Enclosure 1

INADEQUATE CORE COOLING SYSTEM

EVALUATION FOR TMI-1

RCS HOT LEG

AND RV HEAD

TABLE OF CONTENTS

I. INTRODUCTION

History

Following the accident at TMI-2 in March, 1979, a great deal of attention was drawn to the subject of inadequate core cooling (ICC) and additional instrumentation which might be added to monitor the approach to and recovery from ICC. Soon after the accident, GPUN committed to install a subcooling margin monitor and wire the installed core exit thermocouples to the plant computer (June 28, 1979 letter). With the issuance of the TMI-1 Restart Report further details of these systems were provided as well as the expansion of the range of the hot leg RTD (Thot wide range). In the fall of 1980 NRC issued NUREG 0737 which required an investigation of additional ICC instrumentation which should be considered for installation. During the ASLB hearing in the spring of 1981 the issue of inadequate core cooling was litigated extensively and in the December 14, 1981 Partial Initial Decision, the Board recommended that a water level instrument be installed at the Cycle 6 refueling outage. In the fall of 1981, GPUN completed its evaluation of additional ICC instrumentation which employed the service of Dr. Dhir of UCLA and concluded that a Hot Leg Level Instrumentation System (HLLIS) was appropriate. In the spring of 1982 the NRC indicated that the HLLIS was not sufficient to meet their criteria for measuring the approach to inadequate core cooling. On December 10, 1982, NRC issued an "Order of Modification of License" for TMI-1 that required installation of an ICC Instrumentation system that conforms to the design parameters specified in NUREG 0737, Item II.F.2.

REQUIREMENTS

The three principal requirements for instrumentation to detect inadequate core cooling (ICC), as most recently stated in NUREG-0737, are that the instrumentation system must be unambiguous, provide advance warning, and cover the full range of operations. The ICC detection system herein evaluated meets these principal requirements. It consists of three instrumentation components: the saturation meter, RCS Inventory Trending System (RITS) and core exit thermocouples. These three components when considered together are the ICC detection instrumentation.

The installation of a RCS Inventory Trending system (RITS) in the B&W NSS system has been proposed as one of the instruments to satisfy Item II.F.2 of NUREG-0737, Instrumentation for Detection of Inadequate Core Cooling. The purpose of this report is to evaluate the RITS, and provide an engineering assessment of the possible benefits of such a device to a plant operator in the event of plant upsets.

A summary of system uses and an outline of the background, comprise Section 2 of this report. Section 3 is a brief description of the RITS including the physical operating assumptions and characteristics. An overview of Inadequate Core Cooling (ICC) is presented in Section 4. The specific LOCA and non-LOCA transients evaluated are contained in Section 5.

A necessary part of this evaluation involves an analysis of various HPI flow rates and the effects on a small break (SB) LOCA transient. This analysis is covered in Section 6 and leads directly into suggested operator guidance for using the RITS, Section 7. Overall report conclusions can be found in Section 8. Section 9 lists the references used.

II. SUMMARY OF USES OF RITS

Item II.F.2 of NUREG-0737 specifies the requirement for an unambiguous indication of inadequate core cooling (ICC). A part of this ICC indication could involve water level instrumentation. The B&W NSS system's unique design allows for measurement of reactor coolant level in the riser section of the hot leg. Other NSS system designs do not permit measurement of level at the high point and must utilize a measurement of reactor vessel level (refer to Figure 1). The advantage of the RCS Invent. Trending system (RITS) is that hot leg and head voiding will precede a possible ICC situation. The RITS will provide the operator with an indication of voided conditions in the reactor coolant system (RCS) and alert the operator to the potential for core uncovery.

With the implementation of the RITS, the operator will have at his disposal an additional device for early warning of possible ICC events. Based on the level indications, the operator can take confirmatory actions such as assuring maximum HPI flow, the steam generators are depressurizing, and the emergency feedwater level is being raised to 95% of the operating range. These actions, as discussed in this report, will provide a mass accumulation within the reactor vessel to insure adequate core cooling.

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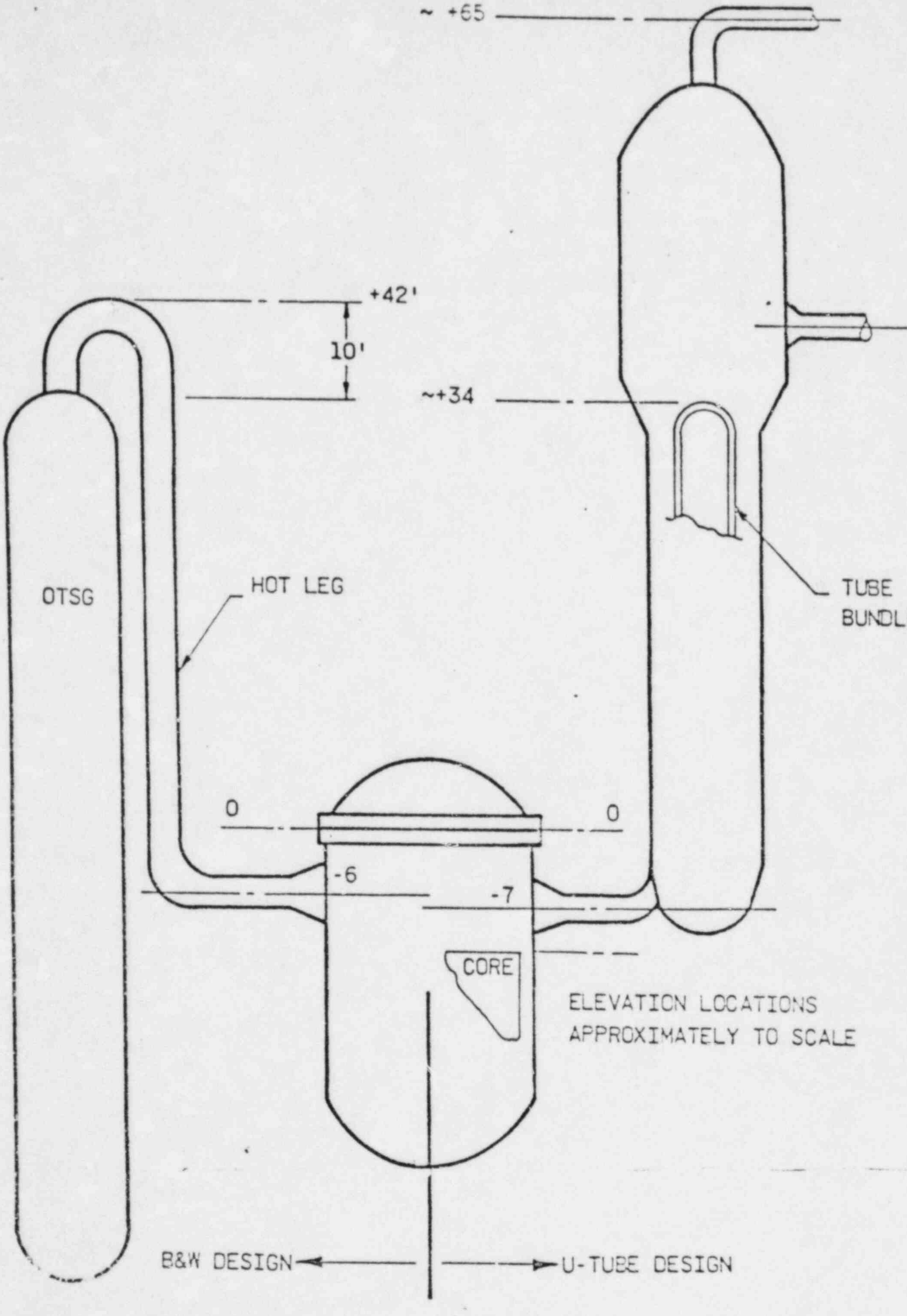
FIGURE 1


~ +65
+42'
10'
~+34
OTSG
HOT LEG
TUBE
BUNDLES
0
0
-6
-7
CORE
ELEVATION LOCATIONS
APPROXIMATELY TO SCALE
B&W DESIGN
U-TUBE DESIGN

III. Design Description

The Reactor coolant Inventory Trending System (RITS) is a system designed to provide a means for the operator to monitor in the control room.

- o The water inventory in the hot leg of each primary loop and in the reactor vessel when the reactor coolant pumps (RCP) are not operating, and
- o the void content of the RCS when the RCP's are operating.

The RITS is composed of two subsystems to provide the above functions. The water inventory trending subsystem is a differential pressure (d/p) measurement system consisting of two identical independent instrument loops to measure hot leg inventory and two identical instrument loops to measure reactor vessel inventory. The "A" loops will measure the primary coolant inventory in the "A" hot leg and in the reactor vessel while the "B" loops will measure the inventory in the "B" hot leg and reactor vessel. The differential pressure transmitters will be located in the Reactor Building outside of the D-rings. The hot leg inventories will be measured by connecting the transmitters to the high point vent connection at the top of each hot leg and to incore instrument guidetube via instrument tubing. The reactor vessel inventory will be measured by connecting the transmitters to the thermocouple vent valve connecting in the vessel head and to incore guidetube . Each transmitter will have a wet reference leg. Temperature elements will be installed on the reference water columns. Process instrument and signal conditioning wil be provided to correct for water density as a function of water temperature and to provide analog meter displays in the control room. (See Figures 2a,2b,2c)

The differential pressure transmitters will be powered from, and have their signals conditioned by, the existing A2 and B2 Signal Conditioning Cabinets located in the Control Building El 338'6" for A2 and El 322'0" for B2. The Signal Conditioning Cabinets are 1E qualified Foxboro Spec 200 equipment powered from the vital AC buses A and B, respectively.

At the Signal Conditioning Cabinets the input signals from the transmitters will be converted from current to voltage signals, compensated based upon primary system reference leg temperature process variables and reference leg temperature, and routed to the Control Room and computer via qualified isolation devices.

The output signals will be displayed in the Control Room. A "caution" sign will be mounted by the inventory indication stating that readings are valid only when the Reactor Coolant Pumps are idle.

The water inventory trending subsystem will be designed such that a single active failure will not prevent indication of the RCS inventory in at least one of the hot legs and in the reactor vessel above the fuel. The range of the hot leg inventory measurement will account for approximately 51 vertical feet of water above the fuel while the range of the vessel measurement will account for approximately 17 vertical feet of water above the fuel. Connections to the primary coolant system will be made via 1/2" tubing so that a tubing break is within the capacity of the make-up pump.

The void fraction trending subsystem consists of two identicial independent instrument loops to measure RCP motor power. One of the instrument loops will be associated with an "A" loop reactor coolant pump and one with a "B " loop pump. The monitored signals will be input to the plant computer where they can be displayed as RCS void fraction via an empirical correlation. Since the RCP's are powered from non-1E sources of electrical power, this subsystem of the RITS will also be non-1E. However, the void fraction trending subsystem will be designed such that a single failure will not prevent indication of the RCS void fraction at all times when the RCP's are in operation. The range of the RCS void fraction indication will be from 0% to100%. Void fraction indicators will be provided in the control room. A "caution" sign will be mounted by these indicators stating that the readings are valid only when the RCP's are in operation.

Figure 2c shows instrumentation for the inventory trending using RCP power. The pump power inputs come from existing power transformers. The Tc inputs come from the cold leg RTD's. In the void calculator portion in the plant computer two operations would be performed:

a) The saturated liquid and vapor densities (ρf and ρg) corresponding to the Tc input would be determined.

b) The densitites determined in a) would be input to the void fraction algorithm with the appropirate pump power and the void fraction computed.

The selector/averager permits the selection for output of void fraction for output of the void fraction for each pump or the loop average. The design concept assumes that all portions of the system are classified non-1E.

An estimate of the expected accuracy of the void fraction indication based on pump current has not been established. The temperature elements and current transformers have well defined accuracies. The pump, however, is not an instrument, and assignment of an accuracy to its performance as a density transducer cannot be expected to be made with the same certainty as for the other inputs. The accuracy of the indication at the time of calibration will be determined by:

a) The accuracies of the temperature and current measurements.

b) The ability of the signal processing circuit to match the pump current vs. density curve.

The subsequent accuracy of the indication will change to the extent that certain conditions deviate from the conditions at calibration. The most significant of these are:

- pump motor efficiency
- motor power supply voltage
- motor power factor
- pump speed
- pump hydraulic torque

In view of the proposed use of the void fraction measurement as a trending indication, we believe that the absolute accuracy is not as important as other characteristics of the measurement. It is more important, in this application, that the measurement reliably follow trends in coolant density and void fraction. We believe that the important information to be derived from this indication is not the value of void fraction at a given moment but the trend of void fraction with time. Our assessment of the scale pump test data indicates that the pump current decreases with increasing void fraction in a manner which can provide clear and adequate trending signal to the operator. The data indicates that the usable range of the signal will be limited to between 15% and 40% void fraction at the pump suction. The process parameters applicable to the RITS are:

Pressure:	0-2500 psig
Temperature:	50°F-650°F
Boron Conc.:	2270-0 ppm
Water Level Range:	approx. 612" from top of Hot Leg.
	approx. 200" from top of RV.

The environmental requirements for the D/P transmitter and associated tubing inside the reactor containment building are:

Normal Conditions

40 year Base Temperature		130°F
Relative Humidity		100%
Pressure		Atmos.
Radiation	MR/hr	0-100
	R/40 yr	3.5×10^4

Accident Conditions

Temperature (Max.)		275°F
Relative Humidity		100%
Pressure (Max)		50.6 PSIA
Radiation	Mr/hr at T=0	0-100
	6 mon. accident exp	2×10^7
Chemical Spray PH		8 to 11

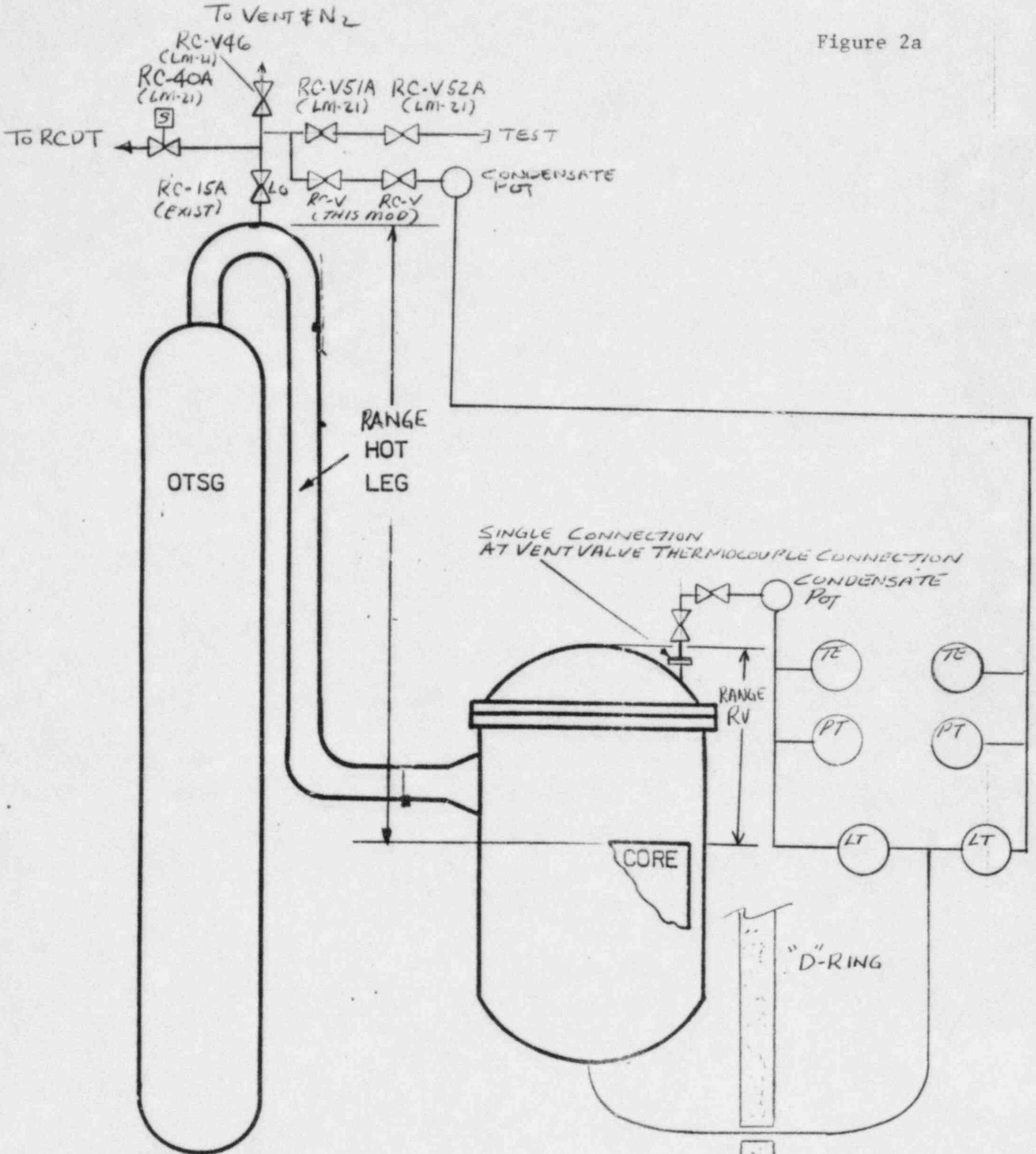
The environmental conditions for the equipment in the Control Building for both normal and accident conditions are:

40 year Base Temperature		75°F
Relative Humidity		65%
Pressure		Atmos.
Radiation	MR/hr	0-10
	R/40 yr	Negligible

GPU NUCLEAR

TMI-1 REACTOR COOLANT INVENTORY TRACKING SYSTEM

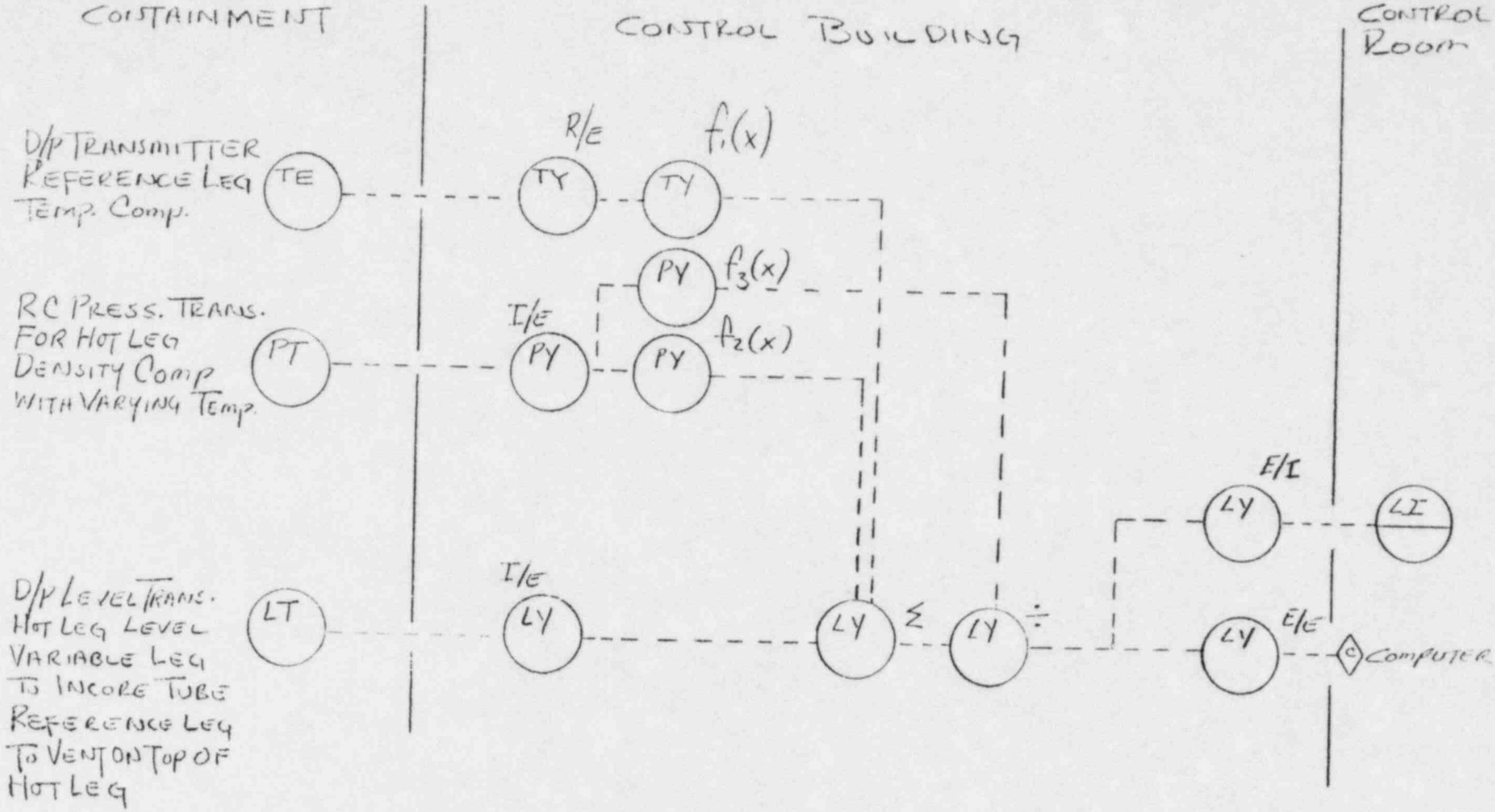
Figure 2a



NOTES:

1- EACH HOT LEG TO HAVE ONE LT. ONE HOT LEG SHOWN.
2- RV TO HAVE TWO LT'S FROM A COMMON INCORE TUBE.
3- PT'S & TE'S USED FOR TEMPERATURE COMPENSATION

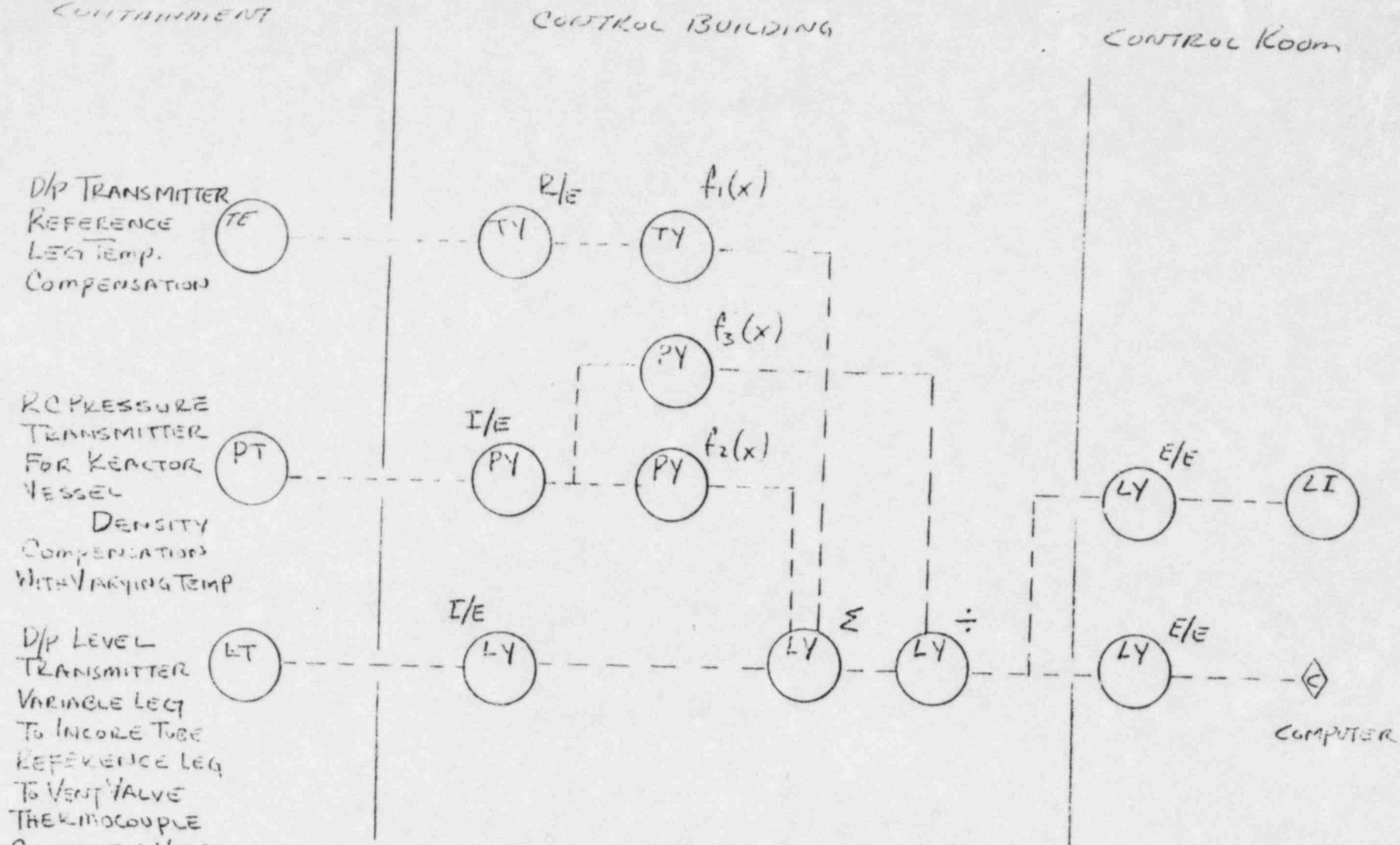
Figure 2b



COMPENSATION IS PROVIDED FOR DENSITY VARIATION IN BOTH THE REFERENCE LEG AND HOT LEG.
ALL HARDWARE IS QUALIFIED TO IEE-323 & 344
TWO REDUNDANT CHANNELS PROVIDED (ONE PER HOT LEG)

REACTOR INVENTORY TRACKING SYSTEM HOT LEG MEASUREMENT

Figure 2c

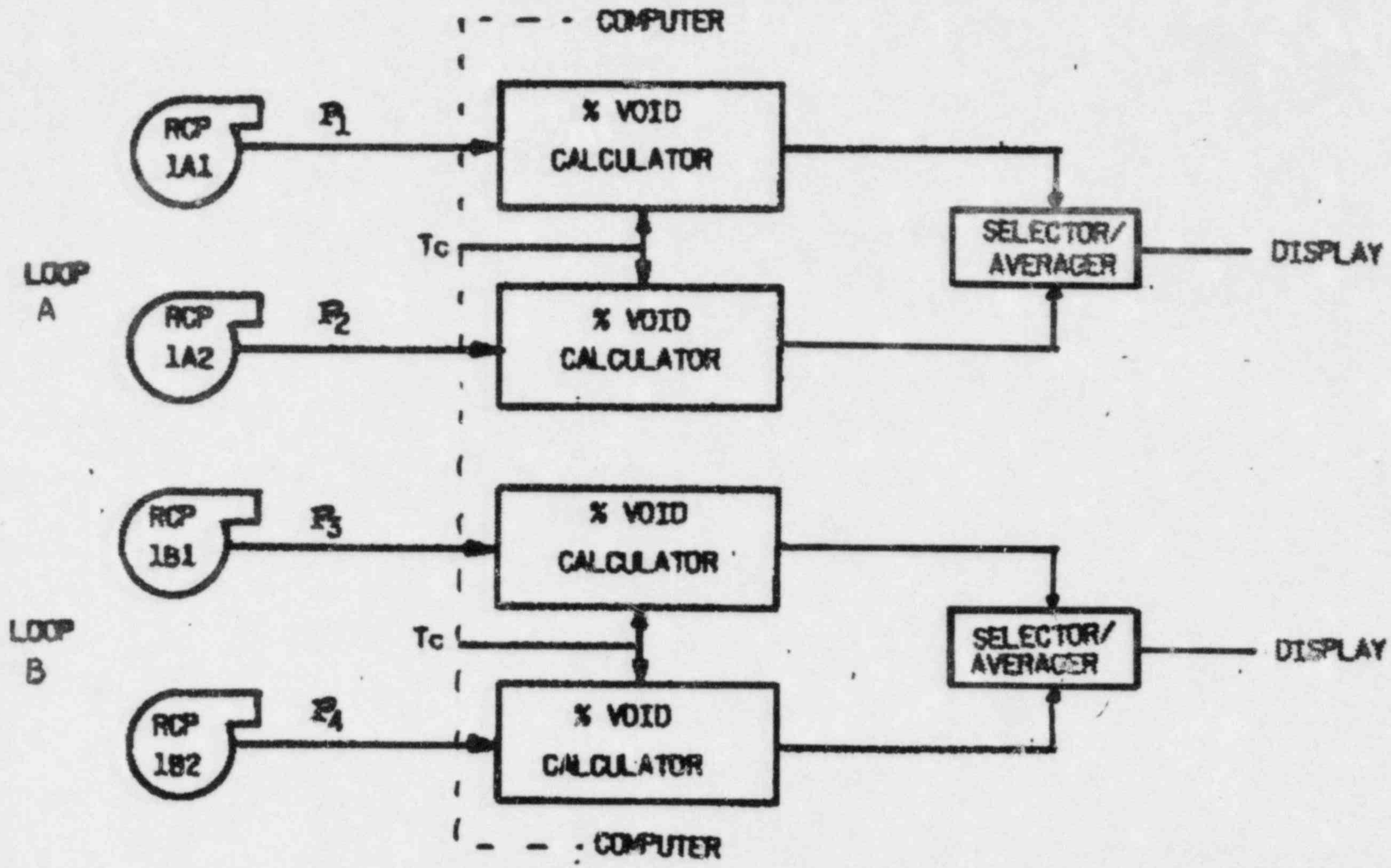


COMPENSATION IS PROVIDED FOR DENSITY VARIATION IN BOTH THE REFERENCE LEG AND REACTOR VESSEL ABOVE THE FUEL. ALL HARDWARE IS QUALIFIED TO IEEE-323 & 344 TWO REDUNDANT CHANNELS PROVIDED ON THE VESSEL

REACTOR INVENTORY TRACKING SYSTEM REACTOR VESSEL MEASUREMENT

Figure 2d

MEASUREMENT OF VOID FRACTION BY RC PUMP POWER



IV. INADEQUATE CORE COOLING DETECTION SYSTEM - OVERVIEW

The condition of ICC can develop only after a well defined set of events occur. This section is intended as an overview of ICC and an ICC detection system. A more detailed discussion can be found in Reference 7, "Evaluation of Instrumentation to Detect ICC".

First, there must be a loss of RCS inventory which leads to the saturation of the RCS. Then the inventory loss must continue such that the core actually starts to become uncovered. This will result in the heat generated in the core not being removed since there will be portions not covered with liquid coolant. This failure to remove the heat can then lead to high temperatures in the fuel. The ICC condition occurs when the heat removal capability of the coolant is exceeded to the extent that fuel temperatures rise to the point of fuel damage. This does not occur until the core becomes at least partially uncovered because when it is surrounded by liquid coolant, even at saturation temperature, there is adequate cooling of the core to prevent fuel damage.

The ICC detection system monitors the prerequisite stages of ICC and the occurrence of ICC. The saturation meter will indicate when saturation conditions occur and thus provides advance warning that ICC is a possibility. However, the onset of saturation conditions does not in itself indicate that ICC will occur. There is a spectrum of LOCA events which will cause saturation conditions to occur but will not proceed to core uncovery or ICC. There are also non-LOCA events which will proceed to saturation conditions but do not have the potential for ICC. Thus the saturation meter provides advance warning of ICC but is not an unambiguous indication that ICC conditions could occur.

In a small break LOCA of the size which could proceed to the ICC condition, the inventory loss continuing through saturation conditions will result in the formation of voids in the RCS. These voids will contain steam and gases released from the coolant. The gas content will remain very small until the onset of ICC. Since there is no forced RCS flow at this point in the SB LOCA scenario, steam and gas will collect at the system high points. The high points that will become void of liquid coolant first in the B&W plant will be the upper RV head and the upper U bend of the hot leg piping (Figure 1). The formation of steam and gas bubbles in the hot leg will cause a liquid level to develop which can be inferred from the differential pressure measured by a differential pressure transmitter connected to the top of the hot leg and to an incore instrumentation tube.

This instrument would indicate the level and thus provide additional information to the operator. The specific nature of the information would be that the inventory loss is continuing (decreasing level) or that the inventory loss rate has been matched or exceeded by ECC injection rate (steady or increasing level). Thus the RITS would be additional advanced warning that conditions are progressing toward the ICC condition.

The RITS not only supplements the advanced warning of the saturation meter but it also increases the range of the monitoring of the approach to ICC. About 63% of the RCS inventory is monitored by the RITS (top of hot leg to the top of the active fuel). This represents about 100% of the total RCS inventory available to cool the core.

The RITS would also indicate that a level existed in the hot leg for some non-LOCA transients which do not have the potential for ICC.

However, the non-ambiguity of the RITS is a time related function. Early in transient time, the LOCA and non-LOCA behave similar regarding hot leg level. But as the transient progresses, the level continues to decrease for the LOCA while, for the non-LOCA, the level will recover.

An incorrect indication of level when a level does not exist could be caused by instrument failure or a break in the RITS instrument sensory lines. However, this would not lead to incorrect actions by the operator because the action to be taken based only on RITS indication would be to ensure that the actions taken at saturation conditions were effected as required. If a RITS instrument malfunction caused an incorrect level indication, the operator would have additional information on RCS conditions provided by the other loop RITS, the saturation meter and other normally monitored parameters. Even if the operator ignored this additional information and initiated HPI based on an incorrect belief that inventory has been lost in one hot leg, this would not be an unsafe action. In the other case where instrument malfunction caused the RITS to indicate full when in fact a level existed, the operator would not be directed to secure HPI based on RITS indication. Rather, securing of HPI would be based on subcooling conditions. Thus, although the RITS could provide ambiguous or incorrect indication, it would not cause unsafe actions to be initiated.

As the SB LOCA scenario continues, the inventory loss is such that the top of the core becomes uncovered. The core exit thermocouples will have indicated saturation temperatures since saturation conditons were reached much earlier in the transient. As inventory continues to be depleted, the core fuel region becomes uncovered and the temperature of the steam at the core exit begins to increase above saturation temperature. This superheated temperature sensed by the core exit thermocouples is additional advance indication that conditions are progressing toward ICC conditions. Ultimately the conditions of heat transfer would be such that core exit thermocouple temperatures would increase to the thresholds for further operator actions. If for some reason, these actions were not affected, then ICC would occur and would be indicated by the core exit thermocouples.

V. TRANSIENTS ANALYZED

The transients to be reviewed for this evaluation required certain necessary modeling characteristics. Of primary importance was an adequate nodalization scheme to allow for void formation in the hot leg during the transient.

Also of importance was to be reasonably assured that a spectrum of small break LOCA's was represented. The .01 ft.^{2} break in the cold leg at the pump discharge is significant in this regard. Break sizes of larger than this .01 ft.^{2} (Reference 6) tend to continuously depressurize the RCS as the HPI and break size are adequate to remove produced energy. The continuous depressurization is also a result of continuous loss of inventory as one HPI pump is insufficient to overcome break flow. However, the depressurization allows for other ECCS to be actuated (CFT and LPI) within adequate time to assure core covery and safe conditions. On the other hand, for break sizes of smaller than .01 ft.^{2} the RCS can be kept at operating pressure and in a subcooled condition through use of the Makeup and HPI systems. Therefore, the .01 ft.^{2} break, being between these two regions, can result in an initial system depressurization but eventual repressurization as decay heat energy production becomes too large for the HPI and break size cooling combination. This repressurization will continue until such time that a condensation surface is established in the steam generators which will then dominate system response with a depressurization trend.

Of the SB LOCA transients reviewed, the B&W "Blue Book" Repressurization Analyses had the desired hot leg configuration (Reference 3). Additional nodes were added (nodes 24 and 25, Figure 3) to more accurately represent formation of a steam bubble between the auxiliary feedwater injection point and the 180° bend in the hot leg. By decoupling these volumes (nodes 24 and 25) from the steam generator, a steam bubble can form within the upper portion of the RCS without being condensed through steam generator interaction. Some points of interest concerning this SB LOCA transient (.01 ft.^{2} break at pump discharge) are as follows:

Sequence of Events	Time (Sec.)
Break occurs (.01 ft.^{2} at pump discharge)	0
Reactor trip, turbine trip, and RC pump coast down occurs	50
Main feedwater coastdown ends	65
Auxiliary feedwater flow to both steam generators	90
Hot leg voiding begins	100
HPI starts	190
Loss of Nat. Circ. in intact loop	340
Loss of Nat. Circ. in broken loop	650
Maximum repressurization reached	1500
Minimum mixture level at 5 ft. above the top of the core	1700
Long term cooling established	about 4900
Peak cladding temperature	720F (initial value)

The RCS depressurizes rapidly over the first 100 seconds to saturation pressure of about 1400 psia (Figure 4). At this point, hot leg and upper plenum steam formation slow the rate of depressurization.

RCS depressurization continues until about 650 seconds when natural circulation ceases as hot leg level continues to decrease. The loss of steam generator heat removal causes the primary system pressure to begin increasing. At 1500 seconds, the maximum system pressure is reached (1750 psia) and begins to slowly decrease because steam condensation by the steam generator is established. This additional energy removal results in a decreasing RCS pressure transient thereafter. The hot leg mixture heights are shown in Figure 5. As can be seen from the figure, natural circulation is lost at approximately 340 seconds in the intact loop and at approximately 650 seconds in the broken loop.

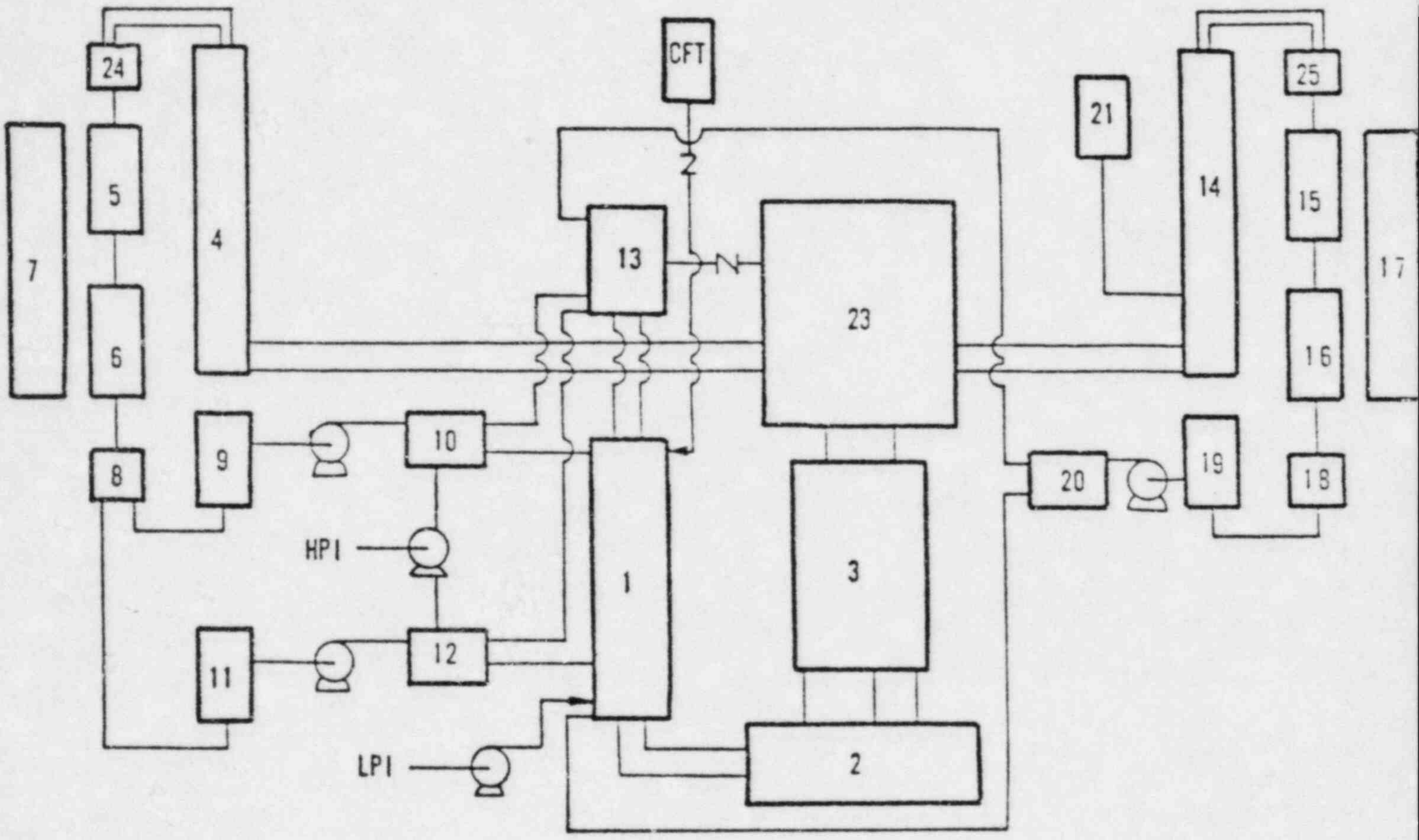
The cases reviewed for non-LOCA events (Reference 1) have a detailed noding scheme arrangement in the upper regions of the hot leg so that the effect of void formation could be observed (NODE 32 and 33, Figure 6). The specific case reviewed is a study of the impact of RC Pump Trip on the ESFAS Low RC Pressure signal. Results (Figures 6-11) show that natural circulation flow was temporarily reduced in the PZR loop to 45 to 100 lb/sec. from 4 to 6 minutes (refer to Figure 9), with flow steadily increasing after this time period. The flow in the non-PZR loop remained relatively unchanged at about 1000 lb/sec. (refer to Figure 10). The steam bubble was collapsed, natural circulation was fully restored, and a greater than 50°F subcooled margin was achieved in the PZR loop.

The other non-LOCA cases reviewed, Reference 2, involved overcooling events analyzed in reply to Denton's 50.54(f) Show Cause, Parts A-B (177 FA Plants). In this report, more than one transient type is analyzed to address different frequency of occurrence classifications and to assure the most severe cases are included in the evaluation. Included are overcooling accidents, such as main and small steam line breaks, and overcooling transients, such as pressure regulator malfunction and main feedwater overfill. All these transients retained adequate core cooling through natural circulation even when analyzed with no operator action before 10 minutes and with only safety systems used to mitigate the event. A typical event is a small steam line break (SLB) case (Figures 12 thru 14). Following are the results of this particular event:

Sequence of Events	Time (sec.)
Steam line break occurs	0.0
High flux trip setpoint	4.67
Rod movement starts	5.07
Low RC pressure ESFAS, RC Pump trip, LOOP	16.25
MSIV closes	23.75
Pressurizer empties	25.0
MFWIV closes	31.25
HPI starts to flow	46.25
Auxiliary FW initiation to steam generator	85.7
Hot leg voiding begins	100
Hot leg solid	600

A general overview of hot leg level response for those LOCA and non-LOCA transients reviewed is given in Figure 15. Not shown on Figure 15 is the level response for other SB LOCA's. However, as stated previously, larger break sizes result in continuous loss of inventory, and hence a decreasing hot leg level, until such time as the depressurization actuates other ECCS that assures long term recovery. Smaller break sizes result in little or no inventory loss. The important point to notice is that within minutes, hot leg level is completely regained in the non-LOCA events due to the RC system regaining the subcooling margin and refilling. Herein lies the fundamental conclusion that the hot leg level can be a determining parameter for distinguishing between the LOCA and non-LOCA events. This will then lead to further differentiation of the appropriate operator actions necessary to mitigate the particular events.

Figure 3 CRAFT2 NODING DIAGRAM FOR SMALL BREAKS



NODE NO.	IDENTIFICATION
1,13	DOWNCOMER
2	LOWER PLENUM
3	CORE
4,14	HOT LEG PIPING
5,6,15,16	STEAM GENERATOR
7,17	SECONDARY, SG
8,18	SG LOWER HEAD
9,11,19	COLD LEG PIPING
10,12,20	COLD LEG PIPING
21	PRESSURIZER
22	CONTAINMENT
23	UPPER PLENUM
24,25	SG UPPER HEAD/TOP OF HL

Figure 4

SYSTEM PRESSURE VS TIME

.01 FT^2 BREAK @ PUMP DISCHARGE

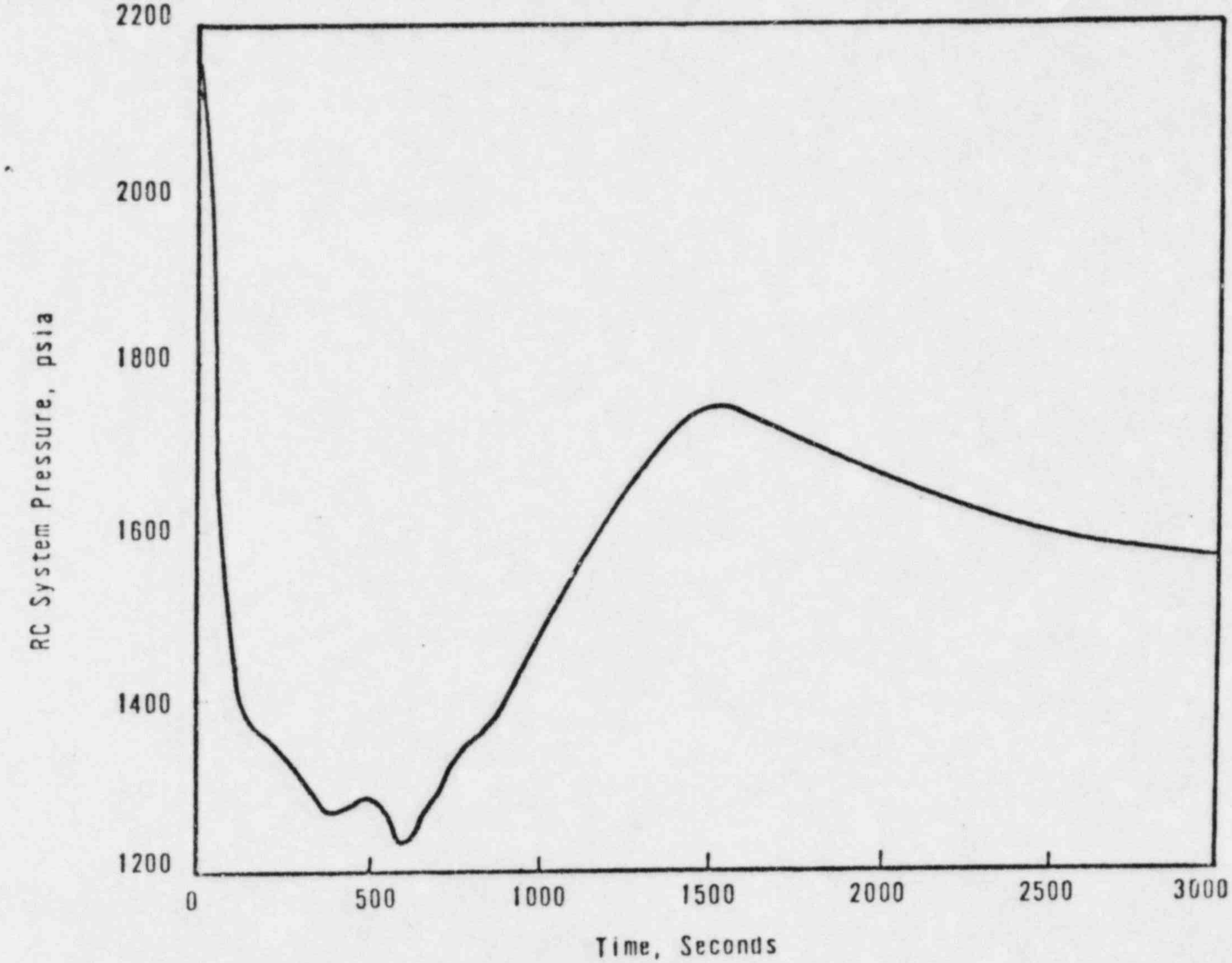


Figure 5

HOT LEG LEVEL

0.1 FT^2 BREAK @ PUMP DISCHARGE

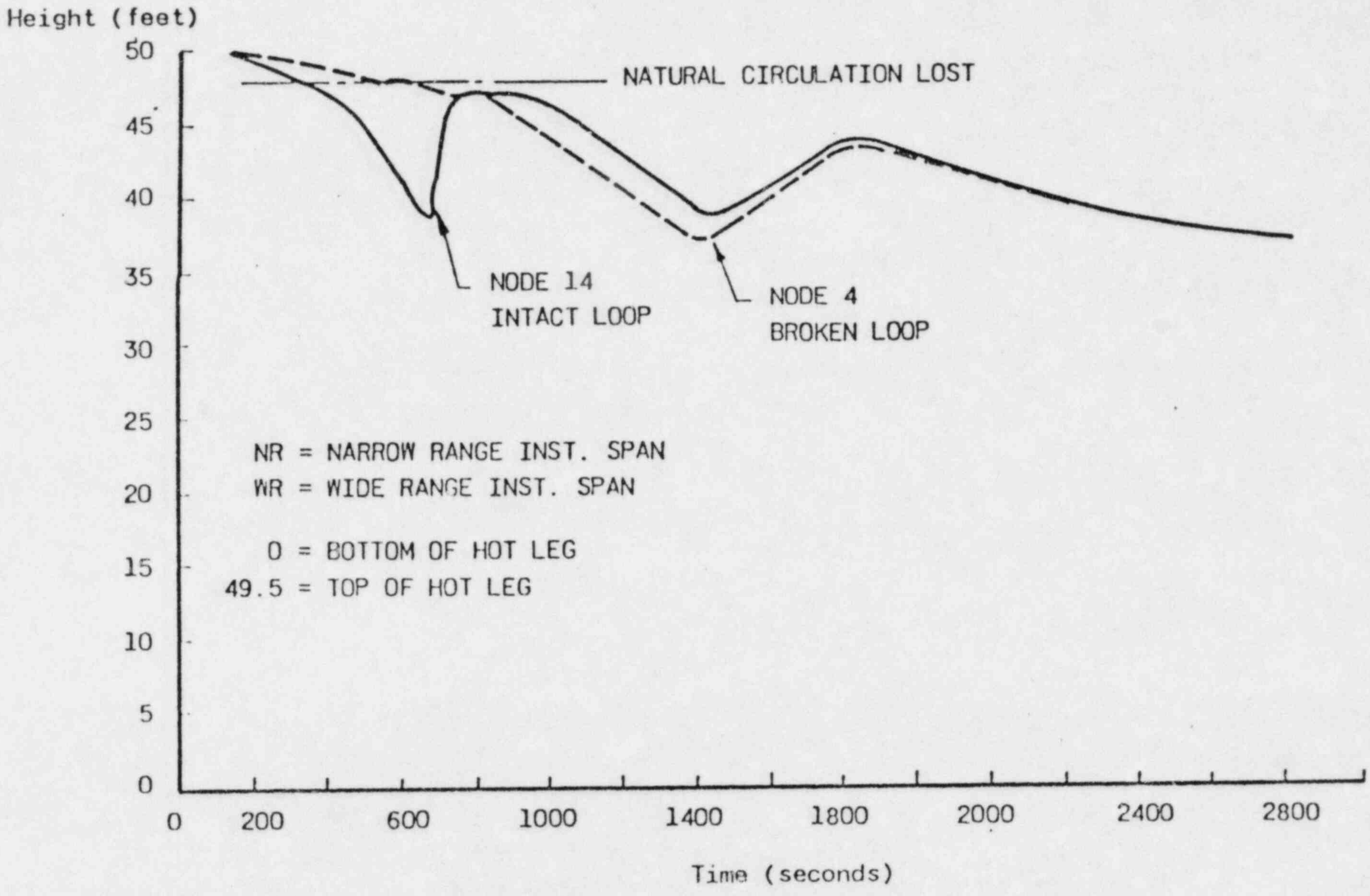
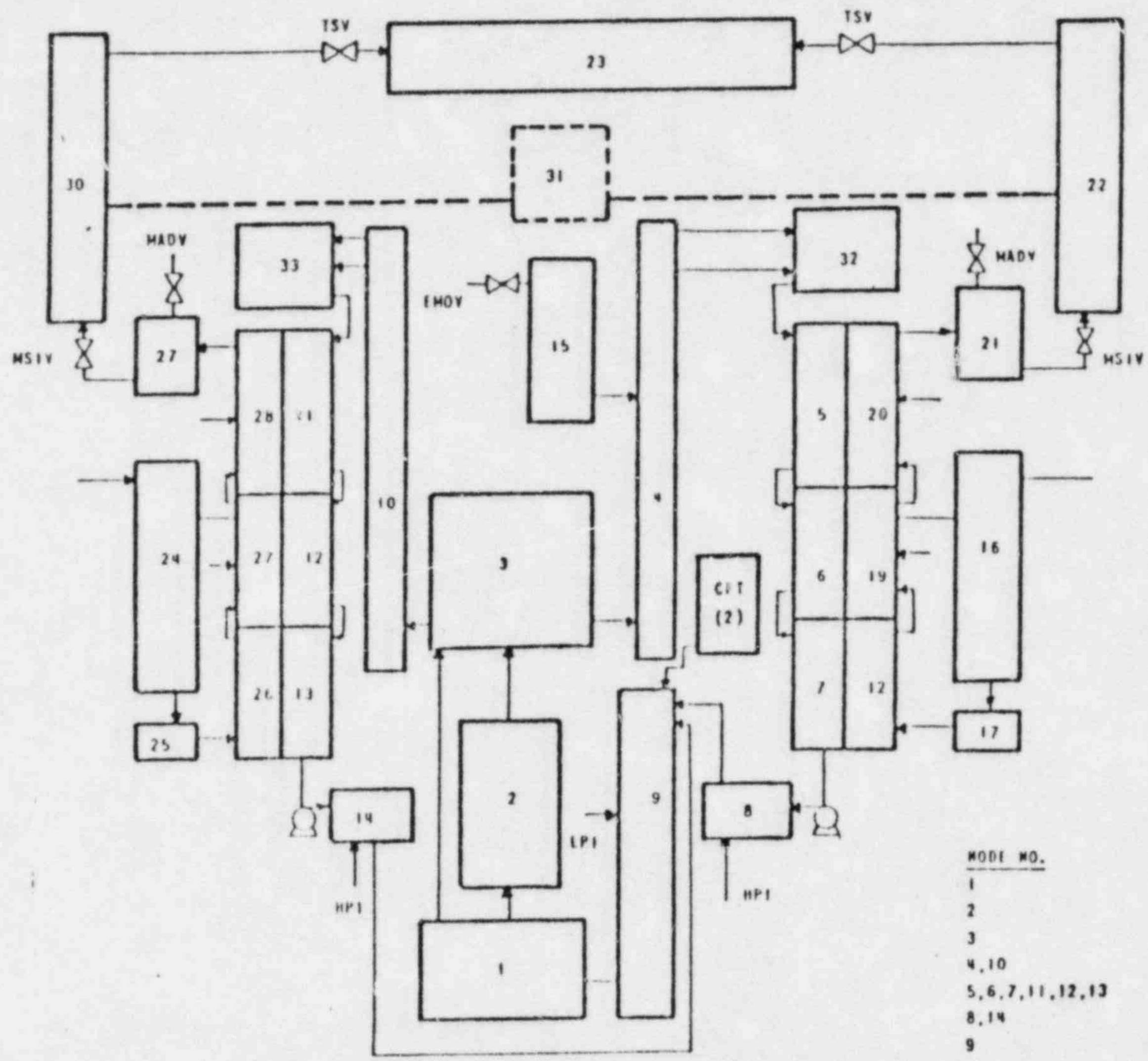


Figure 6
MINITRAP 2 NODING SCHEME NON-LOCA



NODE NO.	IDENTIFICATION
1	LOWER PLENUM
2	CORE
3	UPPER PLENUM/HEAD
4,10	HOT LEG
5,6,7,11,12,13	STEAM GENERATOR
8,14	COLD LEG PIPING
9	DOWNCOMER
15	PRESSURIZER
18,19,20,26,27,28	SECONDARY, SG
16,24	SEC SG DOWNCOMER
17,25	SEC SG LOWER PLENUM
21,29	STM RISERS
22,30	MAIN STM PIPING
23	TURBINE
31	CONTAINMENT

Figure 7

HOT LEG NODING

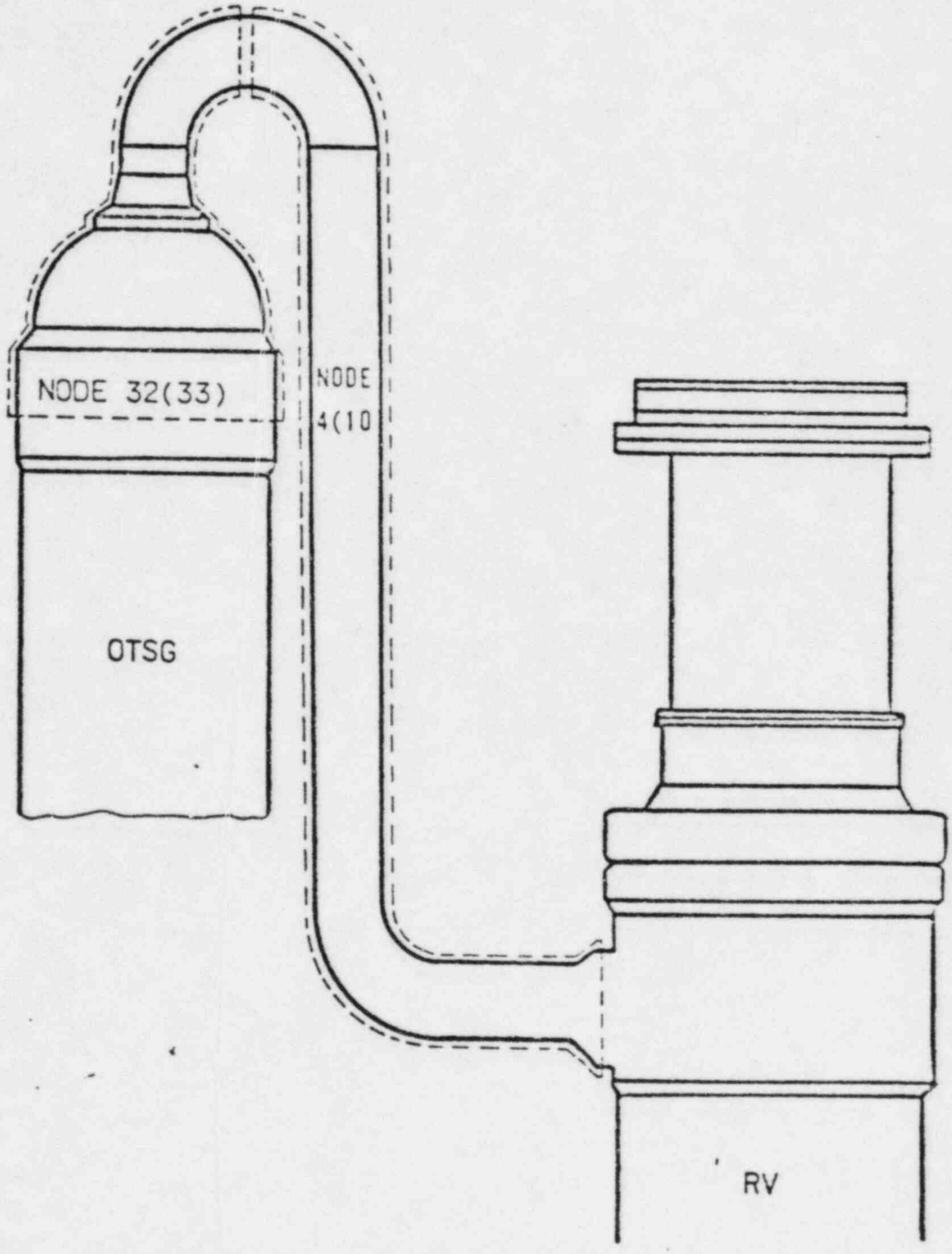


Figure 8

TOTAL STEAM BUBBLE VOLUME VS TRANSIENT TIME (102% FP, 12.2 FT^2 DOUBLE-ENDED UNMITIGATED STEAM LINE BREAK, RC PUMP TRIP)

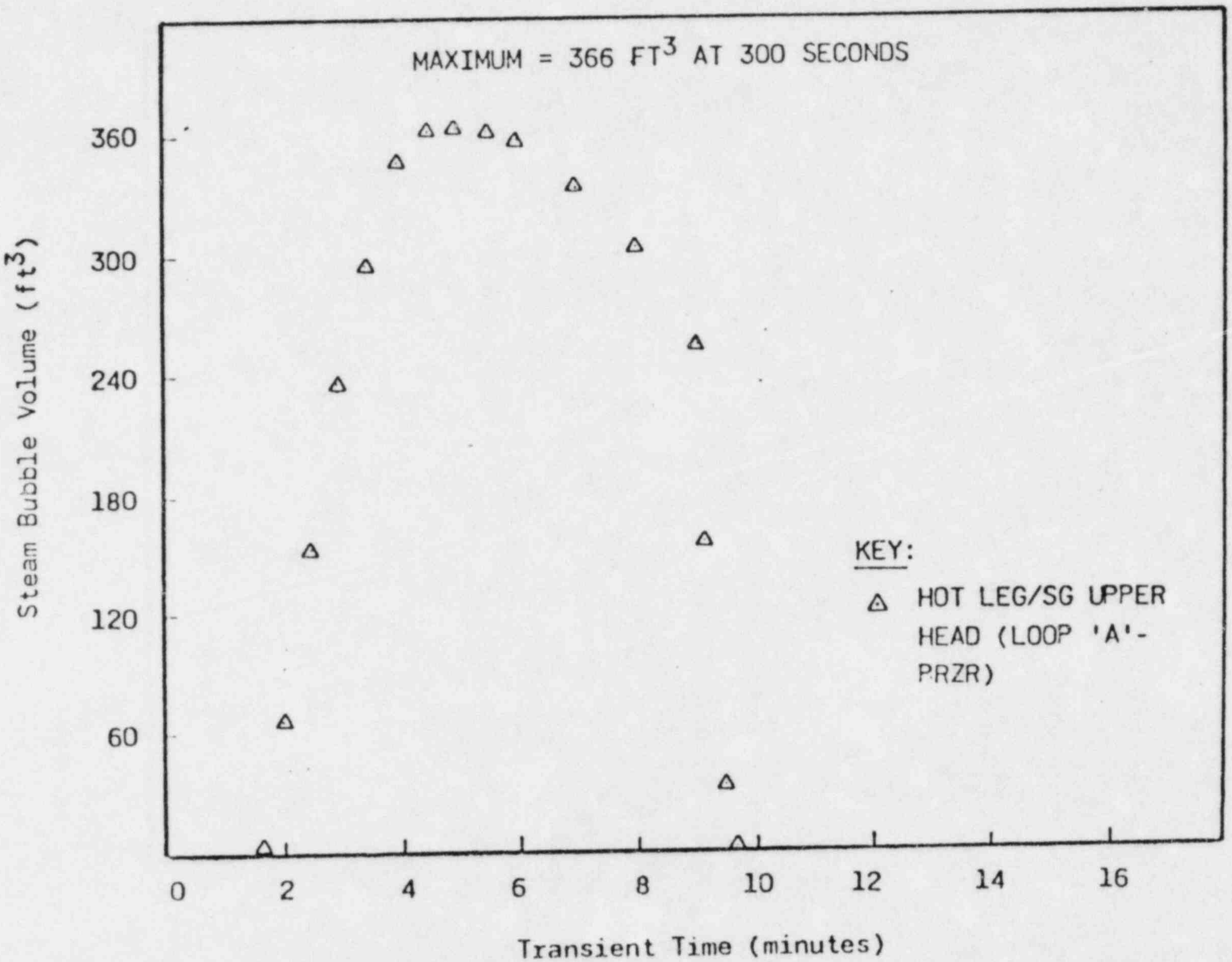


Figure 9

LOOP 'A' FLOW VERSUS TRANSIENT TIME
(102% FP, 12.2 FT^2 DOUBLE-ENDED UNMITIGATED STEAM LINE BREAK, RC PUMP TRIP)

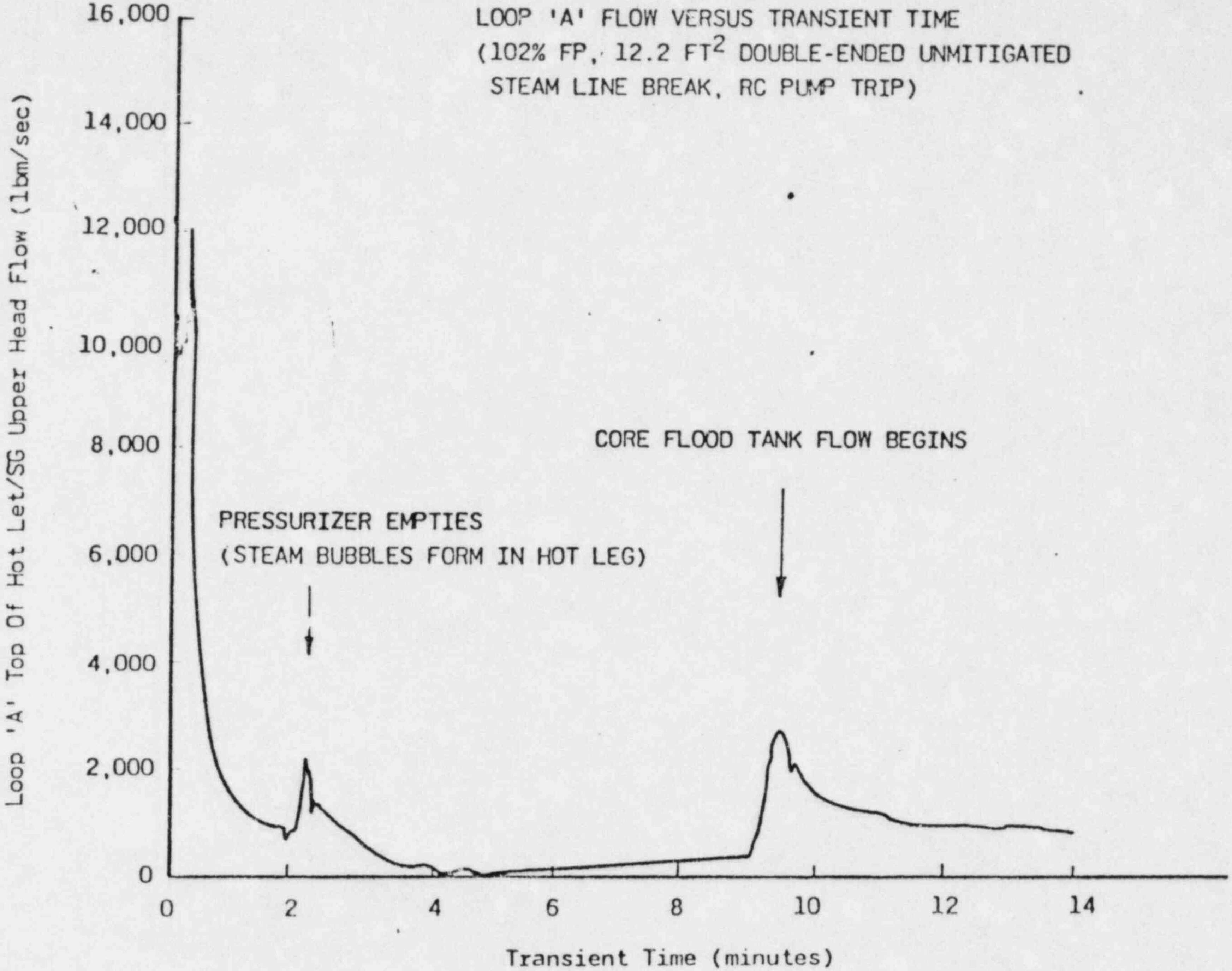


Figure 10

CORE FLOW VERSUS TRANSIENT TIME (102% FP, 12.2 FT^2 DOUBLE-ENDED UNMITIGATED STEAM LINE BREAK, RC PUMP TRIP)

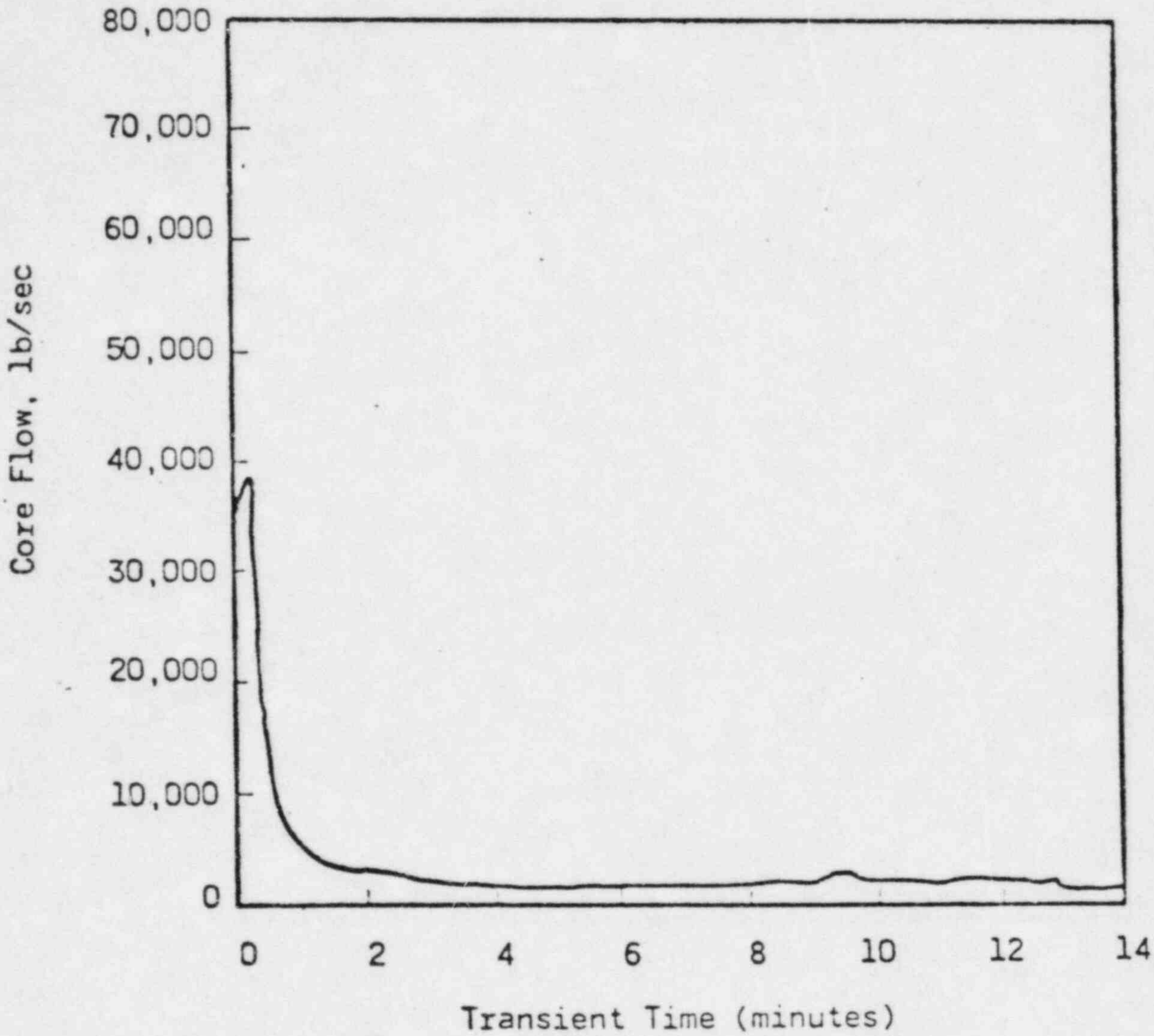


Figure 11

COOLANT TEMPERATURES VERSUS TRANSIENT TIME (102% FP, 12.2 FT^2 DOUBLE-ENDED UNMITIGATED STEAM LINE BREAK, RC PUMP TRIP)

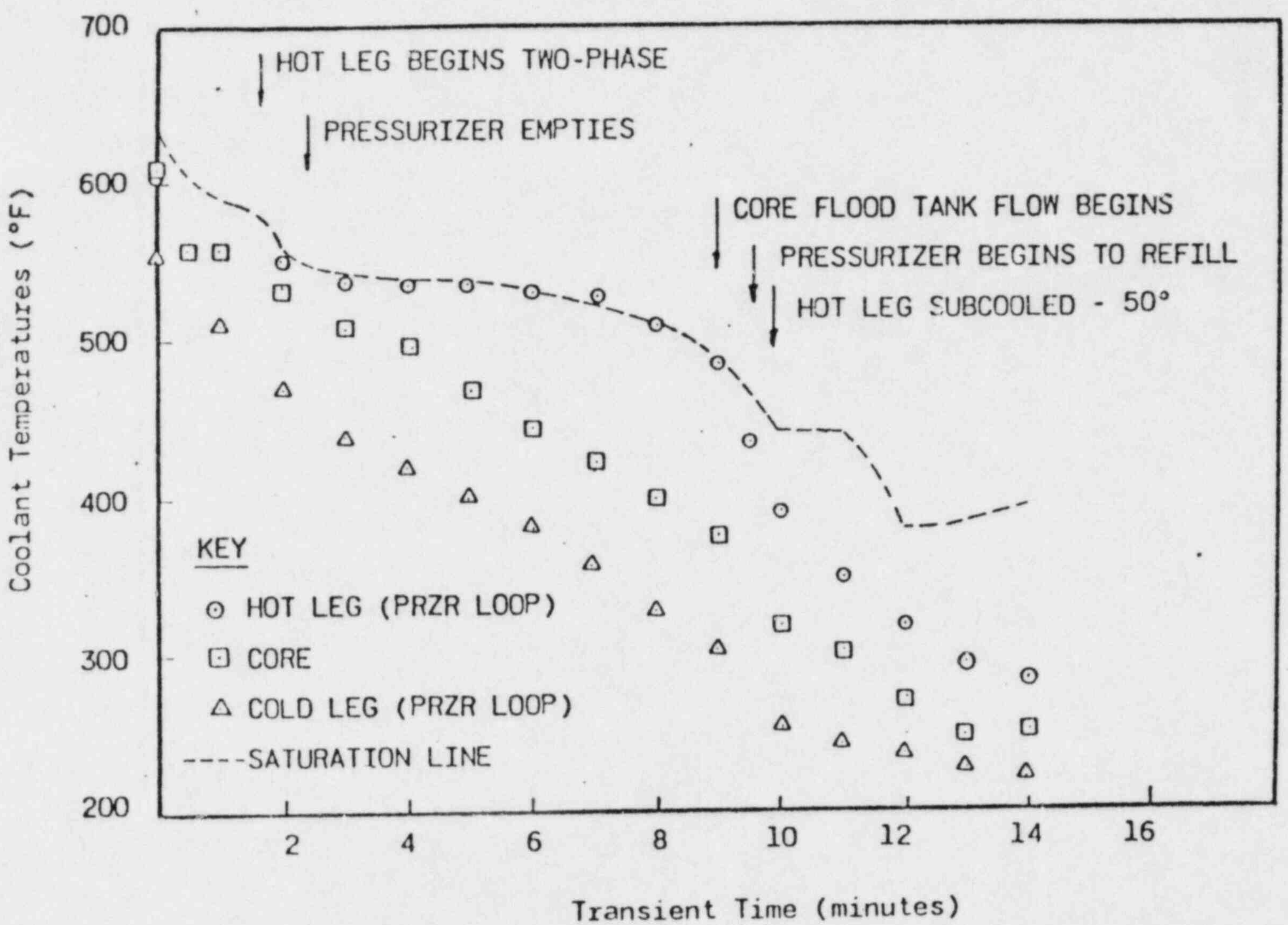


Figure 12

SMALL STEAM LINE BREAK

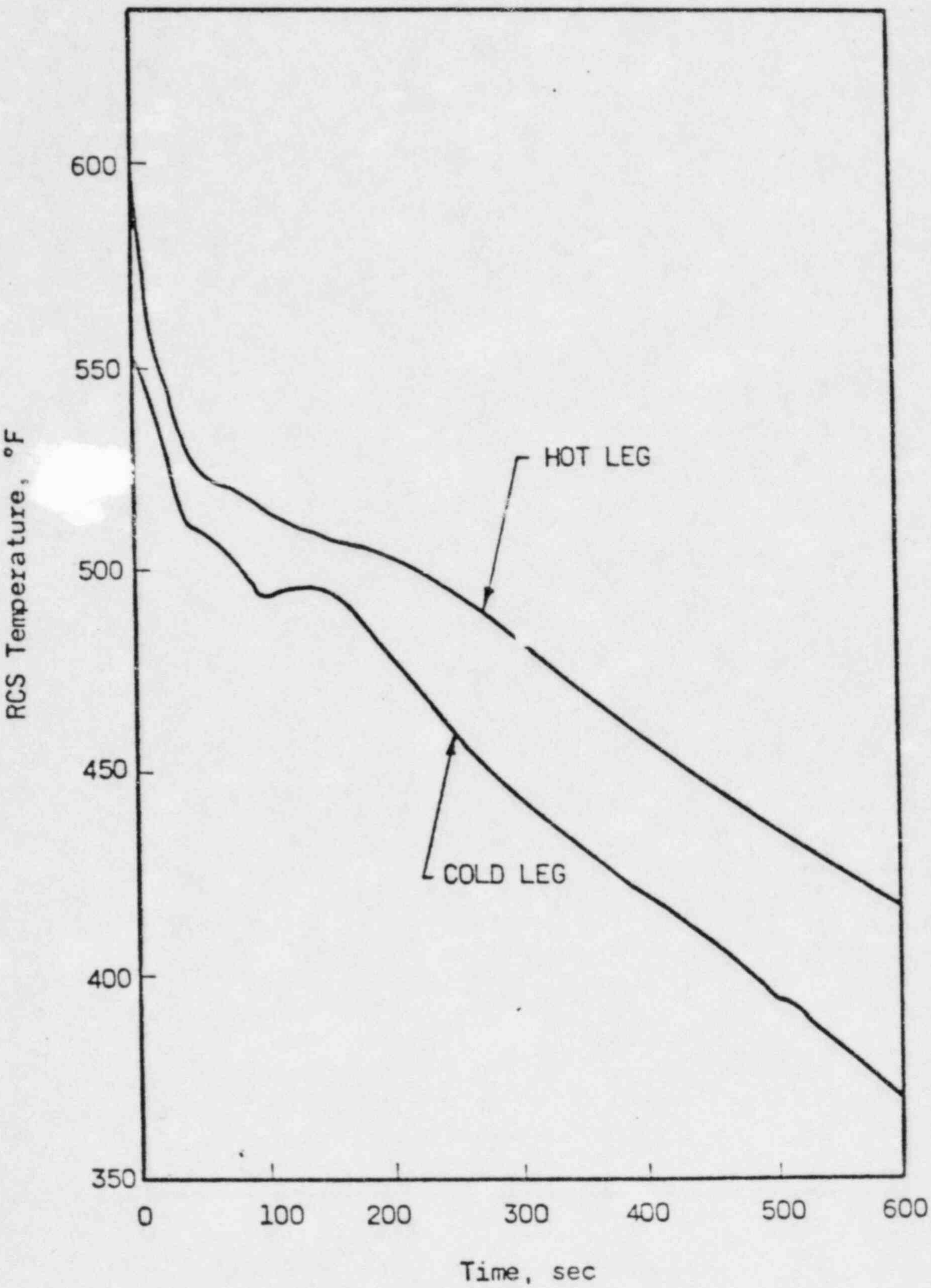


Figure 13

SMALL STEAM LINE BREAK

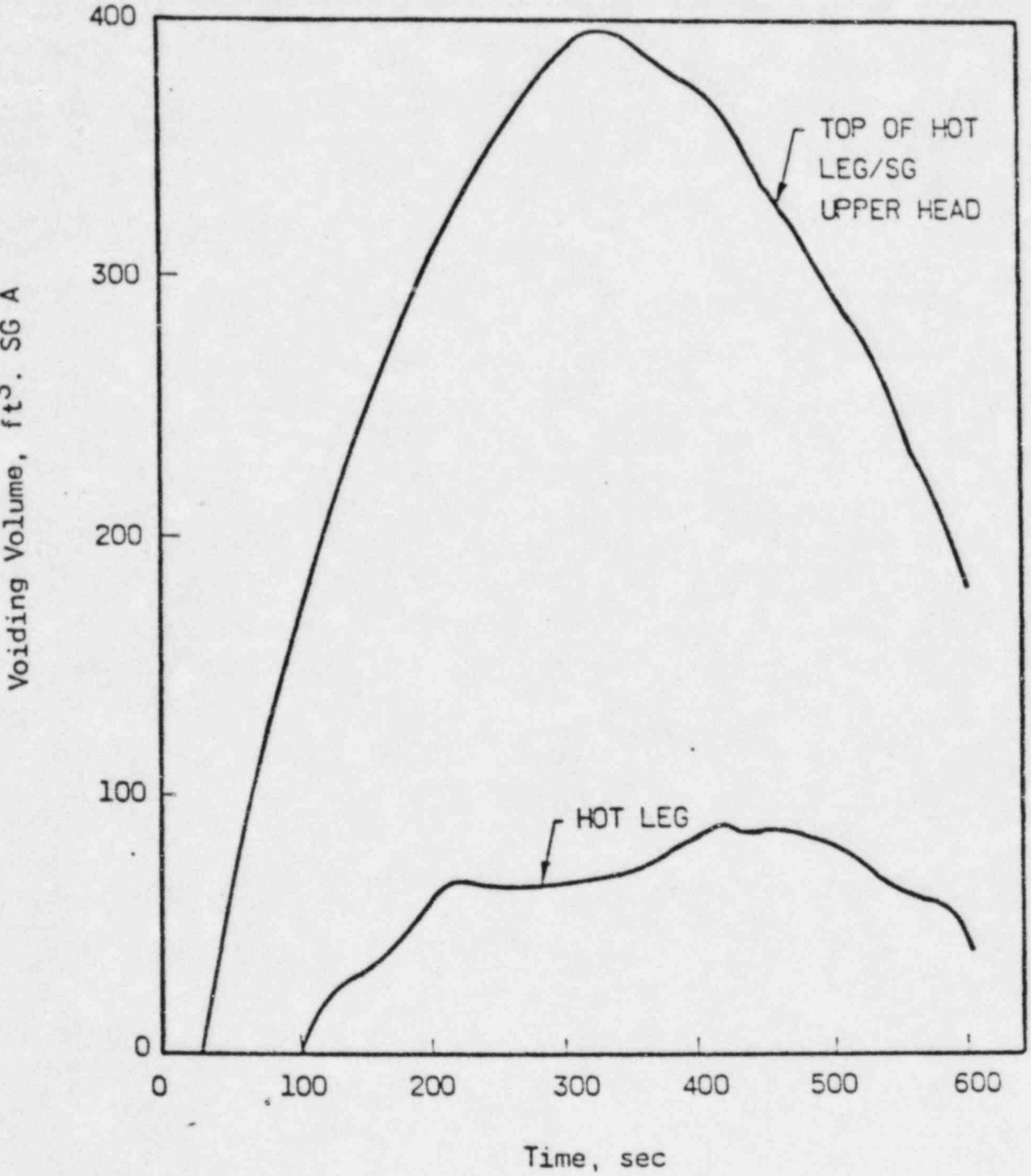


Figure 14
SMALL STEAM LINE BREAK

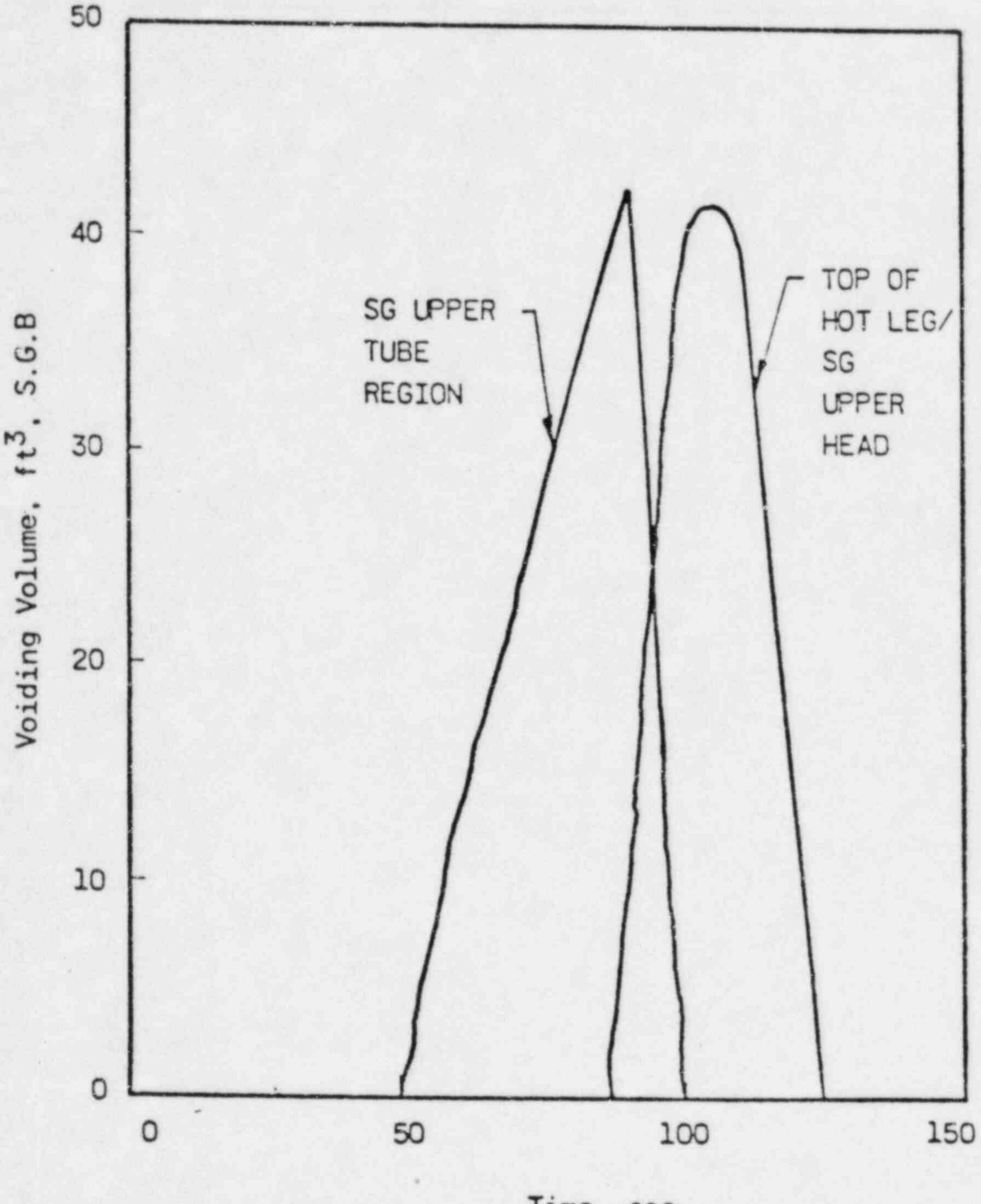
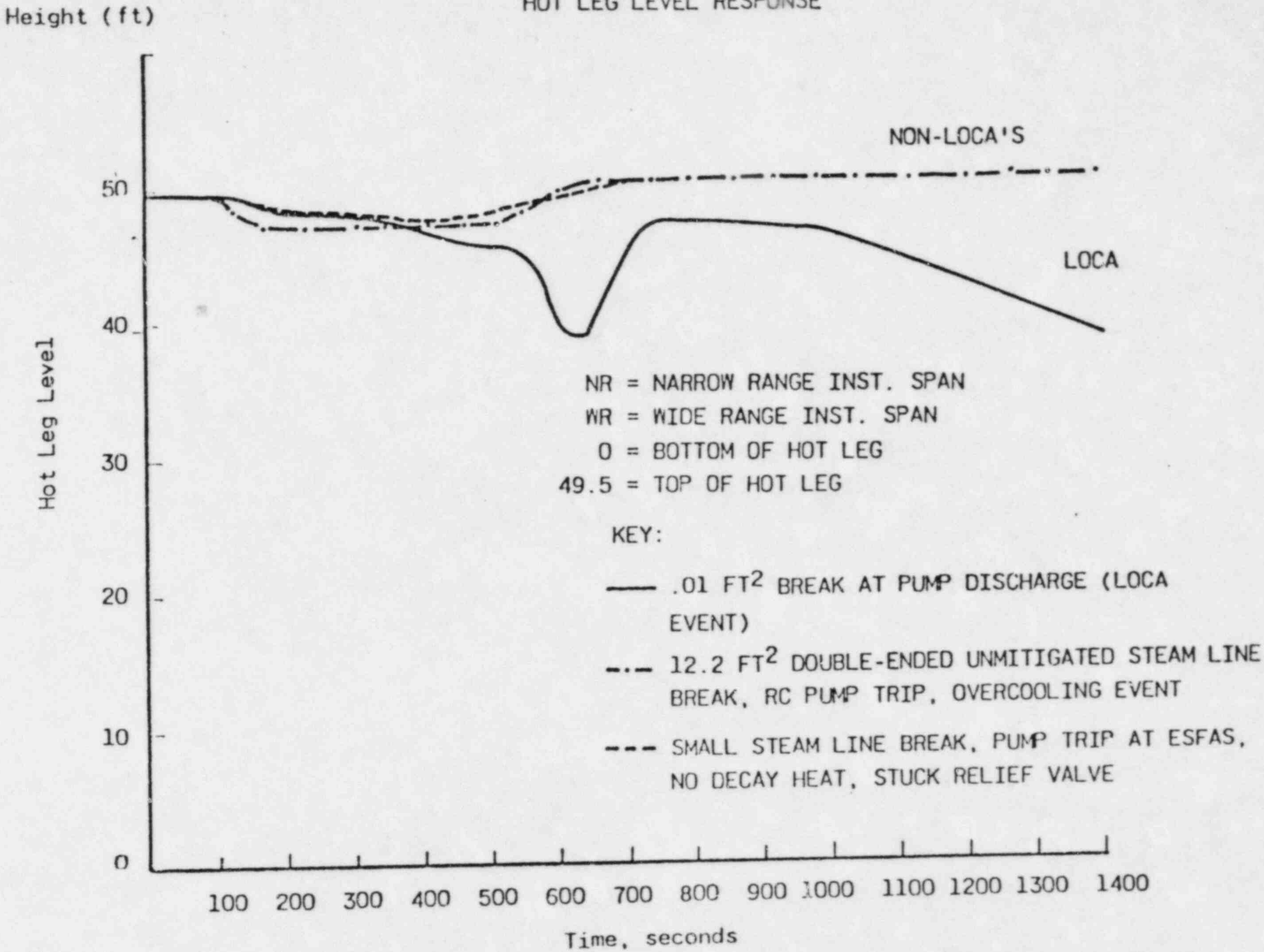


Figure 15

HOT LEG LEVEL RESPONSE



VI. EFFECTS OF HPI

An evaluation of the effects of changes in HPI flow rates has been performed. The transient used as a basis for this analysis is the .01 ft.^{2} pump discharge repressurization break from Reference 3. Calculations were used to show what effects HPI flow rate changes would have on the transient. Flow rates were altered to correspond with the flows expected from 1, 2, and 3 HPI pump operation, and at different times in the transient. Figures 16 and 17 provide a graphical representation of the results.

The calculational technique used for this analysis assumed a semi-steady state system response. The conservation of mass and energy equations provide an iterative process through which HPI flow rate changes alter the system pressure response. Referring to Figures 16 and 17, it is seen that these changes in HPI flow rates effect the system repressurization and refill rates. For this .01 ft.^{2} break, and the HPI flow rates used, the repressurization rates indicate the inability of the primary system to relieve decay energy. As HPI flow increases, the repressurization rate is less severe. This is due primarily to the cold water injection decreasing core steam production. The trade-off between break flow, ECC injection, steam production and condensation results in the particular repressurization rates shown in Figure 16. Figure 17 illustrates the system refilling response as a function of HPI flow rate. It is noted here that the increase in mixture level at 650 to 800 sec. associated with the one HPI transient is not due to refill. But, rather, the loss of natural circulation causes a swell to occur due to the increase in void fraction from steam buildup within the hot leg. After 800 sec., the steam is being released from the liquid via the bubble velocity, and a decrease in mixture level results. The same general trend may be seen with 2 and 3 HPI operation, but should not be as severe. Additional model and technique modification would be necessary to accurately predict this phenomenon. The 2 and 3 HPI results shown on Figure 17 are the trends associated with system refill as the flow associated with these HPI quantities are enough to overcome the break flow. As is expected, more HPI flow results in a faster system refill rate. As ECC injection continues, a mass accumulation occurs within the RCS, and should be indicated by the RITS. At some point in time, system recovery will be dominated by a depressurization due to the establishment of single phase natural circulation or the boiler-condensor mode.

From this analysis, the RITS is seen as very useful. As the hot leg level decreases, the operator has a confirmation of a LOCA. The operator can then confirm that actions taken upon loss of saturation conditions, i.e. HPI maximization, will ensure that RCS stabilization, refill, and long term cooling will occur within a shortened time frame.

Figure 16

RC PRESSURE VS TIME
FOR VARYING HPI FLOW RATES
(.01 FT^2 PUMP DISCHARGE BREAK)

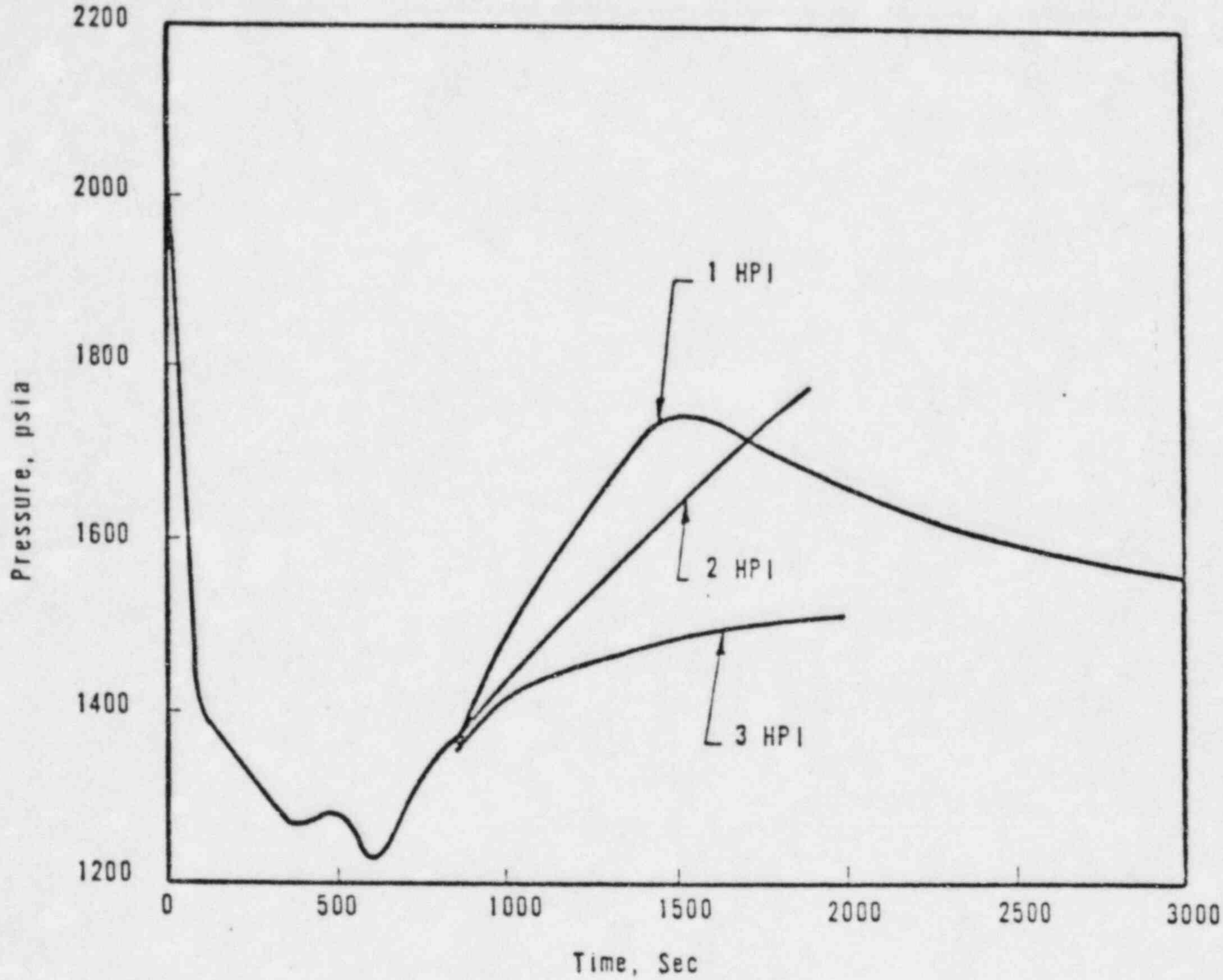
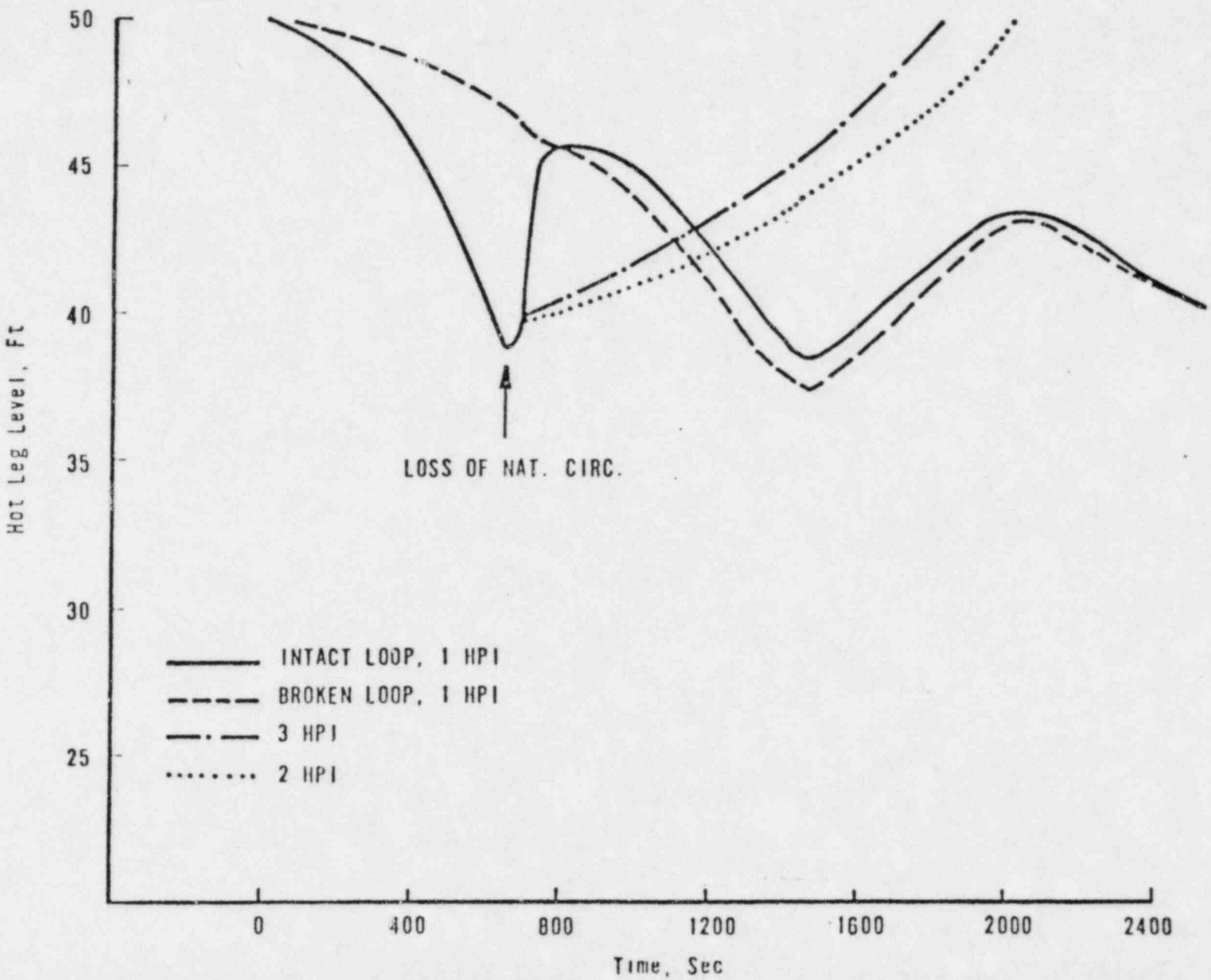


Figure 17. HOT LEG MIXTURE LEVEL RESPONSE .01 FT^2 BREAK, CLPD, VARYING HPI FLOW



VII. OPERATOR GUIDANCE

A. Inadequate Core Cooling

The present NSS instrumentation provides adequate information to allow the operator to respond to transients. Under most transient conditions, the primary system would remain subcooled, as measured by the hot leg RTD's, and a measure of the primary system inventory would be provided by the pressurizer level instrumentation. However, under accident conditions, such as a small break LOCA, the primary system could progress to saturated conditions. Under saturated RC fluid conditions, the pressurizer level ceases to be a reliable indication of the primary system inventory. For a SB LOCA, saturated conditions would occur prior to any possible core uncovery and would last until an actual inadequate core cooling condition developed. The core exit thermocouple indications are used to determine the temperature at the exit of the core region. These thermocouples will indicate above saturation temperatures if the core liquid inventory is insufficient to provide adequate core cooling. Thus, the core exit thermocouples are a direct indication of inadequate core cooling and an indirect indication that the water inventory is below the top of the core region.

Under current operator guidelines described in "Abnormal Transient Operating Guidelines", ATOG, (Reference 4) tripping the RC pumps is the first preventive action required for a loss of subcooling margin. The operator then confirms two actuated HPIs at maximum capacity and a balanced HPI flow. Next the operator raises the steam generator water level to 95% on the operating range.

The water level is raised using EFW in

a continuous and controlled manner as described in the "Best Methods For Equipment Operation" chapter of Reference 4. The last action, which is to attempt to locate and isolate the break is suggested whenever a SB LOCA is suspected.

The RITS would provide the operator with additional information relating to the primary system inventory under saturated fluid conditions. As illustrated in Figure 1, the hot leg piping is the high point of the RC system. Thus, steam or non-condensible gas generated within the primary system will ultimately collect at this high point. The proportion of gas to steam will be very small until such time that excessive fuel temperatures are reached. Steam or gas generated in the RV will vent itself to the hot legs before the core is in danger of uncovery because the RV hot leg nozzles are about 3.5 feet above the core region. A level measured in the hot leg will provide the operator with indication of the primary system inventory trends prior to any indication of the loss of inventory by the core exit thermocouples.

Based on the review of SB LOCA and non-LOCA transients, the initial system responses are similar. For both these types of events, hot leg voiding and possible loss of natural circulation will occur, accompanied by a decrease in the RITS indications. As the RITS instrument decreases off scale low, the operator will be alerted to appreciable inventory loss associated with a LOCA and the potential for core uncovery.

The present instrumentation will indicate that the plant is in an abnormal configuration (saturated conditions). However, there is no indication of potential core uncovery beyond the fact that the RCS is at saturation conditions. When the core exit thermocouples are indicating above saturation temperatures, the operator is alerted that inadequate core cooling is in progress.

The RITS will provide warning and trending information, and will aid the operator in measuring both the approach to core uncovery and the effectiveness of the systems being used for inventory makeup. Using this information, the operator can then take confirmatory action regarding inventory replacement and steam generator cooling. Presently, the ICC guidelines instruct the operator to take these confirmatory actions, but only after the core exit thermocouples indicate superheated conditions. With the RITS available, the operator could begin these confirmatory actions (discussed below) with the RCS still at saturation, and prior to the core exit thermocouples indicating superheated conditions.

Upon loss of level indication on the RITS instrument, the operator should examine the performance of the ECCS. The HPI flow actually being delivered should be compared to the performance curves utilized in the ECCS evaluations to assure that adequate inventory makeup is being provided to the RCS. If the operator finds that inadequate injection is being provided, he then would know that the probability of an ICC situation developing is significant. The operator could then maximize ECC flow and decrease the rate of inventory loss by depressurizing the SG at the maximum rate allowed by the tube-to-shell cooldown limits. The success of these actions could be monitored by the RITS instrument. The inventory trend of the hot leg, as indicated by the RITS, would supply feedback to the operator on the effect of these actions to increase ECC flow and decrease inventory loss. Under SB LOCA situations with the RC pumps tripped, inadequate core cooling will not occur prior to the RCS Inventory Trending System, going off scale low. It may thus be possible to avoid superheated and ICC conditions altogether by confirming these actions when the RITS is offscale low and not waiting until the core exit thermocouples indicate superheated conditions.

It is not intended that RITS indications be used as a basis for action once severe superheating conditions develop within the RCS which would involve such operator actions as starting the RC pumps with the RCS in a highly voided condition, or rapid steam generator depressurization. The requirement for such actions will continue to be based on the core exit thermocouple indications. The real value of the RITS will be to provide the operator with a better opportunity to avoid these circumstances.

Thus, the RITS provides the operator with earlier warning of the potential for ICC. The RITS would indicate inventory trends allowing the operator to monitor the effectiveness of actions taken to avoid ICC. At an appropriate time, these RITS guidelines, as discussed herein, could be integrated into the ATOG procedures on a plant specific basis.

VIII. CONCLUSIONS

RITS will be a determining parameter in the LOCA vs. non-LOCA decision process. Given evidence of a LOCA transient, the operator will be forewarned of, and will then be able to take confirmatory actions to prevent, a possible ICC event. Particular operator actions involve HPI maximization and steam generator depressurization. The RCS Inventory Trending System would provide valuable feedback to the operator concerning inventory conditions and the effectiveness of ECC injection to mitigate the transient. The d/p Instrumentation is not useful while the RC pumps or the high point vents are in operation. A reasonable response time is necessary to inform the operator of inventory conditions. As response time becomes large (i.e. minutes) the primary function of the RITS, that of forewarning the operator of ICC potential, is compromised. However, the complete perspective is that the RCS Inventory Trending System is to be used as an additional device that will confirm existing plant information. The RITS is designed to aid in the determination of RCS conditions by being coupled with information from other plant indications such as primary and secondary temperatures and pressures. It is not to be used as a sole indicator of RCS conditions.

The saturation meter, the RITS and core exit thermocouples (exceeding saturation temperature) satisfy the requirement for advanced warning of the potential for ICC at various stages of the accident. The full range requirement is provided for by the RITS (top of hot leg to top of core) and the core exit thermocouples (top of the core to complete core uncovery). The requirement that the ICC detection instrument system be unambiguous is satisfied by the core exit thermocouples, since the actual high temperature in the fuel region is the only direct measure of whether or not inadequate core cooling is occurring. The principal requirements of NUREG-0737 and how the suggested ICC detection system fulfills these requirements is summarized in the following table.

NR 0737 Requirements	Saturation Meter	Hot Leg RITS	Head RITS	Core Exit Thermocouples
Advance Warning	X	X	X	X
Full Range		X	X	X
Unambiguous		X	X	X

Operator actions are required based on indications from the saturation meter and core exit thermocouple temperatures to preclude the onset of ICC. There are no direct actions that the operator would take based solely on RITS. However, if the inventory trend is down (level decreasing) the operator would verify that actions to be taken at saturation conditions were taken and that these actions had the expected results (e.g. actual HPI flow indicated after starting an HPI pump). The role of the RITS is to provide the operator information on the progress of the transient and confirm that the actions taken to preclude ICC are actually initiated.

Taken in conjunction, the saturation meter, RITS, and core exit thermocouples provide advanced warning and an unambiguous full range ICC detection system.

IX. REFERENCES

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2. Design Memo, "Appendix A - Overcooling Results/Reply to Denton's 50.54(f) Show Cause, Parts A-B (177 FA Plants)", B&W Document #86-1106752-03, 3/18/80.

3. B&W "Evaluation of Transient Behavior and Small Reactor Coolant System Breaks in the 177 Fuel Assembly Plant", Volume 1, Section 6, May 7, 1979.

4. "Abnormal Transient Operating Guidelines" - ATOG, Part II, Volume 2, "Discussion of Selected Transients" (DRAFT).

5. Deleted

6. Letter, J. H. Taylor to S. A. Varga, dated July 18, 1978, Subject, SB LOCA Spectrum Analyses.

7. "Evaluation of Instrumentation to Detect Inadequate Core Cooling", prepared for 177 Owners Group, August 15, 1980, B&W Document No. 86-1120838-00.

ENCLOSURE 2

INADEQUATE CORE COOLING SYSTEM

EVALUATION FOR TMI-1

RC PUMP

MOTOR CURRENT

1.0 INTRODUCTION

1. Background

Following the TMI-2 accident, the capability to monitor the primary system water inventory was identified as a potentially useful accident management tool. Review of TMI-2 data and subsequent small break loss of coolant accident (SB LOCA) analyses[1,2] has revealed that continuous operation of the RC pumps during the transient resulted in a highly voided primary system. When the RC pumps were tripped in this condition, the liquid that was previously dispersed throughout the system via pumping action, collapsed to the low points of the primary system, such as the bottom of the reactor vessel and steam generators. Consequently, the low water inventory at the time of the pump trip could result in an insufficient level for adequate core cooling.

In the fall of 1979, the NRC made a generic assessment of delayed RC pump trips during a SB LOCA.[3] They concluded that due to the uncertainties involved in SB LOCA analysis the prudent course of action would be to trip the RC pumps immediately following an indication that a LOCA had occurred (RC pressure dropping below the HPI setpoint). It was also recognized that the immediate pump trip approach was less than optimum. For example, in overcooling events (i.e., steam line break) which cause shrinkage of the primary system and loss of RC pressure, early RC pump trip (and subsequent loss of pressurizer spray) can aggravate these transients and extend the time required to bring the plant into a controlled shutdown conditon. However, since these transients did not lead to unacceptable consequences, early pump trip was adopted as a course of action.

2.0 PUMP CURRENT

Two mathematical models can be developed which relate pump current to RCS voiding. Each model is formed using an expression for the energy transference from the pump to the coolant.

The input three-phase power, P_m, required to drive a constant speed (constant frequency) squirrel cage induction motor can be expressed as follows:

$$P_m = \sqrt{3}\, IV\, (PF)$$

where
- $\sqrt{3}$ = accounts for the 3-phase input of power
- I = line current (RMS Amps)
- V = line voltage (RMS volts)
- PF = power factor (accounts for energy lost in setting up the magnetic field)

Similarly, the power, P_p, required to drive a pump can be expressed by considering the development of head:

$$P_p = \frac{\rho Q H}{n_p}$$

where
- ρ = fluid density (lb/ft^3)
- Q = volumetric flow (ft^3/sec)
- H = head generated by the pump (ft)
- n_p = overall pump efficiency (accounts for the mechanical friction at the seals and bearings, hydraulic friction at the impeller vanes and the diffuser vanes, and various other hydraulic losses due to eddy formation.

If one accounts for the windage and mechanical friction losses of the motor by considering the motor efficiency, η_m, the transfer of power to the pump can be stated.

$$\eta_m P_m = P_p$$

or, inserting the previous definitions,

$$\eta_m \sqrt{3}\, IV\ (PF) = \frac{\rho Q H}{\eta_p}$$

The change in current relative to varing fluid density can be addressed by denoting a reference point (^{o} superscript) condition.

$$\frac{\rho}{\rho^o} = \frac{\eta_p\ \eta_m\ IV\ (PF)\ Q^o H^o}{\eta_p{}^o\ \eta_m{}^o\ I^o V^o\ (PF)^o\ QH}$$

Assuming that the motor efficiency, voltage, power factor, capacity, and head remain constant, a simple relationship results.

$$\frac{\rho}{\rho^o} = \left(\frac{I}{I^o}\right) \left(\frac{\eta_p}{\eta_p{}^o}\right)$$

Inserting an expression relating void to density,

$$\rho = \rho_f - \alpha\ (\rho_f - \rho_g)$$

will yield the desired relationship between voiding and current.

$$\alpha = \frac{\rho_f - \rho^0 \left(\frac{I}{I^0} \right) \left(\frac{\eta_p}{\eta_p^0} \right)}{\rho_f - \rho_g}$$

A second model can be developed by considering the transference of torque within the pump. In this situation,

$$P_p = \frac{T\Omega}{\eta_I}$$

where

T = hydraulic torque transferred from the impeller to the fluid (ft-lb_f)

Ω = pump speed (rpm)

η_I = pump efficiency accounting for the mechanical friction at the seals and bearings, hydraulic friction and eddy losses within the impeller. Hydraulic friction and eddy losses within the diffuser vanes are not included since only power transfer at the impeller is being considered.

Coupling equation with the homologous or normalized relation for torque,

$$\frac{T}{T_R} = \beta\ (\rho/\rho_R)$$

yields,

$$P_p = \beta T_R \rho \Omega / \eta_I \rho_R$$

Where β = normalized torque

T_R = rated torque (ft-lb_f)

ρ_R = density corresponding to T_R (lb/ft^3)

Assuming that the motor efficiency, voltage, power factor, and operating point of the pump (β,Ω) remain constant, a normalized relationship results.

$$\frac{\rho}{\rho^o} = \left(\frac{I}{I^o}\right) \left(\frac{\eta_I}{\eta_I{}^o}\right)$$

As before,

$$\alpha = \frac{\rho_f - \rho^o \left(\frac{I}{I^o}\right) \left(\frac{\eta_I}{\eta_I{}^o}\right)}{\rho_f - \rho_g}$$

This completes the development of the mathematical models. The four relationships involving gentille ΔP and void fraction, and pump current and void fraction are shown in Table 1.

TABLE 1: VOIDING MODELS

Pump Current

Model 1:

$$\alpha = \frac{\rho_f - \rho^o \; (I/I^o)\; (\eta_p/\eta_p{}^o)}{\rho_f - \rho_g}$$

Model 2:

$$\alpha = \frac{\rho_f - \rho^o \; (I/I^o)\; (\frac{\eta_I}{\eta_{I^o}})}{\rho_f - \rho_g}$$

In summary, these models were based on the following assumptions:

Pump Current, Model 1

1. The motor efficiency, voltage, and power factor remain constant.
2. The pump capacity and head do not degrade.

Pump Current, Model 2

1. The motor efficiency, voltage, and power factor remain constant.
2. Pump speed remains constant.
3. The hydraulic torque does not degrade.

The validity of these assumptions will be discussed further in Section 3.0 when the supporting data is presented.

3.0 SUPPORTING DATA

To utilize the models developed in the last section, supporting data must be found to substantiate the assumptions used to develop the models. Consequently, a literature survey was conducted. This section summarizes the findings of this study.

Figure 3 displays the operating characteristics of a typical pump drive motor. Considering the density variation associated with voiding to be on the order of 0 to 40%, the operating range of interest lies between 6000 and 10000 HP. In this range, when a constant voltage is supplied (6600 volts in this case), motor efficiency and power factor vary by less than ½%. As a result, current varies linearly with power in this range as shown in Figure 3.

The variations in pump speed are small as load changes. Typically, the induction motor can generate 1000 HP for every rpm off synchronous. Therefore, the pump speed can be assumed to be essentially constant when compared to the 1200 rpm synchronous motor speed.

The assumptions of constant motor efficiency and power factor imply constant supply voltage. It is recognized that off normal voltages may occur due to bus transfers, pump starts or grid disturbances. These perturbations are expected to be of short duration and would not have a significant impact on the use of pump current for inventory trending indication. Application of this measurement for alarm or pump trip circuits would require provisions for delaying the alarm or trip signal to avoid spurious actuations.

Operating characteristics of the pump drive motor in the range of interest can be summarized as follows:

1. The motor efficiency remains constant.
2. The power factor remains constant.
3. The pump speed remains constant.

Experimental data has been generated concerning the performance of the pumps under two-phase conditions. These experimental studies are summarized below.

Combustion Engineering, Inc./EPRI

In an effort to refine the analytical model of the reactor coolant pumps under hypothetical large break LOCA conditions, Combustion Engineering constructed a test system which utilized a 1/5 scale pump. Steady state tests were conducted near the operating point (ν_n/α_n = 1.0) and the results are presented in Figures 4 and 5. (Note ν_n is defined as the ratio of the actual flow rate to the rated flow rate and α_n is the ratio of the actual speed to rated speed.) For low void fraction (0-0.1), the pump head (Figure 4) remained at, or slightly above the water or non-degraded value. At 0.15 void, the head degrades almost linearly until the worst case (20% of the water value) is reached at .75 void.

Head then recovers as the single phase steam region is reached. A similar behavior is seen concerning torque, (see Figure 5), but the degradation is less severe. The degradation in head and torque at low pressures is even more pronounced due to the larger density differences between the steam and the liquid. Losses associated with these two-phase mechanisms are three times greater at 500 psia than at 1000 psia.

Babcock & Wilcox Company/EPRI

With the same program objectives, B&W constructed a test apparatus to analyze the performance of a 1/3 scale pump using air/water mixtures to simulate voiding. The results of these experiments are presented in Figures 6 and 7. Restricting our attention to the region around the operating point ($\nu_n/\alpha_n = 1.0$), the same degradation behavior is seen relative to the Combustion Engineering data. However, the degradation effects are exaggerated due to two-phase losses resulting from the large density difference between air and water.

CREARE Inc./EPRI

CREARE Inc. worked in parallel with the two studies mentioned above. In their test rig, a 1/20 scale pump was installed to address the effects of scaling. Figures 8 and 9 show the results of the tests conducted near the operating point for low pressure water/air mixtures. These results compare quite favorably with the B&W data presented earlier.

LOFT Research

As part of the Loss-of-Fluid Test (LOFT) Program, RC pump motor power and current measurements, and their utility as indicators of RCS inventory is being explored. Current research shows a large head degradation at approximately 20% void (See Figure 10). This phenomena is consistent with the other data presented thus far for scaled pumps. It is interesting to note, that power and current measurements made during this transient (See Figures 11 and 12, respectively) do not exhibit the same discontinuity.

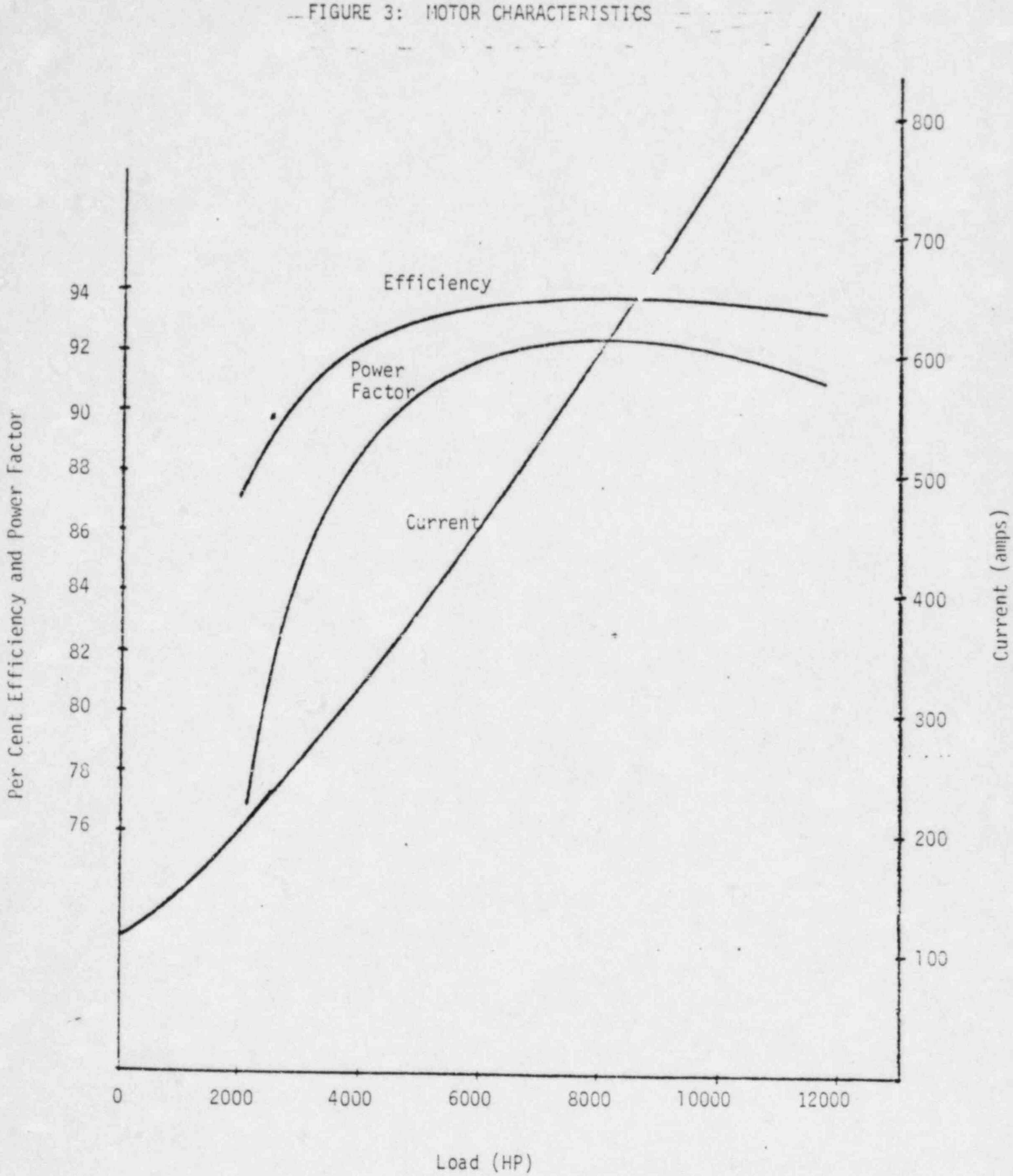
The following can be summarized concerning two-phase degradation of pumps:

1. In all cases, torque did not degrade as appreciably as developed head. This implies that larger losses occur in the diffuser section of the pump than in the impeller section. The LOFT data presented in Figures 10 through 12 shows that this is the case, with the impeller efficiently imparting hydraulic torque to a two-phase fluid at a homogeneous density, while the head abruptly degrades due to two-phase losses in the diffuser section.
2. All degradation effects are minimized at pressures above 1000 psia. This is important since the application of the void measurement will usually be made at elevated pressures (> 1000 psia).
3. Review of the RCS flow for the TMI-2 event reveals that little if any pump capacity degradation occurred. Therefore, it must be concluded that scaling effects have not been adequately addressed by the pump testing summarized in this study. The probable cause for this discrepancy deals with the inability of these tests to scale the bubbles such that the relationship between the size of the bubbles with respect to the vane spacing on the impeller and diffuser is preserved. For example, if ping-pong balls were

suspended in a fluid system, their presence would choke a small pump, whereas a large pump would pass the balls virtually undetected.

4. In developing the technical approach for the pump current measurement, model 2 (based on torque transfer) is a stronger approach since only impeller dynamics are involved. Model 1 (based on head and capacity) would involve resolving the energy losses in the pump casing, thus making this approach less desirable. Therefore, model 1 will not be considered further.

FIGURE 3: MOTOR CHARACTERISTICS



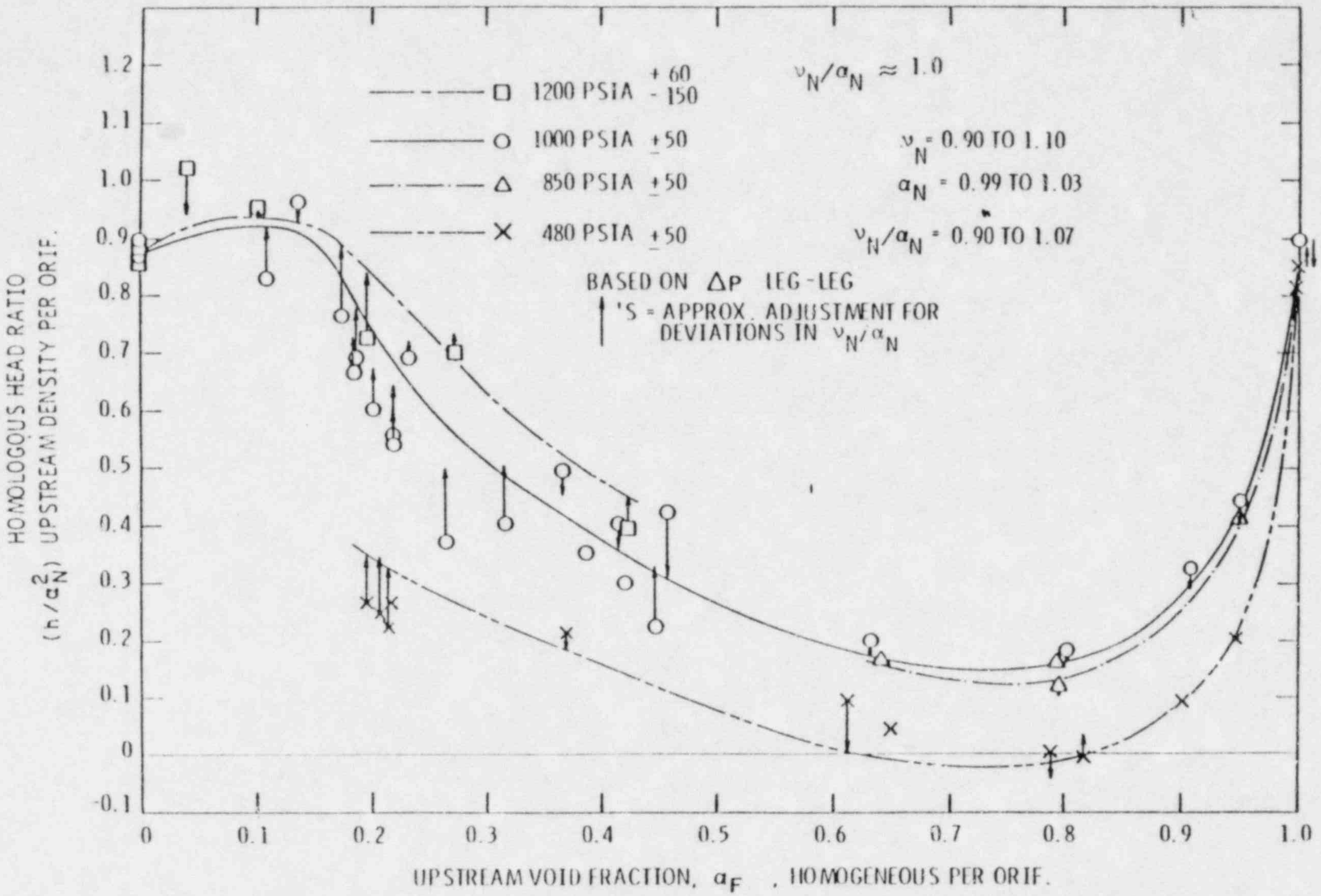


Figure 4: Effect of Void Fraction on Homologous Head Ratio Near Rated Flow and Speed

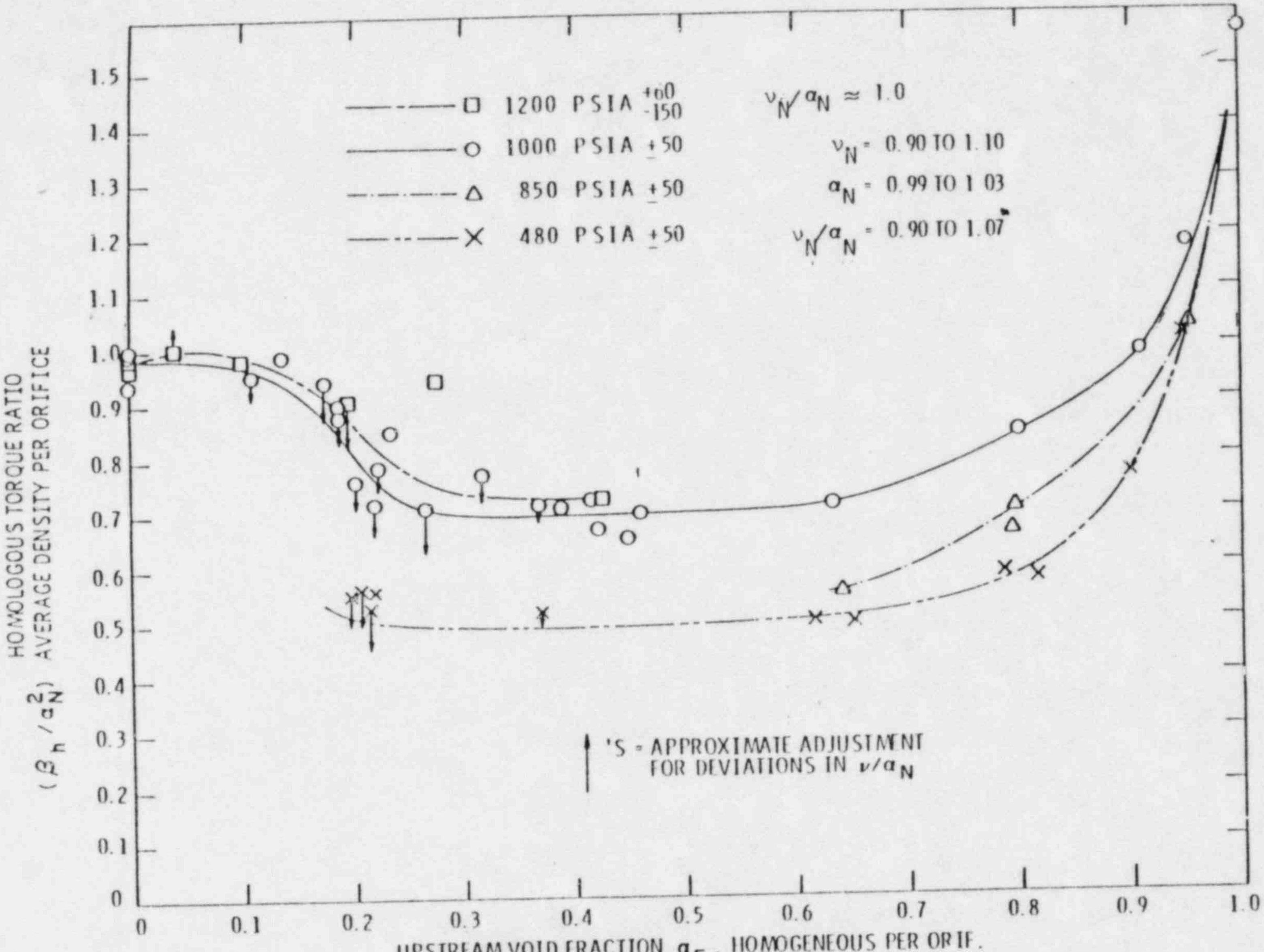


Figure 5: Effect of Void Fraction on Homologous Torque Ratio Near Rated Flow and Speed

FIGURE 6: Homologous Head at Various Pump Inlet Void Fractions for First-Quadrant Pump Operation

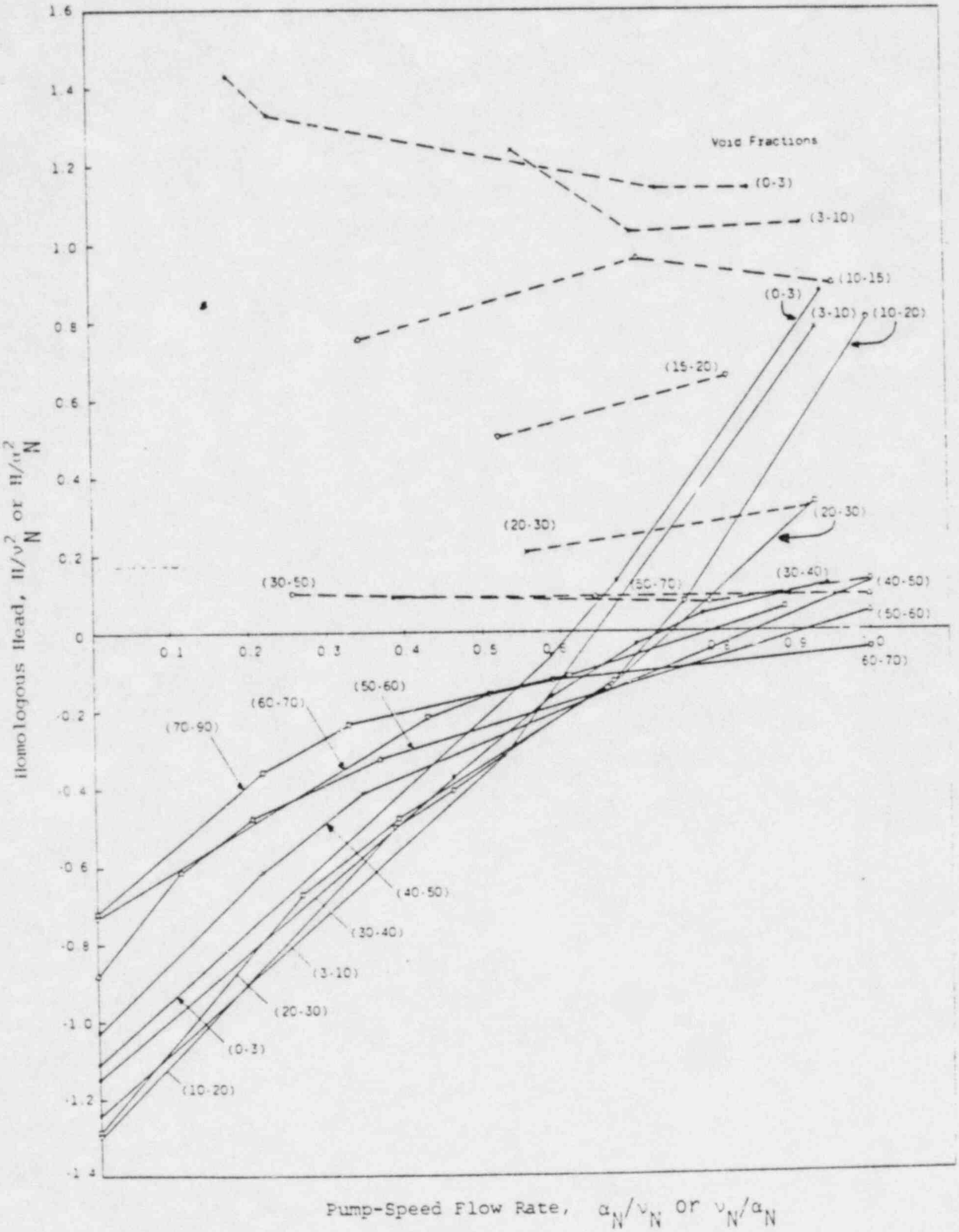
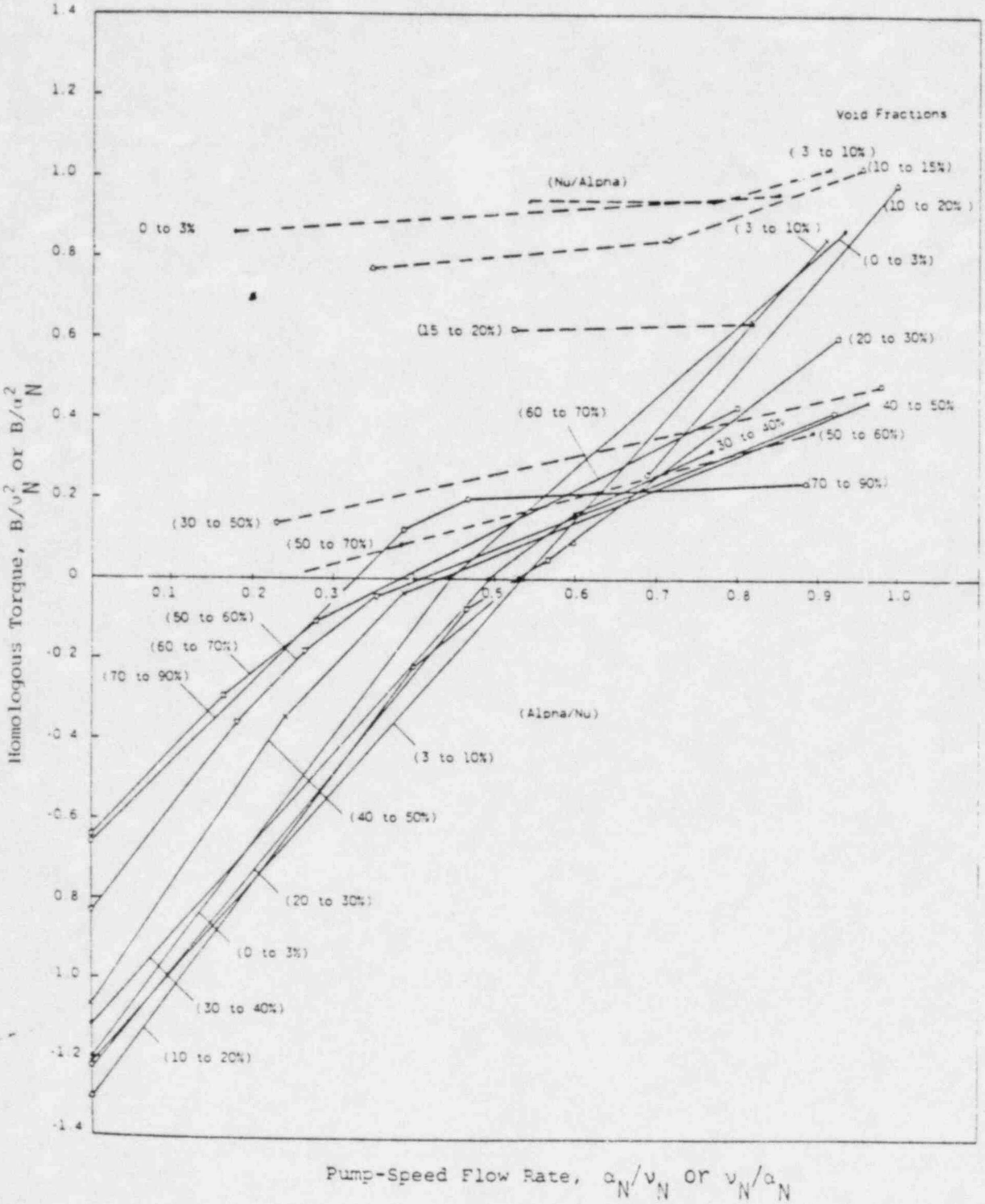


FIGURE 7: Homologous Torque at Various Pump Inlet Void Fractions for First-Quadrant Pump Operation



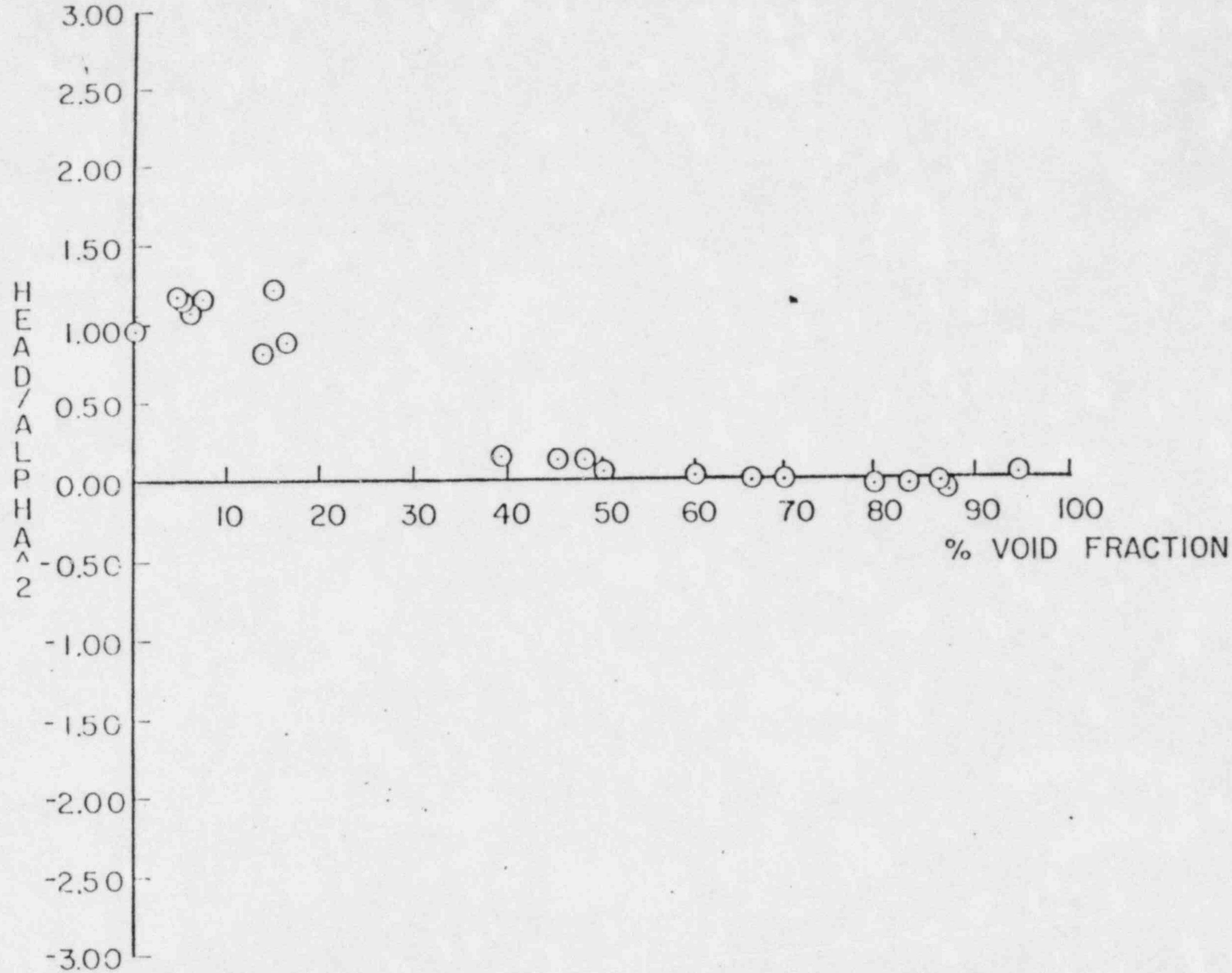


FIGURE 8: HEAD DEGRADATION VS. VOID FRACTION, FIRST QUADRANT, $\nu/\alpha_N = 0.9$

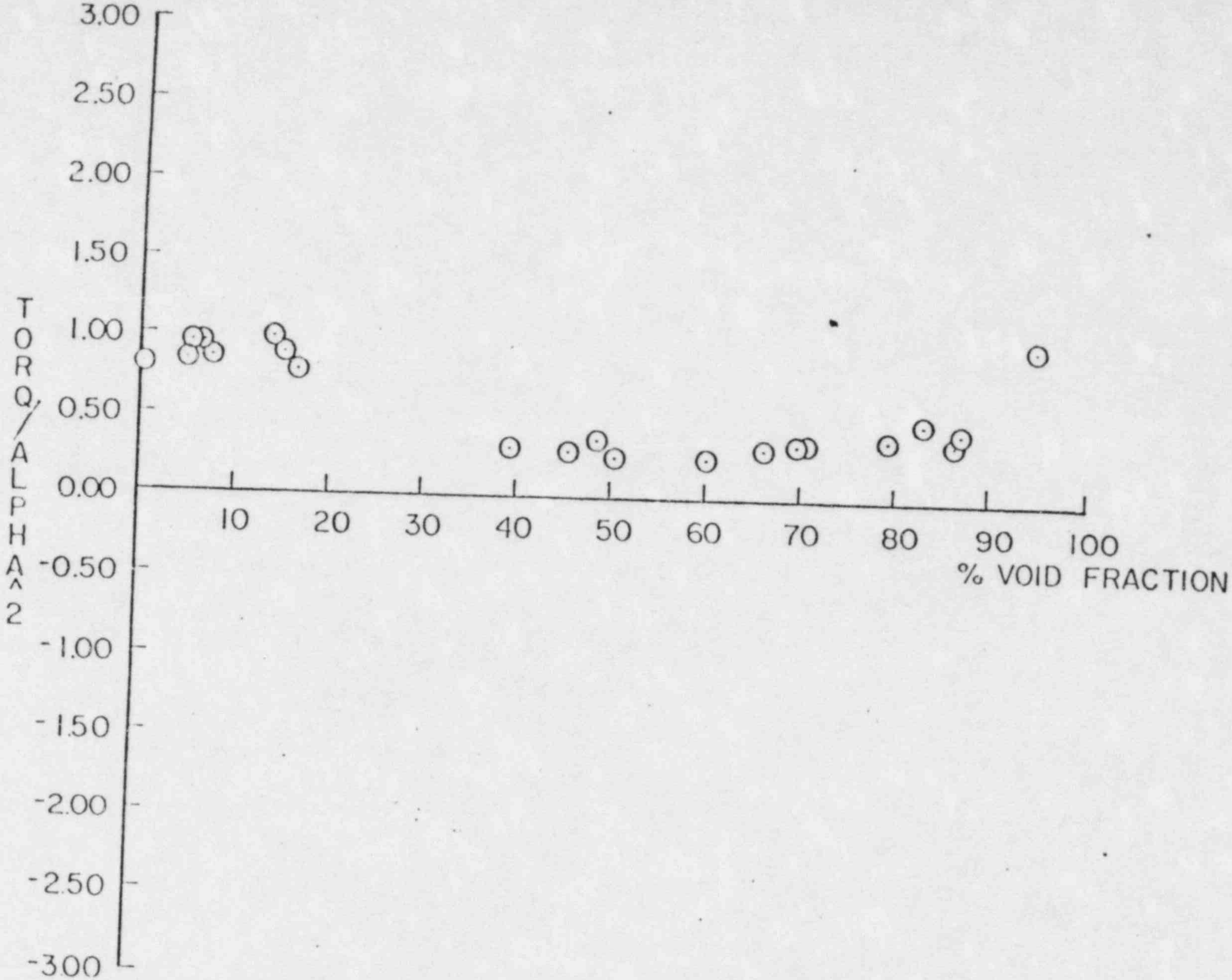


FIGURE 9: TORQUE DEGRADATION VS. VOID FRACTION, FIRST QUADRANT, $\nu/\alpha_N = 0.9$

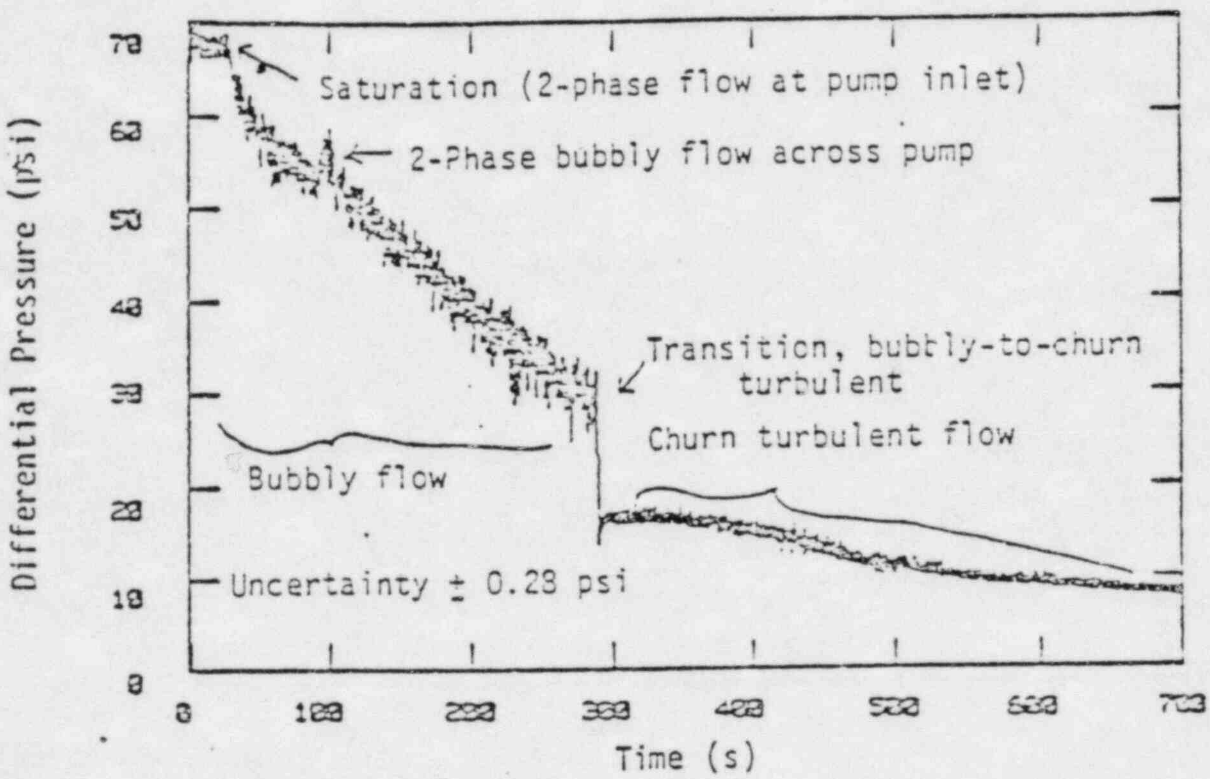


Figure 10: Differential Pressure Across Primary Coolant Pumps

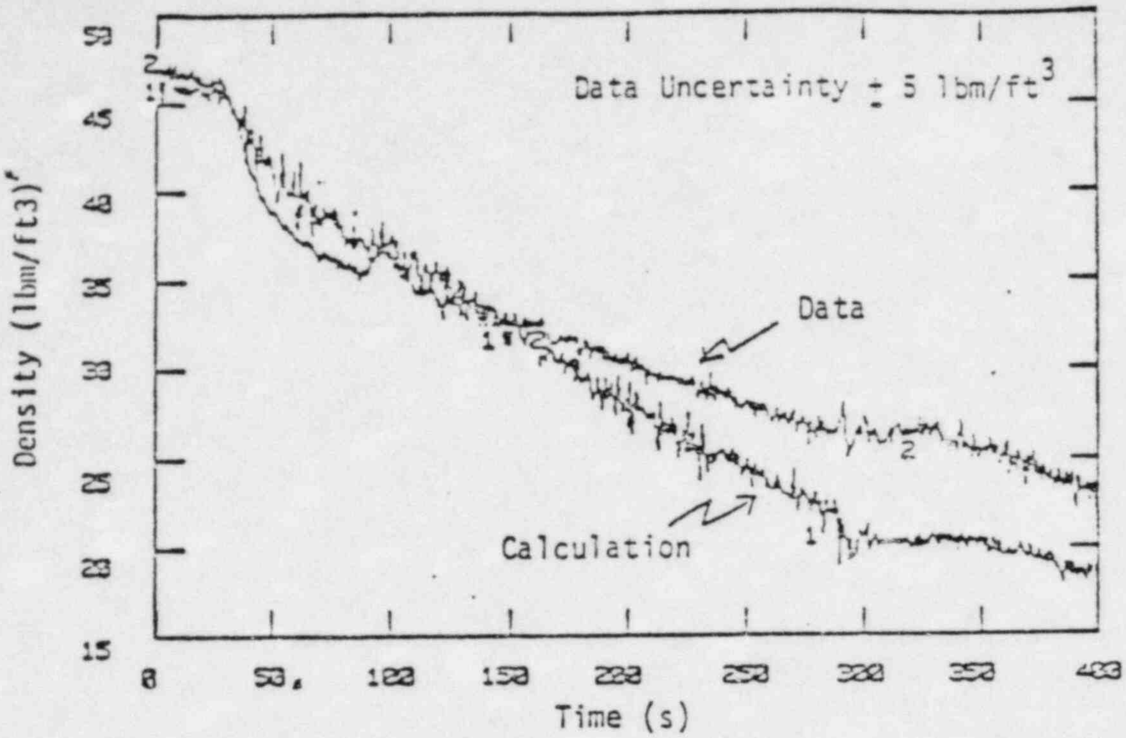


Figure 11. Measured Density Upstream of Pump Compared With Prediction Using Pump Motor Power Assuming Constant Volumetric Flow and Pump Head

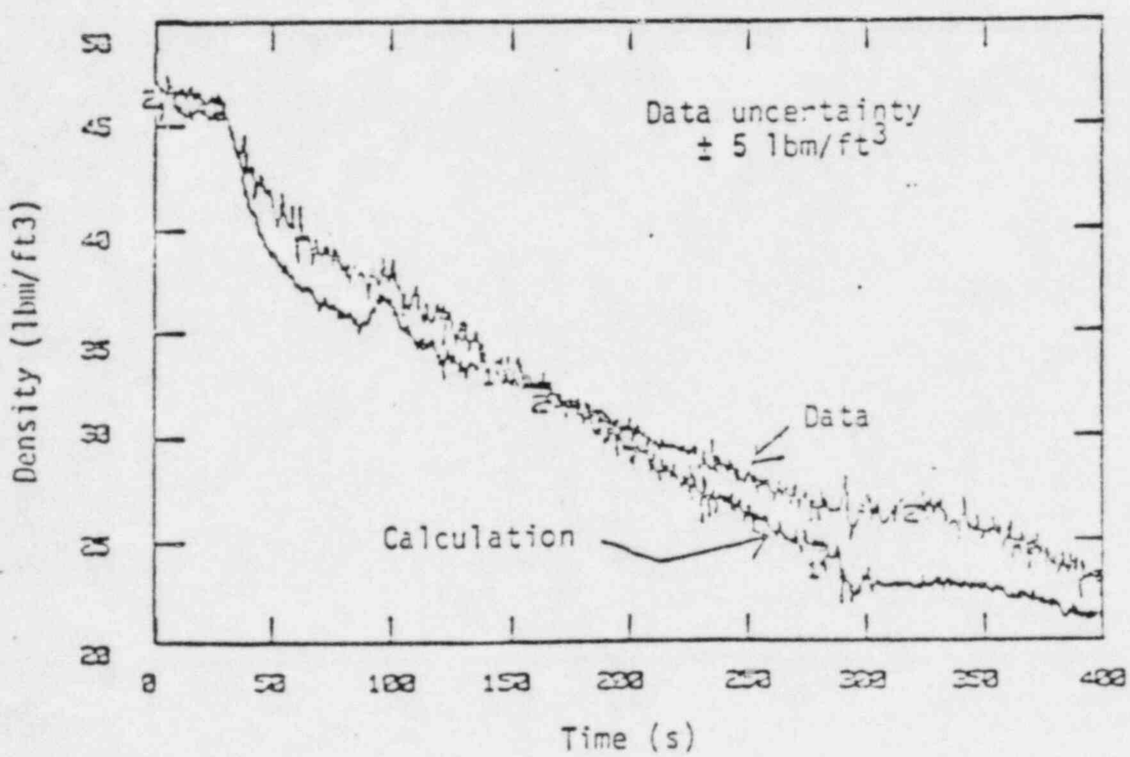


FIGURE 12. Measured Density Upstream of Pump Compared With Prediction Using Pump Motor Current Assuming Constant Volumetric Flow and Pump Head

4.0 POTENTIAL USE OF INVENTORY MEASUREMENT TECHNIQUES IN PUMP TRIP CIRCUITRY

As explained in Section 1.0, the level of RCS voiding must be known to determine an optimum pump trip time in the event that the primary system pressure drops below the HPI setpoint. To use the proposed models and their associated voiding signals in pump trip circuitry, the following criterion were used:[4]

1. The trip should be delayed sufficiently to allow the HPI to make up the inventory lost for the most probable small breaks.
2. The trip should be based on a void fraction sufficiently large to be outside of the normal noise band associated with $\alpha = 0$ line.
3. The trip void fraction should be sufficiently small such that the trip will occur before pump degradation becomes significant.

Pump current/power tests at LOFT have shown that a setpoint of .15 (15%) void will meet the above criterion.

This higher setpoint can be justified since SBLOCA analysis indicates that a system can proceed to approximately 0.4 void (40%) before the pumps must be tripped. In any event, either measurement can provide a conservative indication of void which will yield acceptable pump trip times for small breaks in which the HPI cannot keep up. When breaks in which the HPI can makeup the inventory being lost or when overcooling events occur, an unnecessary pump trip will be avoided and plant shutdown will be made more manageable.

A conceptual design for a void measurement system using pump current would require two inputs:

1. Pump current measurement
2. RCS pressure from the wide range taps located on the hot legs

The current measurement will be used as the time-varying I input and the RCS pressure measurement will be used to estimate the suction pressure at the RC pumps, such that a calculating module can determine the saturation properties ρ_f and ρ_g. The calibration constants I° and ρ° will be recorded

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4. "Reactor Coolant Pump Motor Power or Current Criteria for Reactor Coolant System Inventory Management in Commercial PWR's During Accidents," LOFT Research Memorandum, March, 1982.

APPENDIX

To give the reader a qualitative "feel" for the model , a simple computer code, VOIDCOM, was developed. VOIDCOM model the RCS as a single homogeneous thermodynamic node. Within this node, conservation of mass is determined by considering the addition of mass due to the HPI system and the loss of mass out of a small break. Conservation of energy is maintained by summing the energy contributions to the RCS via the core, steam generators, HPI system, and the break. By considering the RCS as a fixed volume system, the pressure of this large node can then be determined using the conservation of mass and energy principles. A somewhat pseudo primary loop containing a RC pump is then superimposed within the RCS thermodynamic node. The mathematical modeling of the the RC pump is of sufficient detail to allow the data presented in Section 3 to be utilized. The output of these component models is a simulated signal of current for the RC pump. The voiding model presented in Section 2 is then applied to yield an estimate of system voiding (via pump current) which can be compared to the thermodynamic voiding of the system which is known.

A TMI-2 type scenario was used to create a voiding transient upon which the models and data could be applied. The chain of events are as follows: (See Figures 13-18)

1. At time zero, the reactor is at 100% power.
2. Loss of all feedwater begins just after time zero.
3. As the steam generators provide less of a heat sink to the primary system, the RCS pressure rises until the PORV lifts. (t = 15 seconds)
4. The PORV sticks open and water continues to flow out of the break.
5. As the RCS pressure drops below the HPI setpoint, the HPI flow is throttled off. (This is done in this example to create significant voiding in a small period of time.)
6. Auxiliary feedwater is valved in and reaches full capacity (t = 4 minutes)
7. At.20 void, HPI flow is reinstated at full capacity (t = 40 minutes)
8. System inventory then recovers and the RCS returns to a subcooled condition. (t = 56.5 minutes)

The transient mentioned was analyzed twice, once assuming non-degraded pump performance, and then a second time assuming that the pump would experience some degradation. In the second analysis, a pump head and torque degradation multiplier was applied which approximates the data presented in Section 3 for the Combustion Engineering data at pressures around 1000 psia. The expressions which were used for the head degradation multiplier, M_H, are as follows:

$$M_H = 1.0 \qquad 0.0 \leq \alpha \leq 0.14$$

$$M_H = 1.4242 - 3.03\,\alpha \qquad 0.14 < \alpha < 0.25$$

Similarly, for the torque degradation multiplier, M_T, the expressions are,

$$M_T = 1.0 \qquad 0.0 \leq \alpha \leq 0.10$$

$$M_T = 1.2 - 2.0\,\alpha \qquad 0.10 < \alpha < 0.25$$

Note the expressions for the multipliers were limited to the range $0 \leq \alpha < 0.25$ due to the dynamics of the problem analyzed.

Review of figures 13 through 18 gives the reader a quantitative feel for the model presented, and the impact that the pump degradation can have on the resulting estimate of system voiding. With these figures, comparisons can be made which allow the uncertainties associated with each measurement technique to be estimated.

In figure 13, the transient behavior of the RCS system pressure is shown for both the degraded and non-degraded cases. Due to the simplistic nature of the VOIDCOM thermodynamic model, the system pressure is identical for both cases. When a loss of all feedwater occurs, the pressure in the RCS increases from the steady state value until the PORV lifts and sticks open. The pressure then drops until it settles out to a saturation pressure determined by the heat sink provided by the steam generators. At approximately 56.5 minutes, the HPI flow, being greater than the leak flow, has brought the RCS back into a solid condition. The pressure then rises until a pressure level is reached where the leak flow becomes equal to the HPI capacity ($p \approx 2050$ psia).

The loop flow rate versus time is shown in figure 14. In the non-degraded case, the reduction in flow is due to changes in system density only (equation 1, Section 2). By comparison, when the system void exceeds .14, the flow rate is further reduced due to the now degraded pump head (Figure 15). The degradation in flow rate is not large relative to the loss in developed pump head because it is assumed that the flow rate varies as the square root of the ΔP across the pump.

In figure 16, the transient behavior of the hydraulic torque is shown. When non-degraded behavior is assumed, the torque varies as a function of density only. Under degraded conditions ($\alpha > .10$), the transfer of torque becomes less efficient as void increases.

The void estimates predicted using pump current models assuming non-degraded pump performance are compared to the actual thermodynamic void in figure 17. It can be seen that both models produce good estimates of system voiding. Figure 18 depicts the same estimates assuming pump degradation occurs. For the pump current method, the degraded pump performances cause the predicted voiding to be overstated.

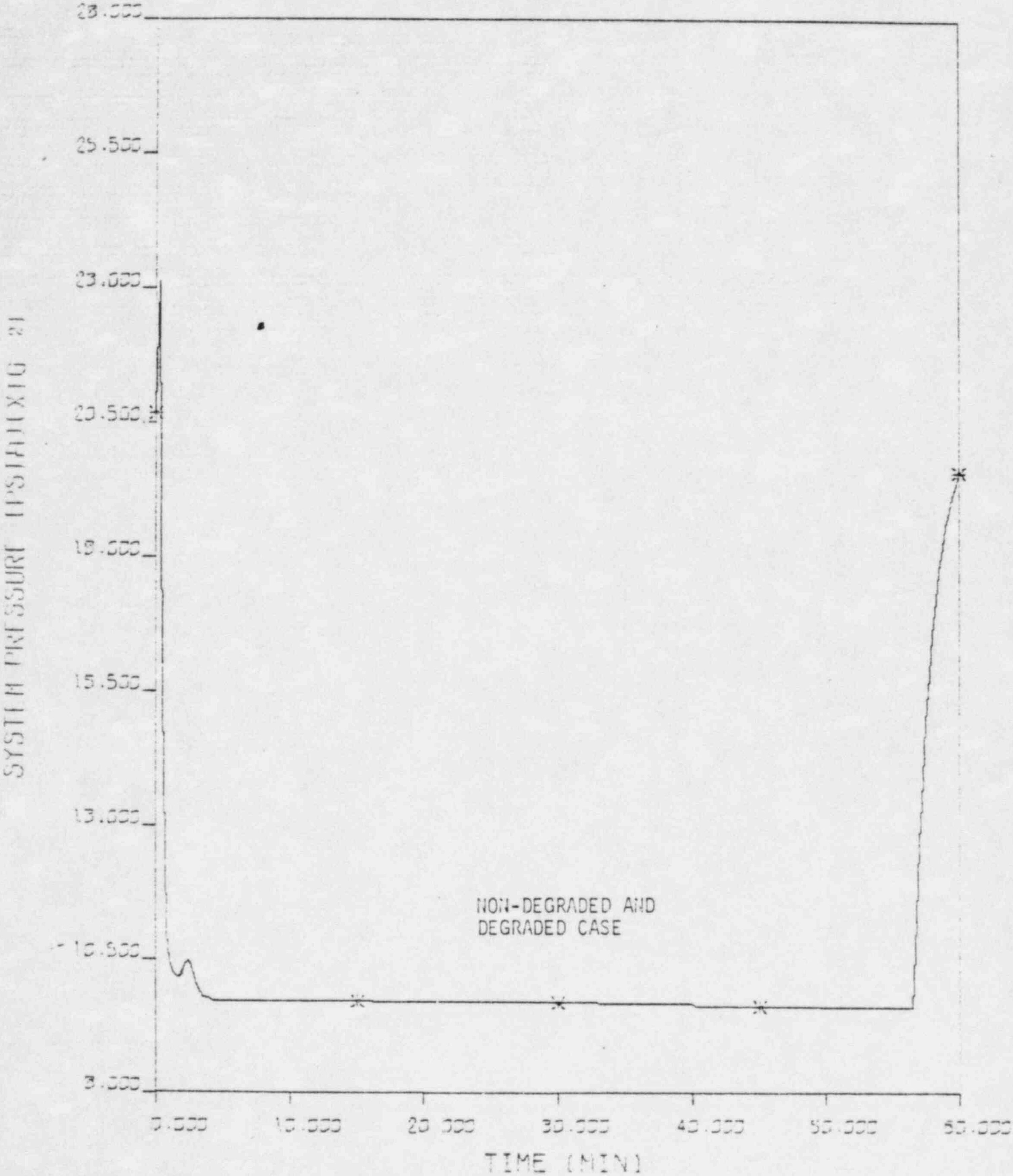

FIGURE 13: SYSTEM PRESSURE VS TIME

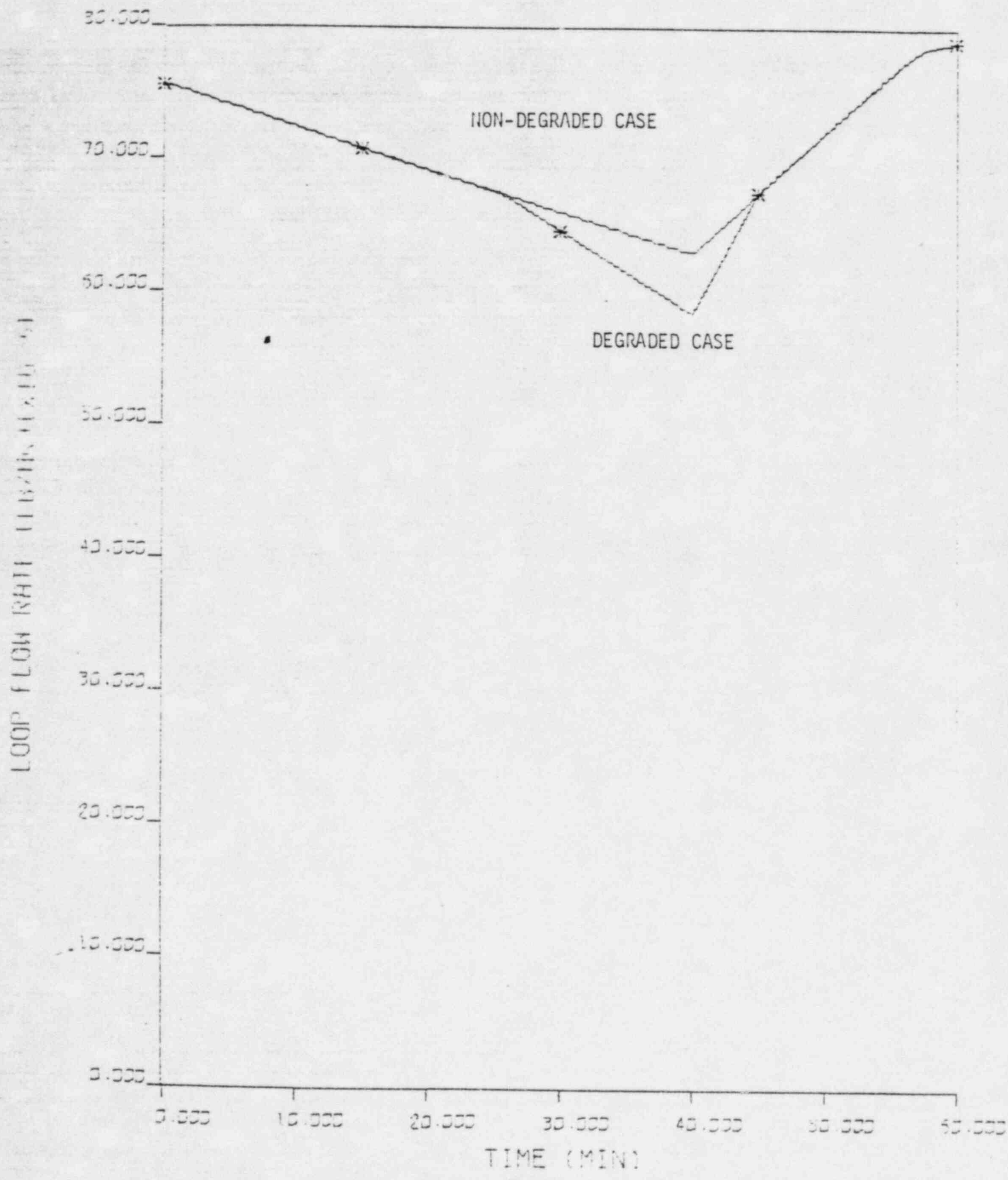

FIGURE 14: LOOP FLOW RATE VS TIME

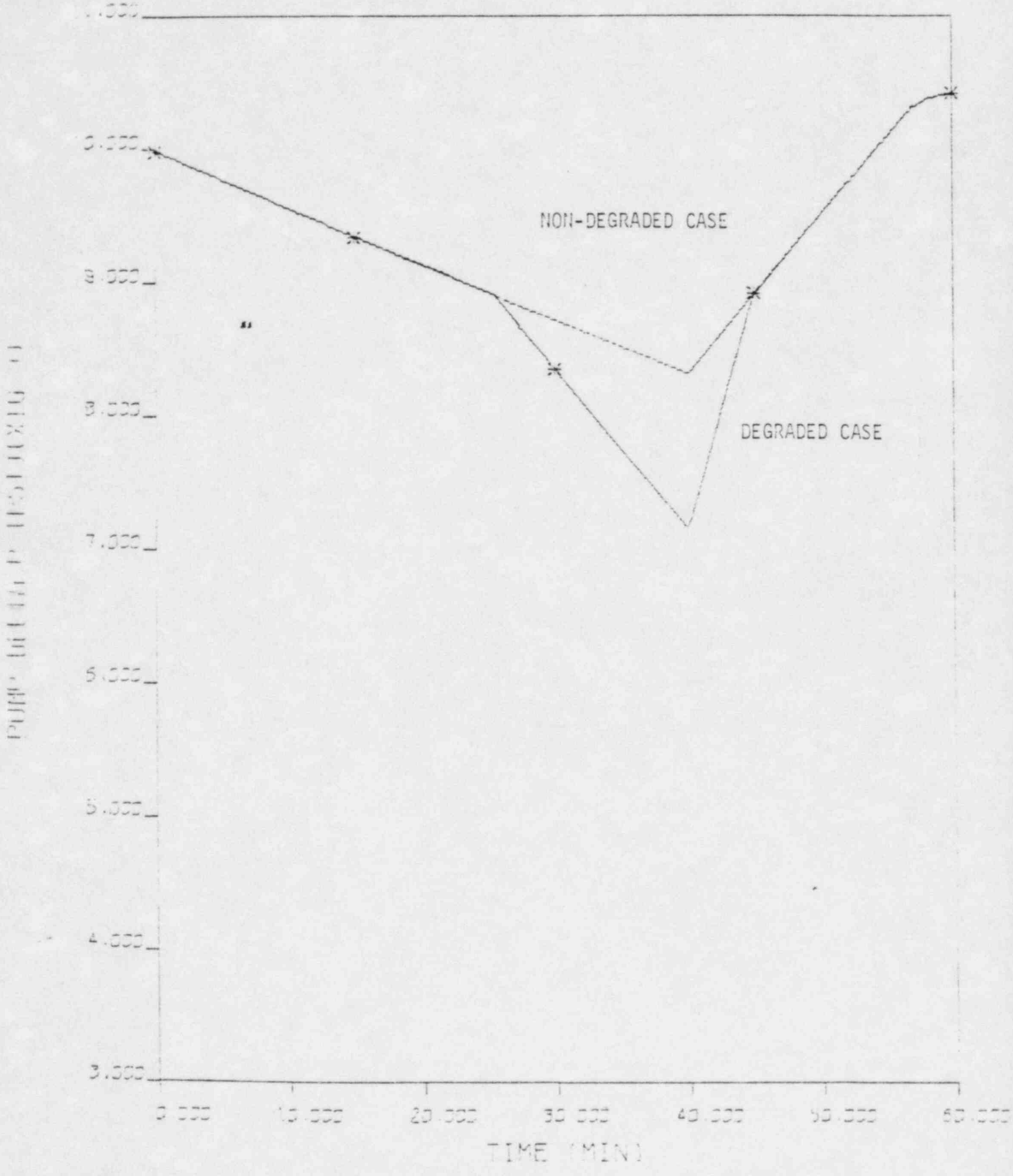

FIGURE 15: PUMP DELTA P VS TIME

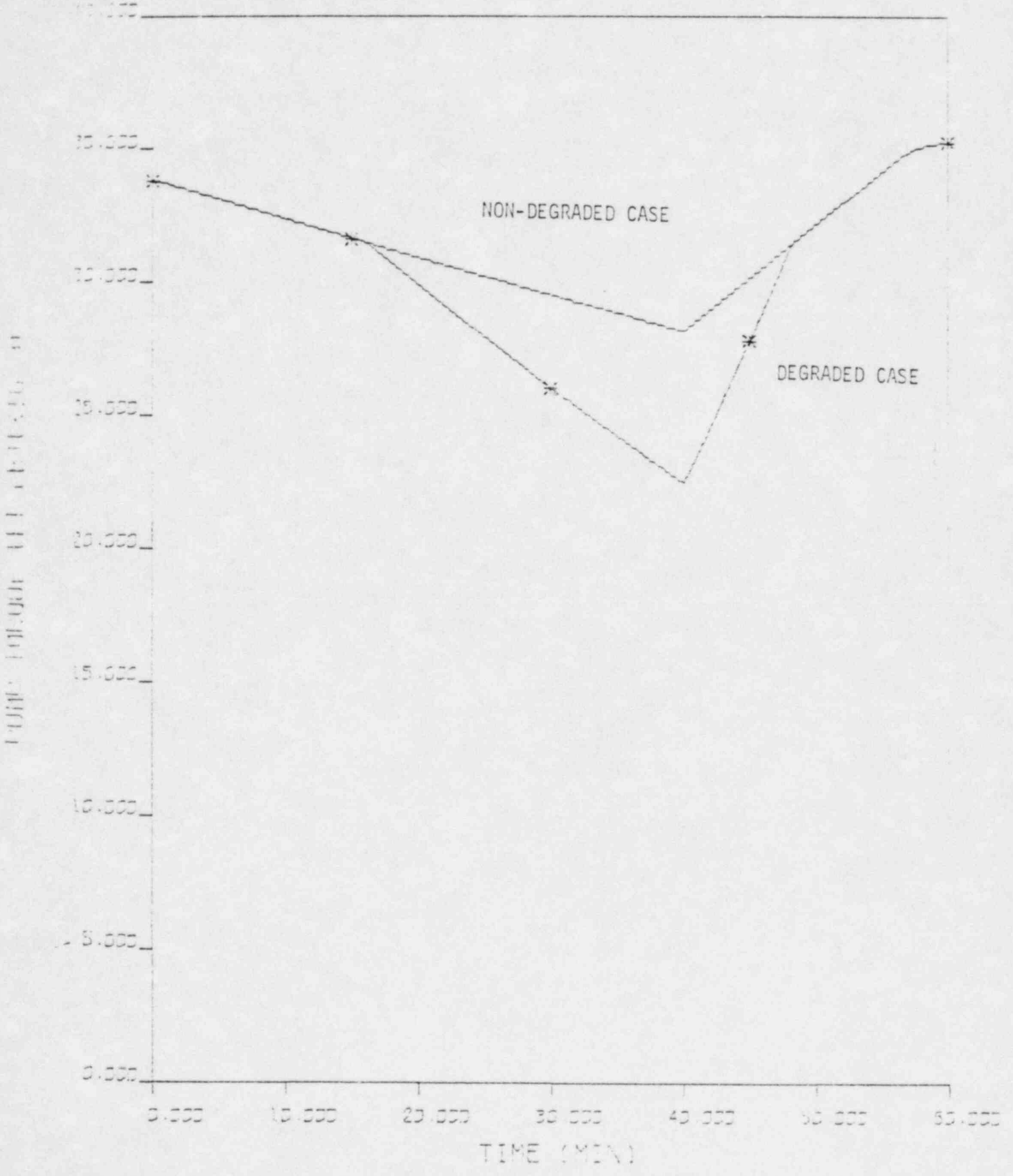

FIGURE 16: PUMP TORQUE VS TIME

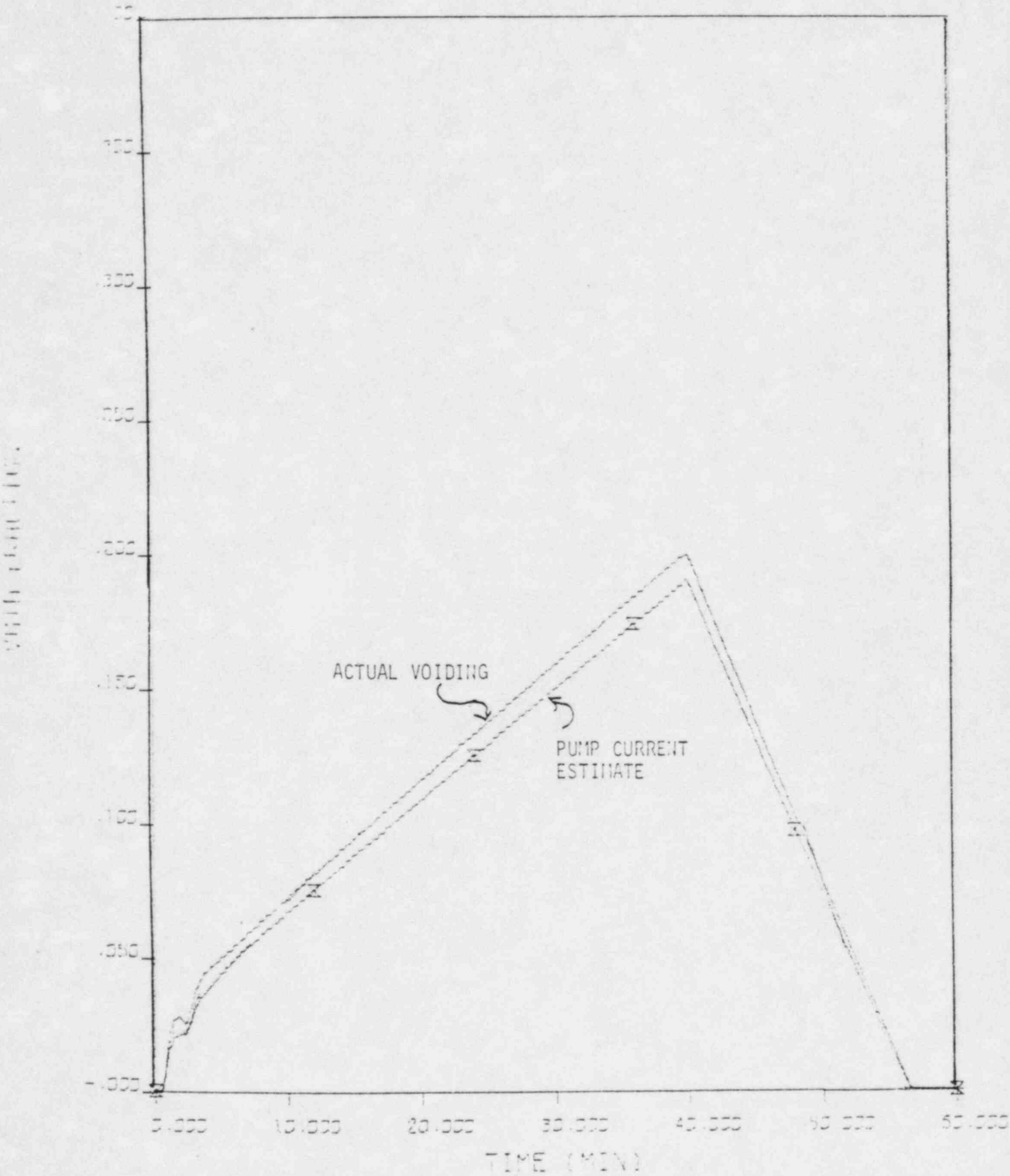

FIGURE 17: VOID FRACTION VS TIME (NON-DEGRADED)

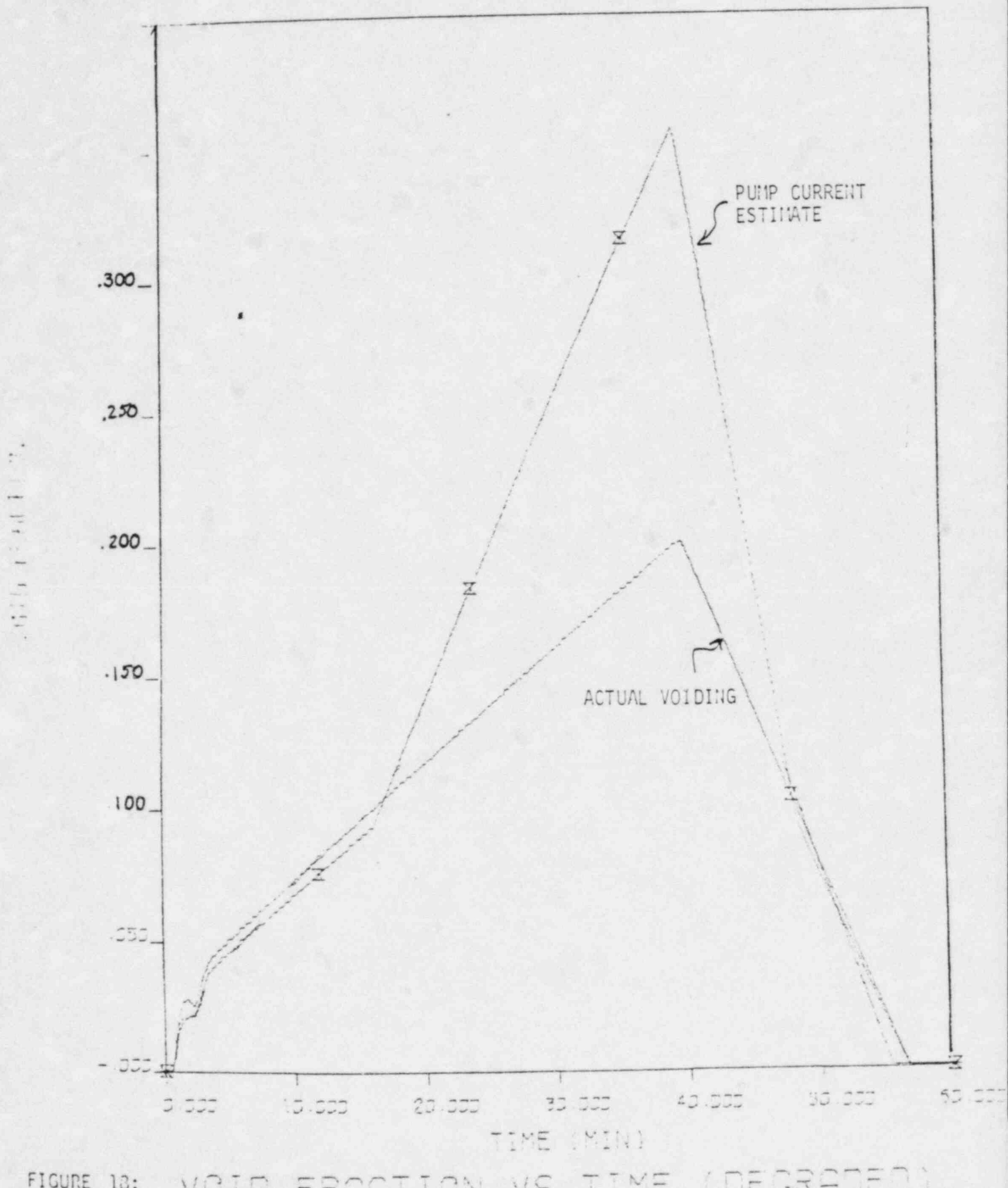

FIGURE 18: VOID FRACTION VS TIME (DEGRADED)

LIST OF SYMBOLS

SYMBOL	DEFINITION
A	Area
g_c	gravitation constant
H	pump head
I	current
K	flow coefficient
ΔP	pressure differential
PF	power factor
P_m	motor power
P_p	pump power
Q	volumetric capacity
T	pump torque
$\bar{V}$	velocity
V	voltage
v	specific volume
W	mass flow rate
x	quality
Y	net expansion factor
α	void coefficient
α_n	normalized pump speed
β	normalized pump torque
η_I	pump impeller efficiency
η_m	motor efficiency
η_p	overall pump efficiency
Ω	pump speed
ρ	density
ν_n	normalized pump flow
Subscripts or Superscripts	
G	gas phase
L	liquid phase
TP	two-phase
f	saturated liquid
g	saturated gas
r,o	reference or calibrated state

ENCLOSURE 3

NUREG 0737

EVALUATION OF ICC SYSTEM

FOR TMI-1

Checklist
for Plant Specific Review of
Inadequate Core Cooling (ICC) Instrumentation System

For Three Mile Island Nuclear Station Unit 1 **Docket No.** 50-289

Operated by: GPU Nuclear

	Reference	Deviations	Schedule
1. Description of the proposed final system including:			
a. a final design description of additional instrumentation and displays;	Encl. 3		Encl. 4 (RITS)
b. detailed description of existing instrumentation systems.	Encl. 3		
c. description of completed or planned modifications.	Encl. 1, 2, & 3		
2. A design analysis and evaluation of inventory trend instrumentation, and test data to support design in item 1.	Encl. 1 & 2		
3. Description of tests planned and results of tests completed for evaluation, qualification, and calibration of additional instrumentation.	Encl. 3		Encl. 4
4. Provide a table or description covering the evaluation of conformance with NUREG-0737: II.F.2, Attachment 1, and Appendix B (to be reviewed on a plant specific basis)	Encl. 3		
5. Describe computer, software and display functions associated with ICC monitoring in the plant.	Encl. 1 & 2		See Encl. 4
6. Provide a proposed schedule for installation, testing and calibration and implementation of any proposed new instrumentation or information displays.			See Encl. 4
7. Describe guidelines for use of reactor coolant inventory tracking system, and analyses used to develop procedures.	See Encl. 1		See Encl. 4
8. Operator instructions in emergency operating procedures for ICC and how these procedures will be modified when final monitoring system is implemented.			See Encl. 4
9. Provide a schedule for additional submittals required**			See Encl. 4

Appendix B (of NUREG-0737, II.F.2)

Confirm explicitly the conformance to the Appendix B items listed below for the ICC instrumentation, i.e., the SMM, the reactor coolant inventory tracking system, the core exit thermocouples and the display systems.

	Reference	Deviations
1. Environmental qualification	Encl. 3	RCP Motor Power/SMM (Seismic)
2. Single failure analysis	Encl. 3	RITS Taps
3. Class 1E power source	Encl. 3	RCP Motor Power
4. Availability prior to an accident	Encl. 3	NONE
5. Quality Assurance	Encl. 3	NONE
6. Continuous indications	Encl. 3	NONE
7. Recording of instrument outputs	Encl. 3	NONE
8. Identification of instruments	Encl. 3	NONE
9. Isolation	Encl. 3	NONE

Item (1)

A description of the proposed final system including:

(a) a final design description of additional instrumentation and displays;

Response:

The final ICC system is composed of the following elements:

1. The core exit thermocouple system which is described in the TMI-1 Restart Report Sections 2.1.1.6.3.1, 2.1.1.6.4.1 and question 95 of supplement 1 part 2. Further information is supplied in GPUN letter dated February 2, 1982.

2. The saturation margin meter which is described in the TMI-1 Restart Report Sections 2.1.1.6.3.3, 2.1.1.6.4.3 and question 20 of Supplement 1 part 1.

3. The wide range Th meter which is described in th TMI-1 Restart Report Sections 2.1.1.6.3.2 and 2.1.1.6.4.3.

4. Other instrumentation which would be useful in monitoring the approach to ICC include Tave, RCS flow meters, source range instrumentation, RCS pressure and pressurizer level which are all described in Chapter 8 of the TMI-1 FSAR.

5. See Enclosure 4 schedule of additional instrumentation.

Item (b) a detailed description of existing instrumentation systems (e.g., subcooling meters and incore thermocouples), including parameter ranges and displays, which provide operating information pertinent to ICC considerations; and

Response:

See response to 1(a)1 and 2 above.

Item (c) a description of any planned modifications to the instrumentation systems in item 1.b above.

Response:

See Enclosures 1, 2 and 4.

Item (2)

The necessary design analysis, including evaluation of various instruments to monitor water level, and available test data to support the design described in item 1 above.

Response:

Our evaluation of various instruments to monitor water level was described in the Restart Report Supplement 1 Part 2 Question 95 and to Mr. R. Jacobs dated December 18, 1981 (Dhir Report), August 26, 1981 and November 13, 1981. See Enclosures 1 and 2 for further information.

Item (3)

A description of additional test programs to be conducted for evaluation, qualification, and calibration of additional instrumentation.

Response

See Enclosures 1, 2 and 4.

Item (4)

An evaluation, including proposed actions, on the conformance of the ICC instrument system to this document, including Attachment 1 and Appendix A. Any deviations should be justified.

Response:

a. Core Exit Thermocouples instrumentation was decribed in our letter of February 2, 1982.

b. Saturation Margin Monitor - see Attachment 1.

c. Additional Instrumentation - see Attachment 2.

Item (5)

A description of the computer functions associated with ICC monitoring and functional specifications for relevant software in the process computer and other pertinent calculators. The reliability of nonredundant computers used in the system should be addressed.

Response

The P/T plot and associated computer functions are described in attachment 2 of our letter of February 2, 1982 (82-007). The reliability of this computer system is also discussed in that letter. Further information on computer function display will be provided in accordance with the schedule of enclosure 4.

Item (6)

A current schedule, including contingencies, for installation, testing and calibration, and implementation of any proposed new instrumentation or information displays.

Response:

Instrumentation described in la have been installed. For the RITS see the schedule in Enclosure 4.

Item (7)

Guidelines for use of the additional instrumentation, and analyses used to develop these procedures.

Response:

See schedule in Enclosure 4.

Item (8)

A summary of key operator action instructions in the current emergency procedures for ICC and a description of how these procedures will be modified when the final monitoring system is implemented.

Response:

Emergency Procedure 1202-6B and 1202-39 have been provided to the NRC for review. Copies of these procedures are also available onsite. These procedures will be modified as necessary pending outcome of negotiations with NRC on additional instrumentation. Enclosure 4 provides the schedule.

Item (9)

A description and schedule commitment for any additional submittals which are needed to support the acceptability of the proposed final instrumentation system and emergency procedures for ICC.

Response:

Additional submittals are shown in Enclosure 4.

Item (10)

Changes to the Technical Specification.

Response:

Changes concerning the saturation margin montior were included with Tech. Spec. Amendment 78.

Changes concerning incore thermocouple Technical Specifications were discussed in our letter of February 2, 1982.

Changes concerning additional instrumentation are pending the outcome of negotiations with NRC and are scheduled for submission in accordance with Enclosure 4.

Attachment 1

DESIGN AND QUALIFICATION OF THE SATURATION MARGIN MONITOR

Environmental/Seismic Qualification - The pressure measurement is obtained from 2 seismic and environmentally qualified sensors. The temperature measurement is control grade, and all signals are seismic Category I and separated for use as redundant signals. The qualification of the meter was recently discussed in our letter of February 14, 1983.

Single Failure - Redundant channels which are electrically independent are used.

Power Sources - The two saturation margin monitors use separate power supplies (115 Vac 60 Hz) powered from safety grade inverters.

Availability - The operability/surveillance requirements of the saturation margin monitor are provided in Amendment dated .

QA Requirements - The quality level of all equipment covered for the saturation margin monitor is designated as Nuclear Safety Related, Class 1E and meets the requirements of the OQA plan Rev. 9. The temperature sensors, plant computer and announciation system are nonsafety related components.

Continuous Operation - The saturation margin monitor will continuously display the margin between actual primary coolant temperature and the saturation temperature.

Recording Instrumentation - Outputs of saturation margin are provided for trending and alarm announciation by the plant computer.

Display Instrumentation - Digital display of the margin between actual RCS temperature and saturation temperature for the existing RCS pressure is provided in the control room on the back panel (PCL).

Isolation - The Tsat computation equipment provides isolation to the pressure and temperature signals through the use of isolation devices at the signal inputs. The Tsat outputs to the announciation system and the computer utilize isolation devices to minimize potential hazardous effects from these system.

Testing - Test signals may be substituted for normal RC pressure and temperature signals to verify operation on the Tsat Margin Monitor equipment. Operating checks can be performed by reading RC pressure and temperature and with calculations obtain the Tsat margin.

Surveillance - See item 4.

Removal From Service - The Tsat Margin Monitor is designed such that all necessary functional tests can be performed on line without affecting other reactor systems. Any testing that is required to be performed offline shall not be required to be performed at less than 15 month intervals.

Access for Adjustment - The Tsat Margin Montiors are rack mounted in signal processing channel A and B equipment cabinets. Accessibility for these cabinets is the same as for normal maintenance.

Anomalous Reading - Anomalous readings are reduced to a minimum by items 2, 3 and 9.

Ease of Repair - See item 13.

Directly Measured Variable Sensors - RCS temperature and pressure sensors provide direct inputs to the saturation margin calculation.

Normal/Accident Ranges - The Tsat Margin Monitor operates over the range of -100° to 400°F which is suitable for normal and accident conditions.

Periodic Testing - Testing is described in item 10 and surveillance will be provided as discussed in item 11.

8. Display Instrumentation

Display information will be brought into the plant computer. Location and type of display will be part of the Control Room Design Review as the detailed design progress.

9. Isolation

Isolation of signal channels will be provided up to the plant computer.

10. Testing

Test signals may be substituted for normal RC pressure/level and temperature signals to verify operation of the RITS. Further information will be provided.

11. Servicing Testing and Calibration

Service, Test and Calibration have not been developed at this stage of the design. They will be provided as shown in the enclosed schedule (Enclosure 4).

12. Removal From Service

The d/p portion of the system will be located inside containment and will be accessible only during plant shutdown. RC pump motor power instrumentation is located outside of containment. Because of the conceptual nature of the design no further details are available at this time.

13. Access to Adjustment

Same as Item 11.

14. Minimize Anomalous Reading

During RC pump operations anomalous readings are in general masked by the trending nature of the information and other available ICC instrumentation. During quiescent operations anomalies are expected to be of short duration and can be checked against other ICC instrumentation.

15. Repair

Location of components for repair will be identified during surveillance and calibration. During operation, because of the simplicity of the system, problem identification will be simplified. For the d/p portion of the system the transmitters are located inside containment and are inaccessible during power operations.

16. Desired Variables

Inventory is not measured directly but is inferred from hydrostatic head. Voiding will result in some error in measurement of actual level but generally in the conservative direction (lower). This differential pressure measurement does not give information about cooling capacity but does indicate inventory. For void fraction trending when RC Pumps running experience at LOFT and TMI-2 together with analytical results of Enclosure 2 show acceptable results using

Attachment 2
Design and Qualification of
The RCS Inventory Trending System

1. Environmental/Seismic Qualification

The RITS will be environmentally qualified for the respective DBE environments and will be displayed in the Control Room via the plant computer (non seismic beyond isolator) to provide the necessary trending information for d/p. The installation will be seismically qualified and the ranges of the d/p instruments will be commensurate with the measure of the top of the RC hot leg/RV head to the top of the active fuel. For RCP motor power, see deviation 1 attached.

2. Single Failure

The RITS is designed such that no single failure of the instrument or auxiliaries prevents the Operator from determining the safety status of the unit. Redundancy is provided by dual instrument trains. However, the two instrument trains have taps in common at the penetration in the RV head and bottom. The commonaltities do not jeopardize the redundancy of the two instrument trains since it is highly unlikely that the tap will fail either from plugging or breaking. Plugging is prevented by using corrosive resistant materials and the absence of flow of concentrated boric acid. Even in the event of tap failure, the RITS is not a protection system but rather a monitoring system with adequate backup from the core exit thermocouples.

3. Power Supplies

Class 1E power source will be provided for the d/p portion of the RITS. The RCP motor power monitoring is non 1E as is the RCP's. Display beyond the isolation device is non class 1E for the computer.

4. Availability

The operability requirements for the RITS will be address in a Tech Spec change request to be provided as discussed in Enclosure 4.

5. QA Requirements

The QA requirements will be those imposed by the OQA plan Rev. 9 for Nuclear Safety Systems which include the appropriate reg guide requirements.

6. Continuous Operation

The RITS will continuously display RCS trending information (pumps on/pumps off).

7. Recording Instrumentation

Outputs of the RITS will provide for trending and alarm in the Control Room via the plant computer.

RCP motor power.

17. Normal/Accident Ranges

The RITS is capable of measuring about 100% of the inventory above the top of the active fuel to the top of the candy canes in the quiescent state. For RC pumps running the RITS measures motor current which is correlated to void fraction from 0-100%.

18. Periodic Testing

Same as item 11.

Deviations

1. Reactor Coolant Pump Motor Power

   a. Deviation

   The reactor coolant pump motor power is not presently classified 1E or environmentally qualified (EQ). Further, it is not intended that this instrumentation will be upgraded to 1E EQ for the final ICC system.

   b. Justification

   The reactor coolant pumps in B&W plants are not classified as 1E or EQ (including Seismic) nor are the associated RCP motor power circuitry. Experience with the RCP and motor current circuit indicates that they are highly reliable and relocation of the pumps circuitry is not cost justified. Present procedures require RCP trip at 1600 psig which is long before voided conditions would exist in the RCS.

   c. Cost/Benefit Analysis

   The RITS is strictly a monitoring system and not a protection system. Relocation of 4 RCP's switchgear would cost hundreds of thousands of dollars large costs in man rem exposure and is therefore not justifiable when evaluated against the small benefit of monitoring in an intermediate phase of the ICC scenario where other ICC instrumentation would also provide indication (SMM).

2. RITS taps (RV head and single Incore Tube)

   a. Deviation

   The RITS taps on the RV head and incore tube are single tap points.

   b. Justification

   The common tap points which minimize penetration of the RCS and particularly the reactor vessel have a very low probability of failing from either plugging or breaking. Plugging is prevented by using corrosive resistant materials and the absence of flow of concentrated boric acid. Even in the event of tap failure the RITS is not a protection system but a monitoring system with adequate backup from core exit thermocouples.

   c. Cost/Benefit Analysis

   Additional taps represent additional penetration into the RCS at the reactor vessel. Added taps would also provide greater man rem exposure. The cost of the additional tap would be on the order of $100,000 which does not appear to be justified as indicated above.

3. Saturation Margin Monitor

   a. Deviation

The saturation margin monitor indicator in the Control Room is not seismically qualified.

b. Justification

See GPUN letter dated February 18, 1983

c. Cost Benefit Analysis

Since no digital seismically qualified instrument is presently available, no cost benefit information is supplied.

ENCLOSURE 4

SCHEDULES FOR RITS

ICC Instrumentation Schedule (RITS)

Proposed Final Engineering Design Description Including Display for Hot Leg d/p RV Head d/p and RC Pump Motor current	12/1983
Control Room Design Review of ICC Instrumentation	12/83**
Start Procurement of RITS Equipment	12/83
Operator Guidelines for RITS Including Analysis Used in Developing Procedures	4/84
Complete Procurement of RITS Equipment	6/84
Commence Installation of RITS Cycle 6 Refueling	7/84
Operating and Emergency Procedure Mods	7/84*
Commence Installation of Safety Grade (S/G) Saturation Margin Monitor (SMM) Cycle 6 Refueling	7/84
Submit Technical Specifications for ICC Instrumentation	7/84
Commence Training of RO/SRO	7/84
Complete Installation of RITS and S/G SMM	9/84
Testing and Calibration of RITS Cycle 6 Refueling	9/84*
Complete training of RO/SRO	9/84
Operation Date of RITS	Based on approval of NRC#
Environmental Qualification of RITS and Incore Thermocouples	3/85

#Following NRC review of asterisked (*) items.

** Based on a May 1, 1983 concurrence by the NRC on the conceptual design.