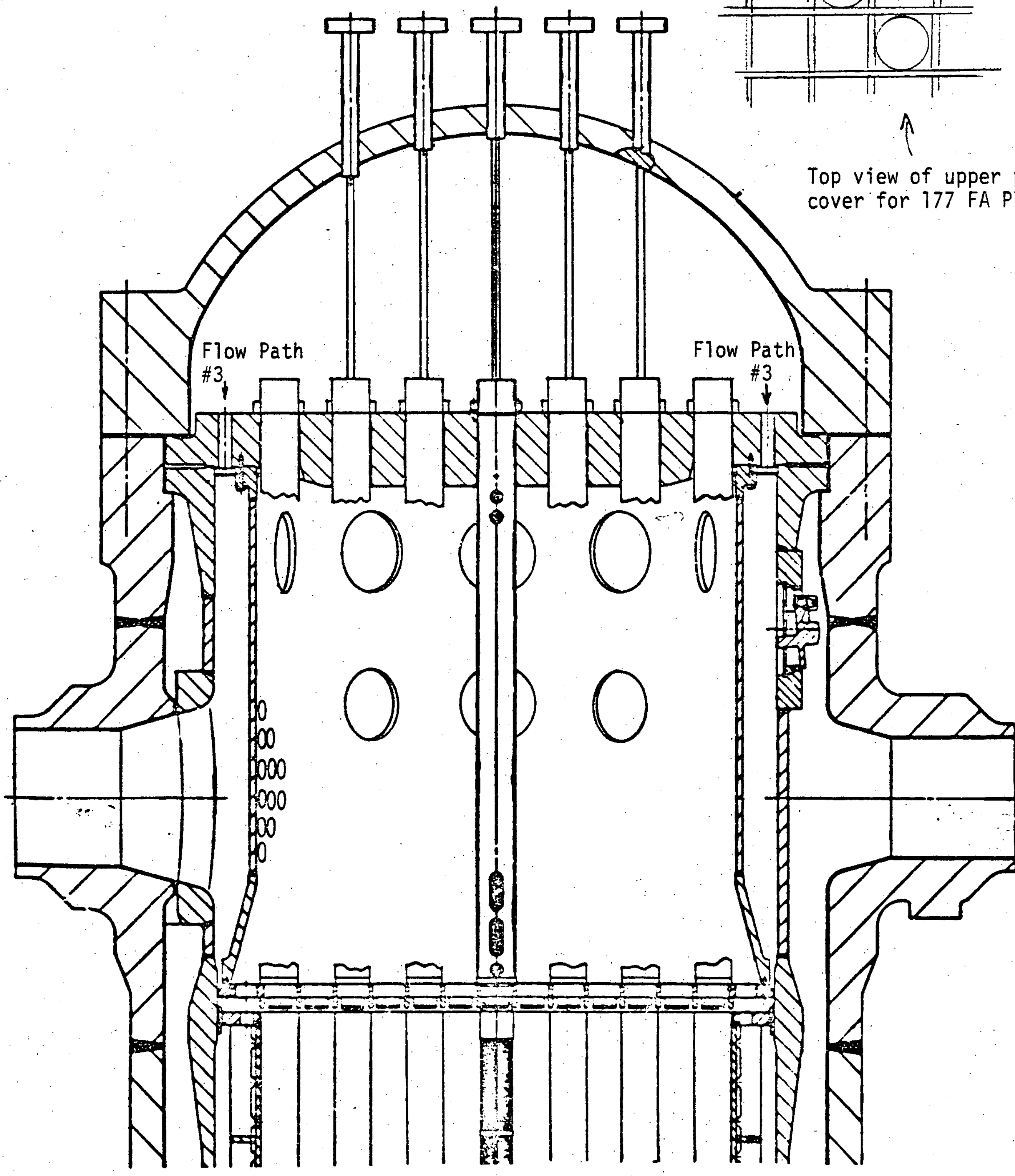
Column Weldment Flow Path Fig. 2.1.1



Upper Plenum Flow Path Fig. [illegible].1.2



Top view of upper plenum cover for 177 FA Plants



2.2.3 Conclusion

Using the conservative assumptions on residual stored heat and hot leg - pressurizer outsurge mixing, the RC pressure which would allow flashing is below 1500 psig. This low pressure should not be reached during normal transients.

2.3 Event Description For Mass/Volume Balance

2.3.1 Description of Analysis

A mass volume balance on the RC system before and after trips was analysed for five cases. These cases were chosen because of their abnormally low pressurizer level, low RC pressure, or were referred to in reference 1.

The method of analysis was basically:

(1) To break the RC system down into 4 different temperature/ pressure volumes (per figure 2.3.1).

(2) Calculate the "shrinkage" of each volume at a lower temperature/pressure condition after a trip and

(3) Determine how much water from the pressurizer is required to maintain a solid system conditions.

(4) Subtract this volume of water from the initial pressurizer volume to get "level 1".

(5) Calculate the amount of water that would have flashed in the pressurizer due to the lower pressure condition. This is "level 2".

(6) Finally, calculate the pressurizer level error per attachment 1. This is "level 3".

(7) Subtract level 2 and 3 from level 1 to get level 4. If "level 4" is less than the plant measured level ("level 5") then a viable explanation would be potential "steam pockets"

in the RCS.

The results of this study show that the indicated pressurizer level (level 5) is less than or equal to the calculation of level 4 and therefore a steam pocket occurring in the RCS is highly unlikely.

2.3.2 <u>Derivation of Equations Used</u>

The equation used for this analysis is:

$$V_1p_1 + V_2p_2 + V_3p_3 + V_4p_4 + V_5p_5 = V_1p_1^1 + V_2p_2^1 + V_3p_3^1 + V_4p_4^1 + V_5p_5^1$$

Where p = Coolant density at Time 0

p^1 = Coolant density at Time 1

V_5 = Volume of water in pressurizer at Time 0

V^1_5 = Volume of water in pressurizer at Time 1

Solving for V^1_5

$$V_5^1 = \frac{V_1(p_1 - p^1_1) + V_2(p_2 - p^1_2) + V_3(p_3 - p^1_3) + V_4(p_4 - p_4^1) + V_5p_5}{p^1_5}$$

For raised loop plants (TECO)

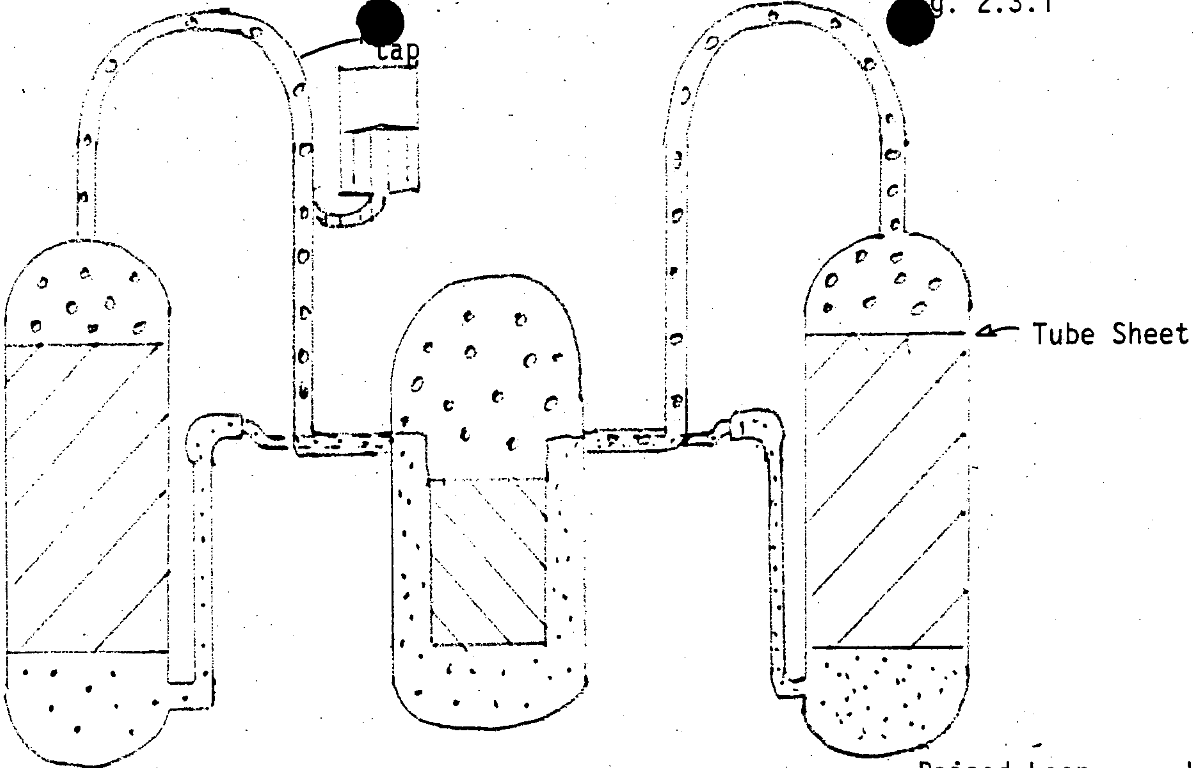
$$V_5^1 = \frac{3739(\Delta p_1) + 887(\Delta p_2) + 3062(\Delta p_3) + 2774(\Delta p_4) + [A_1 + 3.207\ (\text{level})]\ p_5}{p^1_5} \qquad \text{Eq.1}$$

For lowered loop plants

$$V_5^1 = \frac{3800(\Delta p_1) + 887(\Delta p_2) + 3197\ (\Delta p_3) + 2774\ (\Delta p_4) + [A_1 + 3.207\ (\text{level})]\ p_5}{p^1_5} \qquad \text{Eq.2}$$

RC VOLUME BREAKDOWN

Fig. 2.3.1



		Raised Loop 177 NSS (ft^3)	Lowered Loop 177 NSS (ft^3)
V_1 =	Cold Water Volume =	3739	3800
V_2 =	Core Water Volume =	887	887
V_3 =	Hot Water Volume =	3062	3197
V_4 =	Steam Generator Water Volume =	2774	2774
	Total External to Pressurizer	10462	10,658
V_5 =	Pressurizer Water Volume =	A + 3.207 X Level (inches)	A + 3.207 X Level (inches)

A = 263 (Davis Besse)

A = 134 (Oconee)

$P_1 = P_{tap}$ $\rho_1 = f(P_1\ T_{cold})$

$P_2 = P_{tap} + 50$ $\rho_2 = f(P_2, T_{ave})$

$P_3 = P_{tap}$ $\rho_3 = f(P_3, T_{hot})$

$P_4 = P_{tap}$ $\rho_4 = f(P_4, T_{ave})$

$P_5 = P_{tap}$ $\rho_5 = f(P5, T_{sat})$

2.3.3.1 Davis Besse 9/18/79 Trip

At 12:43 on September 18, 1979, while operating at ∿ 100% power a test was in progress on the main steam turbine Electro Hydraulic Control System (EHC) at Davis Besse 1. While transferring EHC pumps a low pressure signal in the EHC initiated a turbine trip. The Anticipatory Reactor Trip on Turbine Trip tripped the reactor ∿ 0.4 seconds after the turbine trip.

The reactor trip caused the RC pressure, RC $T_{average}$ and pressurizer level to decrease rapidly. The pressurizer level indication dropped off scale some 50 seconds after the reactor trip, remained down scale for some 50 seconds and then slowly increased. The RC pressure reached a minimum of about 1710 psig at 1 minute after reactor trip and recovered. RC $T_{average}$ reached a minimum of 546°F following the trip and stabilized at 550°F.

The initial conditions prior to the trip are listed below.

Reactor Power	∿ 100% Rated Power
RC Temperature (T_{ave}):	582°F
R.C.S. Pressure:	2200 psig
R.C.S. Flow:	4 pumps operating
Pressurizer Level:	202 inches
Tests in Progress:	EHC Test

The pertinent data during the transient is shown on figure 2.3.3.1. The data analysis is as follows.

Davis Besse 9/18/79
Reactor Trip

Time (0) Initial Conditions

$T_{hot} = 605^\circ F$ $T_{cold} = 558^\circ F$ $P_{tap} = 2215$ psia

Therefore $p_1 = 46.24$

$p_2 = 44.64$

$p_3 = 42.57$

$p_4 = 44.60$

$p_5 = 37.35$

Time (1) = 42 sec

$T_{hot} = 557^*$ $T_{cold} = 550^*$ $P_{tap} = 1740$ psia

Therefore $p_1' = 46.40$

$p_2' = 46.27$

$p_3' = 45.97$

$p_4' = 46.23$

$p_5' = 41.18$

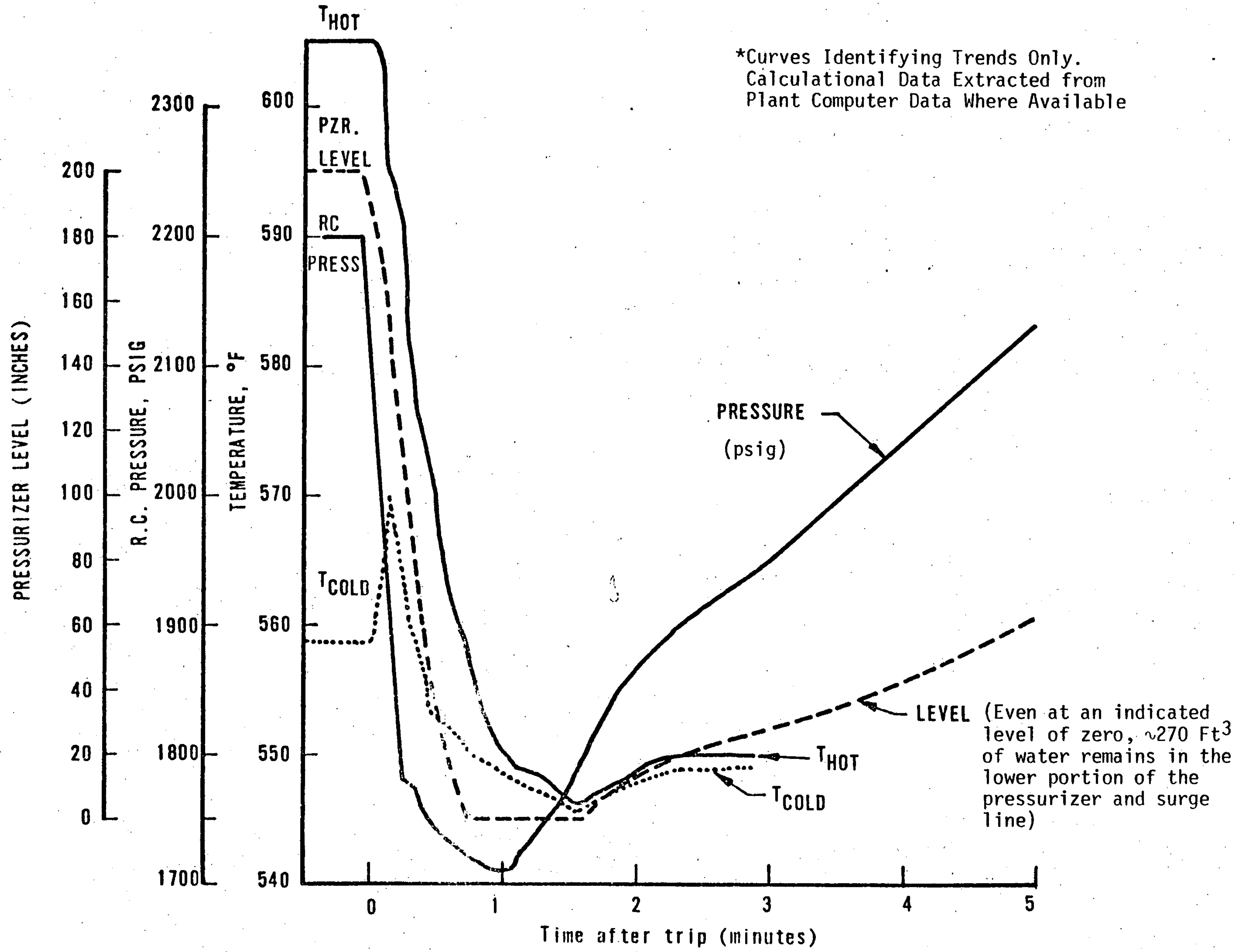
Solving Equation 1 $V_5' = 415\ ft^3$

This corresponds to a calculated pressurizer level of 47.5 inches. (level 1) The indicated pressurizer level was 21.6 inches (level 5). The estimated pressurizer level temperature compensation error (per Attachment 1) is 14" inches (level 3). The initial mass of steam in the pressurizer is 650 ft^3 x 6.21 lb/ft^3 or 4037 lb. The final mass of steam is 1214 ft^3 x 4.37 lb/ft^3 or 5304 lb. This additional 1267 lb (5304 - 4037) of steam will come from ∿10" of water · (level 2). Therefore, level 1 - level 2 - level 3 = level 4 = 47.5-14-10 = 23.5". Level 4 is slightly greater than level 5; therefore, the probability of steam pockets is low.

*A 4 second hot and cold leg RTD response time delay is incorporated.

Note: Where possible, data used in these analyses is based on computer print out. The graphs are representations of this data.

TECO 9/18/79 TRIP

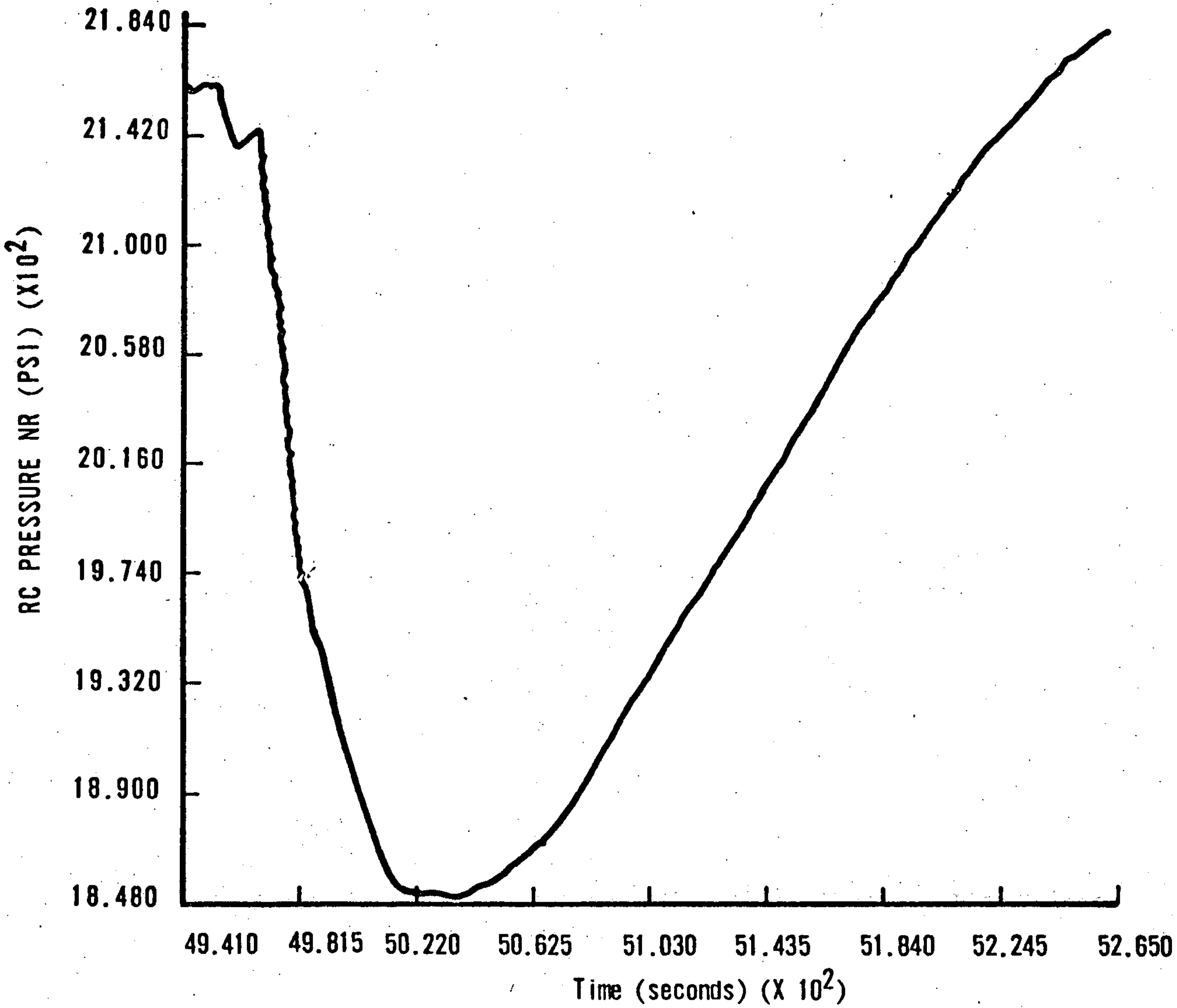


g. 2.3.1

2.3.3.2 Davis Besse 9/15/79 Trip

Figure 2.3.3.2 shows the RC pressure during this trip. Since RC minimum pressure was 1848 psig no steam production was possible per discussion in Section 2.2.

TECO 9/15/79 TRIP



Fi 2.3.3.2

2.3.3.3 Daivs Besse 9/26/79 Trip

At 20:56:33 hours on September 26, 1979, a high turbine throttle pressure limit alarm was received. The throttle pressure limiter is used to protect against an excessive decrease of steam pressure when steam generation of the NSS falls below the steam demand of the turbine. It acts directly to close the high pressure turbine control valves in an effort to maintain steam header pressure. Rapid closure of the control valves caused a mismatch between heat generation and heat removal with a resultant increase in Reactor Coolant System (RCS) temperature and pressure. Seven seconds later (at 20:56:40) the reactor tripped on RCS high pressure and was followed by a turbine trip. RCS temperature and pressure then dropped and the Integrated Control System (ICS) reduced the feedwater flow abruptly.

Reactor Coolant System Tave decreased to 548.5°F approximately 57 seconds after the trip. The pressurizer level indication dropped off scale at 21:57:21 and remained below the indication range for approximately 21 seconds.

The initial conditions prior to the trip are listed below.

Reactor Power:	∿ 100% Rated Power
R. C. Temperature (T_{ave}):	582°F
R. C. S. Flow:	4 pumps operating
Pressurizer Level:	200 inches

The pertinent data during the transient for this analysis is shown on figure 2.3.3.3. The data analysis is as follows.

Davis Besse 9/26/79
Reactor Trip

Time (0) Initial Conditions

$T_{hot} = 605^oF$ $T_{cold} = 559^oF$ $P_{tap} = 2215$ psia

Therefore $p_1 = 46.18$

$p_2 = 44.59$

$p_3 = 42.67$

$p_4 = 44.56$

$p_5 = 37.35$

Time (1) = 50 sec

$T_{hot} = 552$ $T_{cold} = 548$ $P_{tap} = 1700$ psia

Therefore $p_1' = 46.62$

$p_{2_1}' = 46.53$

$p_{3_1}' = 46.22$

$p_4' = 46.35$

$p_5' = 41.00$

Solving Equation 1 $V_5' = 243\ ft^3$

This corresponds to a calculated pressurizer level of 26.4 inches. (level 1) The indicated pressurizer level was 0 inches (level 5). The estimated pressurizer level temperature compensation error (per Attachment 1) is 15" inches (level 3). The initial mass of steam in the pressurizer is 648 ft^3 x 6.21 lb/ft^3 or 4030 lb. The final mass of steam is ~1234 ft^3 x 4.23 lb/ft^3 or 5219 lb. This additional 1190 lb (5219 - 4030) of steam will come from ~ 9" of water. (level 2) Therefore, level 1 - level 2 - level 3 = level 4 = 26.4-15-9 = 2.4". Level 4 is slightly greater than level 5; therefore, the probability of steam pockets is low.

*A 4 second hot and cold leg RTD response time delay is incorporated.

Note: Where possible, data used in these analyses is based on computer print out. The graphs are representations of this data.

TECO 9/26/79 TRIP

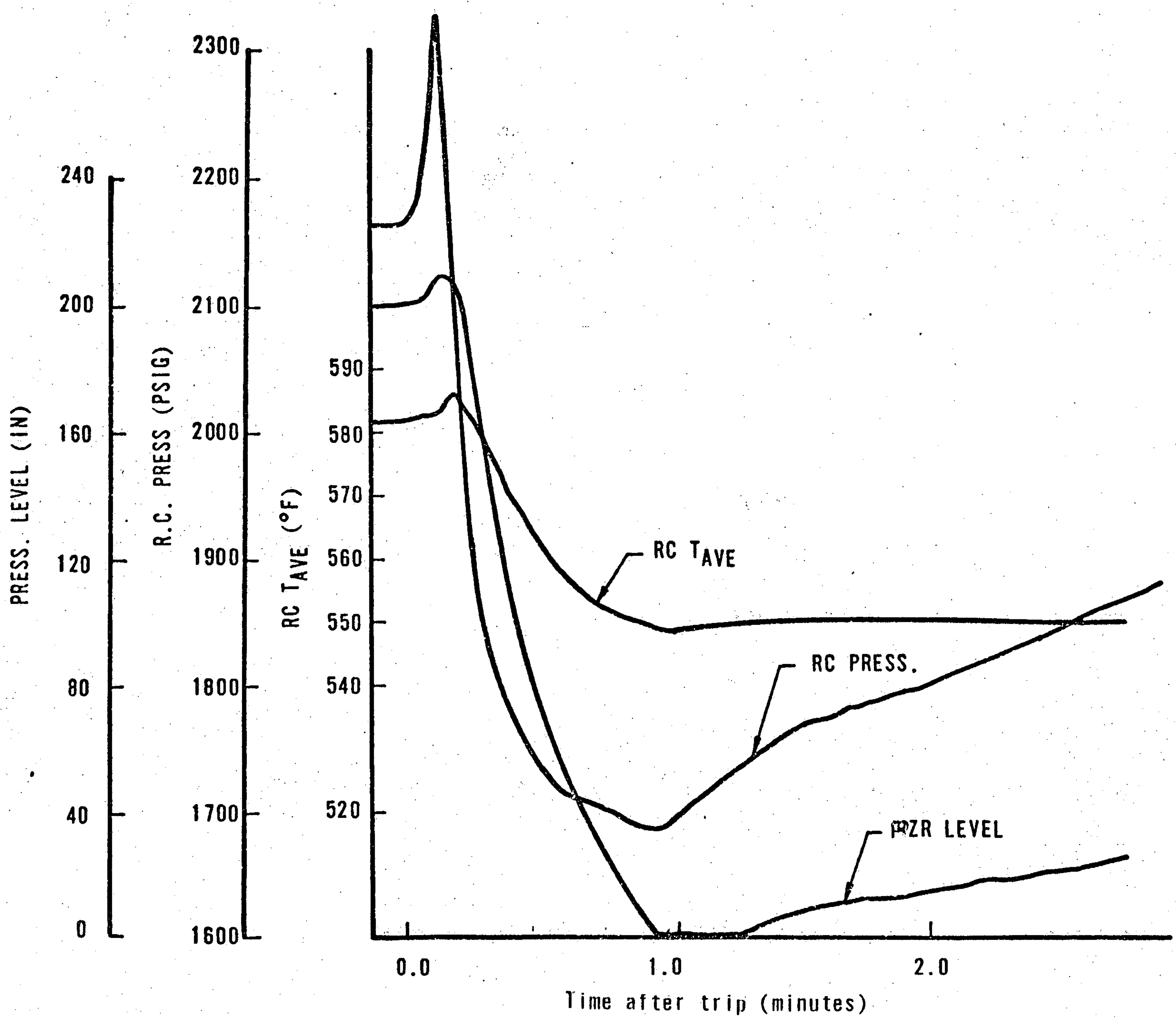


Fig. [illegible].3.3

2.3.3.4 <u>Oconee 1 10/8/79 Trip</u>

On October 8, 1979, Oconee 1 was operating at 100% FP with on line Reactor Protection Tests in progress. At 13:27:35, Oconee 1 experienced a reactor trip attributed to RPS activation of pressure/temperature channels A, C, and D.

Control Rod Drive Breakers CB 3 and 4 were tripped for the test. An additional breaker for Group 5 was opened which caused Group 5 to drop. This resulted in a P/T Trip.

The initial conditions prior to the trip are listed below.

Reactor Power	100%
RCS TAVE	579°F
Pressurizer level	221 inches

The pertinent data during the transient for this analysis are shown on figure 2.3.3.4. The data analysis is as follows.

Time (0) Initial Conditions

$T_{hot} = 602^{\circ}F$ $T_{cold} = 558$ $P_{tap} = 2150$ psia

Therefore $p_1 = 46.26\ lb/ft^3$

$p_2 = 44.75\ lb/ft^3$

$p_3 = 42.87\ lb/ft^3$

$p_4 = 44.70\ lb/ft^3$

$p_5 = 37.69\ lb/ft^3$

Time (1) = 60 seconds

$T_{hot} = 553$ $T_{cold} = 550$ $P_{tap} = 1750$ psia

Therefore $p_1' = 46.55\ lb/ft^3$

$p_{2_1}' = 46.47\ lb/ft^3$

$p_{3_1}' = 46.40\ lb/ft^3$

$p_4' = 46.51\ lb/ft^3$

$p_5' = 40.81\ lb/ft^3$

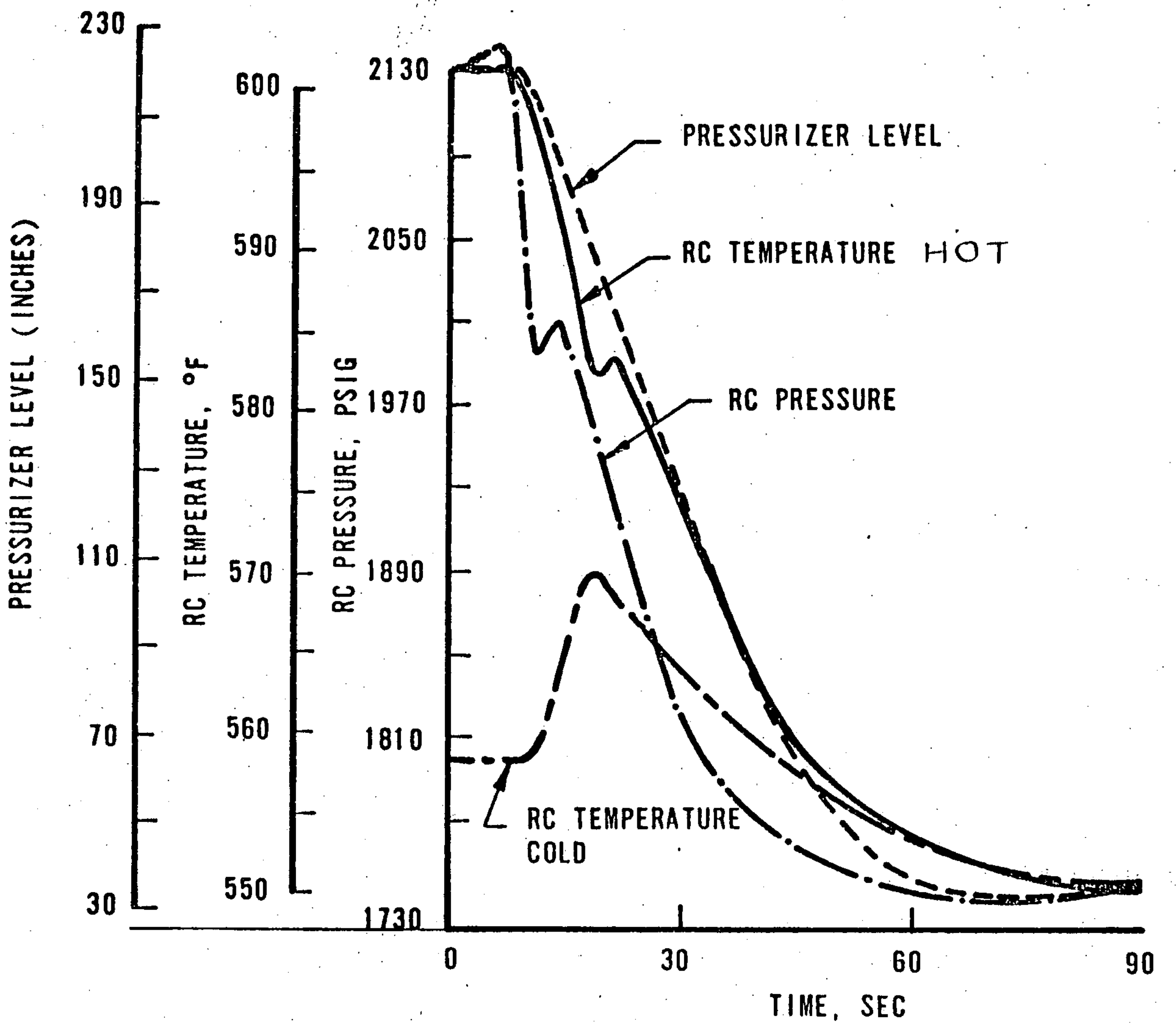
Solving Equation 1 $V_5' = 315\ ft^3$

This corresponds to a calculated pressurizer level of 56.24 inches. (level 1) The indicated pressurizer level was 31.0 inches (level 5). The estimated pressurizer level temperature compensation error (per Attachment 1) is 15.0 inches (level 3). The initial mass of steam in the pressurizer is 709 ft^3 x 5.97 lb/ft^3 or 4236 lb. The final mass of steam is 1283 ft^3 x 4.4 lb/ft^3 or 5652 lb. This additional 1416 lb (5652 - 4236) of steam will come from ~ 10" of water (level 2). Therefore, level 1 - level 2 - level 3 = level 4 = 56-15-10=31". Level 4 is equal to level 5; therefore, the probability of steam pockets is low.

*A 4 second hot and cold leg RTD response time delay is incorporated.

Note: Where possible, data used in these analyses is based on computer print out. The graphs are representations of this data.

OCONEE 1, 10-8-79 TRIP

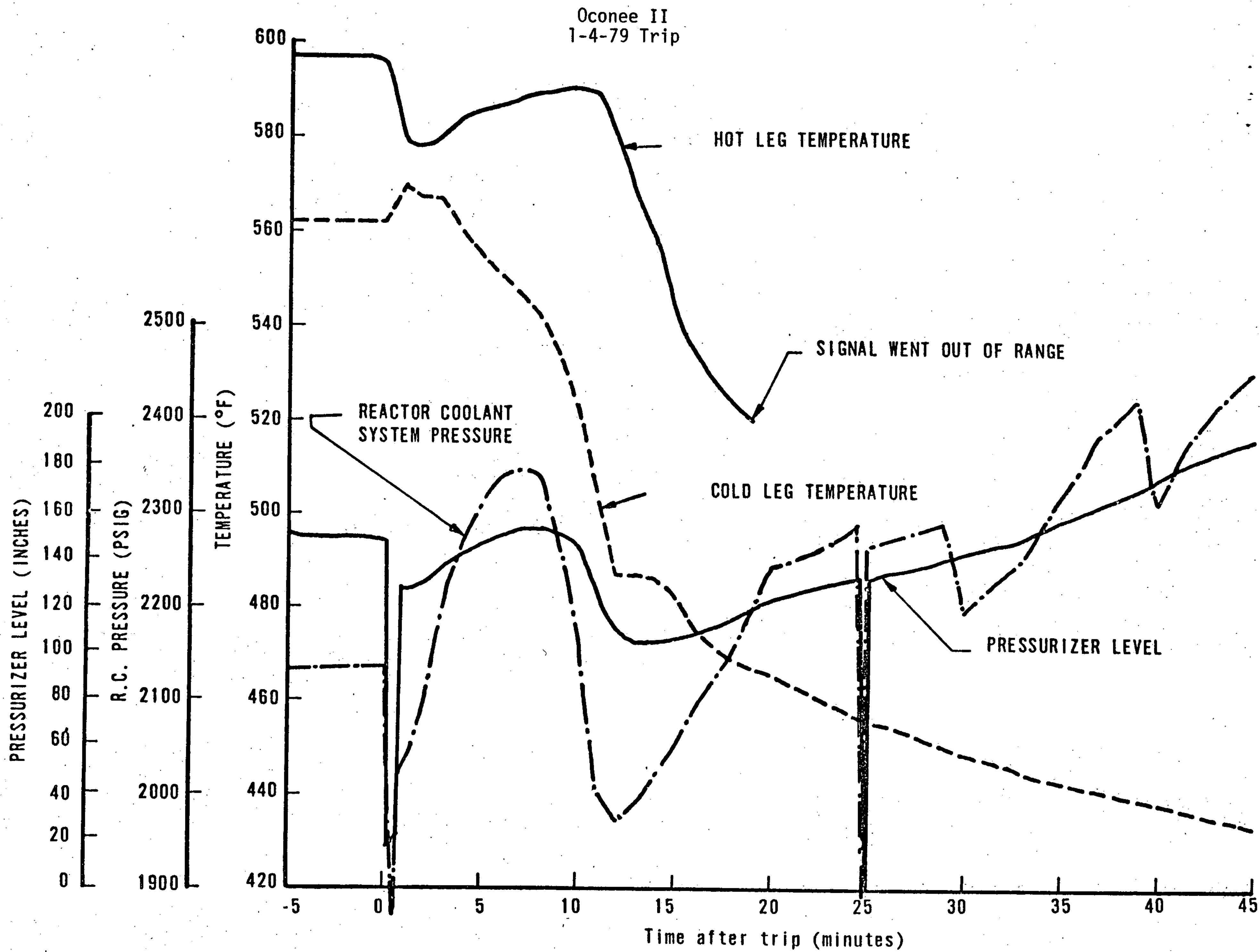


g. 2.3.3.4

2.3.3.5 <u>Oconee II 1/4/74 Trip</u>

Figure 2.3.3.6 shows the pertinent transient results of this trip.

During this transient the minimum Tap pressure attained was ∿ 1900 psig. Therefore, a 1940 psia upper vessel pressure would require a 631^{o}F temperature to produce net steam. This temperature was never attained at any position or time during this transient. While it is given that operator action (or plant responses) could have been better, the steam production possibility did not exist. Furthermore, a review of the sequence of events of this trip indicate that the severe level and pressure changes at the beginning and later in the transient were primarily due to a temporary loss of ICS power.



Oconee II
1-4-79 Trip
HOT LEG TEMPERATURE
SIGNAL WENT OUT OF RANGE
REACTOR COOLANT
SYSTEM PRESSURE
COLD LEG TEMPERATURE
PRESSURIZER LEVEL
PRESSURIZER LEVEL (INCHES)
R.C. PRESSURE (PSIG)
TEMPERATURE (°F)
200
180
160
140
120
100
80
60
40
20
0
2500
2400
2300
2200
2100
2000
1900
600
580
560
540
520
500
480
460
440
420
-5
0
5
10
15
20
25
30
35
40
45
Time after trip (minutes)

Fig. 2.3.3.5

3.0 Conclusion

During any B&W reactor trip where a primary system break does not occur or the pressurizer does not empty and HPI is operable - net steam production in the primary system is highly improbable and generation of a volume of steam required to block natural circulation is virtually impossible.

4.0 References

1. 11/15/79 phone conversation between B&W and NRC, Subject: Potential Voiding in the RCS During Anticipated Transients

ATTACHMENT 1

Pressurizer Level Error

The pressurizer level indication is based on the pounds of mass the pressure taps measure and then distributed to varying amounts of water and steam at the saturation conditions at the pressurizer pressure. Since pressure is not measured in the pressurizer (only temperature) pressure is assumed from the temperature measurement being at T_{sat}.

During fast depressurizations the RTD in the pressurizer does not respond efficiently, especially in cases where the RTD is exposed to steam enviroment. The heat transfer time constant can vary from 30 to 180 seconds. Since most depressurization after trips occur in 30 to 50 seconds the RTD will not respond effectively at the low level point.

Figures A1 and A2 show potential level errors for 400" and 320" pressurizers.

Figures A3 and A4 show what typical errors can be expected as a function of indicated level and system pressure. These curves can be used to correct the indicated level if system pressure (i.e. T_{sat}) and pressurizer RTD temperature are known. The difference between RTD temperature and calculated T_{sat} (Based on P_{sat}) will give the level error.

In a typical trip @ Oconee 1/1/77 the system pressure went from 2150 to ∿ 1800 psig in 27 seconds. The alarms printer monitored a 648° pressurizer temperature at 1800 psig instead of the expected 621°F. At the indicated level of 70" the real level was ∿ 78" (per figure A-3).

46 1470

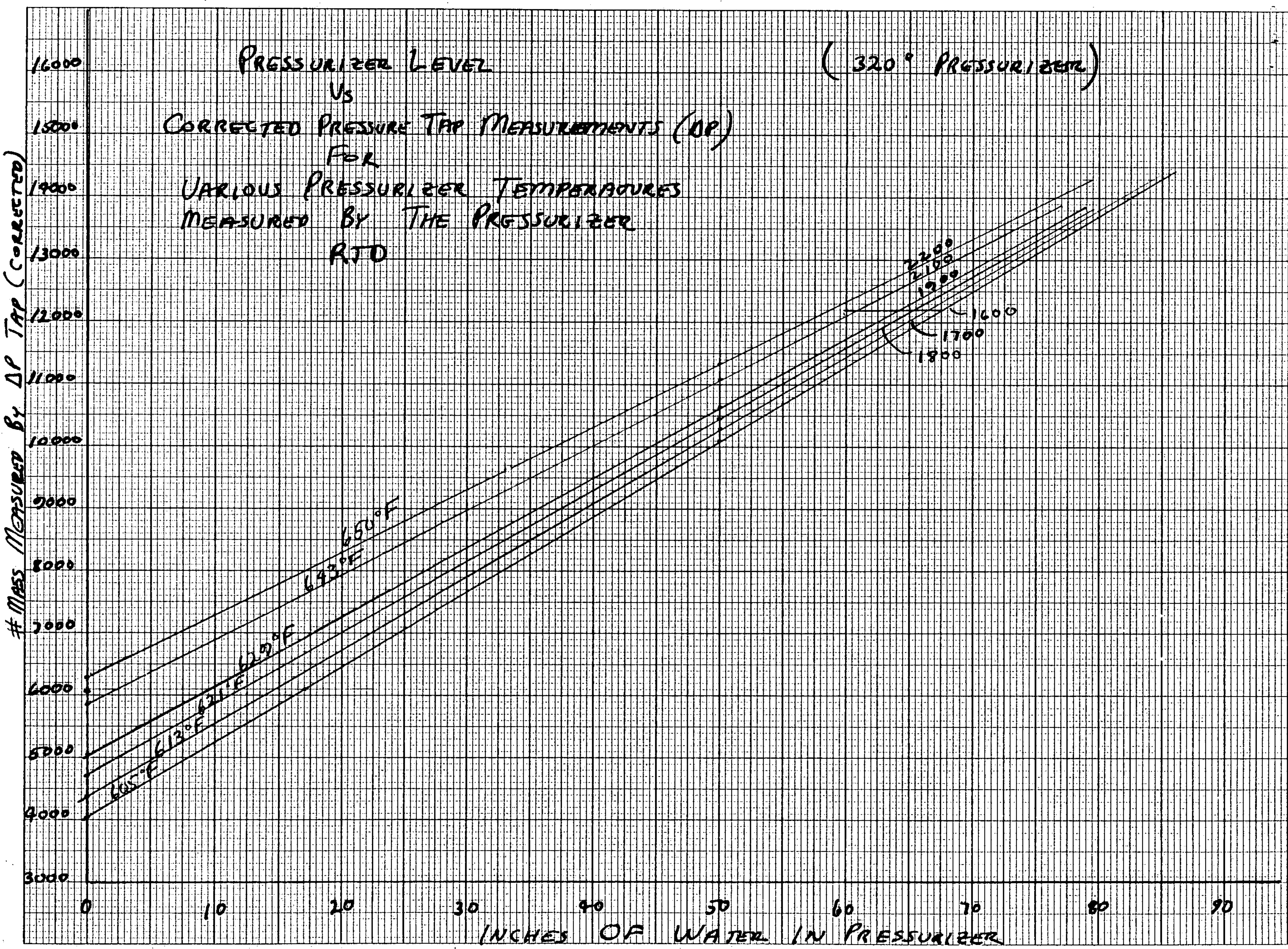


Figure A-1

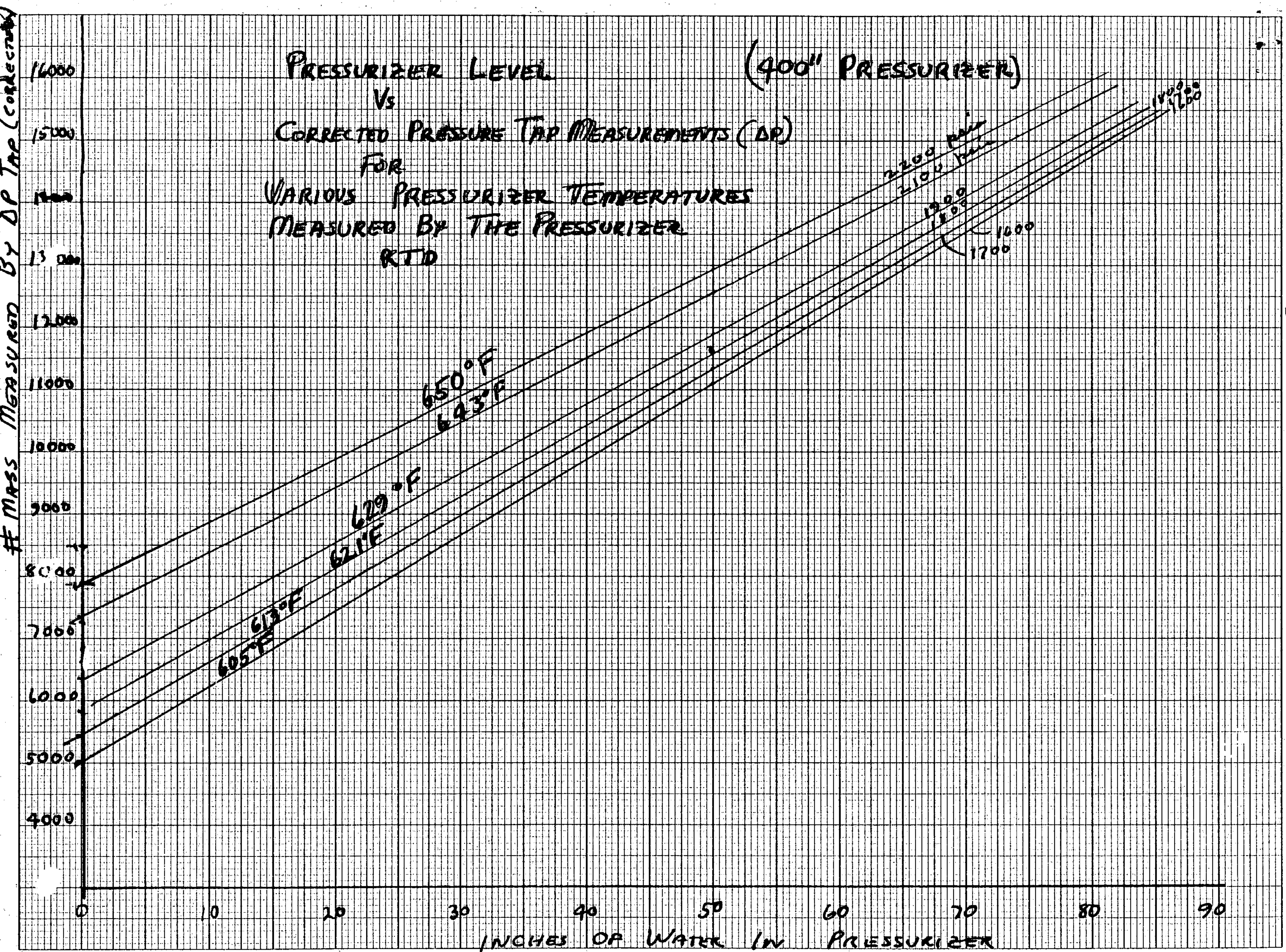

PRESSURIZER LEVEL
Vs
CORRECTED PRESSURE TAP MEASUREMENTS (ΔP)
FOR
VARIOUS PRESSURIZER TEMPERATURES
MEASURED BY THE PRESSURIZER
RTD
(400" PRESSURIZER)
MASS MEASURED BY ΔP TAP (CORRECTED)
INCHES OF WATER IN PRESSURIZER
650°F
643°F
629°F
621°F
613°F
605°F
2200 psia
2100 psia
1900
1800
1600
1700
16000
15000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
0
10
20
30
40
50
60
70
80
90

Figure A-2

46 1510

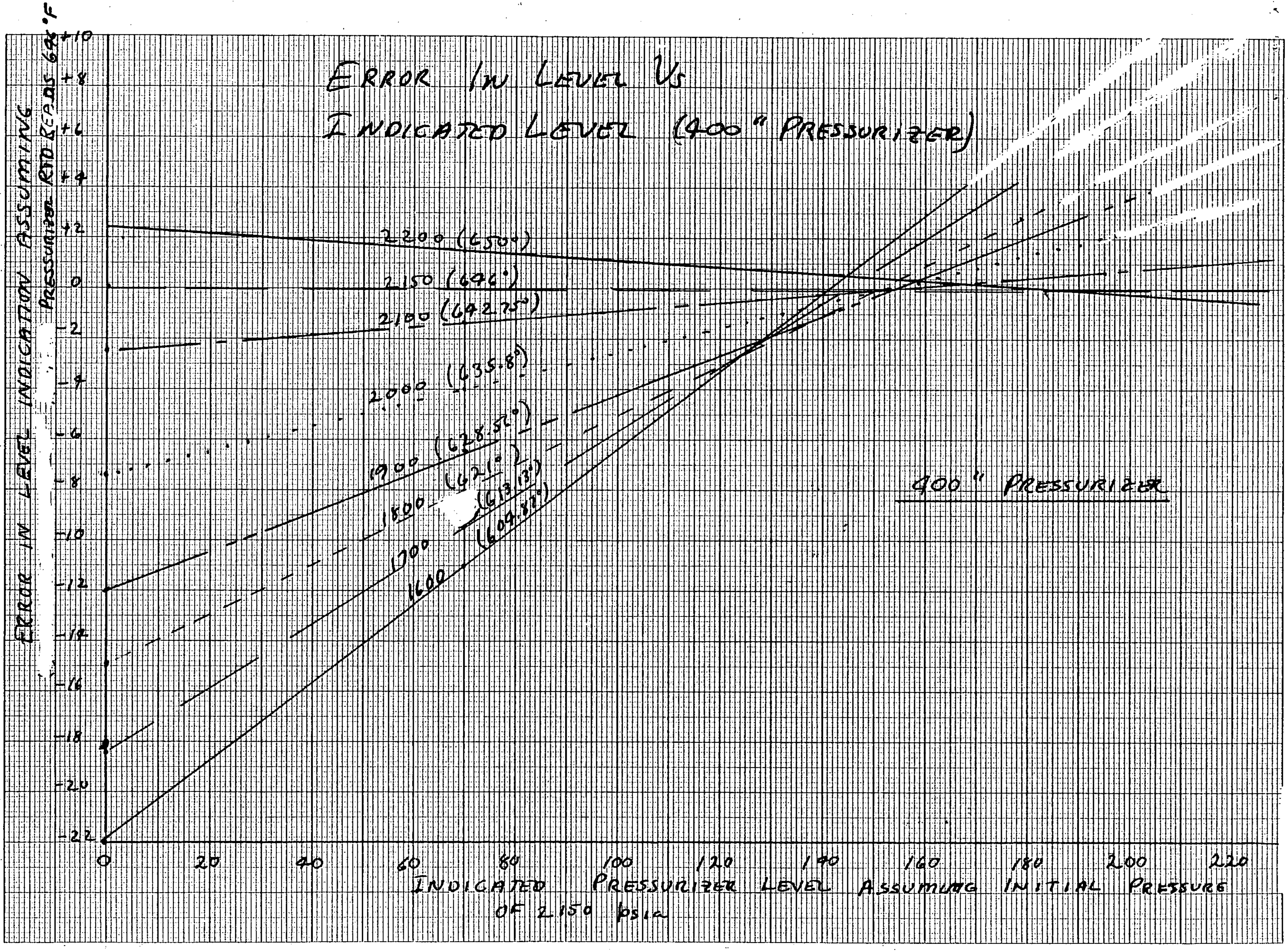


Figure A-3

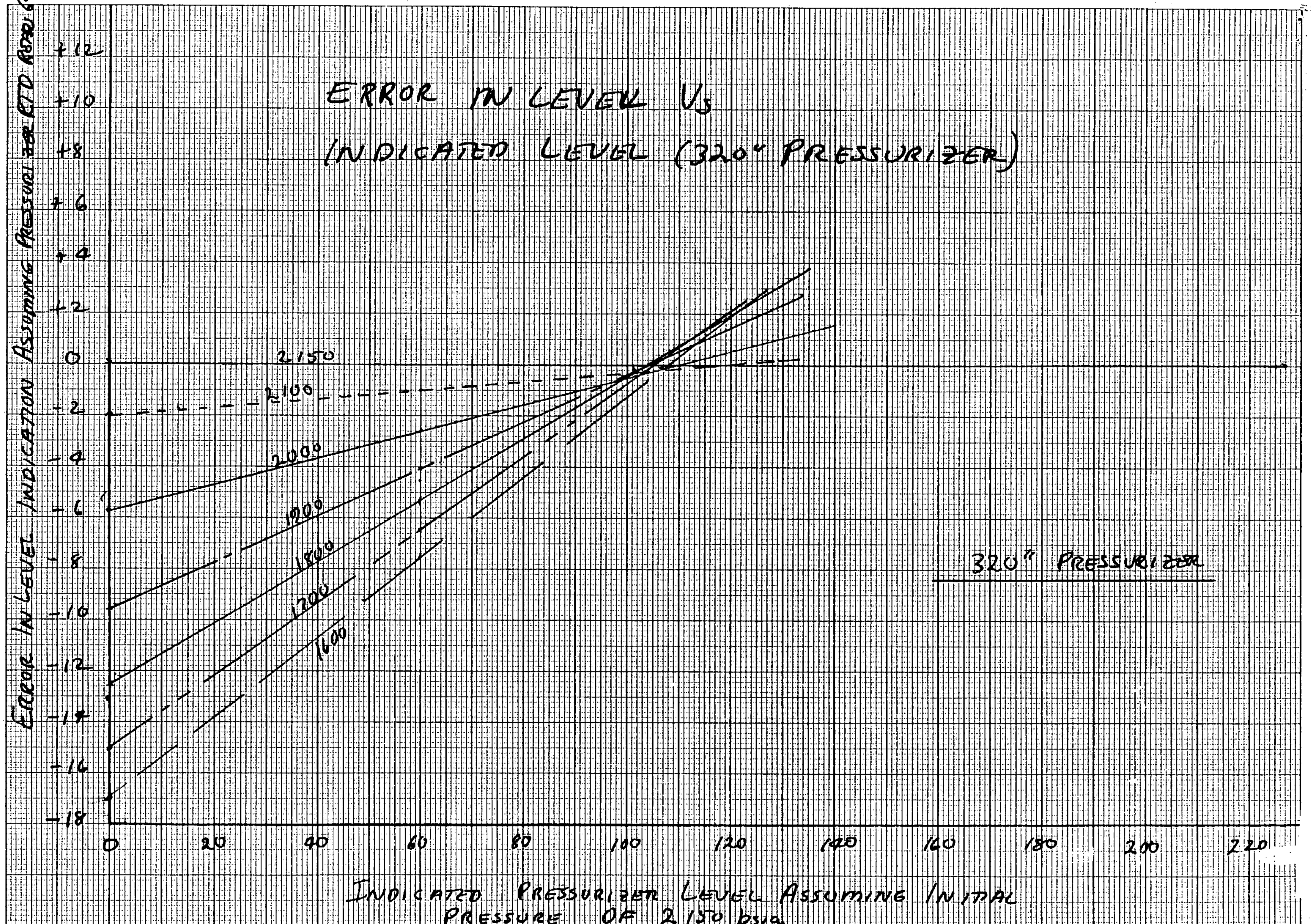

ERROR IN LEVEL VS
INDICATED LEVEL (320" PRESSURIZER)
ERROR IN LEVEL INDICATION ASSUMING PRESSURIZER RTD READ 645°F
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
2150
2100
2000
1900
1800
1700
1600
320" PRESSURIZER
0
20
40
60
80
100
120
140
160
180
200
220
INDICATED PRESSURIZER LEVEL ASSUMING INITIAL
PRESSURE OF 2150 psia

Figure A-4