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Void Fraction Measurement Liquid Level Detection Concept Assessment and Development

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

The Coolant Inventory Monitor System for measuring the amount and the distribution of coolant in the primary system under accident conditions of a nuclear power plant is described in this report. The system is based on measuring the local void fraction of the coolant at selected points in the vessel and piping system and then estimating the coolant inventory. This report summarizes the development of the measurement instrument, the supporting tests and the development of the supporting software. Accuracies of ± 2% as compared with delta pressure cells (as measured in the test facility) can be obtained over void fractions ranging from 0 to 90%. The system can provide local measurements of void fraction and uses probes as small as 0.015 X 1.0 X 0.3 in (0.038 X 2.54 X 0.76 cm). Experimental test data are shown for temperatures up to 570 °F (572K). The system can measure void fractions up to the critical point. The graphics display shows a real time display of void fraction for up to fifteen channels and gives the instantaneous as well as a running average for each channel. This is the first instrument that makes it possible to directly measure the actual distribution of coolant using the local void fraction. The development of this instrument marks a significant difference from the Delta Pressure Cell approach that measures the average collapsed coolant level and the Heat Junction Thermocouple which measures the local heat removal. Both of these two approaches infer the coolant distribution above the core based on correlations.

It is believed that the CIMS instrument meets the intent of the NRC by being able to measure the amount of water above the reactor core under all types of accidents.

EXECUTIVE SUMMARY

This report summarizes the development of a new liquid level or coolant inventory measurement instrument for reactor coolant systems. This is the first instrument that directly measures the void fraction and two phase coolant level and is believed to more than meet the intent of the Nuclear Regulatory Commission (NRC) guidelines for reactor safety instrumentation outlined in references [1,2,3,4] (summarized in NUREG 0737, Clarification Of Three Mile Island Action Plan Requirements, Section 2F2, November 1980). The data obtained from this instrument would significantly increase the level of understanding of the core coolant conditions available to the operator as compared with current instrumentation. The system measures the actual void fraction at specific locations within the reactor core barrel and at other locations within the coolant system. The sensor principle is based on the measurement of permittivity differences between water and steam. Based on these measurements, the amount and distribution of coolant within the system can then be estimated.

This instrumentation approach has overcome the inherent problems of the heated junction thermocouple (HJT) and the delta pressure (DP) cell that are currently being used in many nuclear power stations. The heated junction thermocouple is often not able to determine the difference between liquid and liquid with a high void fraction. Thus it can overestimate the amount of actual coolant that is available. The DP cell can be affected by base system pressure shifts and in changes in the velocity fields that can increase the uncertainty in the estimates of the amount of coolant available.

This Phase 2 SBIR program has concentrated on the development and demonstration of the concepts associated with the instrument that will provide real time measurement of the void fraction in a local region. The hardware and software have been developed to the point that the void fraction can be displayed on a computer CRT on a real time basis.

As shown in Figure 1, a void fraction monitoring system has been constructed with the capability to display data from a multiple number of channels as they are being measured. In the developmental system the data are acquired at the rate of 33 Hz and a display shows the instantaneous value of void fraction as well as the running average for each of the three channels. Software has also been developed so that historical conditions can be recalled and correction in the correlations can be made and the results replayed.

Each void fraction monitoring system consists of a sensor, a connecting transmission line, an analog front end driver and receiver coupled with a series of digital processors (In Line CPUs) to control the analog process, process the data, and present the void fraction results on a CRT or to a file. The sensor probes are constructed of stainless steel and ceramic, and require a separate hardline, 0.090 in (0.228 cm) diameter, for each measurement location. Sensors ranging in size and shape from flat sensors as thin as 0.015 in (0.038 cm) to co-axial concepts as large as 0.75 in (1.90 cm) diameter (0.75 in) have been successfully demonstrated. The sensors and lines can withstand temperatures in excess of 1800 °F (1255K) and can even measure the fraction of sub-cooled liquid surrounded by super heated steam typical of accident conditions.

The instrumentation package has the capability to determine and identify the difference between slug flow and uniformly divided bubble condition of similar effective void fraction. It has a theoretical measurement range of up to the critical point and has been tested up to 572 K (570 °F). The instrument can measure void fractions up to 90% with an average error of ±2% to ±7% depending on the sensor design and the dynamic conditions of the coolant. Side-by-side comparison with a differential pressure transducer shows void fraction correlations with an integrated error of less than 1% over the 0-90% void fraction range.

As indicated in Figure 1, these sensors can be placed directly into the reactor vessel, into the pressurizer and into the critical points in the primary piping. A typical system would consist of 10 to 30 channel with simulation software to interpret the data and provide coolant inventory information. The probes can be either placed in the reactor on a single support through a small single penetration or through a series of penetrations with a smaller number of probes in each group.

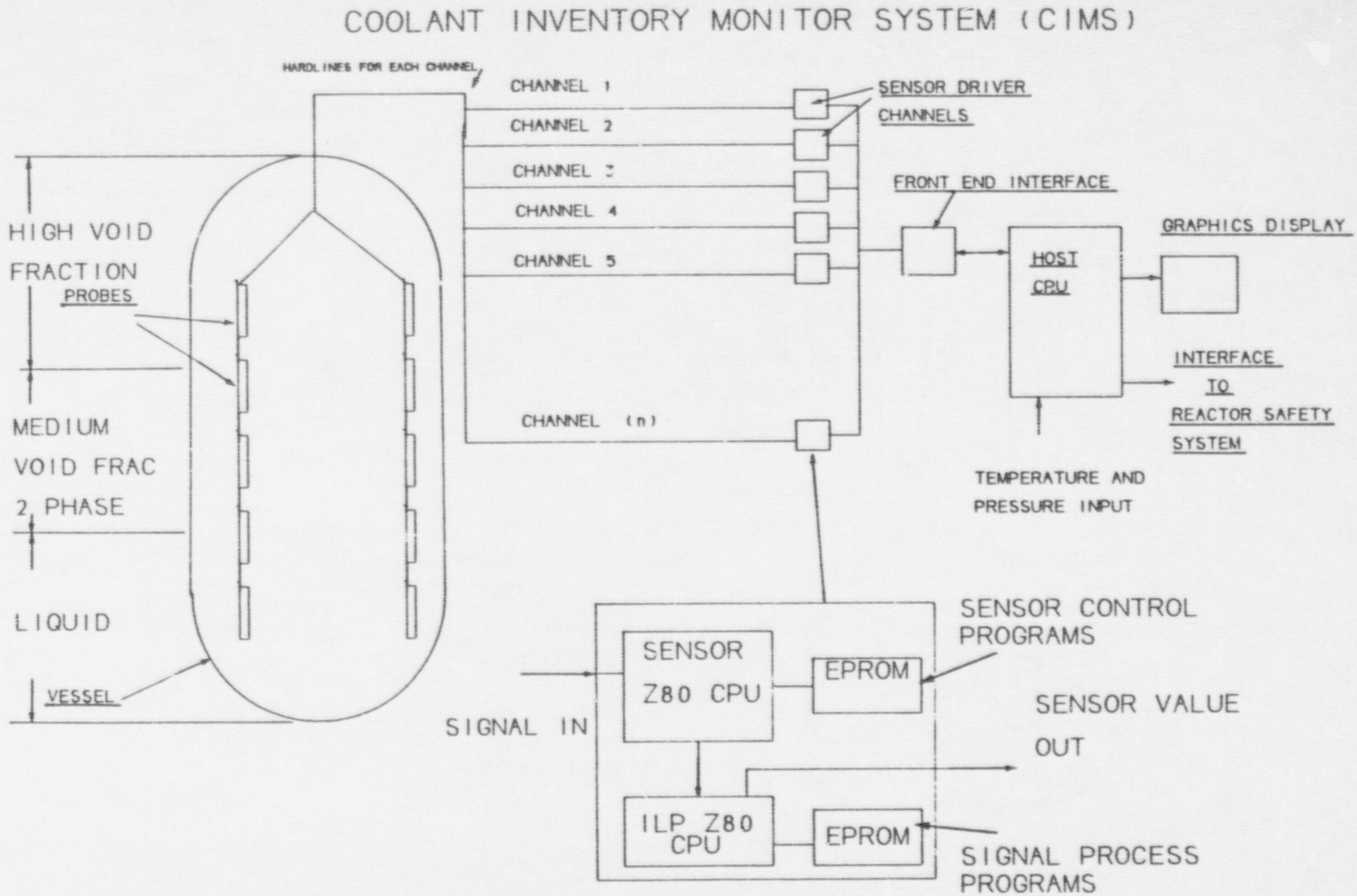

FIGURE 1 Coolant Inventory Monitor System Showing Reactor Pressure Vessel, Probes, Instruments and Control Display with an Interface to the Reactor Safety System.

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1.0 INTRODUCTION

1.1 BACKGROUND

Measurement of liquid level within a LWR reactor core during a Loss of Coolant Accident (LOCA) is essential for effective accident management. The intent expressed by the Nuclear Regulatory Commission (NRC) is that the reactor instrumentation be able to measure the quantity of liquid (lbs) above the core at all times including during possible accident conditions. [1,2,3,4] (summarized in NUREG 0737, Clarification Of Three Mile Island Action Plan Requirements, Section 2F2, November 1980). This information is very important in being able to effectively manage the accident, to make the right decisions, and to bring the reactor to a safe shut down condition. With the correct instrumentation and control logic the entire accident management sequence could be fully automated. Measurement of the coolant inventory and the location of the coolant in the primary and secondary system at any time is a major step.

Several liquid level detector concepts have been developed by reactor vendors and third party suppliers that are based on either delta pressure concepts or heated thermocouple junctions. The majority of the operating reactors in the US have some variation of these concepts installed. The delta pressure measurement concepts have to be conservative to meet the minimum intent of the guidelines and are based on an estimate of the effective collapsed liquid level of the coolant. The heated junction thermocouple is often not able to determine the difference between liquid and liquid with a high void fraction and could over-estimate the amount of water that is actually in the core under some accident conditions.

Delta Pressure (DP) measurements have a long history of problems with calibration and measurement. Partial voids in the transfer pressure lines and problems with turbulence around the pressure taps which cause biases or errors in the measurement are typical with this measurement system. For normal operation these problems can be reduced by using special procedures for bleeding the lines and insitu calibration or perhaps some type of compensation to be applied to the signal. Double jacket lines are often used to make sure that the coolant in the pressure lines remains below saturation temperatures. Baffles can often be placed at the pressure tap entrance to divert flow and reduce the velocity head effects. Under the very best conditions the DP must be able to measure changes in head of 8 in (20 cm) to 12 in (30 cm) under total pressures ranging from 2200 psi (15 MPa) down to 0. For most DP cells there is also a zero shift with increasing pressure. This zero shift will not be a large error but can easily amount to a significant uncertainty in the void fraction when combined with the other potential errors associated with the DP system. (For this program DP cells from three manufacturers were tested, all with specified zero shifts of less than 1% full scale. All of them when actually tested with water in the high pressure system showed zero shifts of up to 5% of the range of interest.)

Under accident conditions, where the measurement is critical to the effective management of the accident, the DP cell can have significant problems. Flow is no longer steady or in the prescribed direction. In this case the local or spatial variation in boiling during blowdown and subsequent reflood phases will cause cross flow and movement of the coolant that will be very difficult to account for or to correct for. As a result, the DP cell measurements will have an unknown error that cannot be accounted for. Depressurization of the pressure lines during an off-normal event can also bias the DP cell reading. The most limiting characteristic of the DP system is not being able to account for the swell of the coolant level as the void fraction changes and to take advantage of this in the management of the accident. To assure that a known amount of water is above the core the DP measurement must assume that the collapsed liquid level exists and that no void is present. This usually results in requiring more water being in the core than is needed.

The Heated Junction Thermocouple (HJT) concept is based on using a rod with a central heater and a series of thermocouples near the surface of the rod that measures the change in heat flux from the surface; solid water having the highest heat removal and dry steam having the lowest. The problem with the heat junction concept is that the heat generation rate is so low that it is not sensitive enough to differentiate between high void fraction two-phase mixtures and solid water. Heat removal capabilities are so close to being the same and the temperature of the coolant is controlled by the saturation temperature. This condition is especially true under slug flow conditions or under two-phase conditions with high turbulence.

An example of this can be seen from the experimental data (see Figure 1.1) obtained during some of the LOCA Simulation in NRU Program. [5] These experimental results were looked at in detail in a prior SBIR Phase 1 program and reported in reference [6]. In the LOCA tests, nuclear powered fuel rod bundles with a peak fuel rod power of 0.5 kW/ft were tested under heat-up and reflood conditions. Thermocouples were welded to the inside surface of the cladding wall adjacent to the fuel pellet surface. Under equilibrium heat transfer conditions the temperature history or DT/dt (the change in temperature with a change in time) would remain constant. This means that the heat generated was being carried away at a constant rate. During these tests the reflood water was raised and the temperatures of the cladding were monitored. A very large two-phase region that ranged from void fractions very close to 1 to 0 were encountered as the level was raised, and as a large swell zone with this range of two-phase conditions were present. Figure 1-1 shows the heat removal capability of this coolant above and below the froth level interface that had a void fraction of at least 0.8. For most cases the heat removal is at least equal to the heat generated. A HJT type probe with a much lower power generation rate would be even less able to distinguish the swell characteristics under these conditions and would act as though it were covered with water or a high density coolant.

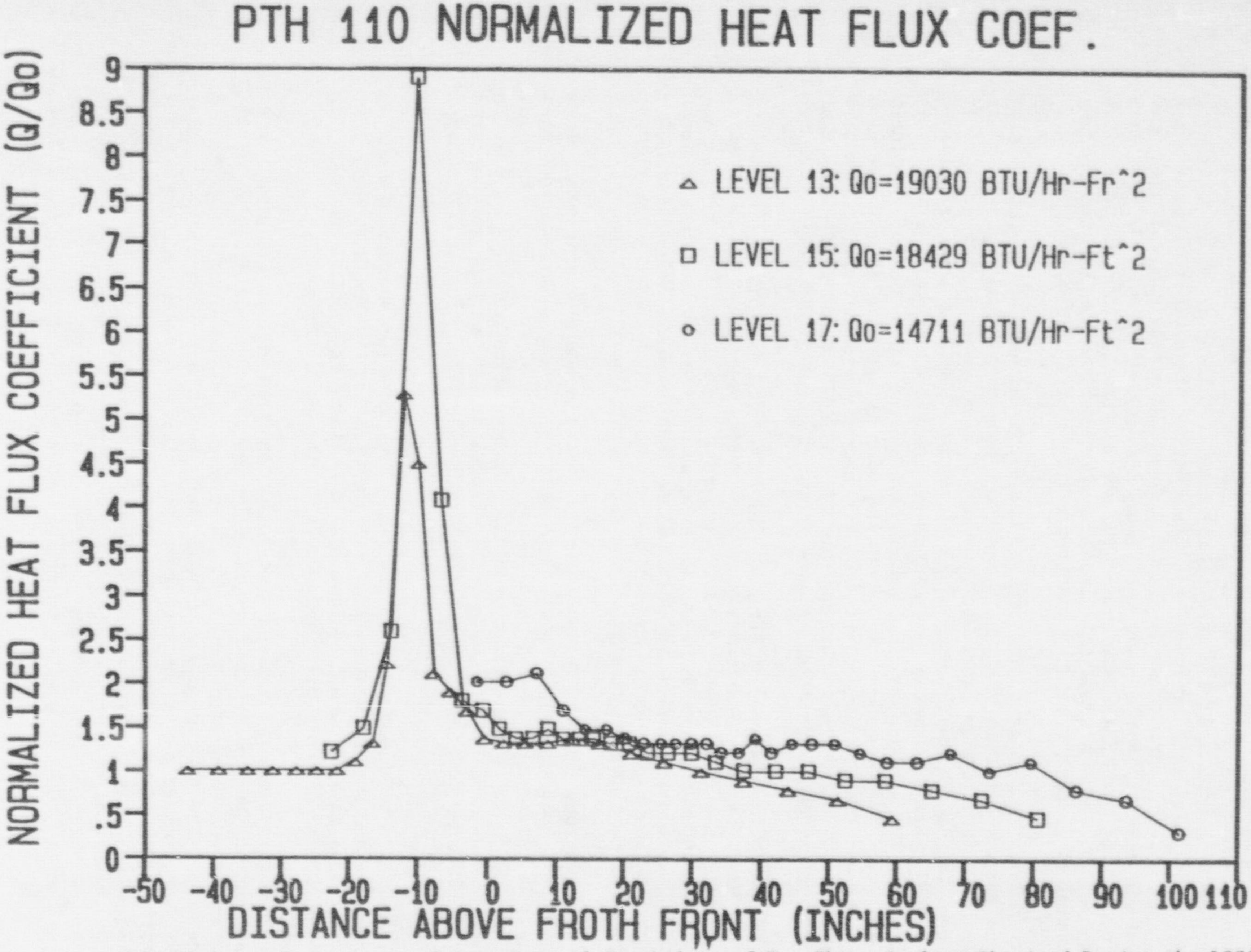


FIGURE 1.1 Comparisons of Heat Removal Capability of Two-Phase Coolant Obtained During the LOCA Simulation Tests [5] Showing that the Heated Junction Thermocouple System, Which Has a Much Lower Power Generation Rate Cannot Segregate Coolant Density Based on Heat Removal. Normalized heat flux of 1.0 means the heat generation is equal to the heat removal, i.e. the clad is at saturation conditions.

As a result of the limitation of the heated junction system, it is apparent that it could indicate a condition of being covered by water when actually only being covered by a low density steam/water mixture. Any change in the core pressure could cause the voids to collapse and immediately drop the coolant well below the current level. (drops of > 5 ft.(152 cm) have been measured) The heated junction thermocouple system would not detect this potential condition and would not provide any automated protection or flag the possibility to the operator.

As can be seen by the comparison of these two systems, the measurement of the liquid level in a boiling reactor coolant system typical of an accident condition is often not a matter of simply measuring liquid level. Depending on the void fraction and the type of boiling that is present, adequate cooling could be maintained using coolant with a high void fraction or low density. Studies have shown, based on NRC sponsored research, that adequate cooling of the fuel systems can be achieved with relatively low density coolant. [6] The early stages of a boil-down type of accident also present combinations of boiling froth of low density that could go largely undetected by some of the proposed liquid level concepts.

NRC sponsored research in the LOCA Simulation in NRU program [7] provided the basis for the instrument that has been developed in this Small Business Innovative Research (SBIR) program. In the NRU LOCA program and the subsequent Severe Fuel Damage program in the NRU Reactor, a froth level interface detection system has been used to help control the coolant flow to the experiment in the reactor and to indicate the coolant level of some unknown density in the experimental test train.

In a previous Phase 1 SBIR effort, analysis and experimental work indicated that the void fraction at the froth /steam interface indicated by this measurement system could be as low as 0.8. [8] It also showed that the froth/steam interface could suddenly drop as much as 60 inches in 0.1 to 0.5 seconds with very small changes in system pressure or could also fall by the injection of slightly cooler water that would collapse the voids in the coolant.[6,8]

The work that was performed in the Phase 1 program showed that it would be possible to locally measure the void fraction of the coolant and, that using this data, it would be possible to estimate the coolant inventory in the core and also the distribution within the core barrel.

The concept that has been developed in this contract provides an instrument that can be used to actually measure the void fraction of the two-phase mixture ranging from 100 % water to 100 % steam and anything in between. The instrument can provide this measurement over the full range of temperatures and pressures common to all light water reactors. The instrument can be used to identify and measure the size of the steam zone above the core, provide indications of boiling, and also provide the measurement of density distributions throughout the remaining portions of the primary coolant system where two-phase conditions exist. The instrument has the ability to measure void related turbulence and froth conditions and is rugged enough to be able to survive and provide data on the total coolant inventory through a severe accident.

1.2 OBJECTIVE

The objective of this Phase II SBIR research and development program was to demonstrate the feasibility of using time domain reflectometry techniques for measuring the coolant inventory in a reactor vessel. The specific objectives included development of basic design data on coolant dielectric properties, identification of probe design concepts, and development of electronics and signal processing instrumentation that would support void fraction measurement probes under real time processing. The results of this work were the development of the Coolant Inventory Monitor System (CIMS).

2.0 INSTRUMENT DESCRIPTION

As indicated in Figure 2.1, the Coolant Inventory Monitor System (CIMS) is composed of probe(s) that are immersed in the coolant, co-axial transmission lines (hardline -stainless steel sheathed co-axial conductor), electronics analog and digital system cards supporting each channel or probe, and a host computer that interfaces with the individual channels. The data rates between the driver cards and the host computer are quite high and very specialized software is required to achieve the required performance. The system performance is based on first determining if water or steam is present and then measuring the void fraction at each sensor location.

The coolant inventory estimate is based on the host computer simulation model using the void fraction data for each location. This software has not been developed, although several approaches have been identified. Future complimentary software development efforts will be needed to provide reactor coolant simulation models that would provide real time or near real time accident management alternatives for the reactor based on the coolant inventory measurements provided. The Phase II work in this report is limited to the development of the actual instrument to measure void fraction and the software needed to support the basic data reduction. This work is the initial series of steps that would be needed for any, more comprehensive application.

The description of the instrument system has been broken into the sensor and coaxial components and features, the electronics, and the software that has been written to support the development.

2.1 SENSOR AND COAXIAL CABLING

The Coolant Inventory Monitor System (CIMS) requires that a probe be immersed directly into the coolant. The electronic circuitry measures the relative impedance of the probe, which is a function of the surrounding liquid and vapor. The measurement zone is based on the electric field that is established around the probe.

The electrical conductivity as well as the permittivity of the coolant are important factors in this impedance measurement. The permittivity of both the steam and water phases are functions of temperature and must be compensated for in the evaluation of the void fraction. The conductivity of the mixture affects the attenuation of the signal and dictates how long the probe can be. High PH solutions (LiOH) require shorter probes than neutral or low PH solutions (Boric Acid). (Depends upon the solution components.)

The size of the probe and the physical arrangement of the central conductor must be designed to allow the two phase material to have free access to the probe elements as shown in Figure 2.2.

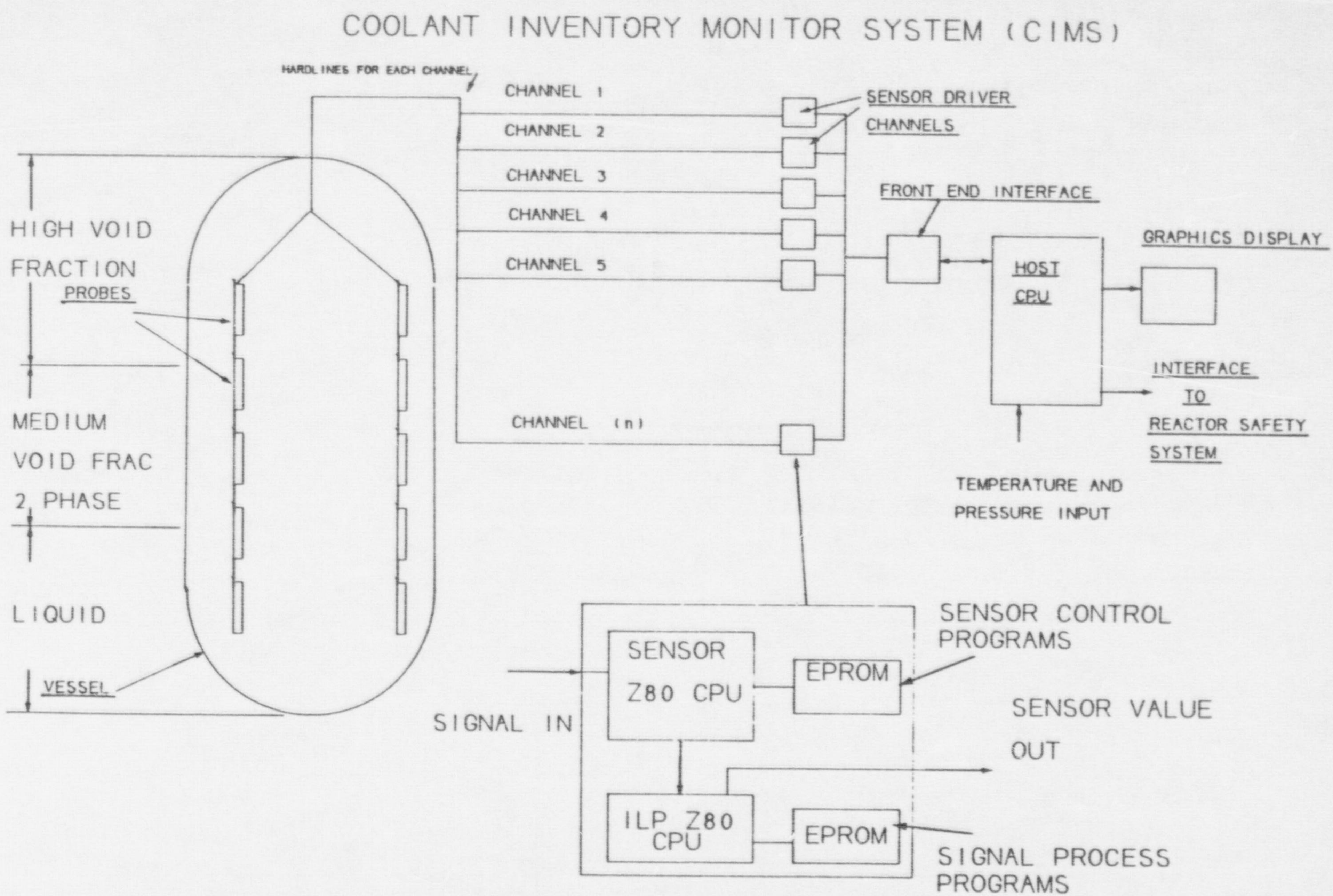


FIGURE 2.1 Coolant Inventory Monitor System Showing Reactor Pressure Vessel, Probes, Instruments and Control Display with an Interface to the Reactor Safety System.

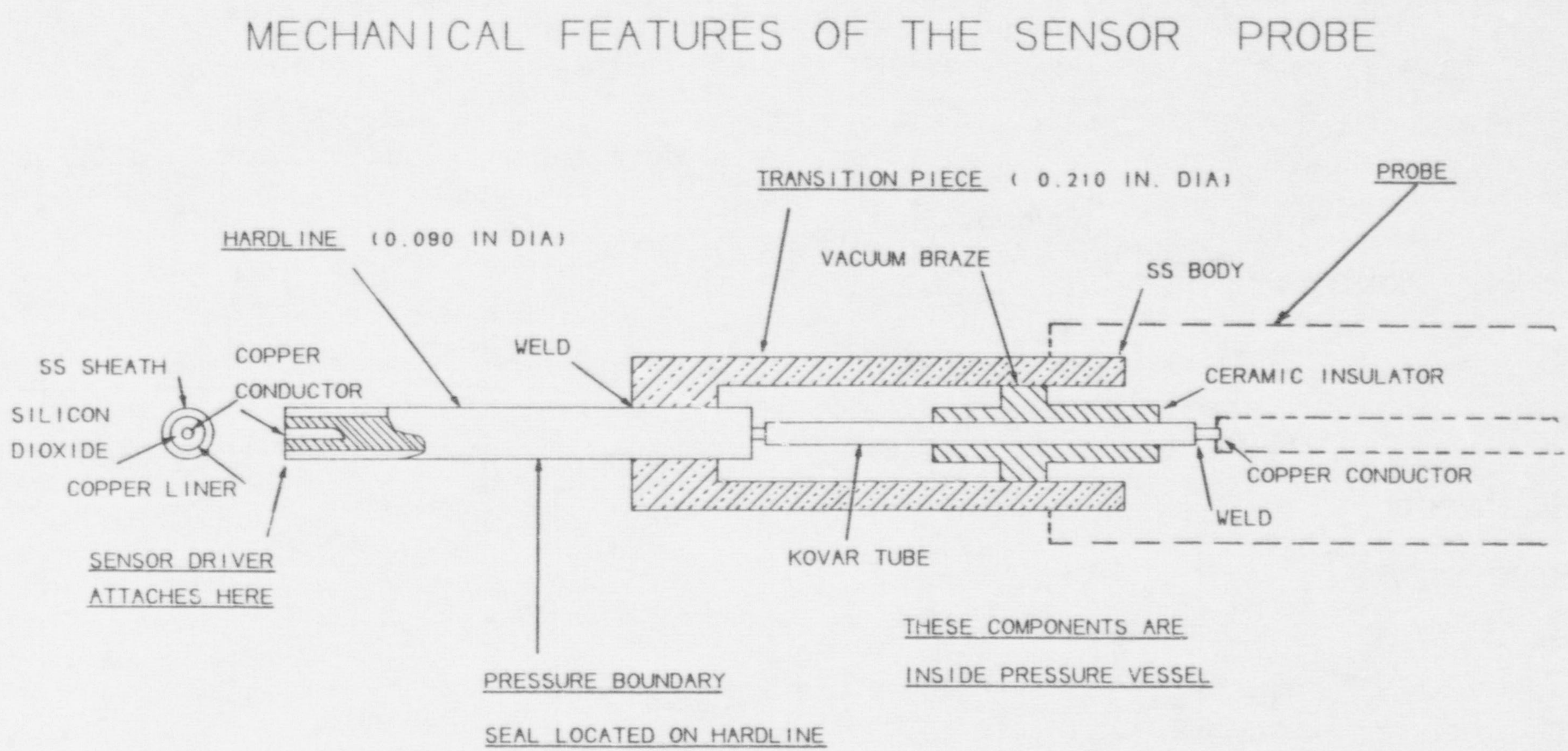


FIGURE 2.2 Mechanical Components for the Probe System. The hardline is terminated with welded SMA connectors for attachment to the sensor driver. The probe is fastened to the transition piece by mechanical techniques (shap rings, welding, etc.). The performance of the transition piece is the most critical of the mechanical parts.

The actual probe system consists of three basic elements: the probe, the electrical coax hardline, and a metal-ceramic transition piece. For this work, the hardline and metal-ceramic transition components were of the same design as those used in the LOCA SIMULATION IN NRU. [7] These two items have been extensively tested under reactor conditions as part of the continuation of the nuclear powered testing in the LOCA program.

The metal to ceramic transition is the most critical mechanical feature of the probe. It forms the primary boundary between the coolant and the insulation in the coax hardline. A failure of this seal would allow coolant to penetrate into the hardline insulation, causing the instrument for this channel to malfunction and produce erroneous readings.

These transition pieces have been fabricated with a stainless steel outer sheath, a vacuum brazable ceramic insulator and a Kovar central tube. The current transition pieces have a 50 ohm impedance, which matches the hardline.

The hardlines, which are used to connect the probe with the electronics package, also have a 50 ohm impedance and are fabricated with a central copper conductor, silicon dioxide insulator, and a copper lined stainless steel outer sheath. The sheath can be welded or brazed to the stainless transition piece to give a very reliable high pressure corrosion resistant closure.

The diameter of the hardline can vary with the application and the distance between the probe and the electronics. The current development was based on using hardline with a 0.020 in (0.50 mm) diameter center conductor and with a 0.090 in (2.28 mm) outside sheath diameter. The size of the sensor probe can then be very small to accommodate small vessel penetrations or applications within actual fuel bundles. The frequency loss characteristics become very important and the highest frequency lines with the lowest attenuation should be sought for all applications.

Probes can be constructed of a wide variety of sizes and shapes depending on the application and the type of environment that is involved. Each probe design has a unique relationship between indicated response and the relative change in void fraction. The responses of all of the probes are non-linear and must be calibrated for the type of solutions and specific design. All calibration must include the surrounding ground plane effects. Table 2.1 summarizes the types of probes that have been tested over the course of this development program. Figure 2.2 shows the typical layout of the hardline and closure used as part of the development.

The longer probes provided very good coolant air (steam) interface information for temperatures in the 250 °F (394 K) range, but provided very little information as to the density of the coolant below the steam / coolant interface. Coolant with void fractions of up to 90 % were sufficient to define the interface. The results of the SBIR Phase 1 study covered the results of the long probe work and were not repeated during Phase 2. [3]

The emphasis of the most recent experimental work was limited to probes No. 5, 6, 7, and 10 in Table 2.1. The most extensive testing was completed with probes 6 and 10. These probes, as will be discussed below, provided the most sensitive void fraction response over the widest range of void fractions.

TABLE 2.1

PROBE DIMENSIONS EVALUATED

NO.	DESCRIPTION AND TYPE	WIDTH/DIA	LENGHT	APPLICATION
1	CO-AXIAL LONG PROBE	0.250 IN	48 IN	STEAM/WATER INTERFACE
2	CO-AXIAL LONG PROBE	0.250 IN	140 IN	STEAM/WATER INTERFACE
3	CO-AXIAL	0.250 IN	12 IN	VOID FRACTION
4.	CO-AXIAL LONG PROBE	0.750 IN	130 IN	STEAM/WATER INTERFACE
5.	CO-AXIAL	0.750 IN	12 IN	VOID FRACTION
6.	CO-AXIAL	0.750 IN	6 IN	VOID FRACTION
7.	CO-AXIAL	0.750 IN	2 IN	VOID FRACTION
8.	CO-AXIAL	0.125 IN	2 IN	VOID FRACTION
9.	PLANER	0.04 X .160 IN	2 IN	VOID FRACTION
10.	PLANER	0.015 X .50 IN	3 IN	VOID FRACTION

2.2 ELECTRONIC FEATURES

The electronic and computer components that have been developed during this project transformed the void fraction instrument concept conceived in the Phase 1 effort into an on-line working instrument. The original data processing system used in Phase 1 required approximately four (4) days of rather intense computer usage to process several minutes of data into void fraction estimates. Using the current equipment this processing is now performed real time at the rate of 30 to 40 Hz. A single host processor can handle at least ten (10) to fifteen (15) channels and possibly more at this rate and both display and archive the data for subsequent re-analysis.

As indicated in Figure 2.3, the basic electronic elements consist of a series of hybrid circuit boards that were developed to provide a very high frequency analog front end with a driver and receiver system; and a digital CPU based on a Z80 to control the analog sequencing and to transmit data on demand to the host computer. A second CPU based on the Z80 was added to act as an In Line Processor (ILP) or co-processor and to provide the initial data reduction. The two Z80 processors operate from separate programs stored in separate Erasable Programable Read Only Memory (EPROM). They each access their own memory space and their mutually dependent operation is synchronized through the use of interrupts and status bits. The timing and data acquisition control are set separately for each analog channel in delay and sampling switch banks. These functions could be controlled through the host computer for future applications. These switch settings adjust the analog channel to fit the sensor and coaxial cable parameters that are connected to this channel.

The data is transferred to a Hewlett Packard 9000/320 (HP) which serves as the host CPU. It is at this point where the basic readings are corrected for temperature and the estimate of the void fraction is computed and displayed on the host CRT.

Data from test operations is received by the HP from two physical entry points, the GPIO interface and the A/D interface (see Figure 2.3):

1. The General Purpose I/O (GPIO) interface (HP98622A board), in connection with the Direct Memory Access (DMA) board enables two-way talk between the HP and the Sensor driver card CPU's at data transfer rates of up to 1 mbyte/s.

   Operationally, an HP program will issue, through the GPIO, a request to the Sensor Drivers (SD) for data from a specified channel. The SD will then respond by sending an array of data to the GPIO which is then mapped immediately and directly to memory by the DMA board. DMA enables transfer of large data blocks asynchronous to host processing, thereby allowing other processing to proceed concurrent to the data acquisition operation.

2. The Analog to Digital (A/D) interface (HP98640A board) is used to measure voltages from the signal conditioners for the thermocouples and pressure sensors. Data from these sensors are read continuously by the A/D card. The analog values are converted to digital values on a periodic basis and stored in special registers. The frequency of conversion, called the Pace, is a user-controlled parameter set programmatically. In test operations, the Pace is set at 500 microseconds.
   Operationally, an HP program will retrieve this analog data by simply reading the A/D repository register corresponding to desired input channel. Timing of these read operations is normally tied to the GPIO data retrieval cycle, so that each

COMPONENT INTERFACE FOR VOID FRACTION DEVELOPMENT

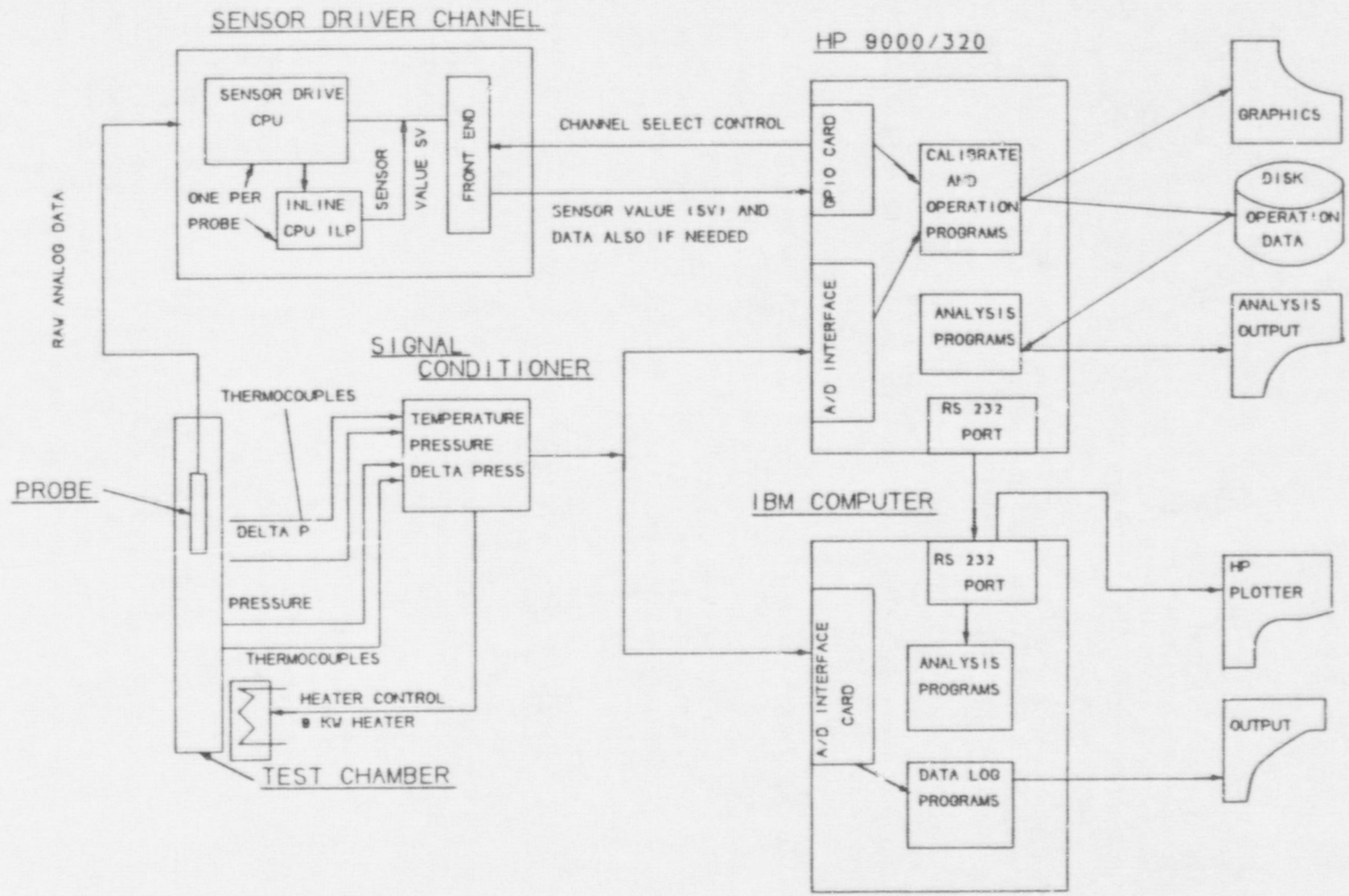


FIGURE 2.3 Electric Circuit Layout Used for the Development of the Void Fration Instrumentation Showing the Test Chamber, Sensor Driver, the HP 9000/320 Host and the IBM-PC Data Logging Computer.

acquisition from GPIO (SD) corresponds to one acquisition from all of the desired A/D channels.

The analog front end for each of the channel drivers has a data rate of approximately 37 Hz. The analog signal is digitized, a single measurement consists of 512 values with 8 bit resolution (0 to 255). These 512 points are evaluated by the ILP and reduced to two bytes which are transferred to the host computer. The transfer takes place on demand at a rate of 250 k bytes/s using Direct Memory Access (DMA) to the host computer. The transfer of the data to the host computer is delayed by one (1) time segment which allows the algorithm in the ILP to evaluate the measurement. This evaluation currently requires approximately 15 ms to 20 ms with a maximum of 22.5 ms available.

The host computer also has an analog signal processor and A/D converter that is used to measure the temperature and delta pressure close to the probes at the same time the sensor readings are being taken. The readings from the A/D board are stored in a rolling series of registers that allow the correct analog measurement to be matched with the SD instrument reading.

The HP processes the raw instrument readings, making corrections for temperature and for signal frequency shifts . This is used to identify flow regimes in the coolant being measured along with the void fraction. This process is completed for each of the channels. The current developmental system has three channels that have been fabricated for evaluation. The timing per channel indicates that at least ten (10) channels and possibly fifteen (15) channels can be handled with the current CPU which operates at 16.5 MHz.

The graphics display on the HP (9000/320) includes the statistical treatment for each channel which includes the actual frequency, the standard deviation of the signal based on a 64 measurement window. The graphic display is shown in Figure 2.4 for three channels and one channel of Delta Pressure used as a comparison. The Delta Pressure cell has been used in the development to evaluate the performance of the void fraction instrument.

The graphic display shows a series of bar graphs. The top bar graph for each channel shows the instantaneous void fraction with the bottom bar showing the average for the counting period specified. The averaging period is user specified with a range between 1 and several hundred.

2.3 SOFTWARE

Software needed to support the instrument development has evolved into two separate areas. Software was developed to support the Sensor Driver control Z80 based CPU and to evaluate the basic signals in the In Line Processor Z80 CPU. Software was also developed to transfer data and to calculate and display the results in the Host CPU (HP 9000).

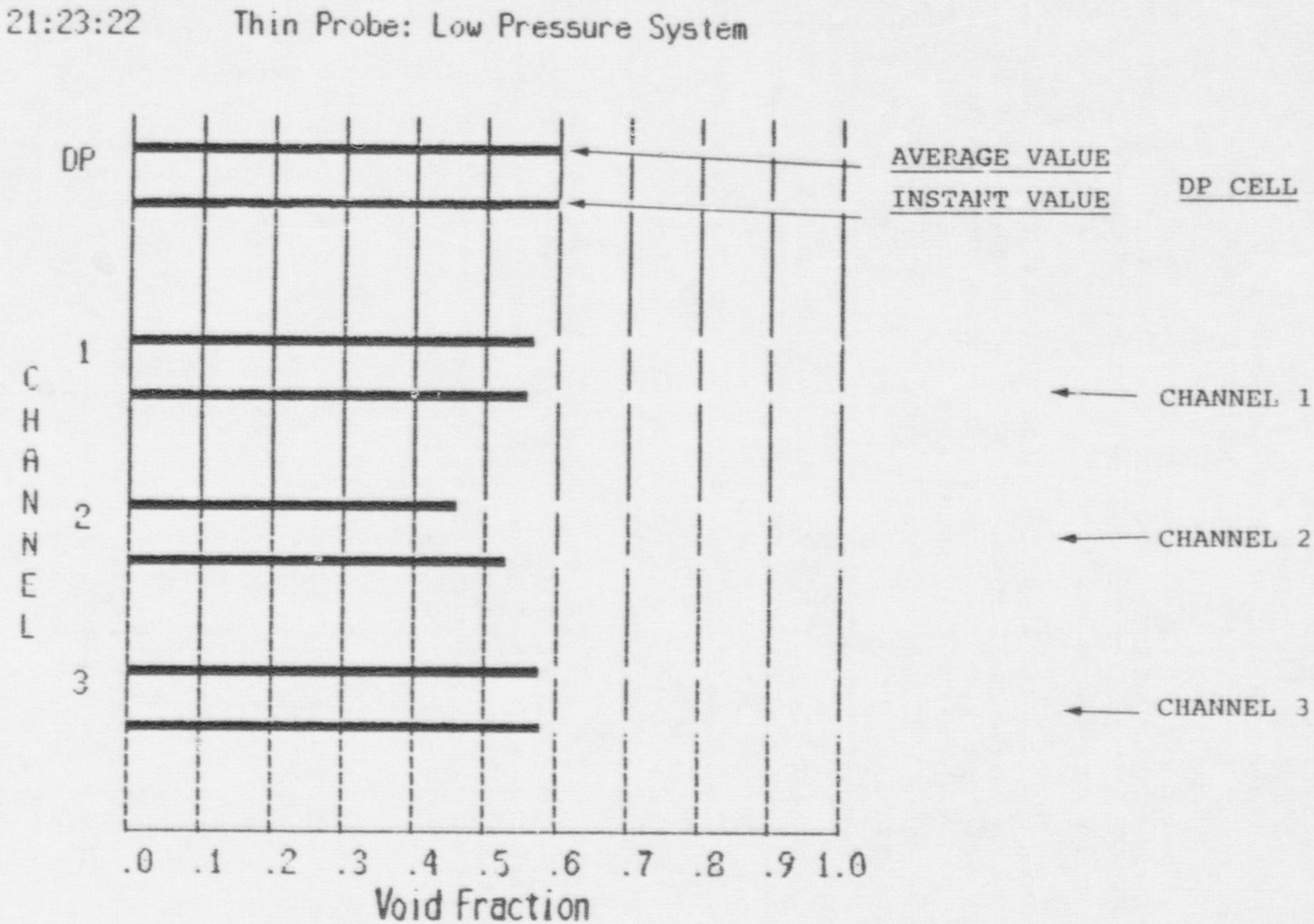


FIGURE 2.4 Graphic Display from Host Computer CRT Showing Three Phase Probe Void Fraction Measurement Taken in the Low Pressure Chamber. DP cell is measuring at zone where Channel 1 is located, with Channels 2 and 3 located at 10 inch increments below Channel 1.

The HP CPU used a Motorola MC 68020 with the math co-processor running at 16.5 MHz. The Z80 CPU's operated at 5 MHz. All of the software for each of the Z80's is coded into separate EPROMS for each CPU and duplicated for each channel. Much of the software for the MC 68020 was coded in FORTRAN with portions in machine level code to speed operation. Figure 2.5 shows the functional relationship of the individual logic process that controls the interaction of each of the elements of the Sensor System.

2.3.1 Z80 SOFTWARE (Sensor Driver and In Line Processor)

For the CIMS, two separate types of Z80 programs were developed. One program controls the SD system CPU and the second controls the ILP. Both programs are duplicated for each channel in the complete system and work independently under control of the Host Computer. (Up to 15 channels for a single Host CPU.)

The SD program is activated by the occurrence of one of two separate interrupts. A timed interrupt (constantly running) which starts the program at its data acquisition entry point. The second is a request for data interrupt (from a signal from the HP) which starts the program at its data transmission entry point. The ILP program is activated by an interrupt generated by logic in the data transmission code.

The Z80 software can be broken into data acquisition, in-line processing, and data transmission. (See Figure 2.5)

Data Acquisition Phase

The data acquisition phase is initiated upon completion of the transmit phase of the program. Operation must be completed within 22.5 ms to not interfere with other operations. The sequence of operation is as follows:

1. Read values of external switches. Initialize buffer pointers and counters. Set Read-in-Progress indicator.

2. Read 512 points from a probe by reading a hardware register containing the digitized value of the analog signal coming from the probe. The timing of the read correlates to the distance of the point on the probe represented. Timing is controlled by a 30 ms clock which restarts (via an interrupt) the program at an interim acquisition phase with each pulse.

3. Scale the observed values and store the desired section of data into the acquisition buffer.

4. Reset Read-in-Progress indicator and lapse into wait state.

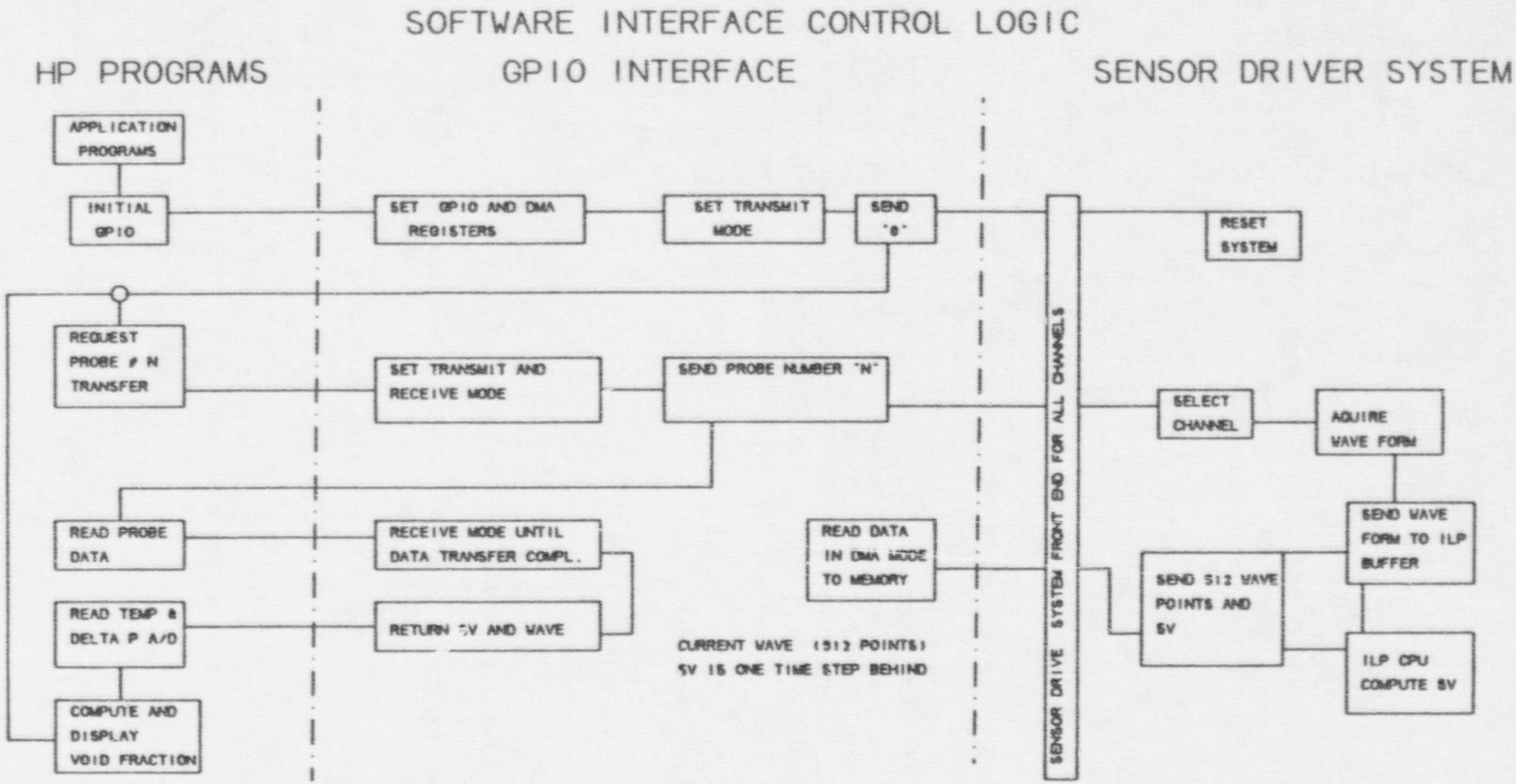


FIGURE 2.5 Functional Relationship of the Software Connection Between the Host Computer, the General Purpose Input/Output (GPIO) and DMA and the Two Separate Processors on Each Channel of the Sensor Drive System. This software computes and displays void fractions for each sensor at a real time rate of 33 Hz for all channels.

Data Transmission Phase

The data transmission phase is initiated by an externally generated interrupt, introduced by a signal from the Host HP. The front-end board receives the signal, reads the data line for the SD channel number, then generates the interrupt on the appropriate SD channel board. Operation sequence is as follows:

1. If Read-in-Progress indicator set, wait until it is reset.

2. If this is the first read attempt, zero the acquisition buffer.

3. Move Sensor Value from IL-processor memory to output register, sending it to HP.

4. Move bytes from the acquisition buffer to the output register, pulsing the control line with each byte so as to send the data serially to the HP. Note: Byte values are complimented (negated) during transmission.

5. Transmitted bytes are hardware-latched into ILP memory.

6. Generate interrupt to start the IL-processor.

7. Jump to wave acquisition phase of program (read another wave) and concurrent Sensor Value (SV) determination by the ILP.

Sensor Value Evaluation

The general algorithm for determining the characteristic Sensor Value (SV) from a digitized wave form has been revised extensively over the course of this development program. The original algorithm was developed on the HP 9000 and then converted to the Z80 in Assembler. The major limitation is that the Z80 operations are best performed in integer arithmetic operations. The coding must also all be done in Assembler which adds to the complexity of working with the unit. The process of evaluation is based on smoothing the raw data and performing a series of comparative calculations. The process is limited to the time required to obtain the basic analog signal and digitize it which must be less than the 22.5 ms.

2.3.2 HP SYSTEMS SOFTWARE

The PASCAL Operating System used on the HP 9000/320 provided many of the systems-level operating needs required for this project. The operating system supplied features such as file management and backup facilities, display and printing capabilities, a fast processor and floating-point co-processor, interfaces for external data transfer. The PASCAL operating system was used with a third-party FORTRAN compiler. Wherever possible, the provided systems software was used. Inadequacies in the system were alleviated by writing systems-level software for specific functions.

Most of this special software was written in MC68020 Assembly language, with FORTRAN and PASCAL being used where more appropriate. The choice of language considered mainly functionality and speed rather than programming ease or maintainability.

Language Enhancements

A library of Assembly language FORTRAN callable subroutines were written to enhance or simplify the data processing tasks of the application programs. These routines provide the following general functions:

1. Bit, character and string manipulations.

2. Number, date and time editing.

3. Numeric array type conversions for more rapid processing of large series of numbers.

4. Computational operations, including polynomial evaluation, averages and running averages, standard deviation, range checking, interpolation, and various trivial real number functions.

5. Fast Fourier transform routine, with real/complex array manager and power spectral density computations.

Timer

The HP 9000/320 is equipped with a 4-microsecond timer, accessible through the operating system in two different resolutions, 4 us and 10 ms. The 10 ms times is based on clock time and is the primary source for time stamping operational data. The higher resolution clock is needed to synchronize GPIO operation. This clock, however, is based on computer "on" time and therefore requires additional software for value management (e.g., when the timer register reaches its highest value, the next value will be zero, and no warning of this event is issued).

GPIO Interface

A specialized GPIO interface was written to direct communications specifically between the Sensor Driver and an operation-mode applications program running on the HP. This software was streamlined to require a minimum amount of overhead, thereby enabling data acquisition at the highest possible speed,with a maximum amount of overlap processing time available on the HP.

Programming the GPIO, and its DMA connections, was a relatively complex task which required a significant amount of sophistication to properly coordinate the requests for multiple data channels and correlate the received data with transmission requests. This was further complicated by the fact that the Sensor Driver response was one cycle behind the transmission request, which made the current Sensor Value (SV) value pair with the previously received wave form. (One transmission delay.)

To retrieve a wave form and the SV, the HP first sends the desired channel number to the Sensor Driver (this alone is a "request for data"), then waits for the Sensor Driver to send its data to the HP, which, when received, is automatically stored into memory. Additional logic then moves the data to application program variables.

All of these functions are controlled by the application program through subroutine calls which operate in three general phases: Initialization phase (called once for each channel at the beginning of a program), and Transmit Request and Data Retrieval phases (called each time data is requested).

Initialization call

1. Reset DMA and GPIO registers and control flags.

2. Send Channel 0 request to Sensor Driver (this resets Sensor Driver and no response is expected).

3. Initialize timer.

4. Set "transmit mode" indicator for selected Channel.

Transmit Request call

1. Exit if selected Channel not in "transmit mode".

2. Wait at least 26 ms since last transmission to this Channel (Sensor Driver needs that much time to read Sensor).

3. Note current time.

4. Send Channel number to Sensor Driver through GPIO.

5. Set "receive mode" indicator for selected Channel.

6. Store receive buffer address and byte count in appropriate DMA registers. Place GPIO and DMA in receive state.

7. Data transfer (Sensor Driver to HP) occurs synchronously. When complete, an interrupt is generated, branching to a routine which sets Receive Complete flag.

Data Retrieval call

1. Exit if selected Channel not in "receive mode".

2. Wait until Receive Complete flag set.

3. Retrieve SV; place in return variable. (Note: this SV applies to the wave form from the previous transmission).

4. If wave data requested, move archived wave data to return array. Data must be complimented to appear in original form.

5. Archive wave data just received.

6. Time stamp returned data with time taken two transmissions back.

7. Set "transmit mode" indicator for selected Channel.

Because of cycle delays on both sides of the transmission, it requires three transmit/receive operations before valid data actually comes through. Once good data is coming, transmit/receive requests must continue uninterrupted until a desired "block" of values is received. This is because the timing mechanism is on the HP, so only a synchronous transmit/receive operation can guarantee that the proper time is assigned the data coming from the Sensor Driver. If transmission is interrupted for any length of time, another three transmit/receive operations are required to put the two processors back in sync.

Analog to Digital Interface

Communication (read only) from the Analog-to-Digital (A/D) HP98640A board consists of Assembly language subroutines functioning in two phases:

1. Initialization phase: requiring a single call at the beginning of a program, to set the pace.

2. Data retrieval phase: requiring a call for each acquisition from each desired channel. The digital representation of the instantaneous analog value of the specified channel, multiplied by the specified gain factor, is returned.

In operation, with the development test chambers the application program needed to read four channels: two connected to thermocouples, one to the high-pressure cell, and one to the Delta-P cell. The two thermocouple readings are averaged and instantly converted to Fahrenheit temperature; the two pressure readings are preserved as raw digital counts, to be converted later by one of the data analysis phase programs.

In a normal installation of the CIMS system these temperature and pressure data would be supplied by some other data acquisition system. The normal reactor instrumentation data would be processed and then supplied to the Host CPU as a digital information.

RS232 Interface

Much of the data processing in the early stages of the development were performed with an IBM-PC using LOTUS 123. This procedure provided the ability to try different analysis models used to compute void fraction and to plot the results. This required the transfer of rather large blocks of data from the Host to the PC. Data transfer capability was developed to allow transfer of data in both directions between the Host (HP 9000/320) and the IBM-PC.

Data transfer from the HP to the IBM-PC was easily implemented by changing a parameter in an HP operating system table which defined the RS232 port as the printer. Data transfer from the IBM-PC to the HP, however, required a specially coded driver which accepted user-designated parameter specifications, and properly interpreted the signals coming from the PC running under anyone of several PC-communications packages that were used. This particular (HP) driver and rudimentary protocol structure, were written to accommodate only the relatively small files needed for this work to be transferred from the PC.

Screen Graphics

Although a screen graphics driver was provided within the operating system, it proved to be unacceptable due to its high overhead and lack of certain features. A customized graphics driver was written which included only the features actually necessary for the project. These included:

1. Screen partitioning (windowing) with various shading options.

2. Dynamic scaling.

3. Rapid straight-line plotting.

4. Coordinate array plotting with optional forward blanking, thereby enabling simulation of wave movement.

5. Font character and numeric display.

6. Special character display.

This software is in the form of Assembler and FORTRAN subroutines callable from FORTRAN application programs.

Printer Control

Printing capabilities were for the most part inherent within the operating system. Special effort was required to print graphic images on the printer. Two methodologies for such were considered:

1. Write and use a command-driven software package that would allow programmatic creation of pictorial images on the printer.

2. Create the image on the screen using screen graphics software already available, then programmatically "copy" that image to the printer.

The first option is costly and was not implemented, but may be considered during a later phase of development. The second option is partially implemented within the operating system and is operable from the keyboard. An additional piece of software was written to perform a screen copy function with scaling and positioning capabilities.

2.3.3 HP APPLICATIONS SOFTWARE

Applications software includes programs written to execute the operation, and provide calibration and analysis functions. These packages include separate routines for special-purpose computations such as void fractions, as well as correction factors and data characterizations. Almost all of these programs were written in FORTRAN, utilizing the system's high-powered processing capabilities.

Calibration Programs

Program D0: D0 uses GPIO interface and graphics display software to retrieve wave form and display it to screen over a displayed grid. Used to position (using external switches on the Sensor Driver) the wave to within parameters necessary for evaluation.

Program D2: D2 uses GPIO interface and graphics display software to retrieve wave form and display it to screen, and marks the location of the sensor value.

Operation Programs

Program D4: D4 uses GPIO and A/D interfaces and graphics display software to retrieve sensor signal (1 probe) and other digitized signal data, optionally displays image of signal on the screen, displays current values (and their running averages) of all data, computes temperature values from thermocouple signals, and optionally collects, organizes and writes operational data (including calibration parameters) to a permanent file for later analysis. Program D4 was the primary operational program used to capture test run data for analysis.

Program D5: D5 uses GPIO and A/D interfaces and graphics display software to retrieve sensor signal from (3 probes in current system) and other digitized signal data, collects readings into 64-element blocks, computes corrected void fractions for all three probes and for the Delta-P cell, pictorially displays these values and their running averages, and displays other relevant numerical information for each device. D5 also has an option for writing all such information to a permanent file for later "playback" using different correction parameters.

Routines D4DENS and D5DENS: These routines are used to compute void fractions for Delta-P cell and Sensor data. Input to these routines include reference temperature, reference full and empty readings for Delta-P and Sensor, current readings from each, current temperature, and polynomial approximations for permittivity and specific volume computations.

Program D4CVF: This program creates void fraction files, with block statistics and power spectral densities, from the output generated by program D4. These files are then used for data analysis and correction factor determination.

Program D4XD5: This program creates a D5 type output file from a D4 output file, enabling D5 replay runs to be made against this data (single-probe only).

Program T3: T3 uses GPIO interface and graphics display software to capture selected wave forms (real time) and write the digitized wave data, along with the supposed SV (normally computed by the HP program) to a permanent file. This file is then used as control data for testing SV computation routines written for the Sensor Driver (Z80).

Analysis Programs

Program TSS: TSS displays, both numerically and pictorially, the data (detail, averages, statistics and power spectral densities) from the files created by D4CVF. Optionally applies correction factors to Sensor void fractions. Optionally prints numeric listings and pictures.

Program D5 (replay option): Executes a pseudo operation using generated data (from D4XD5 or previous D5 run), allowing any specified correction criteria, displaying operational results as with a "real time" run.

Routine TDRCOR: Contains all derived correction algorithms, selectable from the main calling program. Algorithms and parameters are altered as desired, then tested using operational or analysis programs running under real or pseudo operating conditions. This program can be used to re-process the data from prior experiments using different analysis models with the same raw data from the ILP.

3.0 BASIC PROBE CONCEPTS

The performance of the probe in the two-phase medium is a function of the geometry of the probe and the temperature dependent electrical properties of the medium. The geometry of the probe affects both the electrical communication with the surrounding medium and also the transport of the medium to the measurement zone. Minimum size considerations must also be observed in the geometry of the probe to avoid surface tension effects. The effect of temperature must be included in the evaluation to account for the wide range in electrical properties that exist in the liquid and vapor phases of water over the range of 100°F (311 K) to 700°F (644 K).

3.1 BASIC RELATIONSHIPS

The probe and its connecting cable can be considered as two finite lengths of connected transmission line. The electrical characteristics of the connecting cable are fixed and are a function of the cable dimensions (electrode diameters) and the electrical properties of the material separating the cable electrodes. For the signal cable, these properties are a function of the insulating material that separates the inside and outside conductors. The probe is basically an extension of the cable electrodes with the insulation or dielectric being provided by the medium that the probe is immersed in. The electrical properties of the insulator are a function of the insulation resistance (R), the dielectric permittivity (E), and the magnetic permeability (p). Since the insulating material is non-magnetic the magnetic permeability can be assumed to be that of free space without impacting the characterization of the cable and probe as a void fraction measuring device. The same assumption can be made for the probe where the atmosphere will be either steam, water or a combination of these phases.

The driver and receiver analog circuitry is based on using a very fast pulse with a rise time of approximately 80 ns. The reflected signal is recorded and by using a series of delays the electrical discontinuities or changes in impedance along the cable can be measured. The instrument works similar to a radar system in that it sends a pulse down the electrode pair of the cable that will be reflected by the localized changes in the electrical impedance. By mapping the shape of the echo pulses, an image of the impedance profile down the length of the cable is obtained. Since the probe is open, its impedance profile is a function of the changes in the medium surrounding the probe.

The electrical field equations which express the probe and cable impedance in closed form are extremely difficult to use. The solution is basically the electrical response of a finite length of transmission line. Although such a derivation is beyond the needs of this work, a distributed form of the expressions can be used to approximate the response of the cable and probe. The distributed expression assumes that the electrical properties are uniformly distributed along the length of the cable rather than localized as they really are with the probe and cable.

The solution of the distributed transmission line expression provides an approximation for the probe and signal cable and can be used to describe the relative dependence of the probe to the primary mechanical and electrical design parameters. The characteristic impedance (Z_o) for the transmission line is one of the more important relationships that can be used to evaluate the basic geometry of the line and probe. The quantity (Z_o) is a unique function of the distributed circuit coefficients of the line and the signal frequency. For the driver circuits that have been used on this system the input is a pulse with a very short rise time (80 ns) and the characteristic impedance will be a high frequency parameter the can be expressed as shown in Eqn 3-1. [8,9]

$$Z_o = (138 \log(b/a))/(E) \exp(0.5) \quad \text{(ohms)} \qquad \text{Eqn 3-1}$$

Where: b = outer radius of the central conductor
a = inside radius of the outer co-axial member
E = dielectric permittivity

This form of the relationship assumes the magnetic permeability of free space for the material separating the electrodes in the probe and cable and the imaginary components of Z_o are dominant over the real components. This means that:

$$W\ (L/R) \text{ and } W\ (C/G) > 10 \qquad \text{Eqn 3-2}$$

Where: W = Frequency
L = Inductance
C = Capacitance
G = Conductance of the transmission line

Using these same assumptions, the velocity of the pulse propagating down the cable or probe can be expressed as:

$$V = (3 \times 10 \exp 8)/(E)\exp(.5) \quad \text{m/s} \qquad \text{Eqn 3-3}$$

For the probe used in the NRU test series [7] with an inner electrode diameter of 0.042 in (0.106 cm) and outer electrode inside diameter of 0.097 in. (0.246 cm) Eqn (3-3) becomes:

$$Z_o = 138 \log(0.097/0.042) = 50 \text{ ohms}$$

The propagation velocity will be:

$$V = 3 \times 10 \exp 8 \text{ m/s}$$

If the probe is filled with water which has a permittivity of 55 at a temperature of 212 °F (373 K) the characteristic impedance and velocity will be as follows:

$$Z_o = 6.76 \text{ ohms}$$

$V = 4.05 \times 10 \exp 7$ m/s

For a signal cable with a 50 ohm impedance and a probe with a 50 ohm characteristic impedance, the water will basically act as a short circuit and slow down the pulse propagation velocity so that the probe appears longer than it does in air.

3.2 PERMITTIVITY MEASUREMENTS

One of the biggest uncertainties with using the Sensor Driver system to measure void fraction was how the permittivity changed with temperature for both steam and water. Very little data could be found dealing with the change of permittivity with temperature for both the steam and water phases especially up to the temperatures of interest. Permittivity is in reality the complex dielectric constant of what ever medium is being considered, in this case water. This means that the impedance of the dielectric must be measured as a function of frequency and temperature for both a water and steam phase. Data showing the temperature and frequency dependence of the capacitance and resistance of the medium using representative geometries were needed.

During the Phase 1 program one data set was located in the literature that reported the dielectric properties of water and steam up to a temperatures of 690 °F (638K). [10] This work was performed in the USSR by Lukashov in 1979. These data were measured under static conditions with no mention of frequency dependence or experimental method. As one of the very early steps in the development process, these data needed to be verified and to establish what additional effects the frequency that is inherent in the sensor pulse would make.

A separate Task was identified in the Phase 2 program to measure the Permittivity of water and steam at temperatures in the operating ranges of light water reactor plants. These measurements were made by using the Sensor Driver and a large probe that would provide good sensitivity and stability of the signal. Measurements were taken in water, and in steam phases up to a maximum temperature of 560°F (566K). The results of these tests are shown in Figure 3.1.

Figure 3.1 shows the measured relative change in Permittivity scaled to the dielectric value for air which has the value for free space or 1.0. These data are presented for Probe No. 5 (See TABLE 2.1) first tested in steam and then in water. The tests were performed in the high pressure test chamber which involved raising the chamber temperature and recording the change in signal from the probe with water. The permittivity of steam was determined in a similar manner, however, only steam surrounded the probe for this case. The maximum temperature approached 570 °F (572 K) which was used as the upper temperature limit for the test chamber. Figure 3.1 shows the measured data as a dotted line for the steam and as a solid line for the water. The dielectric data reported in Ref [10] for water is shown as circles and for steam as triangles.

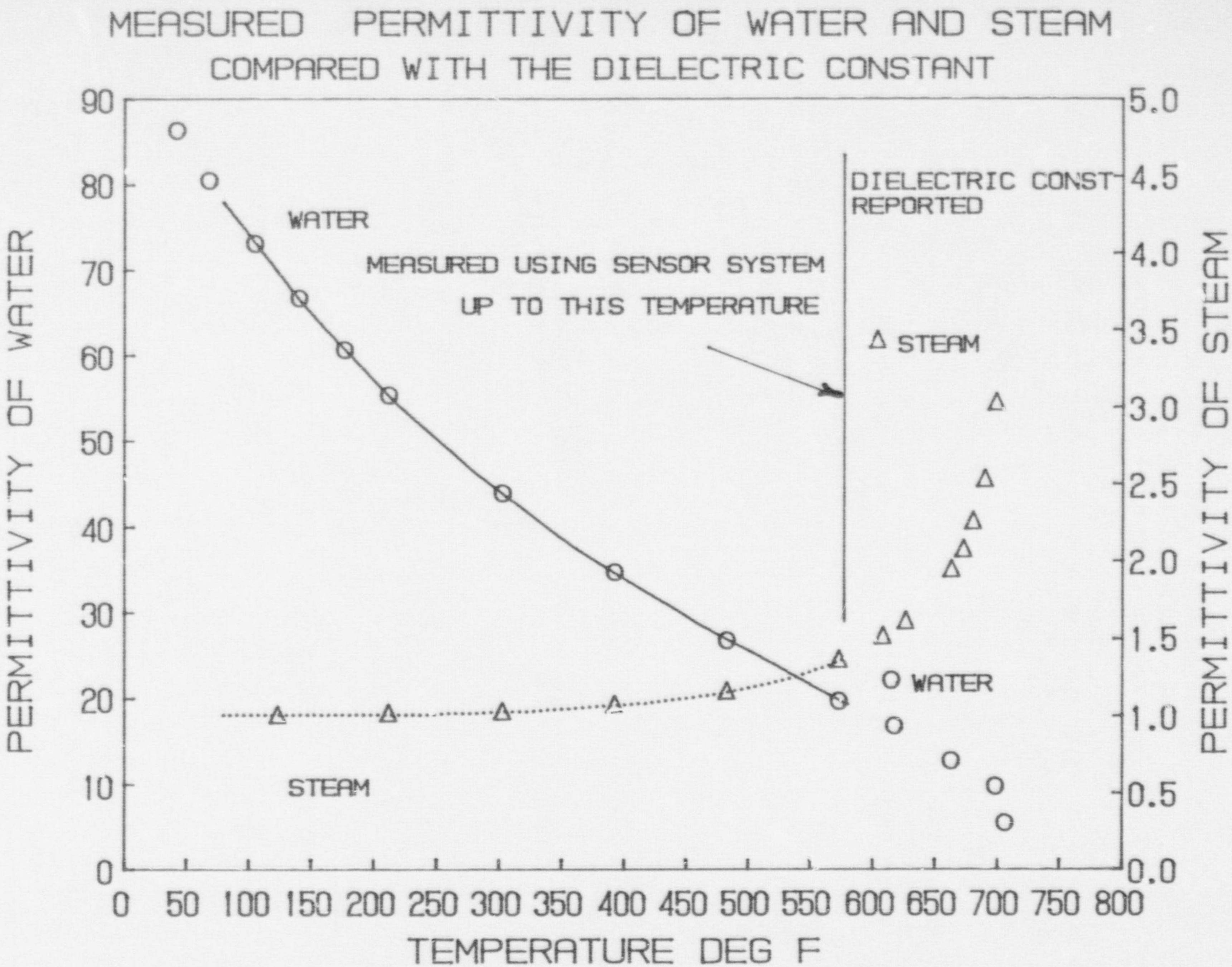


FIGURE 3.1 Experimentally Measured Permittivity for Water and Steam up to 560°F (566K) Compared with Reported Dielectric Constant (Ref. [10]).

Over the temperature range that was covered the agreement was very good which indicates that the sensor should be able to successfully operate up to the critical point. Additional testing at temperatures between 600°F (588K) and 700°F (644K) are needed to verify the relationship between the permittivity and the dielectric constant and that the relationship is well behaved. The results that have been obtained substantiate that there is a good relationship between the permittivity for this frequency and the dielectric constant at the lower temperatures and that there is very strong evidence to suggest that the concept can be used very close to the critical point.

The experimental data obtained for the permittivity for water and steam have been fitted with a polynomial expansion. The form of the equation for water and for steam is shown in Eqn 3-4. The values of the coefficients for each is shown in TABLE 3.1.

$$(E) = C(1) + C(2)*T + \ldots + C(n)*T^{(n-1)} \qquad \text{Eqn 3-4}$$

Where: (E) = Permittivity
C(n) = Coefficients
T = Temperature in °F

TABLE 3.1
POLYNOMIAL EXPANSION COEFFICIENTS FOR THE PERMITTIVITY OF WATER AND STEAM BASED ON EXPERIMENTAL MEASUREMENTS (PROBE No. 5)

COEFFICIENT NO.	WATER	STEAM
C(1)	95.9295	0.993753
C(2)	-2.47601E-01	4.50203E-04
C(3)	3.02568E-04	-6.06354E-06
C(4)	-1.78516E-07	3.07751E-08
C(5)		-6.34162E-11
C(6)		5.08446E-14

Using the permittivity values and the equations shown in Section 3.1, additional velocity and characteristic impedance values for water at other temperatures are shown in Figure 3.2 and Figure 3.3. These data show that as the temperature of the water increases the characteristic impedance increases and the propagation velocity increases. The net result is that at extremely high temperatures the impedance of water approaches that of steam as the temperature approaches the critical point.

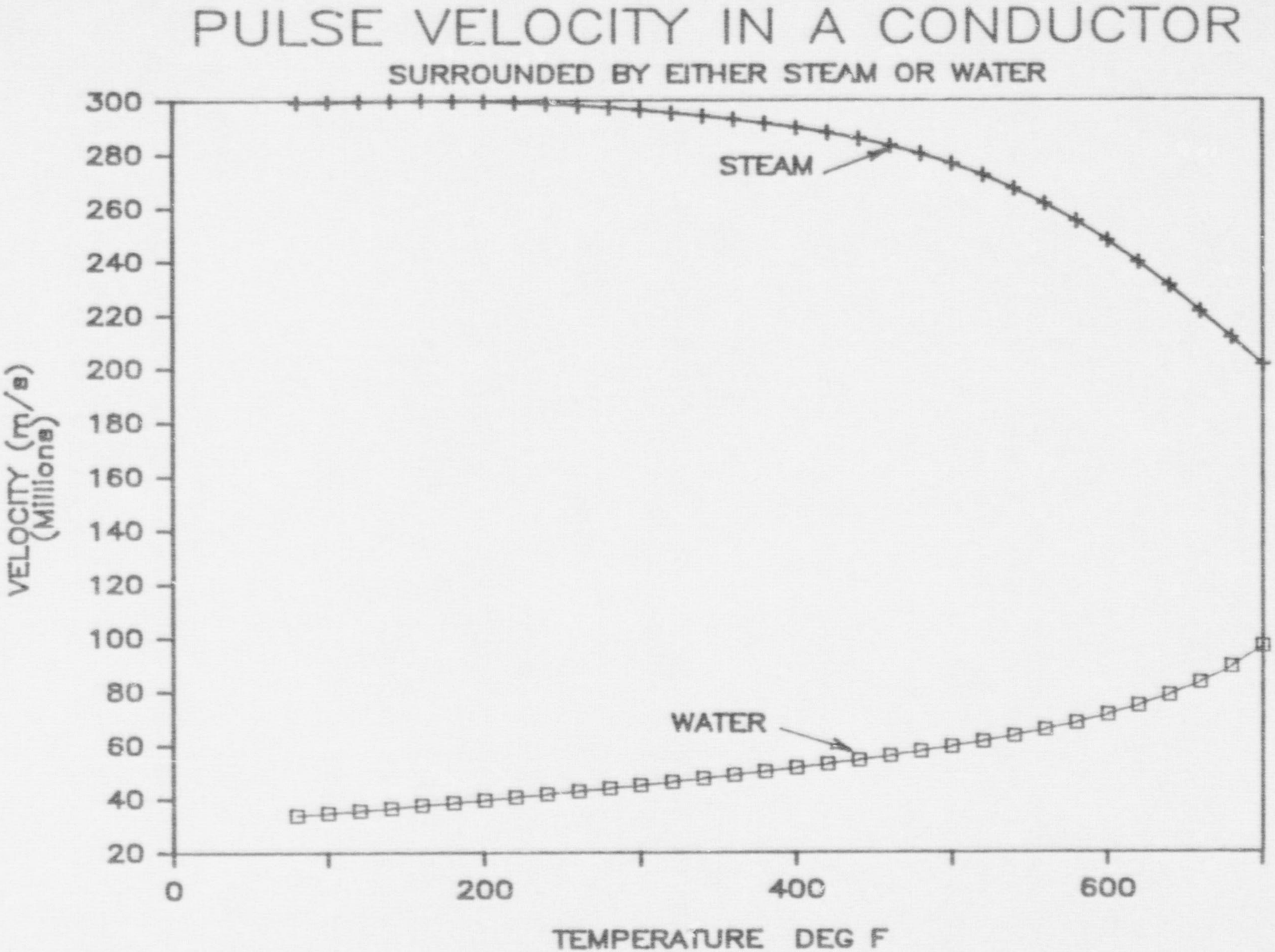


FIGURE 3.2 Pulse Velocity in the Probe as a Function of Temperature for Water and for Steam Surrounding the Probe.

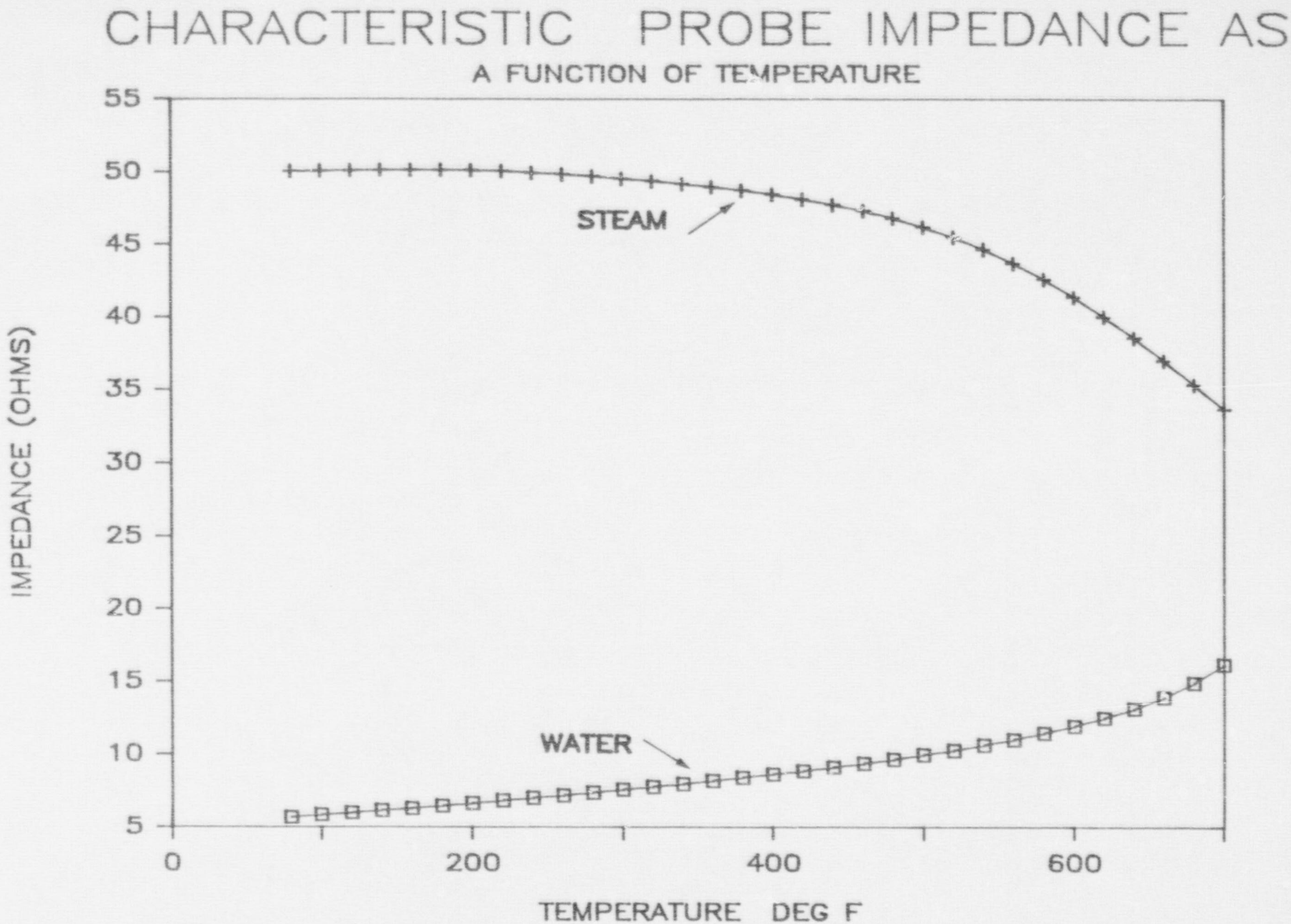


FIGURE 3.3 Changes in the Characteristic Impedance of the Probe as a Function of Temperature for Water and for Steam Surrounding the Probe.

4.0 TEST FACILITY DESCRIPTION

An essential feature of the development of the void fraction instrumentation involved testing the instrument in thermal hydraulic conditions similar to the reactor environment. To support the testing a high pressure chamber was fabricated and an existing low pressure loop that was constructed in the Phase 1 program was refurbished. With these two test chambers void fractions and boiling conditions over a wide range of temperatures and pressures were possible.

The plumbing layout showing the primary mechanical features of both the high pressure and low pressure test chambers is shown in Figure 4-1. Both systems use the same water storage tank and use a water filtration and pump capability to clean up the water used in both chambers.

4.1 HIGH PRESSURE CHAMBER

The primary purpose of the high pressure chamber was to provide the capability of measuring the permittivity of water and steam up to 570 °F (571 K). The secondary objective was to provide two phase transient flow conditions that could be used to test the capability of the void fraction instrument under high pressure conditions.

The high pressure chamber that was designed and constructed was capable of reaching 600°F (588 K) and 1500 psi (10.34 MPa). This is above the operating temperatures of the commercial Boiling Water Reactor (BWR) and in the range of a small break loss of coolant accident condition for a Pressurized Water Reactor (PWR).

The high pressure chamber was constructed of 316 stainless steel pipe with 3.0 in inside diameter and a 3.5 in outside diameter. The closure head was made by Autoclave Engineers and provided quick access to the test chamber. Four quartz view ports made by Pressure Products were included in the chamber walls at 24.5 in and 40.5 in from the top end. The chamber had an overall length of 79 in. Heat was supplied by nine (9) 1 Kw clamp-on type electric heaters that were controlled in groups of three (3) with separate controllers for each group or zone. The control thermocouples were located between the heaters and the wall of the test chamber to protect against overheating the wall. Temperatures were measured at four (4) points inside the chamber (TC-1..TC-4) and the set points for the heater control circuits were adjusted based on these temperatures. A delta pressure cell was located to cover the zone occupied by the instrument in the chamber. A strain gauge type delta pressure cell made by SensoTec was used for making this measurement.

The chamber was fabricated by taking a small autoclave called a Zipper Clave, (Model ZC 0100) and cutting the end off, welding in a series of pipe sections with view ports and then rewelding the end from the old Zipper Clave on the new assembly as closure plug. The chamber was welded in an ASME code welding shop and pressure tested to 2000 psi (13.7 MPa).

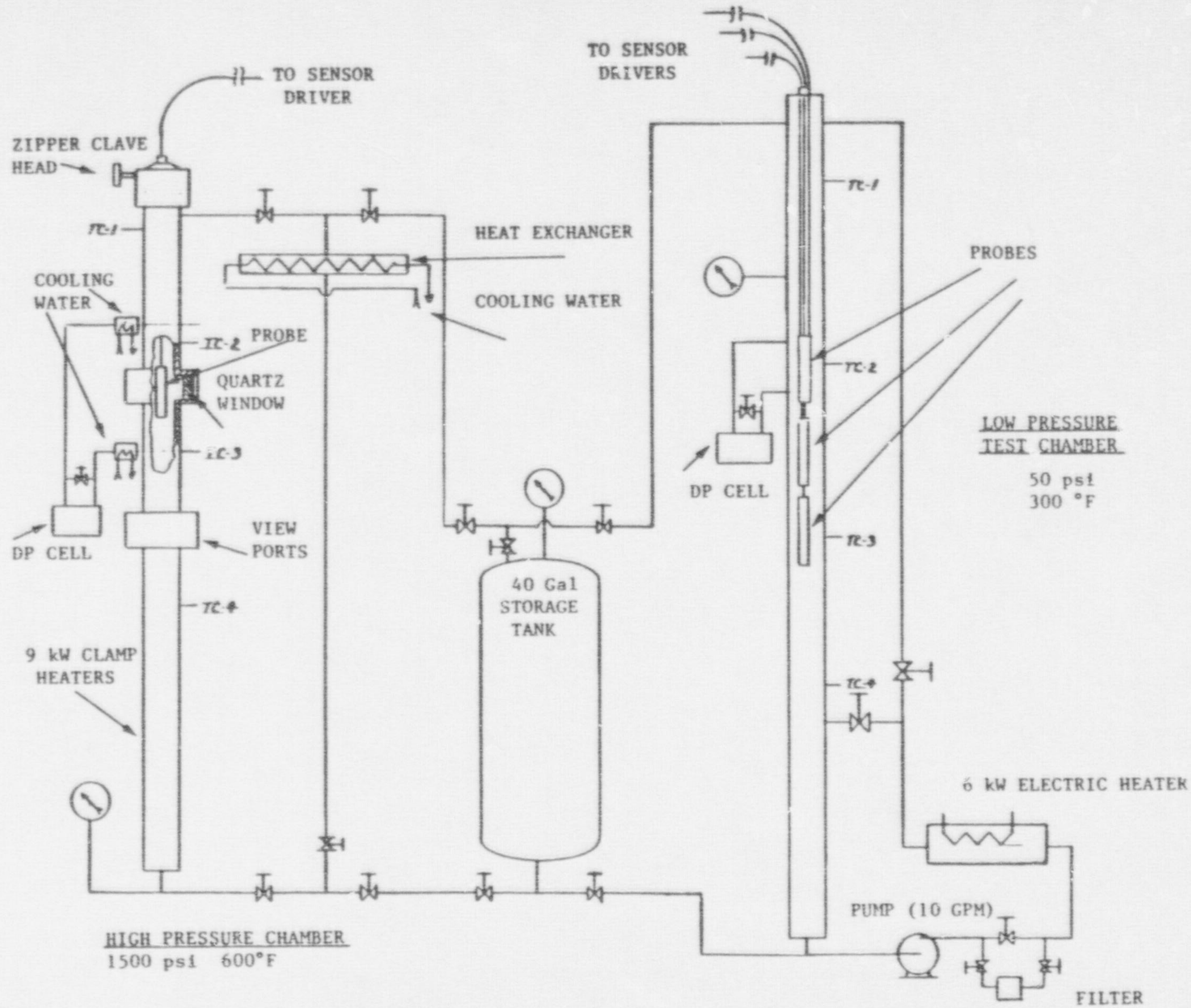


FIGURE 4.1 Primary Features of High Pressure and Low Pressure Test Chambers Showing the Plumbing Arrangement, Heaters, Storage Tanks, Pump, and Filter. The location of the probes in each chamber relative to the location of the Delta P cell is also shown along with the thermocouple locations.

The closure head had been previously pressure tested by Autoclave Engineers to 3150 psi (21.7 MPa).

The Zipper Clave closure head is restrained by a flexible coil spring that is inserted in a groove machined in the outer surface of the closure plug and a mating groove machined in the inside surface of the head sealing surface. The head can be quickly removed from the chamber by extracting the flexible spring and then removing the head.

All of the pressure seals used "O" ring closures which proved to be a very difficult sealing problem. Viton and Kalrez elastomers which were recommended by the manufacturer proved to be unreliable and ruptured at temperatures of 550°F releasing all of the steam and causing the rapid depressurization of the chamber. Solid Teflon seals were tried successfully but were difficult to use. A combination of a Teflon "U" shaped seal and a metal spring constructed like an oil seal to sizes that could be substituted for "O" rings proved to be successful. These seals were made by Bal Seal Engineering as a substitute for the original "O" ring.

The pressure ports were made by Pressure Products and were constructed of stainless steel with a graphite impregnated pressure sealing gland around each circular 2 inch window. The windows were originally made of pyrex glass; however, the steam at 500 °F (533K) proved to be too aggressive and pitted the windows, making them impossible to look through. Quartz was substituted for the glass to avoid the pitting problems. One of the quartz windows cracked after repeated testing to the maximum conditions. The crack propagated across the window was initiated at an internal flaw. The window did not leak or release any steam prior to removal.

Sealing of the joints at the elevated temperature and pressure test conditions was initially a problem requiring constant attention. The thermal cycling, during which the chamber would be filled with water and heated to 570°F (571K) then put through a 30 second blow down to 1 atm and then refilled with 100 °F (341K) water, caused the piping joints and the seals around the view ports to loosen. After several months of constant tightening of the troublesome joints the sealing problems were solved and no more leaking was encountered.

The control and data acquisition instrumentation arrangement for the high pressure system is shown in Figure 4.2. Data acquisition for the basic test conditions were provided by the test monitor computer (IBM-PC) and by the void fraction instrument host computer (HP 9000/320). Delta pressure (DP-1) and temperature data (TC-2 and TC-3) were used in the evaluation of the Sensor instrument. The DP-1 data were used to compare with the Sensor readings and the TC-2 and TC-3 were used to compute the temperature compensations for the measurements.

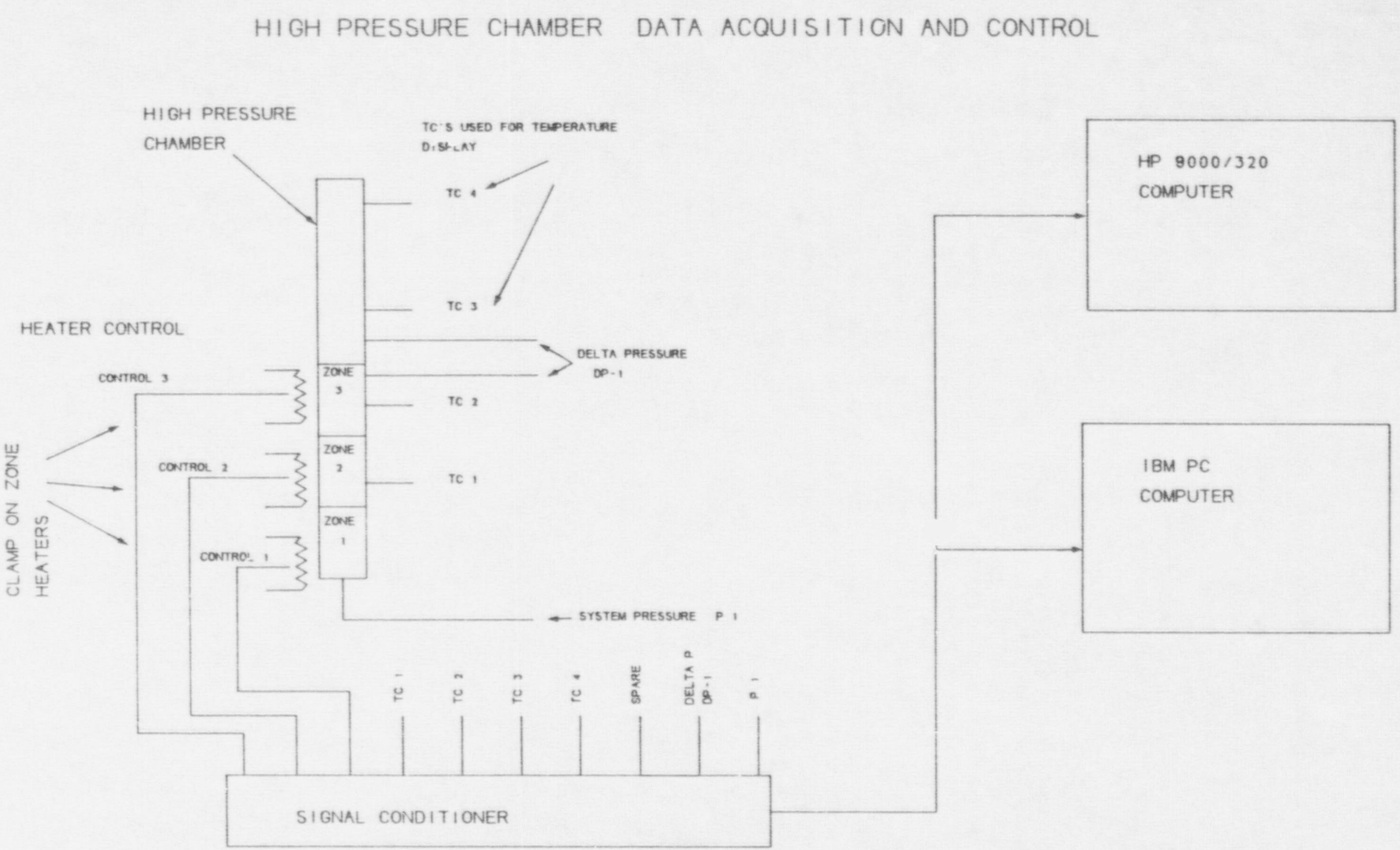


FIGURE 4.2 Data Acquisition and Control Components for the Operation of the High Pressure Test Chamber.

4.2 LOW PRESSURE TEST LOOP

The Phase 1 program low pressure test loop with a 12 ft test section was refurbished, and the length was reduced to 96 in. This loop was used to provide near steady state uniform test temperature conditions with a wide range of void fractions. Temperatures of 240 °F (388 K) to 280 °F (410K) were routinely held for periods of 20 to 30 minutes while at void fractions of 50% and greater. The loop had 6 kW of electric heat and could operate under a controlled blow off conditions to obtain near steady state operation.

The chamber was fabricated with Dow Corning structural glass pipe with pressure taps and locations for thermocouples at each pipe section junction. The layout of the chamber is shown in Figure 4.1. The same data acquisition capability used on the high pressure system was available on the low pressure system. The wiring harness was identical and could quickly be moved from one test chamber to the other. The data acquisition and control instrumentation layout is shown in Figure 4.3.

For this chamber the single control thermocouple was placed directly into the coolant at the outlet of the heater section. There was very little thermal lag with this system and the control was very good over long periods of time.

The low pressure system had a 10 gpm pump and a set of filters that could be valved into the loop. The pump was used during the normal operation to push the water through the heat exchanger. The filters were used as needed to clean up the water in the loop for both the high pressure and low pressure chambers.

4.3 TEST OPERATION

The operation of the high pressure test chamber consisted of the following procedures:

1. High pressure lines to Delta Pressure cell were bled.

2. The Delta P cell range and zero were set.

3. Cooling water to each of the Delta P cell pressure taps were turned on.

4. The closure head with the probe and hardline cabling was placed in the chamber and the closure seated.

5. Initial temperature readings for the four thermocouples located in the chamber were made and checked to see that all of the thermocouples were operating correctly through the data acquisition system. The thermocouples were also checked with a thermocouple meter to assure that correct readings were being made.

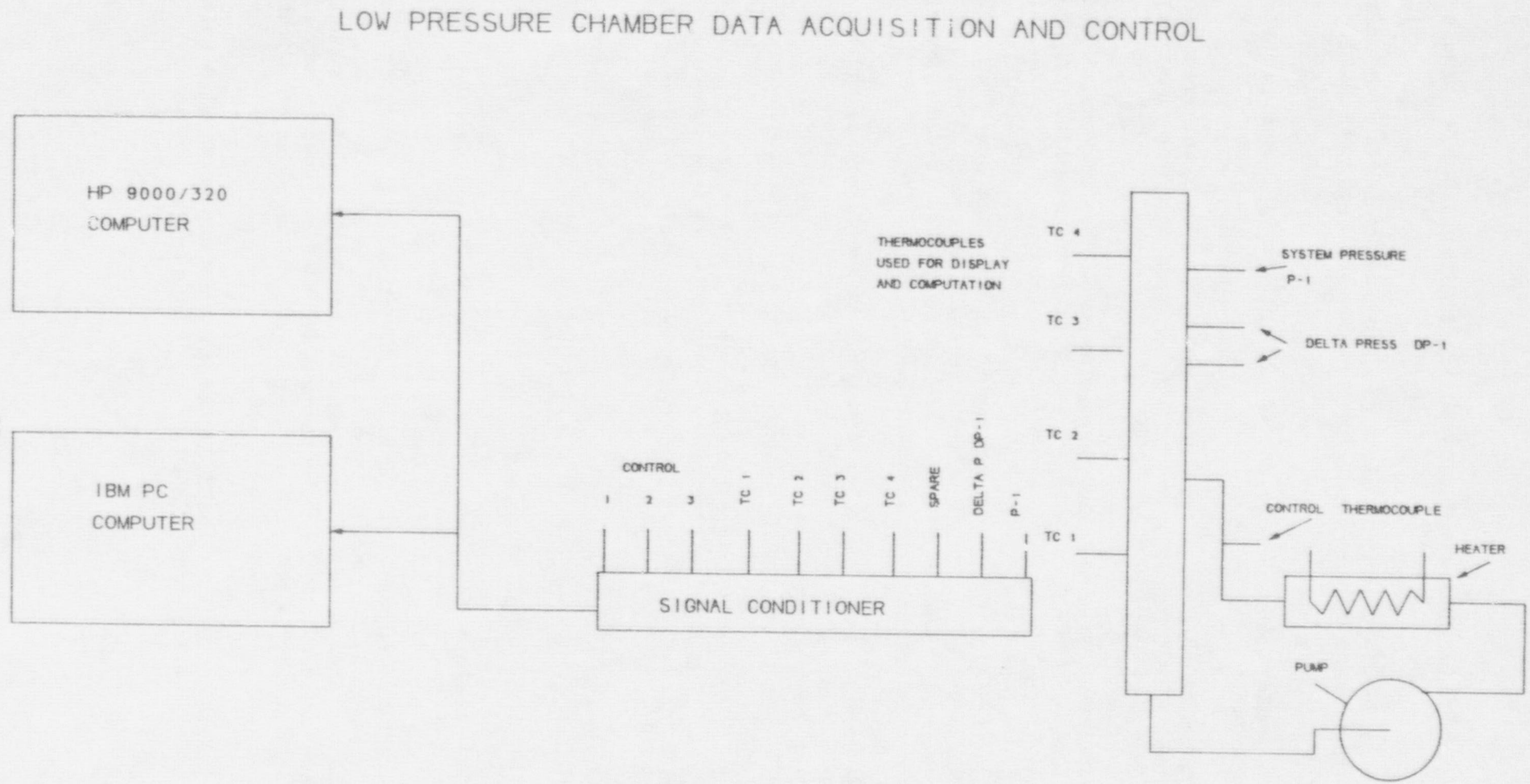


FIGURE 4.3 Data Acquisition and Control Components for the Operation of the Low Pressure Test Chamber.

6. The test chamber was filled to the maximum level with water and all valves were closed.

7. The void fraction instrument readings were taken at the cold condition to assure the correct reference settings had been made.

8. The heaters were then turned on and the set point temperatures selected.

9. System pressure was monitored during the heat up period to bleed off water to keep the chamber from becoming "hard" as the water expanded.

10. Saturation pressure and temperature was checked against the steam table values to assure the correct operation of the thermocouple system.

11. Upon reaching the test temperature to start the blow down, the file was opened on the host computer to record the sensor readings. Initial values were taken to assure the correct operation of the instrumentation.

12. Water was turned on to the chamber heat exchanger and the blow down through the bottom port into the 40 gal water storage tank was initiated.

The operation of the low pressure chamber was very similar to the high pressure system. The major exception was that the low pressure system could operate in a quasi sustained mode for a much longer period of time. (20 min versus 30 s)

1. High pressure lines to Delta Pressure cell were bled.

2. The Delta P cell range and zero were set.

3. The closure feed-through with the probe and cabling was placed in the chamber and the closure seated.

4. Initial temperature readings for the four thermocouples located in the chamber were made and checked to see that all of the thermocouples were operating correctly through the data acquisition system. The thermocouples were also checked with a thermocouple meter to assure the correct readings were being made.

5. The test chamber was filled to the maximum level with water and all valves were closed.

6. The void fraction instrument readings were taken at the cold condition to assure the correct reference settings had been made.

7. The pump was then turned on, the valves adjusted. At this point the heaters were then turned on and the set point temperatures selected.

8. Saturation pressure and temperature was checked against the steam table values to assure the correct operation of the thermocouple system.

9. Upon reaching the test temperature to start the blow down, the file was opened on the host computer to record the sensor readings. Initial values were taken to assure the correct operation of the instrumentation.

10. The valving was changed to allow recirculating hot water enter the test chamber through the lower entrance. The valve opening the top of the chamber to the water storage tank was cracked open to allow a slow depressurization of the chamber to occur. By using a controlled slow depressurization, void fractions of up to 90 % could be obtained at the end of the run after the majority of the water had been removed from the chamber and the coolant had room to expand.

The data taking for the majority of the low pressure tests consisted of recording data on demand when the void fractions of interest could be established in the test chamber. This often took several minutes as the chamber would boil down to a new level and the void fraction could be developed around the area of the probe and the DP-1 Cell.

The software features of the D5 program (See Section 2) allow 64 measurements in a given block to be recorded at a time and stored. These blocks are then used to perform Fast Fourier Transforms (FFT)s to be used in the calculation and display of the void fraction on the CRT. The void fraction for the next 64 measurements uses the FFT computed from the previous block to adjust the computation of the void fraction for the current time period. The computation of the void fraction is based on the instantaneous Sensor Value (SV), corrections for temperature and compensation of the computed void fraction based on FFTs for the dynamic characteristics of the two-phase conditions.

5.0 TEST RESULTS AND ANALYSIS

The cycle of testing and further development have formed the basis for refining the probe Sensor Drivers and software into a working void fraction instrument. Tests have been run to develop the calibration procedures, to refine the probe designs and to improve the software that is needed to analyze the data on a real time basis.

Correlations have been developed for four probes that relate the indicated sensor void fraction to the measured void fraction using a Delta Pressure Cell. These correlations make it possible to now use the Sensor System results to predict the equivalent void fraction that would have been measured by the DP Cell. In general the Sensor system provides a much better indication of the time history of the local void fraction than can be obtained by any other technique. The Sensor system makes it possible to accurately measure the local void fraction in a large vessel or channel which is not possible by any other technique

5.1 TEST CONDITIONS

Two types of tests have been performed using the high pressure and low pressure chambers. The high pressure chamber data is used to provide transient test conditions with a wide range of temperatures and pressures. The test conditions developed in this chamber generally are in the temperature range of 550 °F (560 K) down to 350 °F (450 K). The boiling is generally very vigorous with rapid swings in slug flow type boiling with some uniformly divided bubbles. Detergent was introduced to produce more uniformly distributed bubbles at the higher temperatures and to help provide more control over the flow conditions. The turbulence is very high in this chamber with rapid swings in local void fraction.

The low pressure chamber provided conditions that approached a uniformly distributed bubble condition. By using detergent it was possible to obtain and to sustain near equilibrium conditions with void fractions ranging from .1 up to .8 or even .9 for extended periods of time. The maximum void fraction is limited by the swell space that is available in the test chamber. Typically the majority of the coolant in the test chamber needed to boil off before there was sufficient space in the chamber to allow void fractions of .8 to .9 to be attained.

5.2 PROBE CORRELATIONS

Correlations have been developed that relate the sensor void fraction as calculated by the parameters of the Sensor driver to the measured void fraction using a DP cell. Using these correlations it is possible to translate the Sensor measurements directly into equivalent void fractions as measured with the DP cell. The relationship is shown in eqn 5-1 and the coefficients in Table 5.1.

$$VF = C(1) + C(2)*SVM + C(3)*SVM^2 + C(4)*SVM^3 \qquad \text{eqn 5.1}$$

Where: VF = Equivalent void fraction.

C(i) = Expansion coefficients that are unique for each probe.

SVM = Sensor void measurement as determined by the sensor algorithm.

In practice these correlations are used with the data from the sensor system to calculate the equivalent void fraction. They are unique for the given probe dimensions. Figure 5.1 shows a comparison of the correlations for the Probes No. 5,6,7, and 10.

These correlations are based on a least squares polynomial fit to a series of data points that are averages of a 64 value sample. For a sample rate of 33 Hz this represents 1.939 seconds of data. Averages of the Sensor-based calculated voids and averages of the DP cell-based voids are used in the analysis. These data at this point are not sorted for the frequency spectrum and are used as though they all belong to the same sample set. Figure 5.2 and Figure 5.3 show the data that were used to develop the correlations.

For these tests the temperature and pressure in the chamber are tied by the saturated conditions of the water and steam mixture. The temperature history for several of the test runs using Probe No. 6 and Probe No. 10 (6 in and THIN probes) are shown in Figure 5.4. These particular tests were used to develop the base correlations for these probes and show the range of temperature conditions that are represented in the data sets. The pressure corresponds to the saturated pressure for these temperatures and ranges from 1100 psia (7.58 MPa) down to 30 psia (0.20 MPa).

TABLE 5.1

PROBE CORRELATION COEFFICIENTS RELATING SENSOR VOID FRACTION TO PREDICT MEASURED VOID FRACTION (DP CELL)

PROBE NO.	PROBE TYPE	EQN NAME	C(1)	C(2)	C(3)	C(4)
5	12 IN	12 IN	0.07	1.35	-1.39	1.47
6	6 IN	6 IN	0.04	0.93	0.82	-0.80
7	2 IN	2 IN	0.02	1.35	-1.39	1.47
10	THIN	THIN-1	-0.03	1.76	-0.63	
10	THIN	THIN-2	0.00	1.89	-0.88	

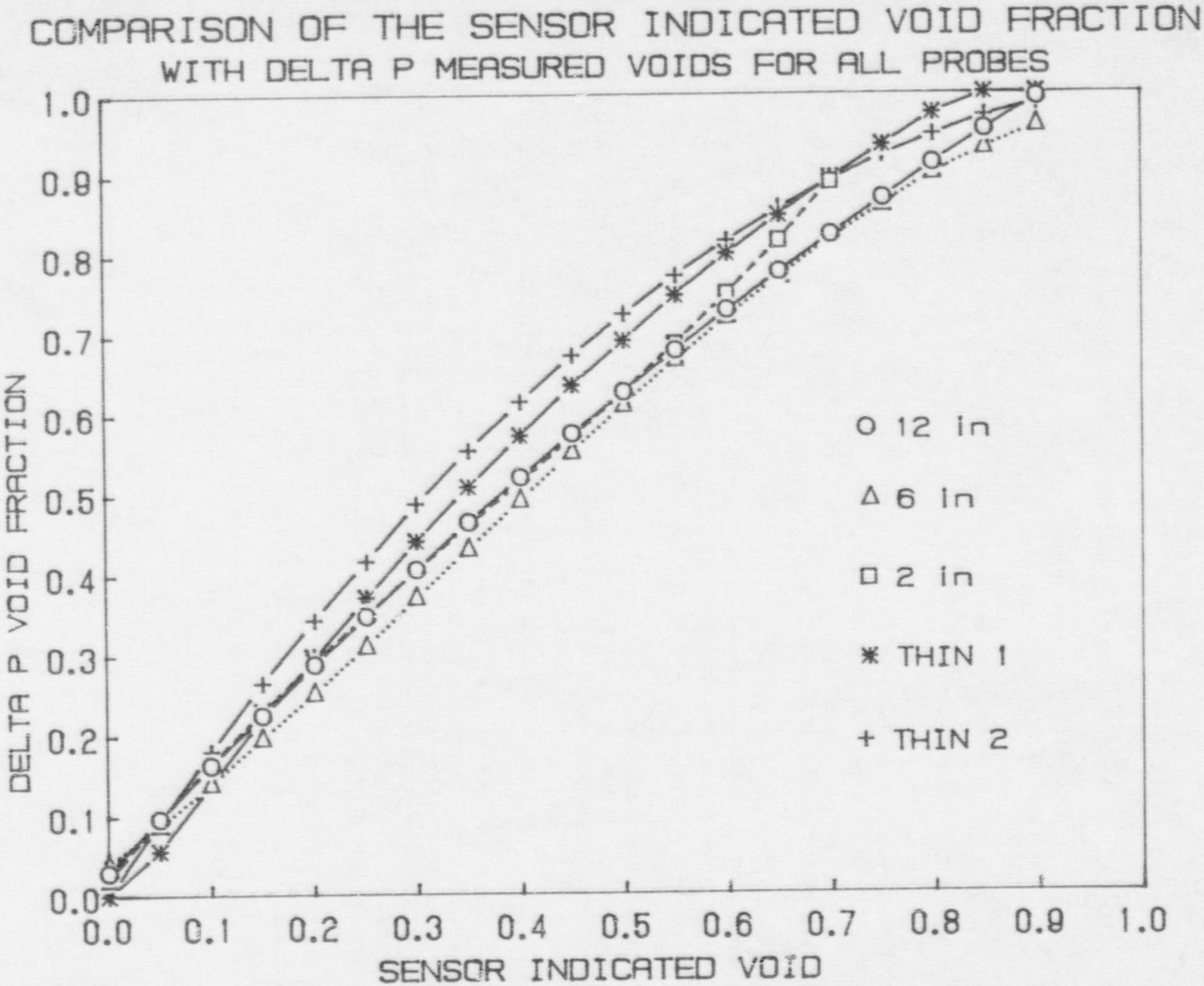
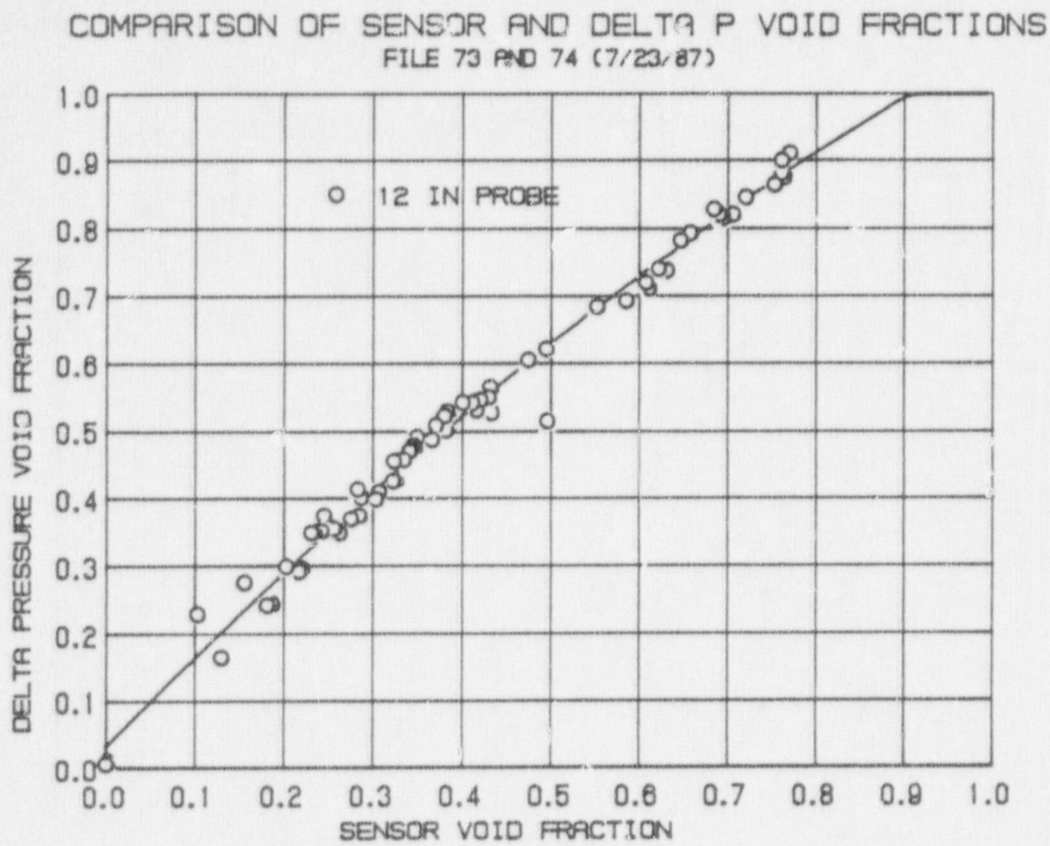


FIGURE 5.1 Comparison of Correlation Between Sensor-Indicated Void Fraction and Void Fraction Measured with the DP Cell-Style Probes. Correlations cover the temperature range of 220°F (377K) to 570° (572K).



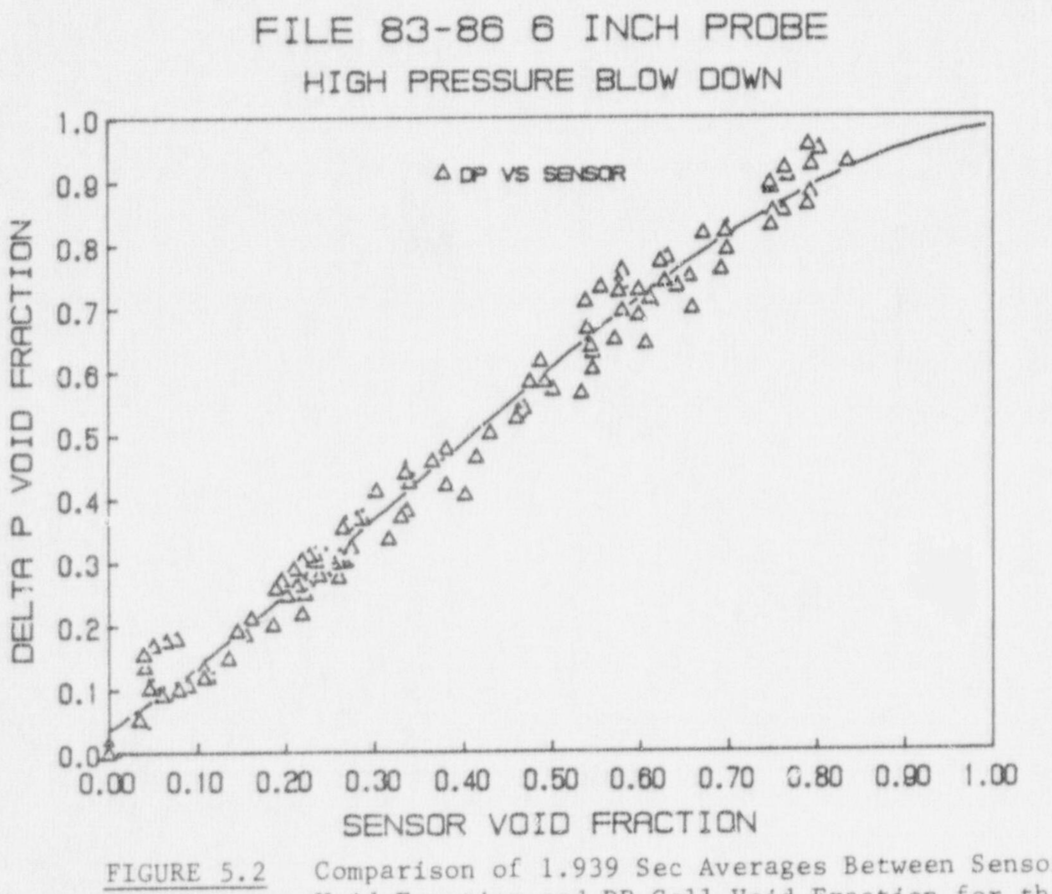
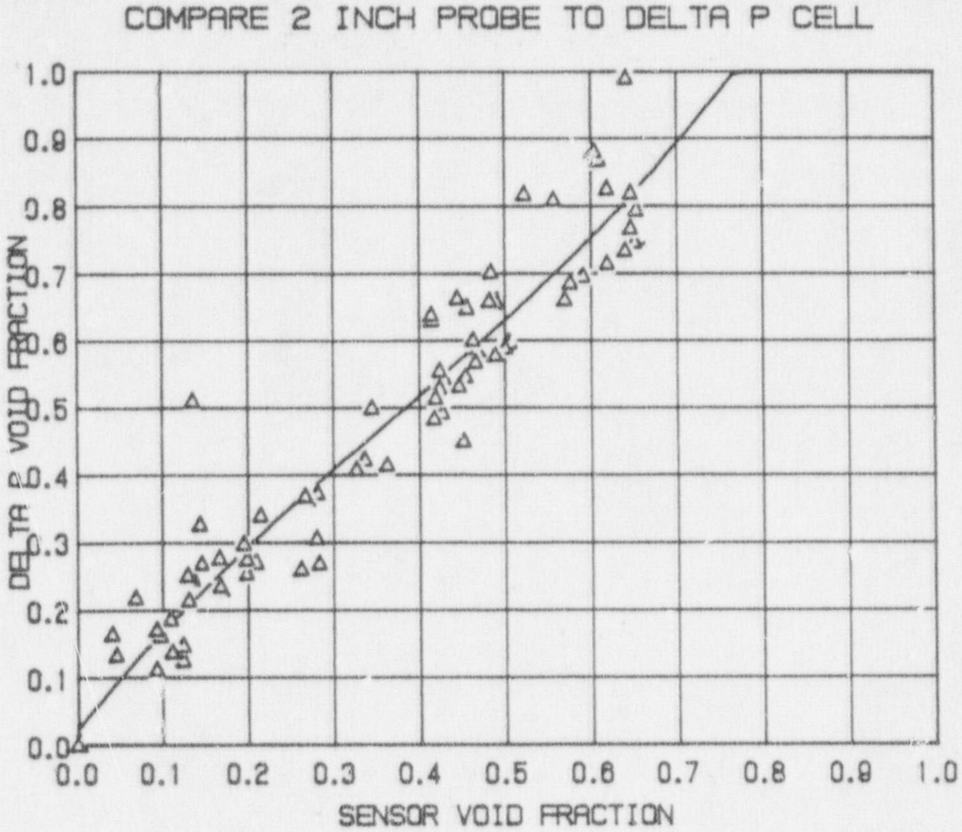


FIGURE 5.2 Comparison of 1.939 Sec Averages Between Sensor Void Fraction and DP Cell Void Fraction for the 12 in and 6 in Probes.



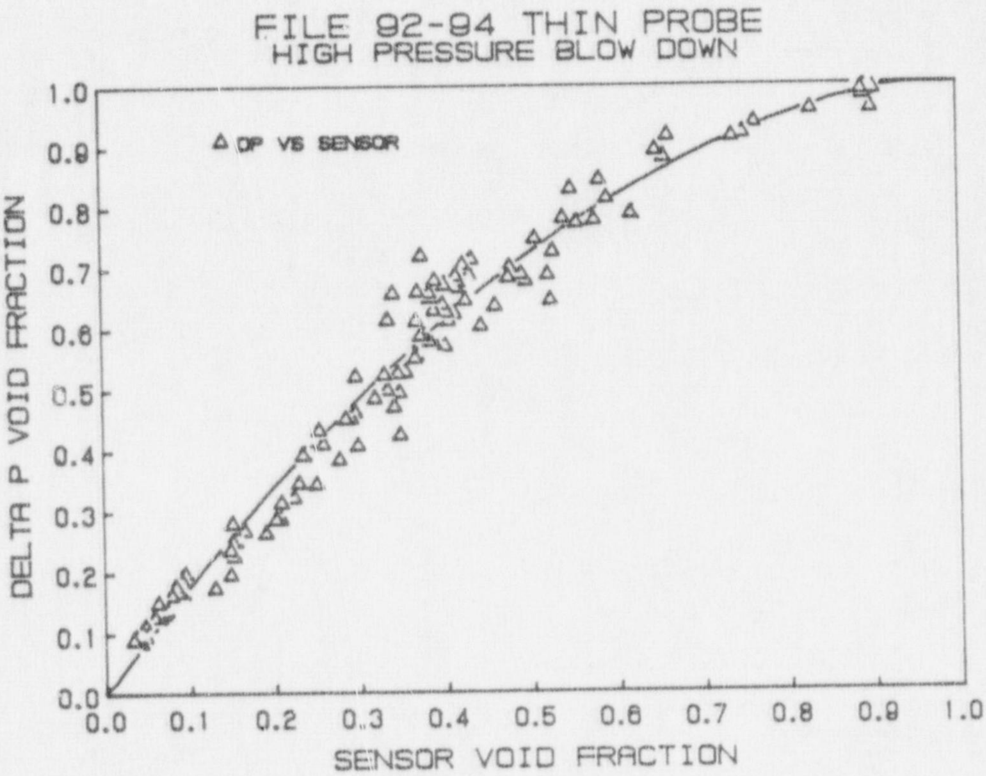
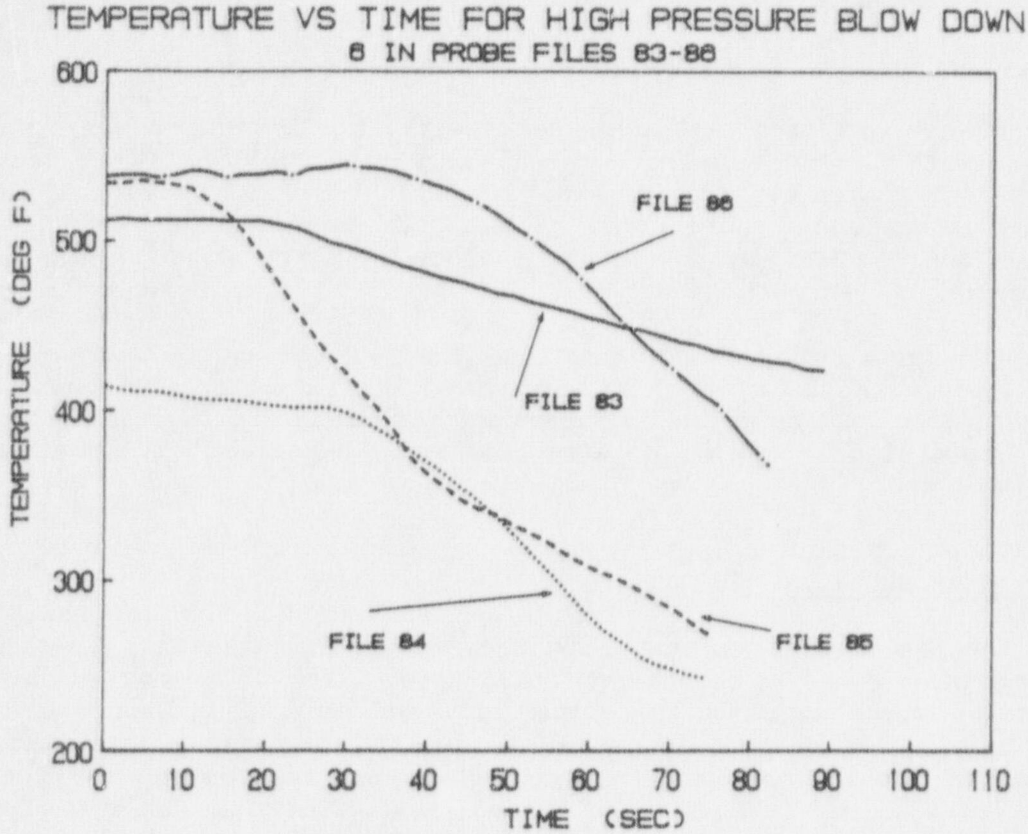


FIGURE 5.3 Comparison of 1.939 Sec Averages Between Sensor Void Fraction and DP Cell Void Fraction for the 12 in and Thin Probes.



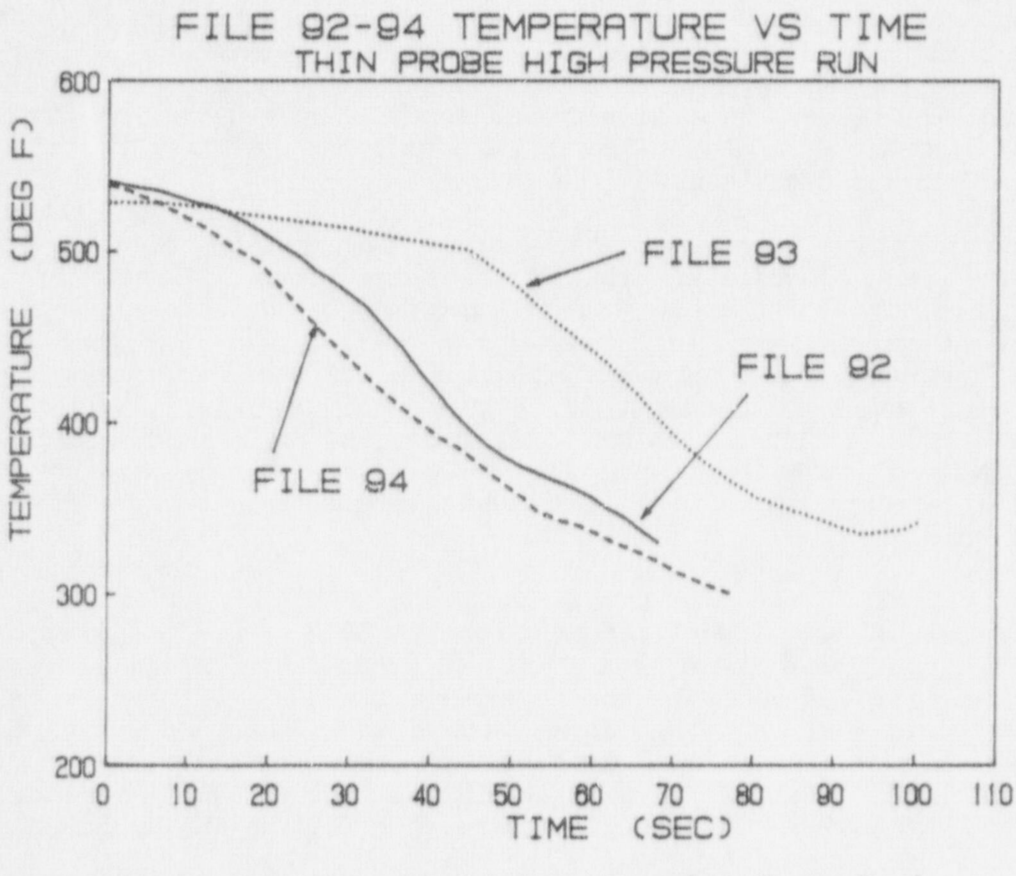


FIGURE 5.4 Temperature Histories from Tests Used to Develop Correlations for Probes 5 and 10 (6 in and Thin Probe).

Similar sets of data were also taken with the low pressure system. For these tests the temperature was held very near constant for the majority of the time. Temperatures of 240 °F ± 5° (388K ± 2.7) were routinely held for extended periods of time with near steady state boiling conditions. Similar data were developed as that shown in the previous figures.

Over the course of the development program several hundred tests have been performed with these two test systems. This experience base has helped develop the procedures and experimental techniques to be able to reproduce test conditions and to obtain desired void fractions or turbulence ranges.

5.3 TURBULENCE EFFECTS

The testing conditions that have been created in the test chambers have had a wide range of turbulent conditions. The frequency of the local pressure pulse variation are quite large and range from less than 1 Hz up to 15 Hz. The DP cell is unable to respond to pressure variations that occur at the higher frequencies. The Sensor system can easily respond and provides an indication of local void fraction changes that are impossible to detect with the normal DP cell with taps through the wall.

An example of the frequency capability of the Sensor as compared with the DP cell is shown in Figure 5.5. These data are taken from File 13 which happens to be taken with the THIN Probe No. 10 in the low pressure chamber. It can be seen from this figure how the DP cell is unable to respond; and there is a significant difference between the local void fraction measured with the Sensor, as compared with the DP cell reading over a 7 in (17.8 cm) zone.

Because of the difference in the way the two systems operate, the time averages of the Sensor and the DP cells are often different by several percent. This difference is as computed by the correlation between indicated and measured void fractions. The plots in Figure 5.5 show these differences and helps to explain some of the differences that can be seen in the raw data shown in Figures 5.2 and 5.3. Figures 5.2 and 5.3 show the combined data set that contains block average data from a wide range of turbulence conditions. There as been no attempt in these figures to compensate for shift in the correlation as a function of local turbulence.

In general, as the Power Spectral Density (PSD) in the frequency range of 0 to 7 Hz increases there is a shift or an increase in the average value void fraction indicated by the Sensor as compared with the DP cell. If the base correlation is developed with a wide range of turbulence than there would be shift both positive and negative about the fundamental correlation. This can be seen in Figures 5.2 and 5.3 where there are points above and below the least squares correlation to the data.

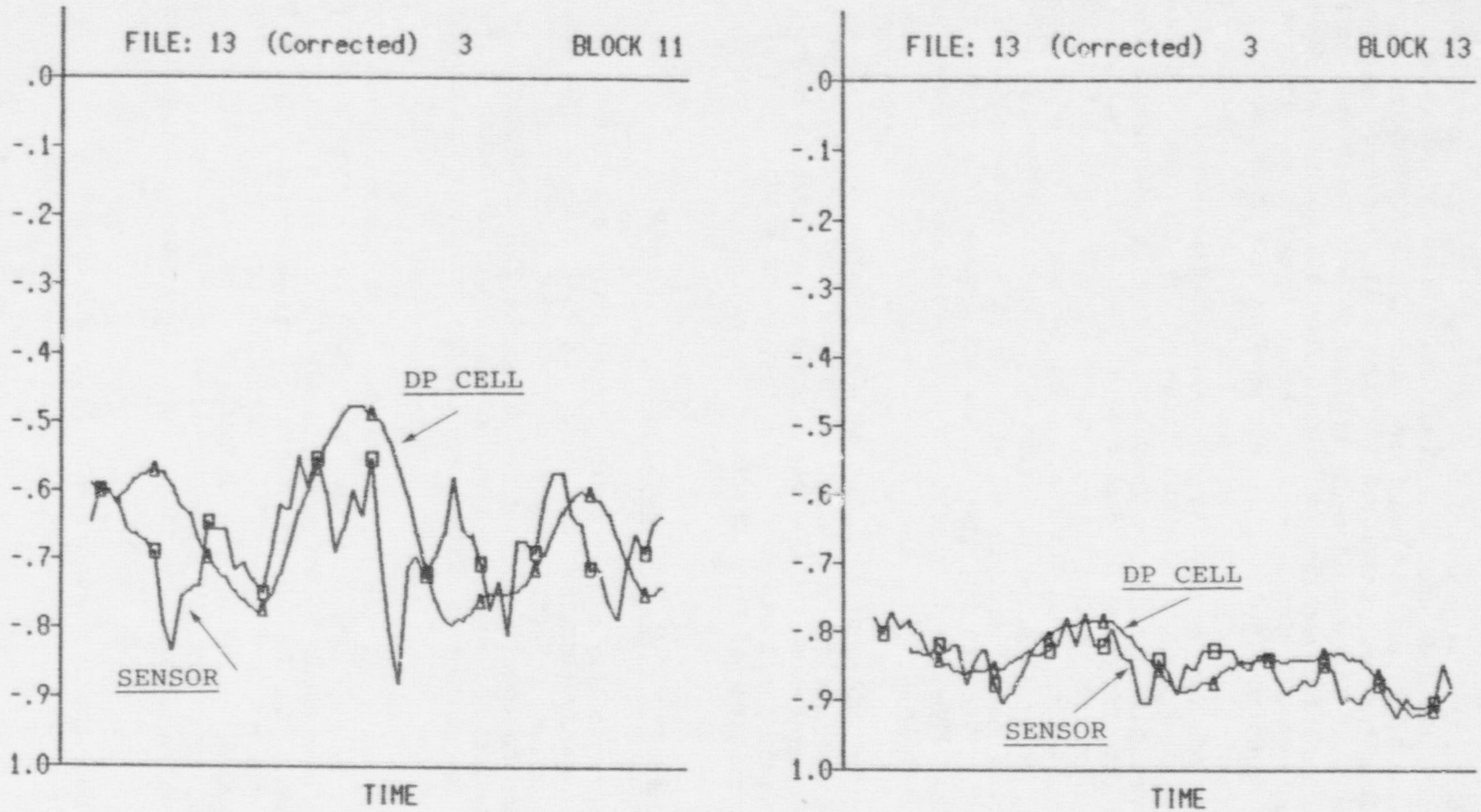


FIGURE 5.5 Comparison of the Sensor and DP Cell Under Turbulent and Quiet Two-Phase Conditions. Plot shows void fractions for 1.939 sec of data or 64 point block for the Thin Probe (No. 10) in the low pressure chamber at 240°F (388K).

The data from these test were sorted in relationship to the Power Spectral Density Content of the indicated void fraction. A relationship was then developed using this distribution to identify a compensation for frequency. This has been developed for the THIN Probe No. 10 and is shown in Figure 5.6. This relationship applies to void fractions over the range of .3 to .6 and covers the turbulence from static bubbles to very violent boiling. Additional data is needed beyond these regions to define another relationship for larger and smaller void fractions.

The application of this concept to the measured data is shown for the THIN-1 equation in Figure 5.7. The limits of the PSD based-correlation shown in Figure 5.6 are plotted here to show the adjustment to the predicted void fraction using the Sensor data. Using this adjustment, the void fraction measured by the DP cell can be predicted to within ±0.02 when compared on a time average basis. A comparison of the equation and the adjustment factor is shown in Figure 5.8. In this figure the Sensor data from tests 14 and 15 are plotted with the THIN-1 correlation and the PSD adjustment. The low PSD line bounds the Sensor data with low PSD values. The high PSD line is within the ±0.02 range for the Sensor data with a high PSD value.

This procedure is implemented in the display programs on the Host CPU. The PSD correction factors are computed by the Host computer for a 64 point block of Sensor data and are then applied to the next 64 point block of data to correct for turbulence. The comparison shown in Figure 5.8 shows only the extremes of the correlation.

5.4 COMPARISONS WITH TRANSIENT CONDITIONS

The predictive capability of the Sensor system has been shown to be able to follow the rapidly changing local void condition found during blowdown of the test chamber. Further improvement in the prediction of the DP Cell void fraction can be obtained by using the PSD adjustment to the Sensor correlation. The adjustment has the biggest effect where the turbulence of the coolant is quite large and the void fractions are in the range of 0.3 to 0.6.

Experimental results for the THIN Probe No. 10 are presented in Figures 5.9 and Figure 5.10. The data that are shown here were taken in the high pressure test chamber and are typical of the type of response that can be obtained. The No. 10 Probe (THIN) has a measurement length of approximately three (3) inches (7.62 cm). The pressure taps for the DP Cell were located fourteen (14) inches (35.56 cm) apart centered above and below the zone where the probe was located. This means that large changes in local void fractions could exist before the DP Cell could sense any changes.

Figure 5.9 shows the averages of each block which has 64 data points. Both the DP Cell and the Sensor data are plotted here. Figure 5.10

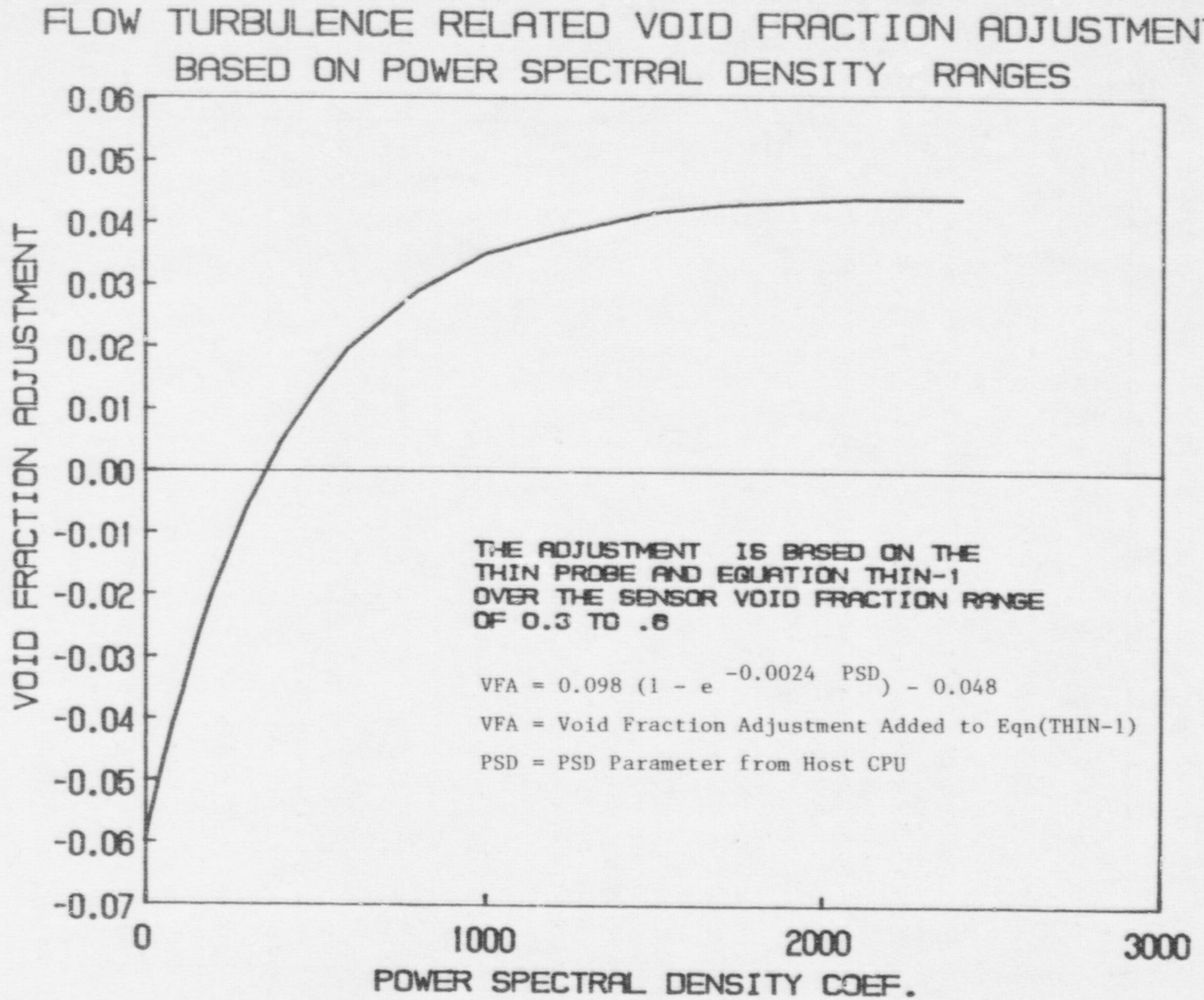


FIGURE 5.6 Void Fraction Adjustment for PSD Coefficients Based on Measured Sensor Void Fractions. This adjustment is added to calculated void fraction to adjust for PSD.

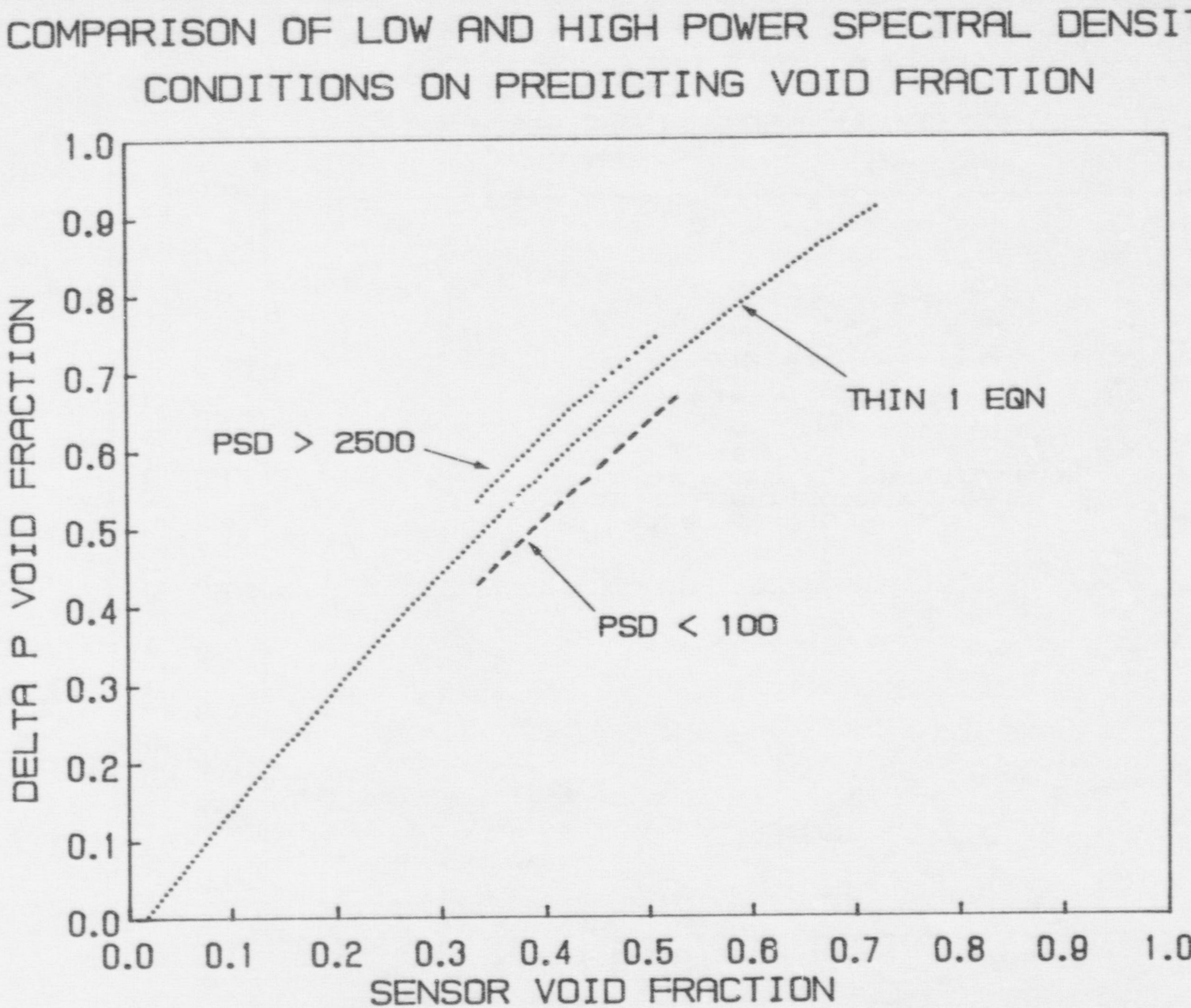


FIGURE 5.7 The THIN-1 Correlation with the PSD Coefficient-Based Adjustment Used to Account for Different Two-Phase Flow Turbulence Conditions Around the Sensor Probe.

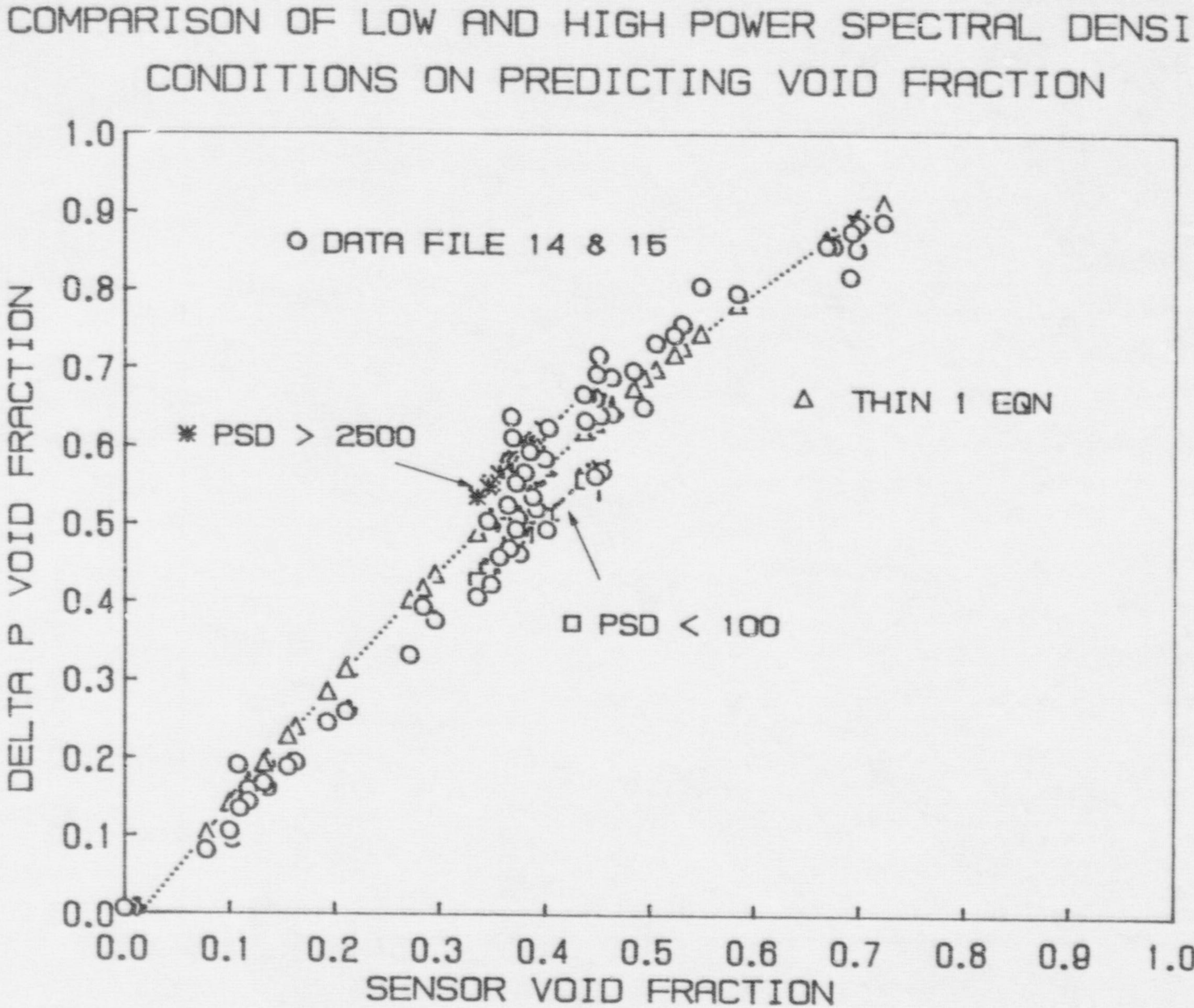


FIGURE 5.8 Data From Tests 14 and 15 Showing Adjustment Factors for PSD Coefficients. Using the adjustment reduces variance between DP and Sensor to ±0.02.

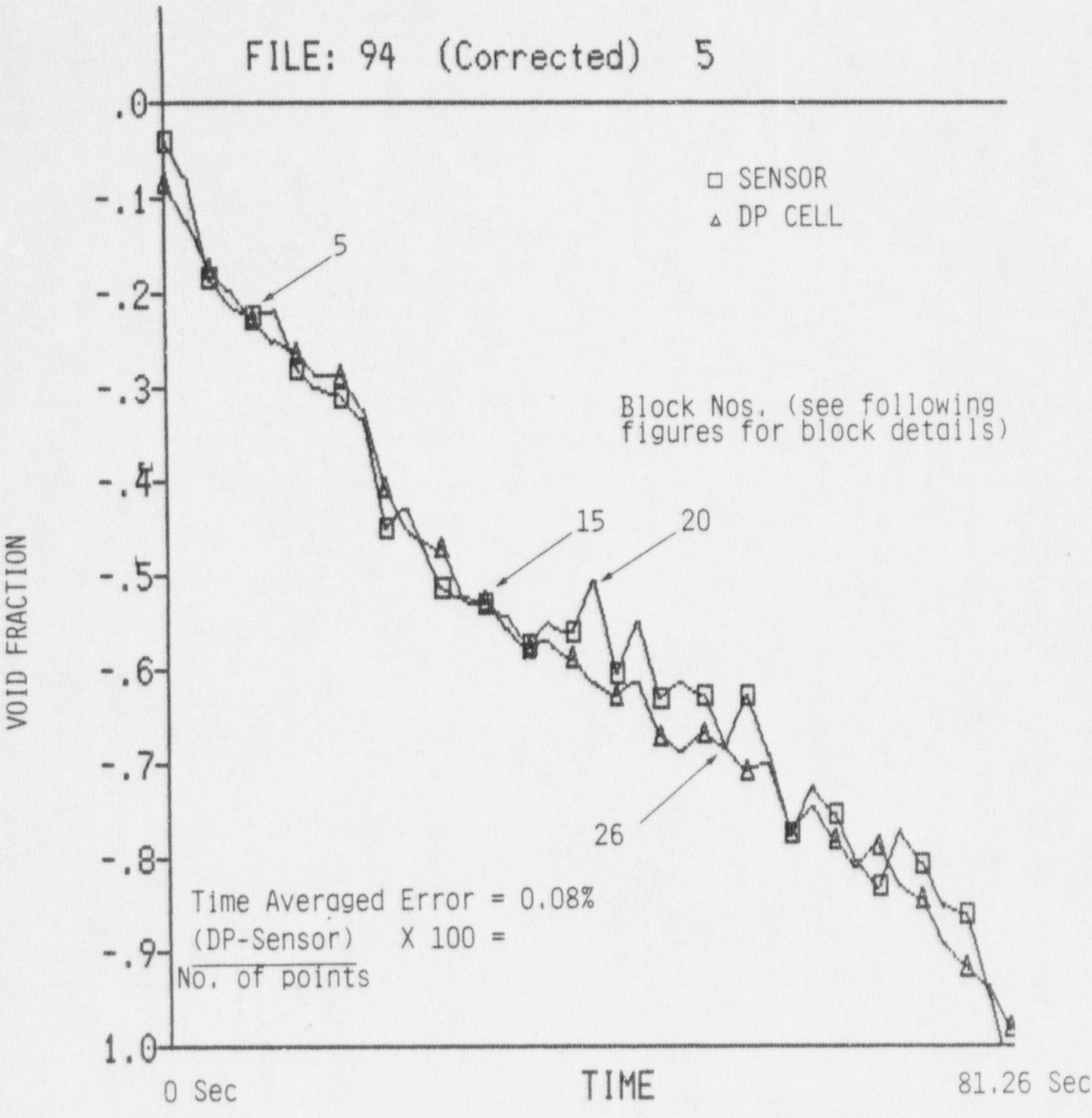


FIGURE 5.9 Void Fractions Measured in the High Pressure Chamber with Probe No. 10 (File No. 94). The time averaged error was 0.08%.

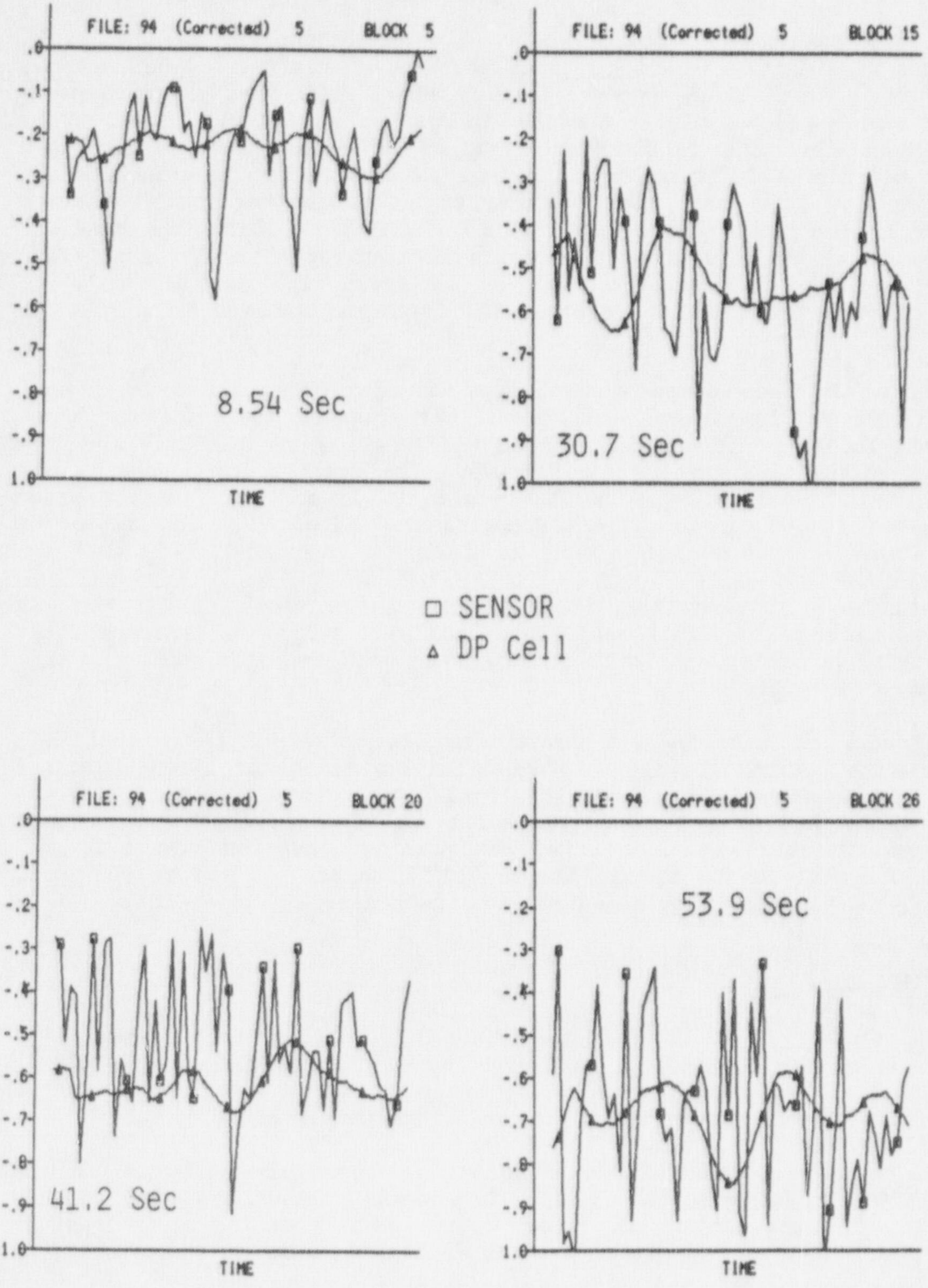


FIGURE 5.10 Block Details for Blocks 5 Through 26 Showing the Sensor and DP Cell Data for the Blocks Identified in Figure 5.9. Each block has 64 points and is 1.939 sec long.

shows the actual data for each block. The time shown for each block is the start time for the block. Each of the blocks represent 1.939 seconds of testing. The DP Cell response is very slow, while the Sensor response is much faster and can easily see the boiling and slugging. The DP Cell will often miss the rapid dynamic swings in local pressure and take several seconds to fully recover. An example of this is shown in Block 20 in Figure 5.10. In this block, a lower void fraction segment of water is surrounding the probe and boiling rapidly while the DP Cell taps have not seen the change in pressure. This looks like an error on the part of the Sensor in Figure 5.9 but, in reality, it shows that the DP Cell is suffering from the sluggish response and is averaging over a much larger zone.

Two sets of data are compared for Probe No. 6 which is the 6 in. Probe. Files 95 and 96 have been selected and the pressure histories for these tests are shown in Figure 5.11. Figure 5.12 to Figure 5.14 show the void fraction versus time history for File 95. The details for Blocks 26 and 27, shown in Figure 5.14, show that a slug of lower void fraction water was blown past the sensor without changing the indicated void fraction by the DP Cell.

The transient blowdown results for File 96 are shown in Figure 5.15 through Figure 5.17. This test shows similar results and indicates that the Sensor system is capable is tracking the void fraction changes over a wide range of conditions.

The correlations used in the predictions were based on other test data and show the comparison with the DP Cell show the predictive capability where only the Sensor was used. The local detail that is picked up by the Sensor shows that it is reading the local void fraction. This has been confirmed by visual examination of the boiling conditions while looking through the observation ports. The DP Cell does not see any of the local changes that can easily be detected with the Sensor.

5.5 WATER CHEMISTRY

The potential application of this concept in reactor primary systems will involve using the Sensor in a range of ion concentrations and pH values. The effect of water chemistry on Sensor performance was evaluated in a series of tests where a range of pH conditions were present.

Typical reactor systems will operate with a range of pH conditions and with different ion concentrations. In general the coolant will contain boric acid and some amount of lithium hydroxide. Depending on the reactor vendor, the boron concentration can run as high as 6600 ppm and the pH, as measured at room temperature, could be 10 or more.

To evaluate this effect, solutions were mixed with boric acid ranging from a pH of 7 down to a pH of 3. Solutions of lithium hydroxide were also prepared with pH values up to 10. These solutions were then tested with

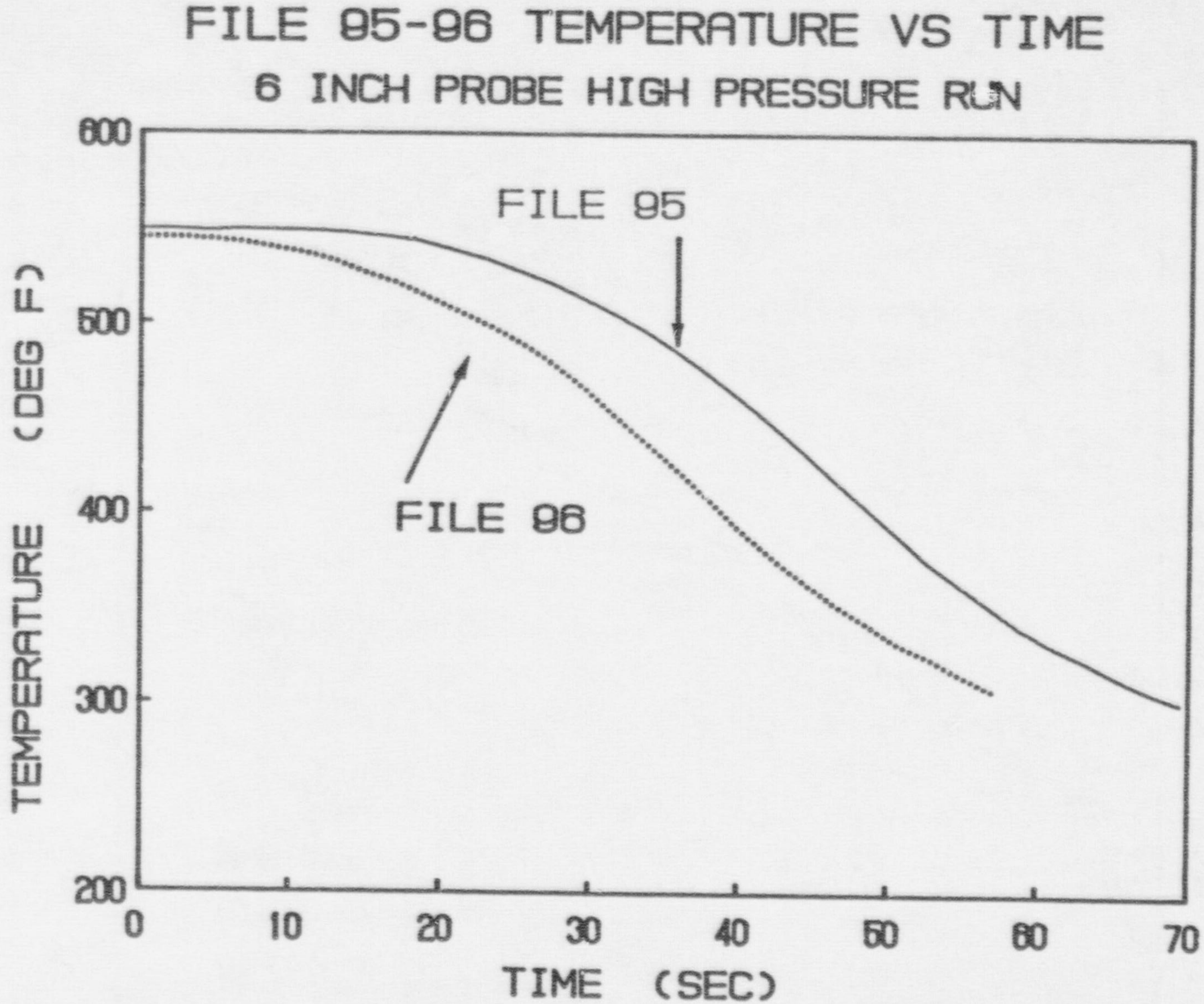


FIGURE 5.11 Temperature Versus Time History for Files 95 and 96 Using the 6 Inch Probe (Probe No. 6) in the High Pressure Chamber. System pressures are at saturated conditions.

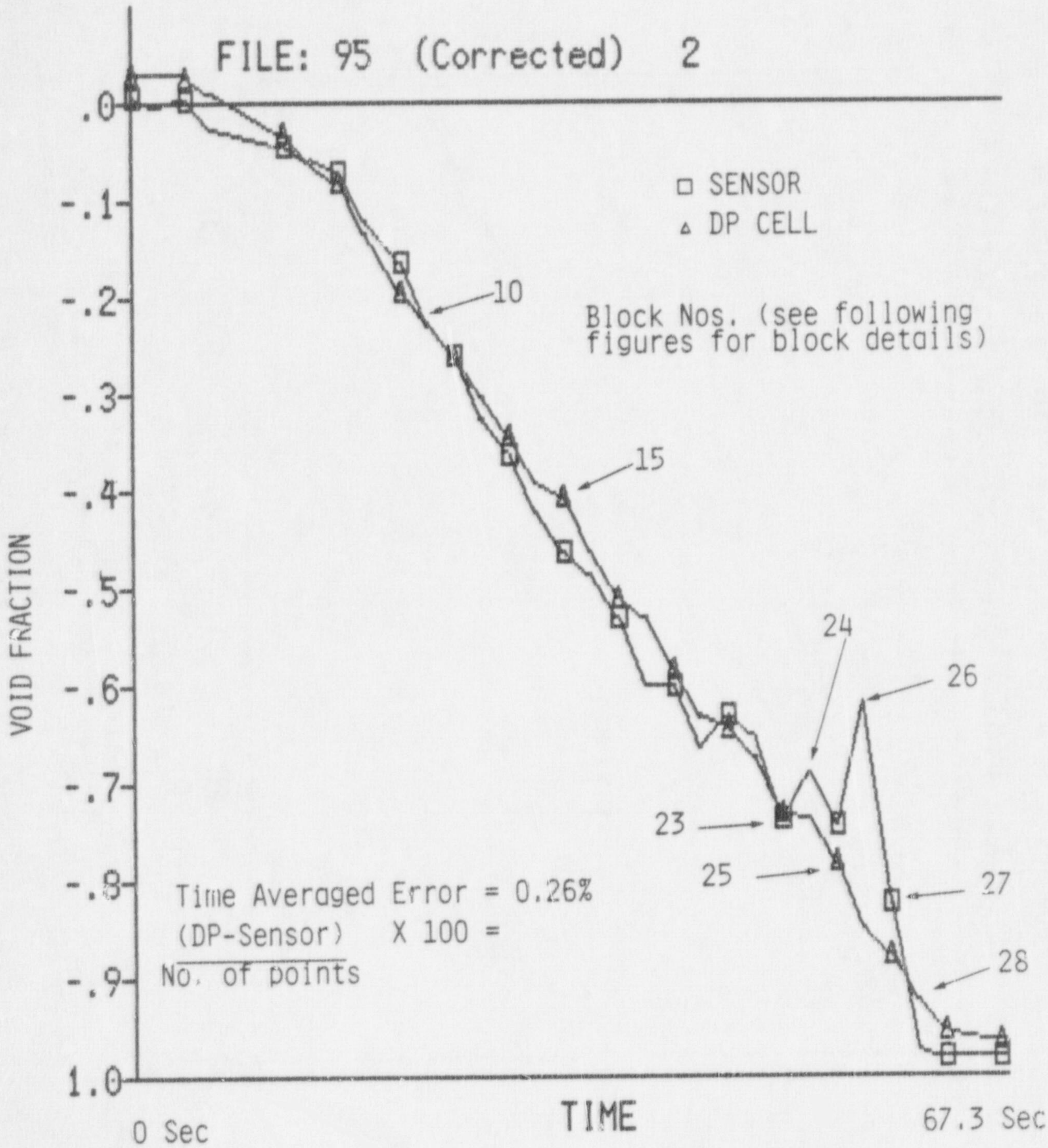


FIGURE 5.12 Block Averaged Void Fraction Versus Time for the DP Cell and the Sensor for File 95. This used Probe No. 6 (6 inch) in the high pressure chamber.

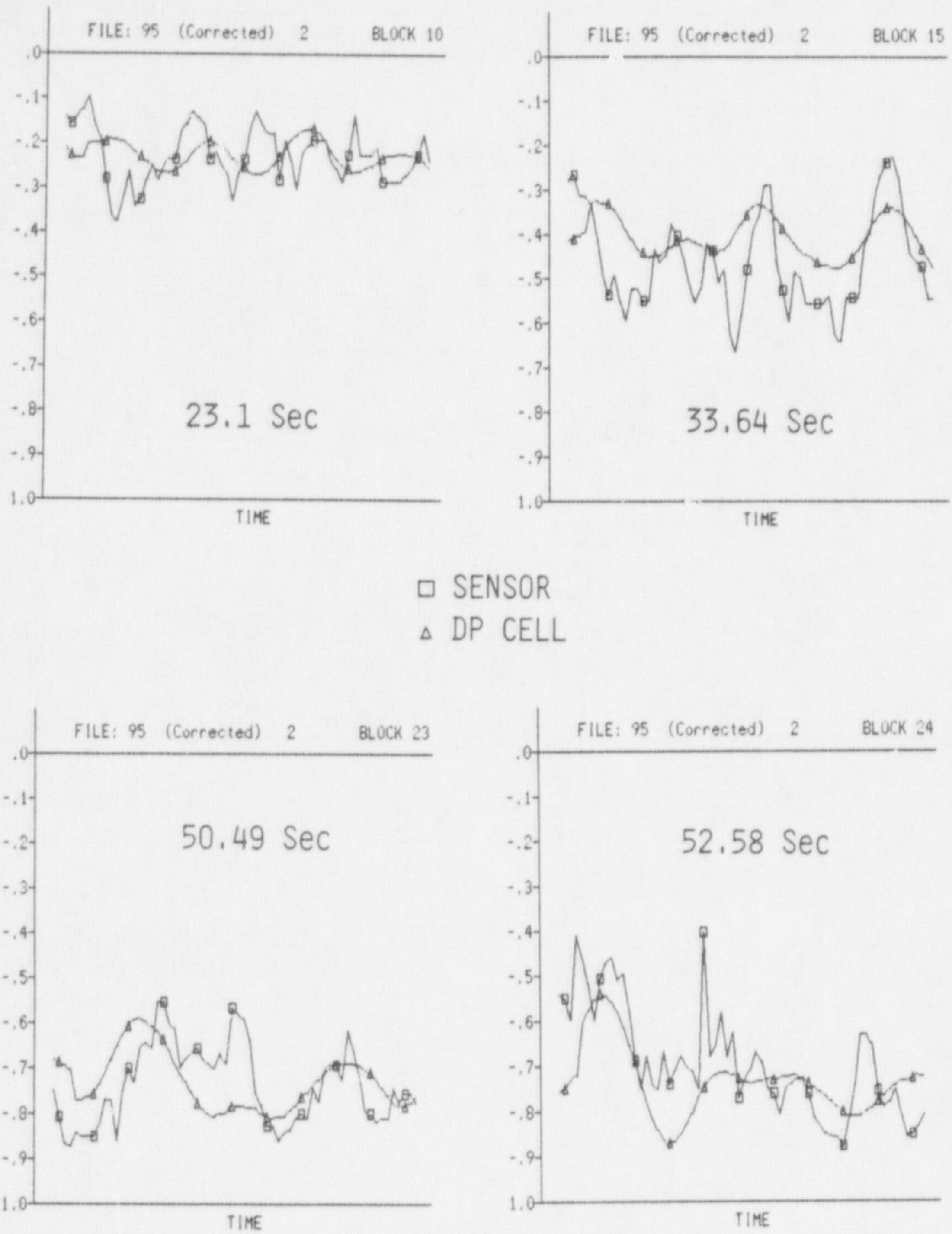


FIGURE 5.13 Block Data for the DP Cell and Sensor Covering Blocks 10, 15, 23, and 24 for File 95. Each block has 64 points and covers 1.939 sec.

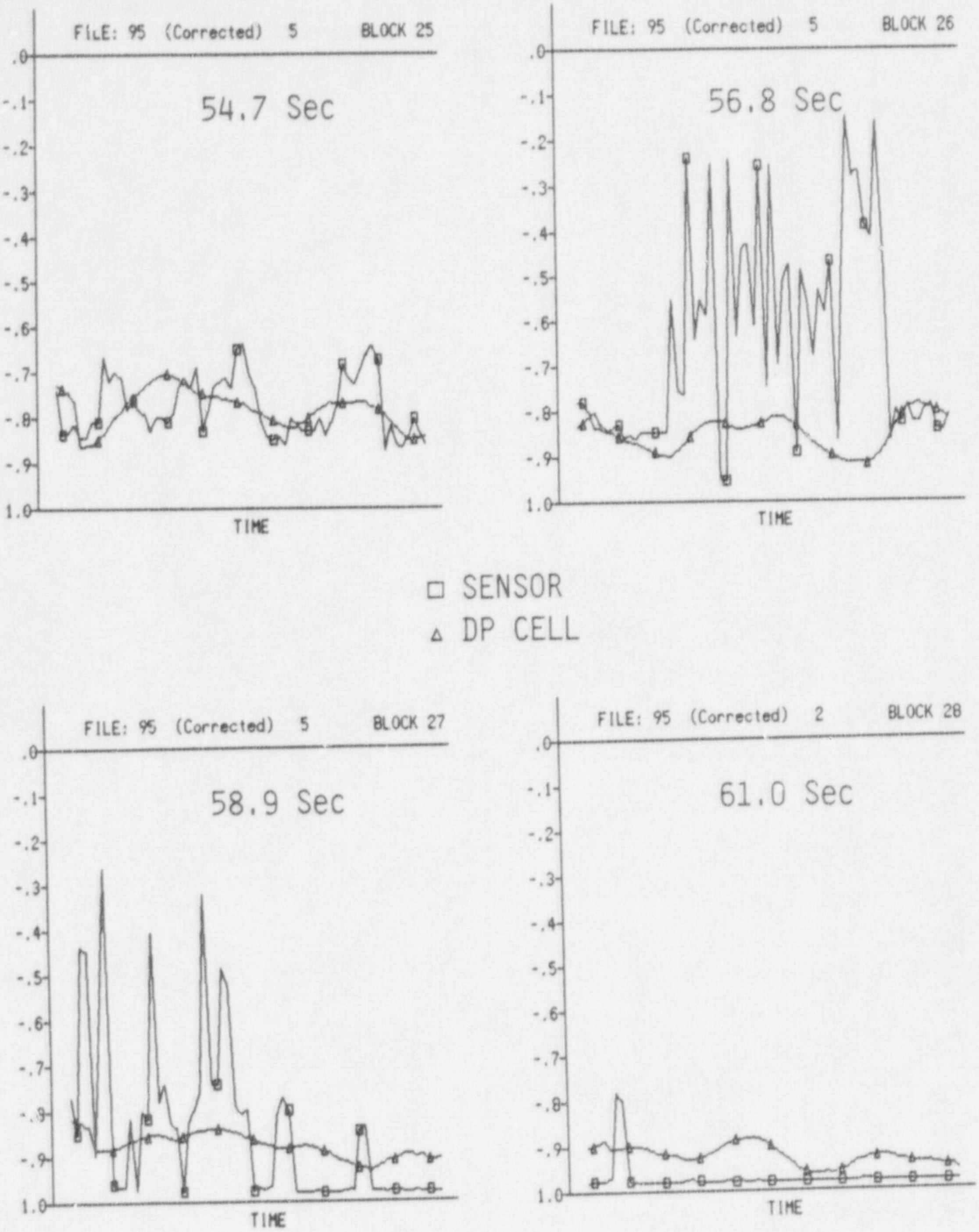


FIGURE 5.14 Block Averaged Details for the DP Cell and Sensor Covering Blocks 25, 26, 27, and 28.

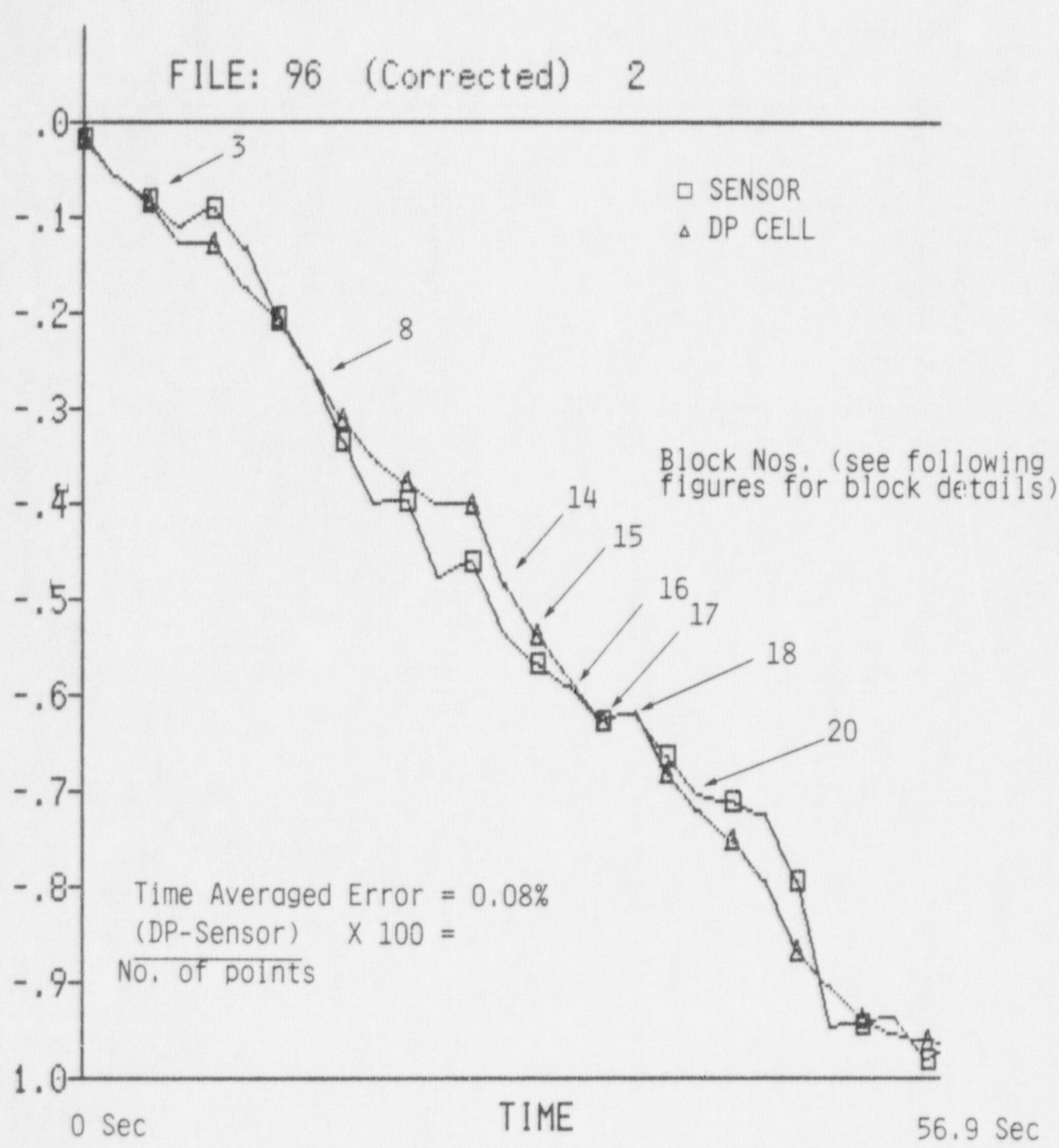


FIGURE 5.15 Sensor and DP Cell Block Averages of Void Fraction Versus Time for File 96. Probe No. 6 (6 inch) was used in the high pressure chamber.

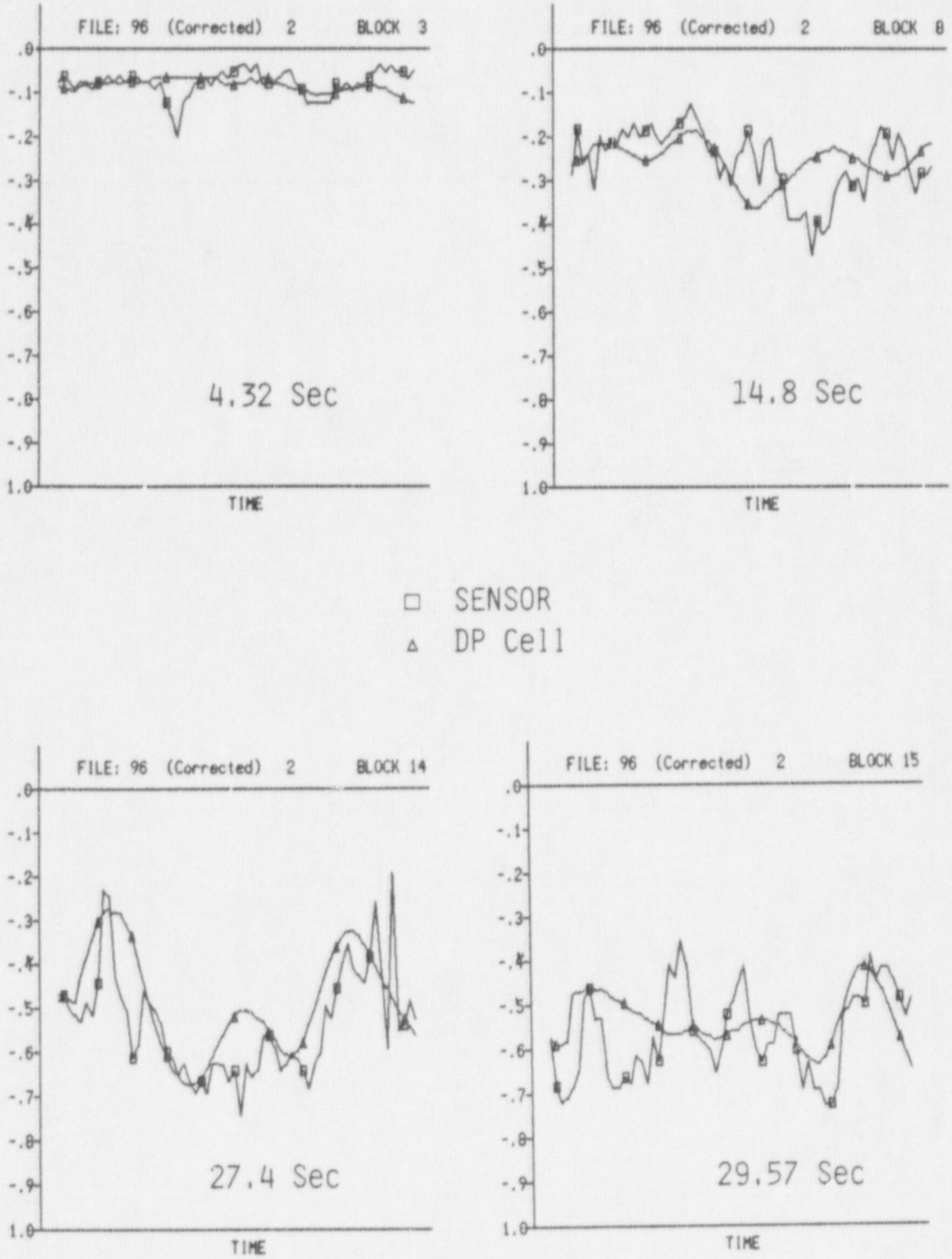
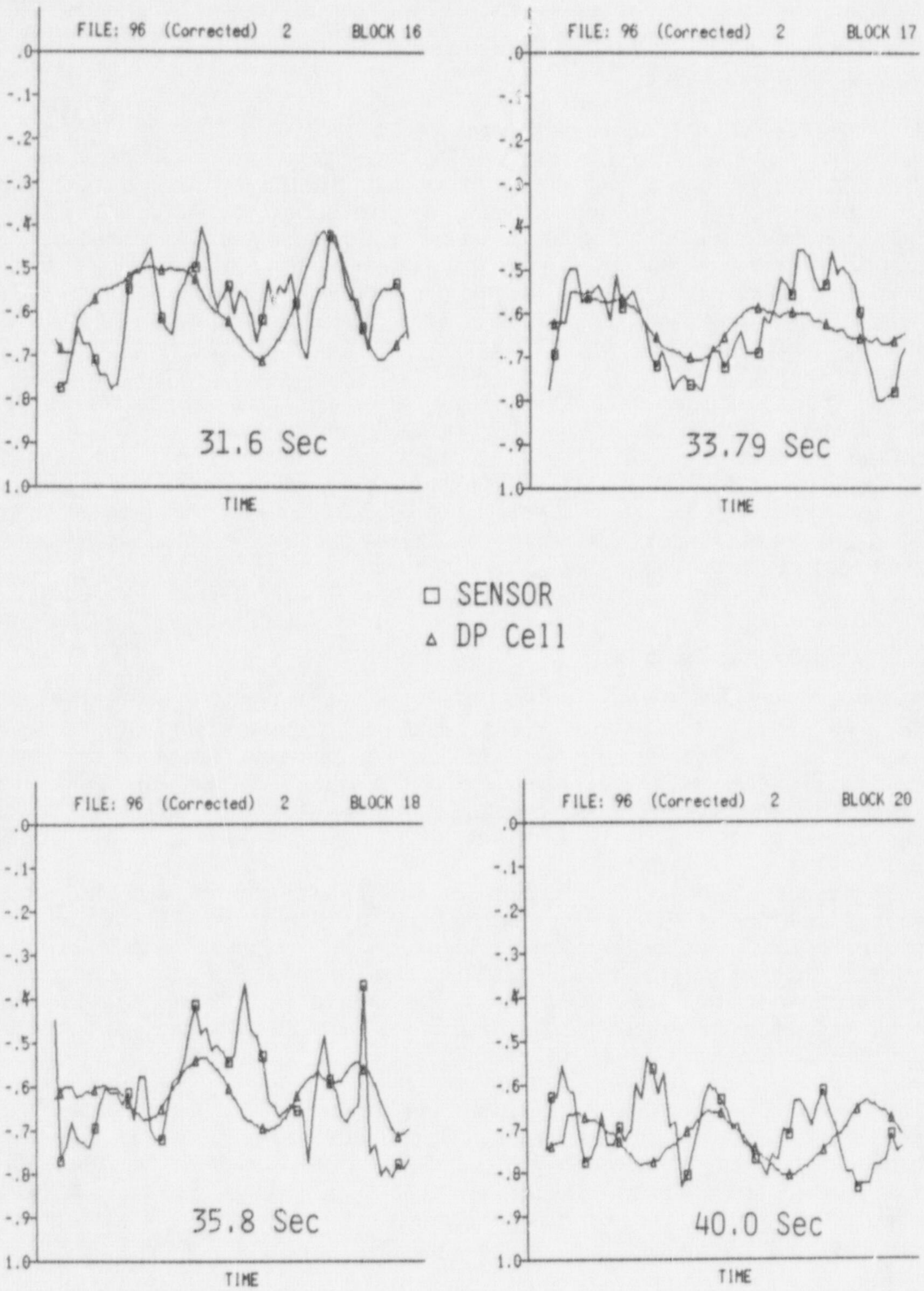


FIGURE 5.16 Block Averages for File 96 Showing Sensor and DP Cell Data for Blocks 3, 8, 14, and 15.



<u>FIGURE 5.17</u> Block Averages for File 96 Showing Sensor and DP Cell Data for Blocks 16, 17, 18, and 20.

the Sensor and probe to determine what effect the change in water chemistry would have.

The results showed that the boric acid had very little effect on the measured response from the probe. The wave form was sharp and the The effects of the high pH solutions of lithium hydroxide were somewhat more restrictive. The conductivity of the solutions of lithium hydroxide tend to attenuate the signal somewhat more than the deionized water that has been used in the development. As a result, the length of the probe that can be used will have to be decreased. Probes of 12 in (30.5 cm) were found to be too long. Probes of several inches in length work without any problem.

These observations and tests were made at room temperature. As the temperature of the solutions are raised the pH tends to drop. It is estimated that a pH of 10 will be very near neutral at reactor operating conditions of 500 °F (533K) or higher. This may have an effect; however, it appears that the ion concentration of lithium has the largest effect. The results show that the probe configuration can be modified to produce a good signal if the probe length is reduced.

5.6 DISCUSSION OF RESULTS

The Sensor System that has been developed has demonstrated the capability to measure the local void fraction under high pressure and temperature conditions. The results also indicate that the effects of rapid changes in density can be compensated for by looking at the PSD of the sensor signal. Adjustment can be developed and applied in real time to correct the signal.

The present stage of development of the Sensor driver and the associated probes provide a basis for evaluating different applications for the instrumentation concept. The electronics and software have been developed to the point that provide reliable data acquisition and data analysis. The amount of data that must be processed is very large and the software that has been developed has a great deal of flexibility that will allow further development as it is needed.

The transient test data comparison is probably the best measure of the capability of both the hardware and the software. One of the transient blowdowns, from 1100 psia to 1250 psia (7.6 to 8.6 MPa) down to atmospheric conditions, covers a significant range in thermodynamic and electrical properties of the coolant. The specific volume ratio, for example, for steam/water at 1 atm is 1620, while the same ratio at 567 °F (570K) is 16.2.

The changes in the relevant electrical properties such as the permittivity have been shown in Section 2. The ratio of permittivity for water to steam at 212 °F (373K) is 52 while this ratio at 560 °F (566K) is 16. There is also a change in conductivity and other parameters which affect the terms used to calculate the void fraction.

The transient test conditions have these changes inherent in the experiment so that the performance of the test combines all of the non-linear relationships and tests them as a composite. The results that have been shown indicate that the time averaged error is very near zero. (The time averaged error is the average of the difference between the predicted void fraction using the Sensor system with the correlation equation for that probe and the void fraction measured with the DP Cell.) The instantaneous value can often show differences of 20% to 50% as indicated by the data plots, due to the poor response of the DP Cell. However, the long term averages between the Sensor and the DP Cell measurements tend to show much excellent better agreement.

6.0 APPLICATION TO COMMERCIAL REACTORS

The CIMS system can be directly applied to all of the existing commercial LWR plants. A significant improvement in safety will be gained even though a retrofit into older plants will limit some of the capabilities of the instrument that could be gained in a new installation. An installation in any plant, either old or new, will significantly increase the understanding of information about the inventory of the coolant in all areas of the plant in an off-normal event.

A typical installation is shown in Figure 6.1. In this case several strings of probes are shown in the primary vessel. Additional probes could be located in the pressurizer, the piping systems and possibly in the heat exchanger.

The installation of the CIMS was investigated for both the PWR and BWR plants. In both cases the installation was possible without any more effort being required than replacing the current instrumentation to the primary vessel. For the current electronics, there is a restriction on the length of line from the probe to the analog portion of the Sensor Driver card. This unit should be located within 150 ft (45.7 m) of the probe to maintain performance. (This is using the current system.) Modifications to the Sensor Driver card could change this restriction if needed.

6.1 BWR APPLICATIONS

The BWR uses a series of DP Cells to detect the level of coolant in the primary vessel and to determine the swell zone in at least six (6) locations. The void fraction in the BWR at the core outlet is in the range of 0.7 to 0.86 for the coolant through the main flow ducts. The by-pass flow is designed to have a void fraction of 0.0 that mixes with the other coolant.

At the present time there is no means of measuring the void fraction in the outlet region of the core. There has never been any confirmation that the design conditions are being met or that the margin could be reduced from the safety analysis.

Discussions with General Electric identified the possibility of installing the system through the vibration connector site. This site is available and is currently unused on the GE BWR plants. It is also feasible to install the system into the upper head assembly and to augment the measurements currently taken by the DP cells.

One possible application for more advanced plants would be to locate each of these probes over the outlet of each fuel assembly or group of fuel assemblies to provide a direct reading of void fraction.

BWR operators currently control void fraction as an operating variable by the indicated local core power as measured with fission chambers. This is a correlation based on calculation. At the present they do not have a direct measure of local void fraction.

The current ranges or distances between the pressure taps are quite large and usually span several feet of head in the vessel. These DP cells are subject to the normal problems of a DP system and can give bad signals. In situ calibration and bleeding of pressure lines is also a problem.

One major advantage of the CIMS system is that it is self calibrating once the initial characterization has been established. The host computer can perform this evaluation whenever a known void fraction can be established in the core.

Additional sites where the CIMS could be located include the heat exchanger and selected parts of the primary piping system. In this case the probe would provide information under accident conditions and, in some cases, also provide information concerning possible water hammer conditions that might be avoided.

6.2 PWR APPLICATIONS

For the PWR, the CIMS is believed to meet the intent of NRC and establishes a new technique for measuring how much water is above the core in an off-normal event. Neither of the two types of instruments currently being sold can directly measure this or meet this criteria for a broad range of accidents.

The HJT system as discussed in Section 1 can be deceived by two-phase coolant conditions that will not provide unique boundary conditions needed to define the coolant conditions. The heat removal capability of the two-phase coolant with a large swell zone is just as good as solid water. The HJT cannot identify or protect against coolant swell conditions that could leave the core uncovered if a small change in pressure occurred causing the swell zone to collapse.

The DP Cell system also has limitations, as pointed out in Section 1. One problem is associated with the velocity head effects that can significantly compromise the estimated delta pressure head reading. The DP Cell system is also subject to line bleeding problems which can cause unbalances. This is especially true with DP cells measuring over small heads. Zero shift in the DP Cell output with increasing system pressure is a classic problem that makes it difficult to measure small changes in differential pressure. This is even more of a problem when the system undergoes large swings in pressure. Any type of off-normal event will usually be accompanied with a large swing in system pressure. The CIMS probe and driver is insensitive to any of these limitations and provides an instrument with much more capability that can easily be calibrated and checked in place in the reactor vessel.

The CIMS can be used as a direct substitute for the HJT installations. In this case the HJT's are placed on a single support rod and suspended in the upper head and plenum area. The CIMS probe would fit in this exact location. Similar installation procedures can be used for plants currently using the Westinghouse DP Cell systems.

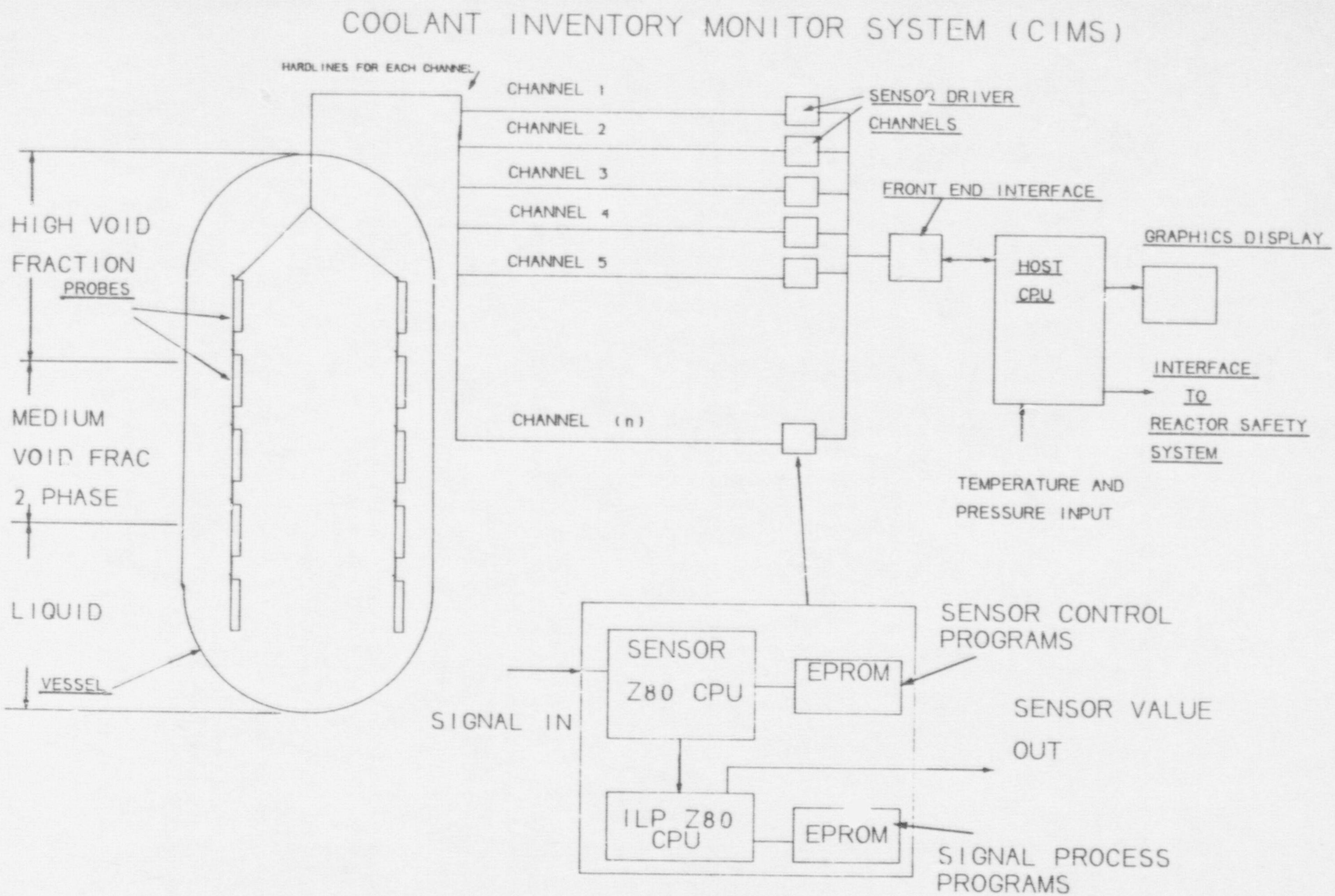


FIGURE 6.1 Coolant Inventory Monitor System Showing Reactor Pressure Vessel, Probe, Instrument, and Control Display with an Interface to the Reactor Safety System.

7.0 SUMMARY AND CONCLUSIONS

7.1 SUMMARY

The results of this experimental program have demonstrated the capability to measure the liquid level and the coolant inventory by measuring the local void fraction. This provides the capability to determine the coolant inventory and the distribution of the coolant in the primary containment system of reactor. The CIMS system is believed to meet the criteria established by NRC for liquid level detection in nuclear plants and is the first to directly measure the local void fraction.

Both transient and near steady-state conditions have been examined with this instrument and have shown that it has the capability to measure the local void fraction of the coolant. The primary correlations have been developed by comparing the measurements of the instrument with the measurements of a DP Cell located over the same region covered by t' Sensor probe. The time averaged error of this type of test has provided indicated agreement of better than 0.2%. Typical absolute deviation between measured and predicted for averages of several seconds is usually in the range ± 0.02 to 0.05 void fraction units.

A mechanical design for the probe has been developed that makes it possible to construct very small probes, as small as 0.015 in (0.038 cm) thick and as short as 1.0 in (2.54 cm) long. A reliable metal to ceramic transition piece for the probe has been fabricated and tested through many transient tests and shown to function without problems. (This same type seal has been used in the Severe Fuel Damage Program in tests in the NRU Reactor over the last 7 years.)

A reliable Sensor Driver system has been developed which is used to acquire the analog data and to preprocess the digitized signal. Two CPU's on each driver channel operate in unison with each other. One of the CPU's controls the data acquisition process and the other is used as a co-processor to evaluate the data. This gives a tremendous computational capability and flexibility in signal processing.

A software package has been developed around the HP 9000/320 host computer that will allow up to 15 channels to operate simultaneously. The software uses the DMA board channels and is coded in Assembler for the MC 68020 and for the Z80. The software is coded to provide maximum data transfer rates and maximum operation capability.

Graphics software has been developed that will display the individual channel void fraction real time. The displayed results are based on the correlation selected and are corrected for temperature effects and for frequency effects. Archive capability has been developed to provide data storage and replay capability.

Supporting tests that have been performed have measured the electrical properties of the coolant up to temperatures in the range of interest for normal reactor operation and have shown that instrument concept as proposed can operate up to the limits of LWR plants. The excellent agreement with data found in the literature provides assurance that the instrument should be able to operate up to the critical point for water if so desired. The data also show that the capability exists to locate interfaces of superheated steam and subcooled liquid.

Advanced designs using more sophisticated CPU's on the driver boards have been identified that will improve the computational power and improve the speed and accuracy of the signal process. Current signal processing is limited by the capability of the Z80. Future development will put the FFT analysis and more comprehensive data smoothing capability on each channel driver board.

Both the PWR and BWR reactor concepts can use this concept as a retrofit with a minimum of plant modification. The small size probes can be placed in existing holes and ports that are available in the primary vessel. The unit will act as a direct replacement for the Combustion Engineering Heat Junction Thermocouple system. It can also be placed through similar type ports available in the BWR system and can be used as a supplement or a replacement for the DP Cell system developed by Westinghouse.

The biggest potential application is for BWR's under normal operation. If these probes were located at strategic locations in the core, the DP Cells that are used to monitor the void fraction above the core could be replaced or supplemented by this instrument. The accuracy would be greatly increased and it would be possible to measure the void fraction distribution across the top of the core. This type of information is not possible to obtain with current core instrumentation but would be very easy with the CIMS system.

Probes can also be placed into the primary heat exchanger and into the pressurizer. These installations are much less critical and offer more flexibility.

Real time core thermal hydraulics computer-based simulator models have been identified. These models would use the data from the CIMS and predict core coolability under off-normal events. It would provide the operator with a real time tool that would help in the management of the accident.

7.2 CONCLUSIONS

The following conclusions can be drawn from the work that has been completed:

1. The CIMS probe and driver system can be used to measure the local void fraction.

2. The probe system provides a real time measure of void fraction that can be either displayed or stored for later analysis.

3. The components and software that have been used demonstrate the essential features of the CIMS system and demonstrate the feasibility of the concept.

4. Installation of the CIMS to both old and new nuclear power plants would greatly improve the instrumentation capability and make it possible to manage the reactor in an off-normal event with greater flexibility and with more understanding of the options available to the operator than is possible now.

5. The CIMS system provides a unique measurement of the coolant distribution in the core and can detect and quantify the two-phase coolant swell zone, as well as the steam foam interface. Neither the DP Cell system nor the HJT system can directly measure or detect these conditions.

6. The CIMS system is believed to meet or exceed the NRC requirements to be able to accurately assess the amount of water above the core under accident conditions. The other approaches cannot provide as accurate a measure.

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13. ABSTRACT (200 words or less)

The Coolant Inventory Monitor System for measuring the amount and the distribution of coolant in the primary system under accident conditions of a nuclear power plant is described in this report. This system is based on measuring the local void fraction of the coolant at selected points in the vessel and piping system and then estimating the coolant inventory. This report summarizes the development of the measurement instrument, the supporting tests and the development of the supporting software. Accuracies of ± 2% as compared with delta pressure cells can be obtained over void fractions ranging from 0 to 90%. The system can provide local measurements of void fraction and uses probes as small as 0.015 X 1.0 X 0.3 in (0.038 X 2.54 X 0.76 cm). Experimental test data are shown for temperatures up to 570°F (572K). The system can be used up to the critical point. The graphics display shows a real time display of void fraction for up to fifteen channels and gives the instantaneous as well as a running average for each channel. This instrument is believed to meet the intent of the NRC by being able to measure the amount of water above the reactor core under all types of accidents.

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