CEN-185-NP
Supplement 3-NP

HEATED JUNCTION THERMOCOUPLE

PHASE III Test Report

September 1982

POWER
SYSTEMS
Combustion Engineering, Inc.

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ABSTRACT

This report provides the documentation of the final Phase III tests for the Heated Junction Thermocouple, Reactor Vessel Level Measurement System. The system was tested under single phase and two-phase fluid conditions representative of the conditions that the Heated Junction Thermocouple probe assembly might be exposed to in a pressurized water reactor vessel. The Phase III tests concentrated on the performance of the total integrated system. These tests verified that the Heated Junction Thermocouple System is capable of measuring and displaying to the reactor operator the water inventory above the core in a reactor vessel.

TABLE OF CONTENTS

TABLE OF CONTENTS, Continued

LIST OF APPENDICES

1.0 INTRODUCTION

The Reactor Vessel Level Measurement System (RVLMS) is an instrumentation system developed by C-E to provide an indication of the approach to, and recovery from Inadequate Core Cooling (ICC). The C-E design uses Heated Junction Thermocouples (HJTC) and a microprocessor to provide this indication. This report provides a description of the Phase III testing that has been performed on the C-E HJTC-RVLMS and together with CEN-185 Supplements 1 and 2 completes the generic reporting requirements for NRC review.

1.1 HJTC-RVLMS OPERATION

The principal function of the RVLMS is to measure and display to the operator the water inventory in the reactor vessel above the fuel alignment plate. The measuring portion of the RVLMS consists of a number of HJTC sensors with individual splash shields distributed axially inside a separator tube. This constitutes a probe assembly. A sensor consists of two thermocouple junctions separated by several inches, one of which is heated by an electric coil. The purpose of the separator tube is to create a collapsed water level inside while a steam-water mixture exists outside the tube. When the collapsed water level falls below a sensor elevation, the heated junction temperature increases due to the poor cooling ability of steam compared to water. When the temperature difference (ΔT) between the heated and unheated junctions increases above a predetermined setpoint value, the sensor is identified by the microprocessor as being uncovered (i.e., surrounded by steam). This information is displayed to the operator, alerting him that primary system water inventory has been lost and that the reactor vessel is not completely full.

Once a sensor becomes uncovered, the final temperature that the heated junction reaches depends on the sensor heater power and the pressure. At low pressures, a higher heater power would result in an excessively high heated junction thermocouple temperature and possible sensor failure. A high heater power is desirable, however, to minimize the system response time. Therefore, a sensor heater power control system is used to limit the heated junction temperature and differential temperature (ΔT) below a maximum value. This is done by uniformly reducing the power applied to all sensors after the temperature of any heated junction (or ΔT of any sensor) reaches a predetermined value. This power cutback system allows the highest possible heater power to be used while still providing protection against excessively high heated thermocouple temperatures and sensor damage.

1.2 OVERALL TEST PROGRAM

C-E has developed a comprehensive test program for the HJTC system to provide design information and to verify its capability as a RVLMS. This test program has been divided into three parts. The Phase I test series, documented in CEN-185 Supplement 1, consisted of feasibility and proof-of-principle tests where the concept of using HJTCs as a water level measurement device was confirmed. Phase II tests, documented in CEN-185 Supplement 2, verified the performance of a complete HJTC probe assembly under thermal-hydraulic conditions representative of what the instrument would be expected to encounter in a PWR.

Phase III, documented in this report, is the final testing of the prototype RVLMS including the probe assembly, sensor heater power controller, and signal processor. In the Phase III tests, the integral operation of the HJTC probe assembly and electronics are verified under normal and accident thermal-hydraulic conditions that the probe may be exposed to in a PWR.

2.0 PHASE III TEST OBJECTIVES

Phase III is a test series for the final design of the HJTC probe assembly and associated electronics. The purpose of the Phase III testing is to verify the performance of the complete prototype HJTC system under normal and accident thermal-hydraulic conditions that the probe may be exposed to in a PWR. Since the thermal-hydraulic performance of the probe assembly has already been verified by the Phase II tests, these tests concentrate on the integrated system performance. Specific objectives of the Phase III tests are listed below:

1. Verify the integral operation of the probe assembly, the signal processing electronics, and the heater power control system to ensure that the overall system functions together as expected.

2. Verify the individual performance of the HJTC probe assembly and signal processing electronics (covered/uncovered indications, percent level output) when the probe is exposed to conditions that might exist in a PWR.

3. Verify the performance of the HJTC sensor heater power control system to limit the maximum heated thermocouple temperature while ensuring acceptable performance as a RVLMS.

4. Obtain data to be used in determining the final covered/uncovered ΔT setpoint value, sensor heater power, and setpoints for the sensor heater power control system so as to achieve optimum system performance.

3.0 SUMMARY OF TEST RESULTS

In the Phase III tests the HJTC system was tested under conditions similar to those it would be exposed to in a PWR during an accident. Single phase, two-phase, blowdown, and repressurization transients were run. The tests covered a pressure range from about 50 to 2000 psig and two-phase void fractions from 0 to 0.62. The integrated HJTC system, consisting of the probe assembly, signal processor, and sensor heater power control performed very well in measuring the collapsed water level.

The probe assembly thermal-hydraulic performance, which has been verified in the Phase II tests, has been reconfirmed in these tests. That is, the collapsed water level is formed and measured inside the separator tube while a two-phase mixture exists outside.

The signal processor generates an uncovered or covered signal when the sensor ΔT (temperature difference between heated and unheated thermocouples) reaches the setpoint value of [ ] used in these tests. When this occurs for each sensor, the percent level display changes to show the new collapsed water level.

The sensor heater power control system successfully limits the maximum temperature and ΔT by reducing the power supplied to the heaters. The heater power control system maximizes the power supplied to the sensor heaters (to minimize the response time) while preventing damage to the sensor due to high heated junction temperatures. Even at low pressure where the heater power is reduced, the HJTC system still provides a good indication of the collapsed water level.

The response time during drain transients (i.e., time from uncovery of the heated junction to the time when the percent level display changes) varies between [ ] depending on the pressure. The longer response times occur at low pressure (200 psig) because the sensor heater power is cutback the most at low pressure. The response time for refill transients, where the heated junction thermocouple is quenched, is much shorter, being between [ ].

The data obtained during Phase III testing will be used to determine the final uncovered/covered ΔT setpoint, sensor heater power, and heater power control setpoints for use in a PWR installation. The final selected values should not be very different from that used in these Phase III tests.

4.0 TEST FACILITY DESCRIPTION

4.1 TEST FACILITY

The test facility used for Phase III is the same as was used for the Phase II tests. A diagram of the facility is shown in Figure 4-1. The major components are a 70 gallon autoclave, test vessel, heater tube, and circulating pump. The facility is capable of circulating flow in two parallel loops, from the autoclave to the test vessel and from the autoclave to the heater tube. Heat-up of the test vessel to the appropriate test pressure and temperature is accomplished by heating the water in the autoclave and circulating it through the system. During testing the autoclave is used as a reservoir of hot water for injection into the test vessel during refill transients. It also provides hot water to the heater tube for producing steam during two-phase tests.

The test vessel is a 4 inch, Schedule 160 pipe (3.5 in. I.D.), 15 feet long into which the HJTC probe assembly is installed. Steam is injected at the bottom by a slotted 3/4 inch tube. A perforated diffuser plate, located above the point of steam injection, is used to control steam bubble size and distribution. Steam exits from the top of the test vessel through a manually adjusted valve used to control test vessel pressure. Fill and drain lines are connected at the bottom of the test vessel below the diffuser plate. Band heaters distributed along the length of the test vessel serve to maintain the fluid temperature when the vessel is isolated from the autoclave.

The purpose of the heater tube is to produce steam for two-phase testing. It consists of an electrically isolated, 3/4 inch diameter, 15 foot long Inconel tube. Electric cables attached at both ends of the tube provide a direct current to heat water flowing inside the tube and generate steam. The power to the heater tube is adjustable from 0 to 250 kw. A thermocouple attached to the heater tube wall provides a high temperature safety trip for burnout protection.

4.2 TEST INSTRUMENTATION

The test instrumentation has been selected to provide data on the test conditions, probe assembly performance, and microprocessor output. Twelve important parameters which relate the performance of the HJTC system are monitored on multichannel strip chart recorders. These parameters are listed in Table 4-1.

A differential pressure gauge (DP cell) is used to provide an independent measurement of the collapsed water level in the test vessel. The DP cell pressure taps are connected to the top of the top flange and to the side of the test vessel at the same elevation as the bottom holes in the HJTC probe assembly. Thus, it measures the collapsed water level that exists inside the vessel in inches of water at atmospheric conditions.

A gamma densitometer is used to measure the fluid density, and hence void fraction, inside the test vessel. The densitometer is positioned so that the gamma beam traverses the annulus between the probe assembly support tube and the test vessel (see Figure 4-2). It is located at the same elevation as the heated junction thermocouple of the fifth HJTC sensor from the top. The densitometer also shows when the single phase or two-phase level passes the elevation of sensor #5.

The differential temperature (ΔT) for each of the HJTC sensors, except sensor #3, is recorded. This provides information on individual sensor response and allows the percent level output from the microprocessor to be verified. One sensor ΔT is not recorded because of limitations on the number of recording pens available. The heater power control signal is also recorded to provide information on the performance of the sensor heater power control system.

4.3 HJTC PROBE ASSEMBLY

The HJTC probe assembly tested in the Phase III tests consists of eight HJTC sensors inside a 12 foot long separator tube with an outer diameter of [ ] Each sensor consists of a heated and unheated Type K thermocouple separated axially by [ ] A splash shield surrounds each heated junction thermocouple to protect against stray water droplets that might cool the heated junction when in a steam environment. The electrical connection of the sensors allows the measurement of the absolute temperature of each thermocouple, as well as the differential temperature. The elevation of the heated junction for each sensor is shown in Figure 4-3. The installation of the probe assembly in the test vessel is shown in Figure 4-4.

The separator tube has [ ] near both the top and bottom of the tube. These holes allow water to drain and steam to escape from inside the probe. The flow area of these holes is [ ] which is approximately equal to [ ]. This is also twice the hole area that was at the bottom of the Phase II probe assembly.

The probe assembly is surrounded by a support tube similar to the way it would be in a PWR. The support tube, which has a [ ] are located near the top and bottom of the support tube and are [ ] (Figure 4-3). This configuration (similar to that tested in Phase II) aids in preventing steam bubbles from entering the bottom of the separator tube since the bubbles would have to flow downward in the separator-support tube annulus.

4.4 SIGNAL PROCESSING

The signal from the HJTC probe assembly is input to a microprocessor where the percent level is calculated, the correct sensor heater power is determined, and several fault condition diagnostics are performed. The interface between the microprocessor and the rest of the system is shown in Figure 4-5. The microprocessor accepts the thermocouple signals from the heated and unheated junctions. The output from the microprocessor consists of an analog percent level signal, temperature of each heated and unheated thermocouple, differential temperatures, two identical sensor heater power control signals (one to each power supply unit), and fault condition signals.

The level logic used by the microprocessor, illustrated in Figure 4-6, is based on both the differential temperature (ΔT) and the unheated junction temperature. The differential temperature is obtained by subtracting the unheated junction temperature from the heated junction temperature. When the ΔT of any sensor increases above a predetermined setpoint value, then that sensor is considered to be uncovered. The setpoint value used in the Phase III tests is [ ] The collapsed water level, in percent of measurement span, is then calculated based on the number of sensors that are uncovered. A sensor is also considered to be uncovered if the unheated junction temperature exceeds a preset value. In the Phase III tests, this value is [ ]. The purpose of this logic is to maintain an uncovered indication when the environment steam temperature and therefore, heated junction temperature, is high enough so that the sensor heater power is completely cut off and the ΔT is less than [ ]. This situation could occur in a PWR when the core is uncovered and superheated steam surrounds the HJTC probe assembly and sensors. Either one of the two conditions is sufficient to cause an uncovered sensor indication.

The microprocessor also functions as a sensor heater power control system. The purpose of the heater control system is to limit the temperature of the heated junction to prevent damage to the sensor due to overheating. The control logic, shown in Figure 4-7, uses both heated junction temperature and sensor ΔT from all eight sensors in the probe. Heated junction temperature is used to limit the maximum thermocouple temperature. Sensor ΔT is used to limit the thermal stress on the heated thermocouple when it is quenched. The input to the control logic is the maximum heated junction temperature and maximum sensor ΔT from all sensors. When the temperature or ΔT reaches a preset value, the power control signal is reduced linearly as a function of temperature or ΔT from 5 volts at full heater power to 1 volt at zero power. The control signal is reduced until the heated junction temperature no longer increases. In the Phase III tests, the setpoint where the control signal starts to decrease power is [ ]heated junction temperature and [ ]ΔT. The control signal yields a zero power at [ ]respectively. The minimum of the heater power control signals from heated junction temperature and sensor ΔT is used to cutback the sensor heater power.

The minimum control signal goes to each of two heater power supply units. Each power supply is connected in series to four sensor heaters and has an on/off duty cycle of 0.8 seconds. The sensor heater power is varied by changing the time span (percent of the duty cycle) that full power is applied to the heaters. When the power control signal is at its maximum 5 volts, full power is supplied to the heaters all the time (for the entire cycle). When the control signal is reduced, full power is supplied to the heaters for only a portion of the duty cycle. For example, if the control signal is at 3 volts, then power is on for 0.4 seconds and off for 0.4 seconds every duty cycle. In this way the sensor heater power is cutback and the heated junction thermocouple is protected from overheating.

Output from the microprocessor goes to the display panel. The display information is updated by the microprocessor every two seconds. The display panel used in the Phase III tests is a four digit display box with three function switches. The display is capable of showing (by using the function switches) the percent level, individual thermocouple temperatures, sensor ΔT's, and fault indications.

The microprocessor is designed to detect and display several fault conditions. Faults such as an open thermocouple circuit or a loss of sensor heater power are identified. A flashing display on the four digit box indicates that a fault condition exists. The operator can determine what the fault is by using a switch on the display panel.

TABLE 4-1

Recorded Parameters

Parameter	Range	Purpose
Pressure	0-2000 psig	Measure vessel pressure
DP Cell Water Level	0-160 in.	Independent test vessel collapsed water level measurement
Analog Percent Level	0-100%	Monitor level output from microprocessor
Heater Power Control System	0-5 volts	Monitor performance of heater power control system
Fluid Void Fraction (Gamma Densitometer)	0-100% (Liquid/Steam)	Record void fraction, and passage of two-phase and single phase level at middle sensor
Sensor ΔT_1 (Top)	0-600°F 0-1000°F	Record sensor ΔT output
Sensor ΔT_2	0-600°F 0-1000°F	Record sensor ΔT output
Sensor ΔT_4	0-600°F 0-1000°F	Record sensor ΔT output
Sensor ΔT_5 (Middle)	0-600°F 0-1000°F	Record sensor ΔT output
Sensor ΔT_6	0-500°F 0-1000°F	Record sensor ΔT output
Sensor ΔT_7	0-600°F 0-1000°F	Record sensor ΔT output
Sensor ΔT_8 (Bottom)	0-600°F 0-1000°F	Record sensor ΔT output

FIGURE 4-1

PHASE III TEST FACILITY

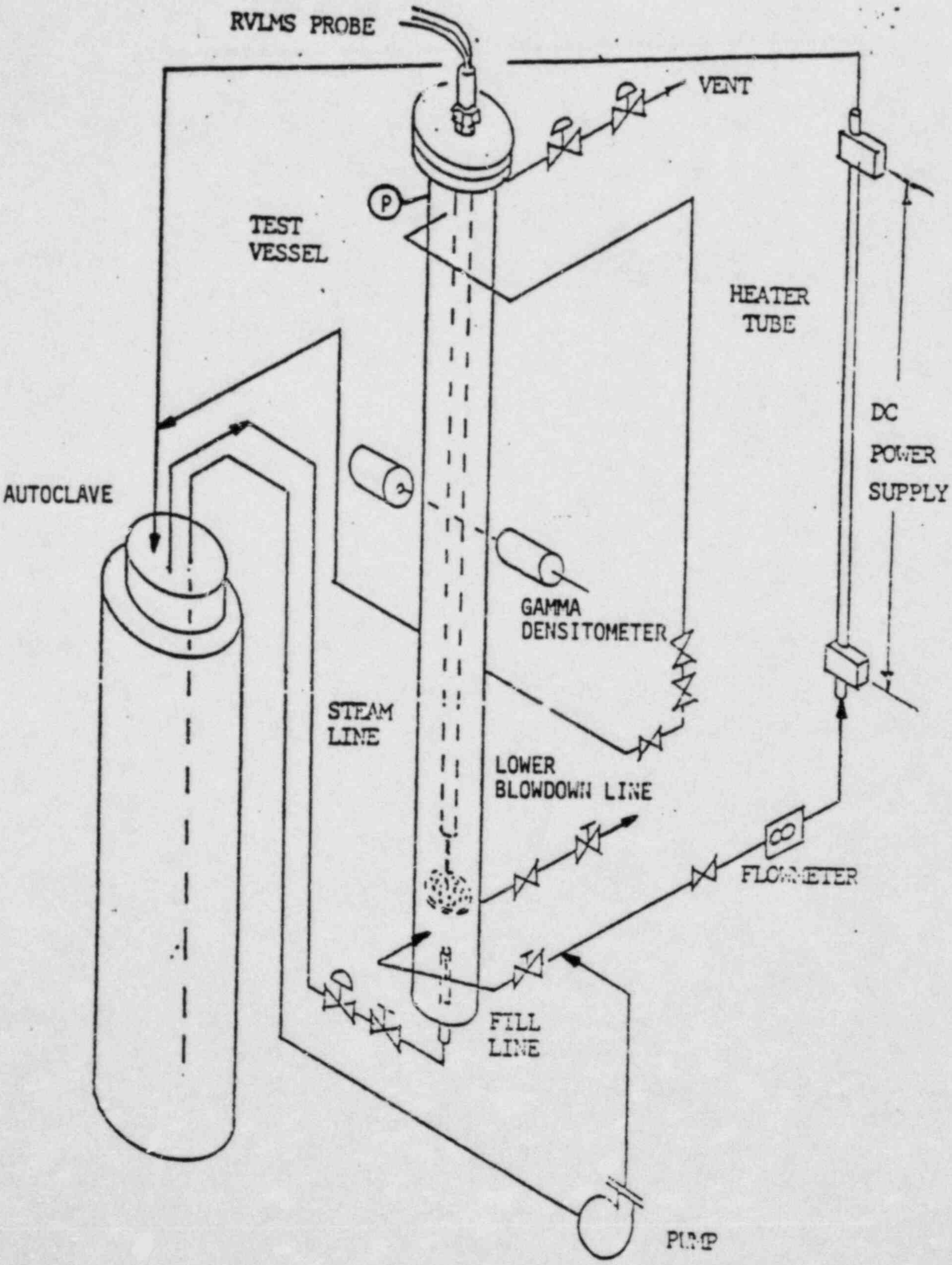


FIGURE 4-2
TEST VESSEL CROSS SECTION

FIGURE 4-3
HJTC SENSOR ELEVATIONS

FIGURE 4-4

PROBE ASSEMBLY INSTALLATION

FIGURE 4-5

HJTC SYSTEM FUNCTIONAL INTERFACE

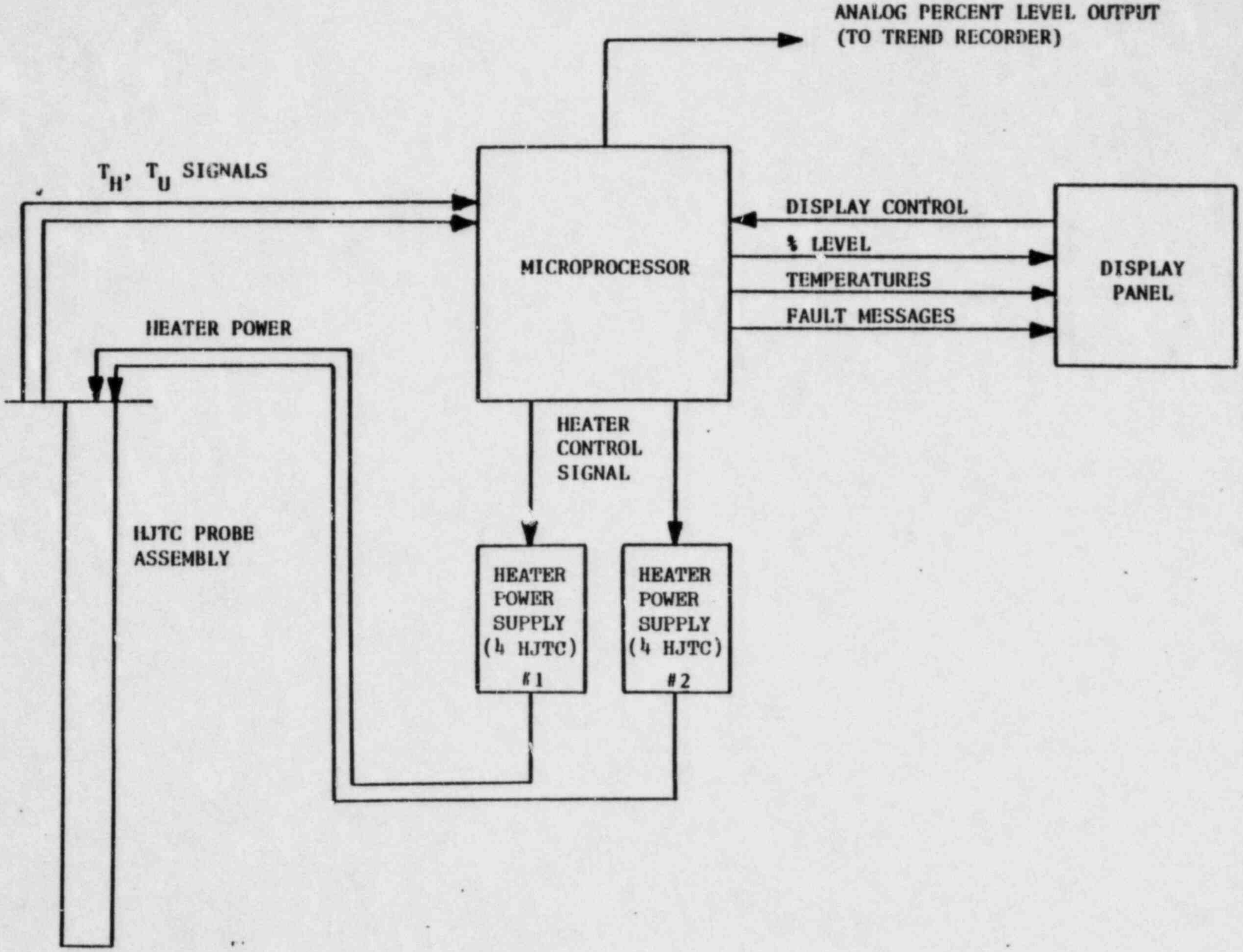


FIGURE 4-6

MICROPROCESSOR LEVEL LOGIC

FIGURE 4-7

HEATER POWER CONTROL LOGIC

5.0 TEST DESCRIPTION

In Phase III, the prototype HJTC system has been tested under thermal-hydraulic conditions which the probe might be exposed to during an accident in a PWR. Single phase, two-phase, blowdown, and repressurization tests were performed. The pressure ranges from 50 to 2000 psig with fluid void fractions for 0 to 0.62. Depressurization rates from 0 to 10 psi/sec were obtained. A list of the tests performed is given in Table 5-1.

5.1 SINGLE-PHASE TESTS

Steady state and transient (drain and refill) tests are performed under single phase conditions. The steady state tests are to determine the covered and uncovered sensor ΔT output as a function of sensor heater power and pressure. The purpose of these tests is to obtain data for use in establishing the sensor heater power, heater power control setpoints, and the uncovered/covered ΔT setpoint. Transient tests are performed to provide information on the performance of the HJTC system (probe assembly, signal processor, and sensor heater power control) during drain and refill tests. These tests also provide a comparison for the two-phase transient tests and with the Phase II tests.

5.2 TWO-PHASE TESTS

Steam-water, two-phase mixture drain and refill tests are performed to simulate conditions which might surround the HJTC probe assembly during inventory loss events. The purpose of these tests is to determine the HJTC system performance when the probe assembly is exposed to conditions similar to what might exist in a PWR. It also provides a comparison with the Phase II tests where the probe assembly design was verified. Void fractions and drain rates in the range of what might be expected during a small break LOCA are used.

5.3 BLOWDOWN TESTS

Blowdown tests are conducted to determine the HJTC system performance during depressurization events. The purpose is to determine the effect of flashing inside the probe assembly on sensor response. The rate of depressurization is controlled by the amount that the blowdown valve at the bottom is opened. Depressurization rates similar to what would occur during a small break LOCA are used.

5.4 REPRESSURIZATION TESTS

The HJTC system is also tested under conditions of increasing pressure. The purpose for this is to determine if condensation due to a pressure increase would affect the system response. Repressurization rates that might occur after a small break LOCA are used. The test vessel pressure is increased by refilling the vessel after a blowdown transient. It is expected that the sensor heater power control system would aid in preventing a decrease in ΔT due to condensation (since heater power is increased as pressure increases), and therefore, minimize the effect.

5.5 SIGNAL PROCESSOR FAULT CONDITION TESTS

Tests are performed on the ability of the microprocessor to detect and display several fault conditions associated with the thermocouple inputs and heater power. The purpose of these tests is to ensure that the microprocessor can recognize a fault conditions and correctly identify the fault. The tests are performed by simulating a fault condition and observing the display panel response.

The fault conditions that can be detected are a loss of sensor heater power, loss of heater power control signal, and open thermocouple circuits. For a loss of heater power the sensor ΔTs decrease. When a sensor ΔT falls below a low ΔT setpoint value, a fault condition should be identified with a flashing display and the appropriate error code. The error code is a number preceeded by the letter E which specifies the fault condition that exists. A loss of the heater power control signal results in the same low sensor ΔT fault condition. An open thermocouple circuit causes the displayed temperature to read at the top of the scale (2460°F). If the unheated thermocouple circuit is open, a low ΔT error code is also displayed.

TABLE 5-1

LIST OF TESTS PERFORMED

TYPE OF TEST	PRESSURE (PSIG)	VOID FRACTION	DRAIN/FILL RATE (IN/SEC)	COMMENTS
A. Single Phase Sensor Output vs. Power and Pressure	50	0	0	Manual Power Control-Fig.7-1
	300	0	0	
	500	0	0	
	1000	0	0	
	2000	0	0	
Transient	200	0	D= 0.1	Fig 7-3
	200	0	D= 1.0	
	200	0	D= 3.0	
	200	0	F= 0.05	Fig. 7-4
	200	0	F= 0.1	
	500	0	D= 0.1	
	500	0	D= 1.0	
	500	0	D= 3.0	
	500	0	F= 0.05	
	500	0	F= 0.10	
	500	0	F= 1.0	
	1000	0	D= 0.1	Fig. 7-5
	1000	0	D= 1.0	
	1000	0	D= 3.0	
	1000	0	F= 0.05	
	1000	0	F= 0.10	Fig. 7-6
	1000	0	F= 1.0	
	2000	0	D= 0.1	
	2000	0	D= 1.0	
	2000	0	D= 3.0	
	2000	0	F= 0.05	
	2000	0	F= 0.1	
	2000	0	F= 1.0	
B. Two-Phase Quasi-Steady State	300	0.35-0.50	D ≤ 0.05	
	300	0.35-0.50	F ≤ 0.05	
	1000	0.05	D ≤ 0.05	
	1000	0.05	F ≤ 0.05	
	1000	0.25	D ≤ 0.05	
	1000	0.25	F ≤ 0.05	
	1000	0.50	D ≤ 0.05	
	1000	0.50	F ≤ 0.05	
	2000	0.60	D ≤ 0.05	
	2000	0.60	F ≤ 0.05	

TABLE 5-1
(Continued)

TYPE TEST	PRESSURE	VOID FRACTION	DRAIN/FILL RATE	COMMENTS
Transient	300	0.35-0.50	D = 0.1	Fig. 7-7
	300	0.35-0.50	D = 1.0	
	300	0.35-0.50	D = 3.0	
	300	0.35-0.50	F = 0.1	Fig 7-7
	300	0.35-0.50	F = 1.0	
	1000	0.05	D = 1.0	
	1000	0.05	F = 0.1	
	1000	0.25	D = 1.0	
	1000	0.25	F = 0.1	
	1000	0.35-0.50	D = 0.1	Fig. 7-8
	1000	0.35-0.50	D = 1.0	
	1000	0.35-0.50	D = 3.0	
	1000	0.35-0.50	F = 0.1	Fig. 7-9
	1000	0.35-0.50	F = 1.0	
	2000	0.60	D = 0.1	
	2000	0.60	D = 1.0	
	2000	0.60	D = 3.0	
	2000	0.60	F = 0.1	
	2000	0.60	F = 1.0	
C. Blowdown				
	2000	-	≈0*	
	2000	-	1*	Fig. 7-10
	2000	-	2*	
	2000	-	3*	
	2000	-	10*	
	2000	-	10-plateau*	Fig. 7-11
	2000	-	6 - top*	Fig. 7-12
	2000	-	23*	Fig. 7-13
D. Repressurization				
	500-2000	-	≈5*	Fig. 7-14
E. Fault Conditions				
Loss fo Heater Power	1000	0	0	Vessel Full
Loss of Heater Control Signal	1000	0	0	Vessel Full
Open Thermocouples	1000	0	0	Vessel Full

* Pressure change rate (psi/sec).

6.0 TEST PROCEDURE

6.1 TEST SYSTEM HEAT-UP

Prior to each series of tests, the test vessel temperature and pressure must be increased to the appropriate value. This is done by heating the water in the autoclave and circulating through the system. When the desired test vessel condition is reached, the vessel is isolated from the autoclave and band heaters set to maintain its temperature. For the two-phase tests, the autoclave temperature and pressure are kept higher than the test vessel by about 100°F. This is done so that a high steam injection flow rate, and therefore high void fraction, can be achieved as a result of the pressure difference between autoclave and test vessel.

6.2 SINGLE PHASE TESTS

Steady state transient tests are performed with single phase water. Steady state tests are done by changing the water level so a sensor is either covered or uncovered and recording the sensor output after it has reached equilibrium. To lower the water level, a valve in the drain pipe at the bottom of the test vessel is opened. To refill and increase the water level, water from the autoclave is pumped through an opened fill line into the test vessel. The heater power control system is not used for the steady state tests. A constant, but variable, heater power source is used to determine sensor ΔT versus heater power. For the transient tests the rate at which the water level changes is controlled by the amount that the drain or refill valve is opened. The heater power control system is also reconnected.

6.3 TWO-PHASE TESTS

To perform the two-phase tests, steam is injected into the test vessel which is half filled with water. To produce the steam, water from the autoclave is pumped through the heater tube with an electric current applied to the tube. The steam-water mixture produced in the heater tube is directed back to the steam space in the autoclave. The steam line that taps into the steam space of the autoclave is opened and steam is injected at the higher autoclave pressure into the bottom of the test vessel. A valve at the top of the vessel provides a steam vent for controlling vessel pressure. To adjust the steam flow for a higher void fraction, the heater tube power is increased and the steam line valve opened accordingly to maintain autoclave pressure. To raise and lower the water level, refill and drain valves are opened as in the single phase tests.

6.4 BLOWDOWN TESTS

The blowdown tests are initiated with the test vessel isolated and completely filled with water at about 2000 psig and 605°F. A drain valve at the bottom is opened by an amount depending on the depressurization rate desired. The blowdown is continued until the vessel is empty. Then the valve is closed and the vessel refilled with water from the autoclave.

6.5 REPRESSURIZATION TESTS

Tests on the HJTC system response when the pressure increases are conducted during the refill after a blowdown tests. As the water level in the test vessel increases, the steam is compressed and the pressure rises. The rate of pressure increase is controlled by the refill rate. The sensor ΔTs are monitored to determine if there is a significant change due to condensation as the pressure rises.

6.6 FAULT CONDITION TESTS

The ability of the microprocessor to correctly detect and display several fault conditions associated with the thermocouples and sensor heater power is tested. The tests are performed by simulating a fault condition and observing the response of the display panel. A loss of sensor heater power is simulated by turning off the heater power supply units. A loss of the heater control signal is simulated by disconnecting the heater control cables from the microprocessor to the heater power supplies. For open thermocouple circuits, each heated and unheated junction thermocouple signal is disconnected from the microprocessor.

7.0 TEST RESULTS

The HJTC system has been tested under conditions that it may be exposed to during a transient in a PWR. The Phase III test results concentrate on the performance of the signal processor, sensor heater power control, and the integral operation of the HJTC system. The thermal-hydraulic performance of the probe assembly has already been adequately verified by the Phase II tests.

7.1 SINGLE PHASE TESTS

Steady state and transient tests have been conducted under single phase conditions. These tests provide information on the sensor ΔT versus heater power and pressure, the system response time, and the integral system operation.

7.1.1 HJTC Sensor ΔT

Figure 7-1 shows the HJTC sensor ΔT versus sensor heater power for several different pressures. The filled in symbols represent covered sensor ΔTs. The uncovered sensor ΔT increases with higher heater power and decreases with higher pressure. The covered sensor ΔT behavior is the same, but the sensitivity is much lower. The lower uncovered ΔT at higher pressure is due to the greater heat transfer coefficient to steam at high pressure.

Figure 7-2 is based on the data in Figure 7-1, but is presented as sensor ΔT versus pressure for several heater powers. The heater power control and covered/uncovered setpoints used during the Phase III tests are also shown. As can be seen, the covered/uncovered setpoint value of [ ] is above the covered ΔT value by an amount large enough to preclude spurious uncovered signals. It is still low enough, however, so that the time required to reach the setpoint once the sensor has become uncovered (response time) is acceptable (i.e. less than 1 minute). The setpoints at which heater power starts to be cut back are [ ] heated junction temperature. These setpoints provide adequate protection against overheating, but are high enough to allow a relatively high heater power to be applied to all sensors so that the uncovering response time is short even when the heater is cut back, Also, the heater power is always high enough so that an uncovered indication can occur if a sensor becomes uncovered. Since the heater power is cut back the most at low pressure, the response time is longest at low pressure. At pressures above about 1525 psig, the heated junction temperature limits the heater power. At lower pressures, the ΔT limits the heater power.

7.1.2 System Response

Transient tests are conducted by draining or refilling the test vessel at different rates. These tests provide information on the integral system operation and response time. The system response time is defined as the time from uncovery (covery) of a sensor to the time when the display changes to a new level. This time is made up of several components. The first component is the time to drain the splash shield and probe assembly in order to uncover the HJTC sensor. Second is the time required to evaporate a water film that remains on the sensor sheath in the heater coil region. The Phase II tests determined that these first two components contribute [ ] to the response time. The third component is the time for the sensor ΔT to increase to the setpoint value. This is the major component of the total response time. The final component is associated with the microprocessor cycle time. The maximum microprocessor delay time for the Phase III tests is about 2 seconds.

Figure 7-3 shows the results of a drain transient at 200 psig. The test vessel pressure and collapsed water level, as measured by a differential pressure gauge (DP level), are shown at the top of the first page. The microprocessor output, analog percent level and the sensor heater power control signal are shown below. A control signal of 5 volts results in a full power of [ ] per sensor heater; 1 volt yields 0 watts. Next, the gamma densitometer provides an indication of the void fraction and the time when the top of the two-phase level passes the sensor #5 elevation. At the bottom of the first page is the ΔT output for sensor #1 (top). The second page presents the remaining sensor ΔTs (except sensor #3).

In Figure 7-3 the test vessel is initially full at 200 psig when the drain line is opened. The drain rate, taken from the DP level measurement is about 0.1 in/sec. When the top sensor #1 uncovers, the ΔT increases rapidly because the pressure is low and the full [ ] is still applied to all the sensor heaters. The system response time for the first sensor uncovery is therefore short, about [ ] This is made up of [ ] for the first two components (drainage and evaporation of the water film) and [ ] for the third and fourth components (temperature increase and microprocessor delay time). The third and fourth components are taken directly from the figure as the time from the start of increase of ΔT_1 to the time when the analog percent level changes. When the ΔT exceeds [ ] the heater power is cut back as shown by the control signal. The drop in power can also be seen on the ΔTs for the other sensors that are covered. The ΔT stabilizes at a value where the power applied balances the heat lost to the surrounding steam. When the second sensor uncovers, the response time is longer because the heater power is lower. The system response time for the second sensor uncovery is about [ ]

The HJTC system response times obtained during the Phase III tests at different pressures are presented in Table 7-1. The initial uncovery response times are for the top sensor, which uncovers first while the other sensors are still covered. Since the heater power has not yet been reduced and is at its full value, these response times are faster than that for the other sensors that subsequently become uncovered when heater power has been reduced. As can be seen, acceptably short response times are achieved even when the heater power has been reduced. Also, the refill (covering) response times are quicker and show much less variation with pressure (heater power) than the uncovery response times. This is due to the rapidity of the quenching process as the water level covers the heated junction thermocouple.

Figure 7-4 shows a refill transient of 0.05 in/sec at 200 psig. The ΔT drops rapidly as the water level covers sensor #5 and quenches it. The response time for a refill (covering) transient is therefore very short. The response time in Figure 7-4 is about [ ] Since the pressure is low, the heater power is cut back as indicated by the heater power control signal. The gamma densitometer output shows that, for this test, the water level passes its elevation about 35 seconds before sensor #5 is covered. This is due to the very slow refill rate, the densitometer not being exactly lined up with the heated junction, and the gamma beam width.

A single phase drain transient at 1000 psig is shown in Figure 7-5 and a refill in Figure 7-6. The drain rate is about 0.2 in/sec. When the top sensor uncovers, the response time is short since the full power is applied. When the top sensor ΔT reaches [ ] the heater power is reduced. The reduction in power is less at 1000 psig than at 200 psig since the heat transfer coefficient at the higher pressure is better and a higher heater power can be tolerated. The jagged behavior of the heater power control signal is due to the on/off design of the heater power supply and the 2 second cycle time of the microprocessor. This causes a small cyclic variation in the sensor ΔTs of less than 15°F. The variation does not effect the performance of the system, however

7.2 TWO-PHASE TESTS

The HJTC system was tested with two-phase conditions in the test vessel at drain and refill rates similar to that for the single phase tests. These tests provide a comparison with the single phase performance and provide information on the system performance under two-phase conditions. Most of these drain and refill transients are done around the middle sensor.

In Figure 7-7 a drain and refill transient at 300 psig and a void fraction of 0.35 is shown. The rates are both about 0.1 in/sec. Since the first five sensors are already uncovered, the sensor heater power has been reduced to avoid overheating of the uncovered sensors. The gamma densitometer output indicates that the two-phase level is well above the collapsed water level in the probe assembly (i.e., the two-phase level is around sensor #5 and the collapsed level in the probe is around sensor #6). The uncovery time response with the reduced heater power is about [ ] and for refill it is less than [ ]

Two-phase drain and refill transients at 1000 psig and a void fraction greater than 0.40 are shown in Figures 7-8 and 7-9. The behavior is similar to the previous transients described. In Figure 7-8, sensor #4, #5, and #6 are uncovered at a drain rate of 0.1 in/sec. The sensors uncover in sequence before the top of the two-phase level passes the elevation of sensor #5. The ΔT for sensor #1 is the highest and therefore is used to limit the heater power for all sensors. This is generally true for all the Phase III tests because the first sensor is located close to the upper head. This area has no external heaters and is therefore slightly cooler than the rest of the test vessel. Thus, the unheated junction temperature is slightly lower than for the other sensors resulting in a higher ΔT for the top sensor. In Figure 7-9, a refill is initiated with an empty vessel. The collapsed level rises in the probe and covers each sensor in sequence.

During the two-phase testing, an "out of sequence" indication was noted for the top sensor. The cause of this indication resulted from a production problem with the interface between the splash shield and sensor sheath for the top sensor. As a result of this problem water droplets could get inside the splash shield and cool the heated junction when the top sensor was surrounded by steam. The splash shield was repaired and the tests where the out of sequence indication was noted were repeated The heated junction of the top sensor did not cool off and the out of sequence indication did not occur during the repeat tests. A more detailed description of this occurrence is presented in Appendix A of this report.

7.3 BLOWDOWN TESTS

Blowdown tests are run in Phase III from both the top and bottom vent lines. These tests provide information on the system response during a depressurization event. Depressurization rates representative of small break LOCAs, 1 to 10 psi/sec, are used. In addition, a much faster depressurization (23 psi/sec) test is done to evaluate the system response for a larger break. It should be noted that this fast depressurization is outside the design basis for the HJTC system since the transient proceeds too fast for the operator to take action.

A blowdown at about 1 psi/sec that is initiated by opening the bottom drain line is shown in Figure 7-10. The test begins with the vessel completely filled with subcooled water. When the valve is opened, the pressure falls quickly to the saturation pressure and then continues at a rate dependent on the amount of the valve opening. As can be seen, the sensors uncover in sequence with a response time of about [ ] The heater power control system reduces the power enough to limit the ΔTs to acceptable values.

The blowdown test shown in Figure 7-11 simulates the pressure response for a small break LOCA where a pressure plateau is reached. In this test the blowdown valve is opened to give an initial depressurization rate of about 10 psi/sec. The valve is then closed when the collapsed water level, as measured by the DP cell, is just below sensor #5. This causes the pressure to stop falling so flashing also stops. The two-phase mixture in the test vessel and the probe assembly therefore collapse to form a single phase water level as the steam bubbles are released. This process is shown by the gamma densitometer output as it rises to show an increase in void fraction due to flashing, falls back when the flashing stops and the bubbles escape the two-phase mixture region, and then increases again as the mixture level collapses past its elevation. During the rapid depressurization, the HJTC sensors respond to the top of the two-phase mixture level inside the probe. The time from the closing of the blowdown valve to the time that the sensor #5 ΔT increases is a measure of the time it takes for steam bubbles to escape from the probe and for a collapsed water level to be formed again. This is [ ] Thus, after the initial blowdown period of a small break LOCA, it takes only a very short period of time for the collapsed water level to be formed and measured inside the probe. After the water level in the test vessel stabilizes, the blowdown valve is opened again the same amount. The remaining HJTC sensors uncover in sequence as the vessel is drained.

The results of a blowdown transient initiated by opening a valve at the top of the vessel are shown in Figure 7-12. The vessel starts full of water at 2000 psig when the top vent valve is opened. The depressurization rate of about 6 psi/sec causes significant flashing to occur in the vessel. The HJTC sensors uncover in sequence from top to bottom as a high quality two-phase mixture flows out the top vent line. This demonstrates that for a top blowdown in a PWR, a two-phase mixture that might keep the sensors cooled does not flow up the probe assembly. Thus, the HJTC system can be expected to provide a decreasing water inventory indication for this event.

A rapid blowdown transient where the depressurization rate is about 23 psi/sec is shown in Figure 7-13. This rate is much greater than the depressurization rate for which the HJTC system is expected to provide information. However, the HJTC system is expected to provide information after such a rapid blowdown transient. Even for this rapid transient, the HJTC system trends the loss of water inventory from the vessel. In general, the HJTC sensors indicate uncovery [ ] in sequence from the top to the bottom of the vessel. About 30 sec. after the start of transient, when flashing inside the vessel has stopped and the vessel has essentially drained, the HJTC system gives the correct indication that the vessel is empty.

7.4 REPRESSURIZATION TESTS

Tests are performed on the HJTC system response during an increase in pressure simulating that following a small break LOCA. These tests determine if the increase in heat transfer coefficient or condensation during the repressurization adversely affect the HJTC response. Repressurization rates slightly above those that might occur in a PWR after a small break are used. The tests are performed by refilling the test vessel with hot water after a blowdown. The rising water level compresses the steam space in the test vessel and the pressure rises. The repressurization rate is controlled by the refill rate.

Figure 7-14 shows a repressurization at about 4 psi/sec. The vessel starts empty of water, but with hot steam since it is immediately after a blowdown from 2000 psig. The water level in the vessel increases as can be seen by the DP level, analog percent level, and sensor ΔTs. As the pressure rises, the uncovered sensor ΔTs decrease slightly due to the increase in heat transfer coefficient. The sensor heater power increases also, thereby contributing to offset the decrease in sensor ΔT. In no case does the uncovered sensor ΔT fall enough to come close to the covered/uncovered setpoint. Thus, a misleading indication during a repressurization does not occur.

7.5 SIGNAL PROCESSOR FAULT CONDITION TESTS

Tests are performed on the microprocessor to ensure its ability to correctly identify and display several fault conditions that may occur while the HJTC system is in operation. These tests are performed by simulating the appropriate fault condition and observing the response of the microprocessor on the four digit display panel.

The fault conditions tested are loss of sensor heater power, loss of heater power control signal, and open thermocouple circuits. In every case, the microprocessor responds correctly with a flashing display, the expected sensor ΔT and/or thermocouple temperature, and the appropriate fault message (error code). The results are given in Tables 7-2 through 7-4. Once a fault condition has been identified, the microprocessor causes the display panel reading (normally percent level) to begin flashing. Then, upon further interrogation (pushing buttons), the individual sensor ΔTs, thermocouple temperatures, and error codes are displayed. The error code consists of the letter E, followed by a number which corresponds to a fault message.

TABLE 7-1

System Response Time
(Seconds)

\+ Recovery of all sensors independent of position.

* Uncovery of the top sensor while full heater power is applied.

** Uncovery of sensors below the top sensor when heater power has been cutback.

FIGURE 7-1

SENSOR ΔT VERSUS HEATER POWER

FIGURE 7-2

SENSOR ΔT VERSUS PRESSURE

FIGURE 7-3 a)

SINGLE PHASE, DRAIN, 200 PSIG, 0.1 IN/SEC

FIGURE 7-3 b)
SINGLE PHASE, DRAIN, 200 PSIG, 0.1 IN/SEC

FIGURE 7-4 a)

SINGLE PHASE, REFILL, 200 PSIG, 0.05 IN/SEC

FIGURE 7-4 b)
SINGLE PHASE, REFILL, 200 PSIG, 0.05 IN/SEC

FIGURE 7-5 a)

SINGLE PHASE, DRAIN, 1000 PSIG, 0.2 IN/SEC

FIGURE 7-5 b)
SINGLE PHASE, DRAIN, 1000 PSIG, 0.2 IN/SEC

FIGURE 7-6 a)
SINGLE PHASE, REFILL, 1000 PSIG, 0.1 IN/SEC

FIGURE 7-6 b)

SINGLE PHASE, REFILL, 1000 PSIG, 0.1 IN/SEC

FIGURE 7-7 a)

TWO PHASE, DRAIN & REFILL, 300 PSIG, 0.1 IN/SEC, VOID = 0.35

FIGURE 7-7 b)

TWO PHASE, DRAIN & REFILL, 300 PSIG, 0.1 IN/SEC, VOID = 0.35

FIGURE 7-8 a)

TWO PHASE, DRAIN, 1000 PSIG, 0.1 IN/SEC, VOID = 0.44

FIGURE 7-8 b)

TWO PHASE, DRAIN, 1000 PSIG, 0.1 IN/SEC, VOID = 0.44

FIGURE 7-9 a)

TWO PHASE, REFILL, 1100 PSIG, 0.25 IN/SEC, VOID = 0.50

FIGURE 7-9 b)
TWO PHASE, REFILL, 1100 PSIG, 0.25 IN/SEC, VOID = 0.50

FIGURE 7-10 a)

BLOWDOWN, 1.0 PSI/SEC

FIGURE 7-10 b)
BLOWDOWN, 1.0 PSI/SEC

FIGURE 7-11 a)

BLOWDOWN, 10 PSI/SEC WITH PRESSURE PLATEAU

FIGURE 7-11 b)

BLOWDOWN, 10 PSI/SEC WITH PRESSURE PLATEAU

FIGURE 7-12 a)

TOP BLOWDOWN, 6 PSI/SEC

FIGURE 7-12 b)
TOP BLOWDOWN, 6 PSI/SEC

FIGURE 7-13 a)

BLOWDOWN, 23 PSI/SEC

FIGURE 7-13 b)

BLOWDOWN, 23 PSI/SEC

FIGURE 7-14 a)

REPRESSURIZATION, 4 PSI/SEC

FIGURE 7-14 b)
REPRESSURIZATION, 4 PSI/SEC

TABLE 7-2

Fault Condition Test Results

Loss of Sensor Heater Power

Fault - Loss of Sensor Heater Power
Simulation - Disconnect Heater Power Supply
Microprocessor Response - Flashing Display

Sensor	ΔT (^oF)	Fault Message
1	-1 to 4 (oscillating)	ΔT_1 Low
2	-1 to 0 (oscillating)	ΔT_2 Low
3	-1 to 0 (oscillating)	ΔT_3 Low
4	-2	ΔT_4 Low
5	0	ΔT_5 Low
6	0	ΔT_6 Low
7	0	ΔT_7 Low
8	-2 to -1 (oscillating)	ΔT_8 Low

TABLE 7-3

Fault Condition Test Results

Loss of Heater Power Control Signal

Fault - Loss of Sensor Heater Power Control Signal

Simulation - Disconnect Microprocessor Output From Power Supply Units

Microprocessor Response - Flashing Display

Sensor	ΔT (^{o}F)	Fault Message
1	1 to 4 (oscillating)	ΔT_1 Low
2	0	ΔT_2 Low
3	0	ΔT_3 Low
4	-1	ΔT_4 Low
5	0	ΔT_5 Low
6	0	ΔT_6 Low
7	0	ΔT_7 Low
8	-1	ΔT_8 Low

TABLE 7-4

Fault Condition Test Results

Open Thermocouple Circuit

Fault - Open Thermocouple Circuit

Simulation - Disconnect Thermocouple Signal From Microprocessor

Microprocessor Response - Flashing Display

Open Thermocouple	Sensor ΔT (°F)	T_H (°F)	T_u (°F)	Fault Message
T_{H1}	1923	2460	544	T_{H1} Open
T_{u1}	-999	654	2460	ΔT_1 Low, T_{u1} Open
T_{H1} & T_{u1}	0	2460	2460	ΔT_1 Low, T_{H1} Open, T_{u1} Open
T_{H2}	1928	2460	532	T_{H2} Open
T_{u2}	-999	618	2460	ΔT_2 Low, T_{u2} Open
T_{H3}	1916	2460	543	T_{H3} Open
T_{u3}	-999	633	2460	ΔT_3 Low, T_{u3} Open
T_{H4}	1920	2460	540	T_{H4} Open
T_{u4}	-999	616	2460	ΔT_4 Low, T_{u4} Open
T_{H5}	1923	2460	536	T_{H5} Open
T_{u5}	-999	609	2460	ΔT_5 Low, T_{u5} Open
T_{H6}	1919	2460	542	T_{H6} Open
T_{u6}	-999	635	2460	ΔT_6 Low, T_{u6} Open
T_{H7}	1925	2460	535	T_{H7} Open
T_{u7}	-999	635	2460	ΔT_7 Low, T_{u7} Open
T_{H8}	1925	2460	533	T_{H8} Open
T_{u8}	-999	596	2460	ΔT_8 Low, T_{u8} Open

8.0 APPLICATION OF TEST RESULTS TO PWR HJTC INSTALLATIONS

8.1 TEST CONDITIONS

The Phase III tests were conducted to verify the performance of the integrated HJTC system under thermal-hydraulic conditions that it might be exposed to in a PWR installation. This section relates the test results to the conditions that would occur in a PWR.

The largest small break LOCA for which the operator can be expected to have enough time to utilize the information provided by the HJTC system is a break of about 0.1 ft^2. This break provides the bounding thermal-hydraulic conditions used to test the HJTC system. A comparison of the two-phase void fractions, depressurization, repressurization, and level change rates is shown in Table 8-1. As can be seen, the expected parameter ranges are adequately covered by the Phase III tests.

8.2 PWR HJTC INSTALLATION DESIGNS

There are two design variations of the HJTC probe assembly. These are a full length probe and a split probe design. The full length probe is used for installation within a Control Element Assembly (CEA) shroud of a C-E PWR, while the split probe is used for installation outside of a CEA shroud (see Figure 8-1). The full length probe has flow holes only at the top and bottom of the probe assembly. The split probe design can be viewed as being two separate probes vertically stacked which measure the collapsed level between each set of flow holes. Thus, the split probe configuration is simply two single probes, each with fewer HJTC sensors and shorter in length than the full length configuration.

The probe design which is tested in the Phase III tests is a full length probe since it has flow holes only at the top and bottom. The performance of the probe assembly and signal processing electronics used in the Phase III tests directly relates to the performance in a PWR of a full length probe, as well as to the performance of the upper and lower sections of the split probe configuration. Thus, the Phase III tests are applicable to both design variations.

8.3 OVERALL CONCLUSION FROM PHASE III TESTS

The integrated HJTC system (HJTC probe assembly, signal processing electronics and sensor heater power control) has been tested in Phase III under conditions simulating the thermal-hydraulic conditions in a PWR during an inventory loss accident. The Phase III test results show that the integrated HJTC system performs excellently in all cases. Thus, it can be concluded that an HJTC system will provide to the reactor operator the status and trend of the water inventory in the reactor vessel during an accident.

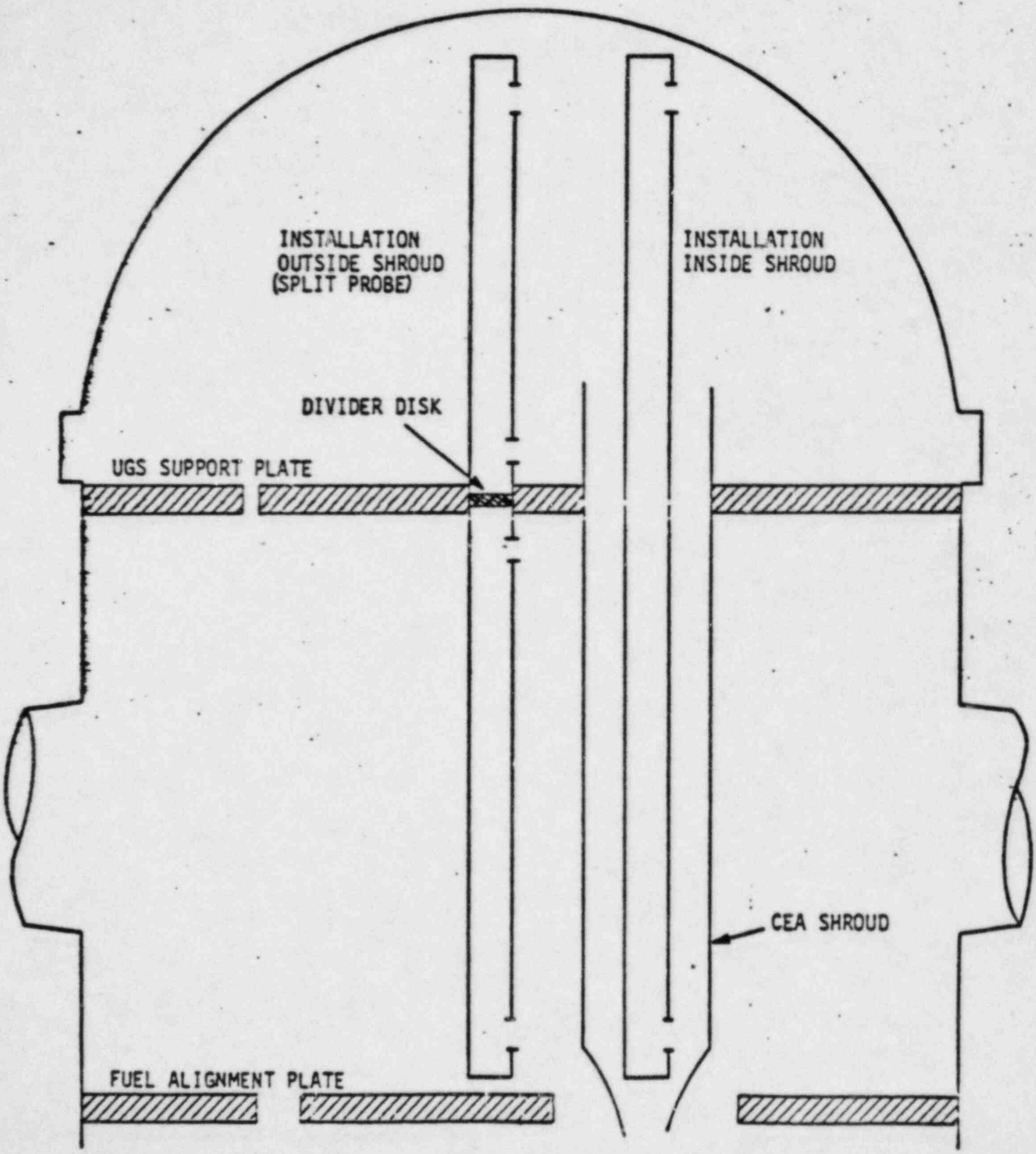
TABLE 8-1

Comparison of Test Condition Parameters to 0.1 ft^2 LOCA

	Blowdown	Pressure Plateau	Break Uncovery	Refill
Depressurization Rate (psi/sec)				
PWR	10	0	1.0	0
Phase III	2-10	0	1.0	0
Collapsed Level Change Rate (in/sec)				
PWR	3	0.1	0.2	0.07
Phase III	1-3	0.1-1.0	0.1-1.0	0.05-1.0
Two-Phase Void Fraction				
PWR	0-0.1	0.1-0.2	0.2-0.4	0.1-0.4
Phase III	0-0.2	0-0.6	0-0.6	0-0.5
Repressurization Rate (psi/sec)				
PWR	-	-	-	1
Phase III	-	-	-	4

FIGURE 8-1

HJTC PROBE ASSEMBLY DESIGNS



APPENDIX A

DESCRIPTION OF TOP SENSOR OUT-OF-SEQUENCE INDICATION

During some two-phase tests, the top sensor ΔT was observed to decrease slowly when the collapsed water level was well below the top sensor elevation. The ΔT would decrease enough to give a covered indication. This is an "out-of-sequence" indication since the top sensor showed covered while sensors below it were uncovered. At some later time, usually less than 2 minutes, the top sensor ΔT would increase again as if it became uncovered. This behavior occurred only for the top sensor.

Based on the ΔT response, the test facility, and probe assembly installation, it was thought that water droplets formed by condensed steam in the cooler upper head region were contributing to the cooling of the top sensor. When steam was injected during two-phase testing, some of the steam was condensed on the cooler metal surfaces in the upper head region. Since the holes in the probe assembly are located within the upper head (see Figure 4-4), it is relatively easy for condensed water droplets to form inside the probe and run down the sensor sheaths. When the upper head was externally heated so that condensation would not occur, this effect was not observed. Thus, it was deduced that water droplets from condensation were causing the top sensor ΔT to decrease enough so that a covered indication was given.

The splash shield is designed to prevent these droplets from contacting the heated junction and cooling it. However, upon disassembly of the probe it was found that the splash shield for the top sensor did not fit tightly to the sensor sheath. Thus, water droplets were able to run down the sheath inside the splash shield and cool the heated junction. The splash shields for the other sensors were tight and kept water out. The splash shield fit was corrected and the probe reinstalled in the test vessel. The tests where cooling of the top sensor was observed were repeated. In the repeated tests, the top sensor ΔT did not cool down. Thus, it can be concluded that the initial behavior of the top sensor was caused by water droplets leaking through the loose splash shield fit around the sensor sheath. To prevent this occurrence, special care has been taken during the manufacture and testing of the probe assemblies to ensure that a tight fit exists between splash shield and sensor sheath.

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