BWR Refill-Reflood Program—Single Heated Bundle Experimental Task Plan
Volumes 1 and 2

NP-1524, Volumes 1 and 2
Research Project 1377-1
NUREG/CR-1708
GEAP-24865

Interim Report, April 1981

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

A major consideration in the design of engineered safety systems and licensing of boiling water reactors (BWRs) is that sufficient emergency core coolant be provided to cool the reactor core in the event of a loss-of-coolant accident (LOCA). There are at present two major research efforts addressing the entire LOCA transient that are jointly managed and funded by the U.S. Nuclear Regulatory Commission, Electric Power Research Institute, and General Electric Co. These are the BWR Blowdown/Emergency Core Cooling Program (RP495) and the BWR Refill-Reflood Program (RP1377). Though these efforts are closely related, they are being performed under separate contracts. The present study is a part of the Refill-Reflood Program, which addresses the thermal-hydraulic behavior of most BWR plants during the refill and reflood phases of LOCAs on a generic basis.

PROJECT OBJECTIVE

Tests in an atmospheric pressure, single heated bundle facility will be performed for both model development and for qualification of the adiabatic steam injection technique that will be used in the large-scale 30°-sector test facility. In particular, the model development tests involve the collection of core spray heat transfer and bundle thermal-hydraulic data over a wide range of conditions. The adiabatic steam injection technique will be evaluated by performing tests with a heated bundle and by attempting to reproduce the system response with the adiabatic bundle.

PROJECT RESULTS

This report describes the experimental test plan that has been designed to meet the required objectives. It includes a description of the experimental facilities, a specification of the test matrices, and a plan for utilizing the data obtained. Related work on the core spray distribution has been presented in EPRI Interim Reports NP-1523 and NP-1580.

This report should be useful to those interested in model development and computer code assessment of BWR LOCAs.

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SUMMARY

One of the tasks in the EPRI, NRC, and G.E. sponsored boiling water reactor (BWR) Refill-Reflood program is to utilize an atmospheric pressure, single bundle test facility to perform a series of system and separate effects experiments. This document describes the test facility and the various system configurations which will be used, the planned test matrices, and the measurement and data utilization plans.

The main purpose of the system effect experiments is to qualify the adiabatic steam injection technique which will be used to simulate heated bundles in the large scale 30° sector test facility. This will be accomplished by performing a set of reference experiments utilizing both the heated and adiabatic bundles, and subsequently comparing some predefined test parameters which characterize the system response.

The separate effect tests will be performed primarily for model development and qualification. For various test phases the jet pump, bypass and guide tube, or combinations thereof, are blocked off to isolate various regions. Some of the quantitites of interest during these tests are core spray, reflood and core to bypass heat transfer; CCFL at the upper tieplate, side entry orifice, and top of bypass; vaporization rates and void distribution in the core; and flow distribution between various components.

A schedule for the performance of the tests is also presented.

Volume 1

ABSTRACT

An experimental task plan for the Single Heated Bundle Task of the BWR Refill-Reflood Test Program is presented. The test program is designed to demonstrate the applicability of adiabatic steam injection to simulate the vaporization from heated rods in a bundle and will assess the validity of scaling from LOCA transient pressures to conditions in an atmospheric pressure test facility. The technique for determining adiabatic steam injection rates for the Lynn 30 degree Sector Steam Test Facility will also be developed. Individual test conditions, the measurement plan, and the data utilization are discussed. Low flow core spray heat transfer tests will be addressed in a later addendum to the experimental task plan.

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ILLUSTRATIONS

TABLES

Section 1

OBJECTIVES

The objectives of the Single Heated Bundle (SHB) Task are:

1. To obtain test data at near-atmospheric pressures to identify and evaluate system interaction phenomena controlling heated bundle thermal-hydraulic performance during the refilling and reflooding phase of a boiling water reactor (BWR) loss-of-coolant accident (LOCA).

2. To provide reference single bundle system response data as a basis for determining the feasibility and development of the technique for adiabatic steam injection in the Lynn 30-deg Sector Steam Test Facility (SSTF).

3. To develop an adiabatic steam injection technique for use in the 30-deg sector facility that simulates steam generation resulting from heated bundles.

4. To evaluate single heated bundle separate effects and system interactions data in support of model development and model qualification tasks.

Section 2

TASK ROLE IN PROGRAM

Tests under the SHB Task will be performed for the purposes of facility qualification and model development. The facility qualification tests involve the evaluation of steam injection into an adiabatic bundle to simulate the generation of steam by a heated bundle. Verification of the adiabatic steam injection technique is necessary to ensure the adequacy of the technique for use in the Counter-Current Flow Limiting (CCFL)/Refill Separate Effects Test (SET) in the 30-deg SSTF under Task 4.4.[1] The SHB tests will also provide a data base for developing the methodology for analytically determining the adiabatic injection rates to be used for the SSTF. The model development tests involve the collection of core spray and reflood heat transfer data over a wide range of conditions to develop and qualify low flow heat transfer models.

Three stages of testing have been identified for the SHB Task. Each stage will be performed in the Emergency Core Cooling System (ECCS) Test Loop and will utilize different bundle test assemblies. The inherent simplicity of the ECCS Test Loop, and the relative ease with which test parameters and facility configuration may be varied, make it ideal for performing tests with the varied objectives of this task.

Stage 1 Tests will be performed using an existing bundle which has electrically heated simulated fuel rods. The tests are characterized as SETs with a heated bundle and will be utilized to evaluate system performance for comparison with adiabatic bundle (Stage 2) tests.

Stage 2 Tests will be performed using a bundle which simulates the bundles installed in the 30-deg SSTF to be used for Task 4.4. A steam injection tube replaces the heater rods and is used to introduce steam to simulate the generation of steam by heated rods. The tests are SETs with an adiabatic bundle, and will be used to determine the validity of adiabatic injection and to achieve the best simulation of heated bundle system response so that steam injection rates can be specified for the Task 4.4 tests at the 30-deg SSTF.

Stage 3 Tests will be performed using a new bundle having electrically heated simulated fuel rods. The tests are characterized as SETs with a heated bundle and will be used to identify and evaluate phenomena and subsystem interactions, and to provide data to support model development and model qualification tasks.

The approach to be used to verify the adiabatic simulation of heated bundle responses involves: (a) identification of a set of reference initial conditions and independent test parameter values which are representative of a typical BWR LOCA transient; (b) selection of dependent test parameters which characterize the system response during ECC injection for comparison between reference tests; (c) running reference tests with a heated bundle (Stage 1) to simulate this BWR-like transient; (d) running reference tests with an adiabatic bundle (Stage 2) to simulate this BWR-like transient; and (e) comparison of the reference tests to determine if the responses are similar.

The ECCS Test Loop operates only at near atmospheric pressure and therefore cannot produce a blowdown (BD) transient. A pressure-scaling technique has been formulated so that initial conditions and boundary conditions can be determined which will produce a system response in the heated bundle that resembles or is typical of a transient BWR response. Data obtained in the two-loop test apparatus (TLTA) under the BWR BD/ECC Program will be used as a scaling basis to establish conditions for SHB tests. The approach used to verify the pressure-scaling technique involves: (a) application of scaling technique to a TLTA-5A transient test (Test 6422 Run 3) to define base case initial conditions and independent test parameter values; (b) running a base case test and parametrics in the ECCS Test Loop with a heated bundle (Stage 1) to simulate the TLTA transient; and (c) comparison of the SHB response to the TLTA response to determine that the responses are similar.

The relationships between the Stage 1 and 2 tests and the TLTA tests are shown in Figure 2-1 as a graphical interpretation of the approach to meeting the objectives. (Information pertaining to test parameters and data utilization presented in Sections 6 and 7 further defines the approach.)

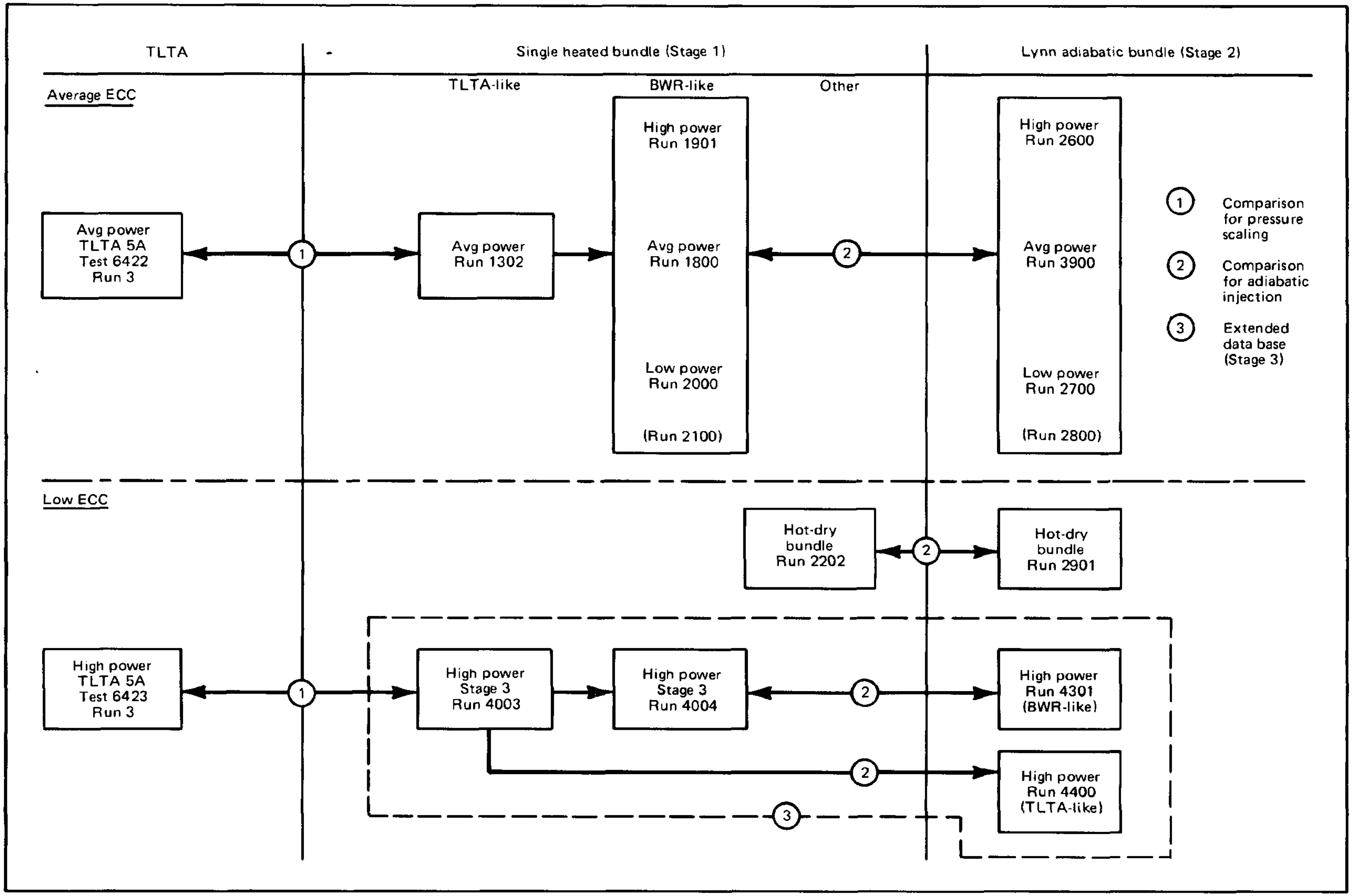


Figure 2-1. Adiabatic Bundle Simulation Qualification

The figure indicates the direct usage of Stage 1 and 2 results to demonstrate the adequacy of the pressure scaling basis and the adiabatic bundle simulation/ methodology. Stage 1 and 2 results are used with analytical methods to develop the methodology for specifying inputs for the 30-deg SSTF.

Section 3

FACILITY DESCRIPTION

The ECCS Test Loop is a 1/624-scale mock-up of the BWR-6/218 reactor. The major features of the facility are shown in Figure 3-1. These features include a full-scale simulated fuel bundle and a system mock-up. The system mock-up includes the lower plenum (LP), guide tube (GT), core, bypass, upper plenum (UP), separator, steam dome, annulus, and jet pump. The height of the core is full scale (length C). The height of the top of the jet pump above the bottom of the heated length of simulated fuel pins (length A), and the height of the first spillover point in the steam separator above the top of the fuel channel (length B), are also full scale. A comparison of these heights in the reference reactor, the ECCS Test Loop and the TLTA is presented in Table 3-1. The reference reactor regions and scaled facility volumes are shown in Table 3-2. As can be seen, the facility as-built volumes agree well with the ideal volumes. A scaling compromise was required in the steam separator and standpipe region because the standpipe diameter must not be so small as to cause an uncharacteristic flow restriction. The ECC systems are simulated with (a) liquid injection 26 inches above the upper tie plate for high pressure core spray (HPCS) and low pressure core spray (LPCS) flows, and (b) liquid injection into the bypass region on all four sides of the fuel channel at 18.7 inches below the upper tie plate for low pressure coolant injection (LPCI) flows. The spray and the LPCI share a common controlled temperature water supply, and thus are injected at the same temperature. The spray and LPCI flows may be individually varied from 3 to 30 gpm and 1 to 10 gpm, respectively, at temperatures from ambient to near saturation. The generation of steam by flashing is simulated by the injection of steam into the GT and LP. Each of these flows may be set separately at up to 1000 lbm/hr. The flow areas for various locations in the ECCS Test Loop are summarized in Table 3-3.

Stage 1 Tests will be performed with an existing bundle which is made up of an 8x8 array of electrically heated simulated fuel rods including two water rods. This bundle was used for previous testing and contains some heater rods which

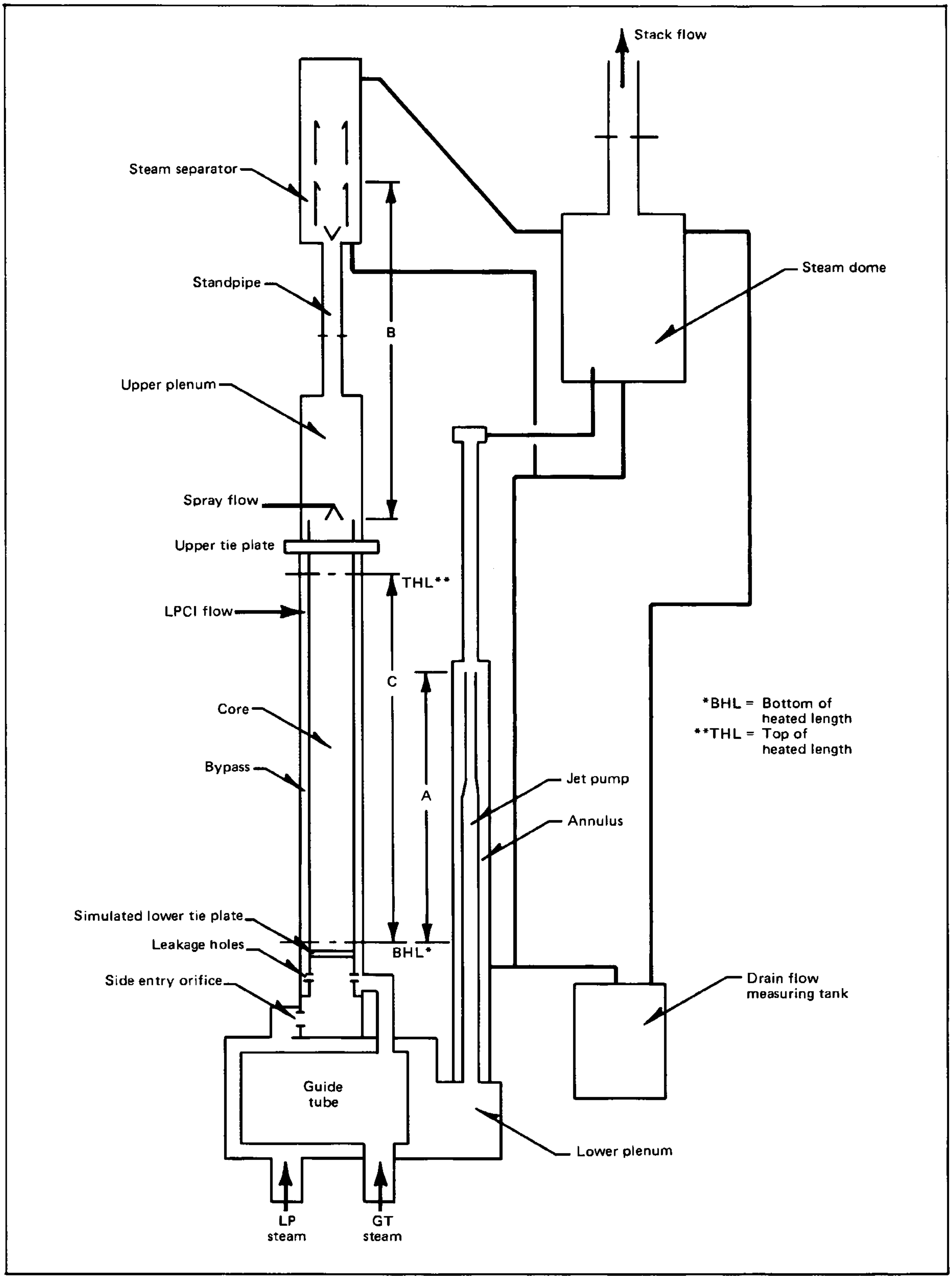


Figure 3-1. ECCS Test Loop

Table 3-1

REFERENCE HEIGHTS VERSUS ECCS TEST LOOP

	A Height of Top of Jet Pump Above Bottom of Heated Length (in.)	B Height of First Spillover in Separator Above Top of Fuel Channel (in.)	C Active Fuel Length (in.)
BWR/6-218	100.5	192.0	150.0
Stage 1 Heated Bundle	100.7	192.1	149.0
TLTA-5A	24.6	83.0	150.0

Table 3-2

ECCS TEST LOOP VOLUMES

Regional Volume	Description	Reactor Volumes (ft^3)	Ideal Facility Volume* (ft^3)	As-Built Facility Volumes TLTA-5 (ft^3)	As-Built Facility Volumes SHB (ft^3)
Lower Plenum	Bottom of vessel below lower tie plate	1904	3.05	3.09	3.04
Core	Fuel bundle from lower tie plate to top of fuel channel	1011	1.62	1.38	1.58
Upper Plenum	Above top of the fuel channel to top of the shroud	938	1.50	2.78	1.39
Annulus	Region outside core shroud from top of shroud to bottom of jet pump	1800	2.88	2.88	2.79 + piping volume
(Below Top of Jet Pump)		(1175)	(1.88)	(-)	(1.9)
(Above Top of Jet Pump)		(625)	(1.00)	(-)	(0.89 + piping volume)
Jet Pump	Jet Pump	181	0.29	0.29	0.30
Bypass	Leakage volume between tie plates	686	1.10	1.01	1.21
Steam Dome and Steam Separators	Region outside core shroud above top of shroud and region inside steam separators plus standpipe	8651	13.86	17.05	15.75 + piping volume
Guide Tube	Free GT volume and control rod-index tube	1103	1.77	1.90	1.83
TOTAL		16274	26.08	30.38	27.89 + piping volume

*Ideal Volume = Reactor Volume ÷ 624

NOTE: There are differences in the definitions used to calculate volumes between TLTA and SHB, specifically in the core and UP. The SHB definitions were used in determining all values above except those for TLTA as-built and result in larger core volume and smaller UP volume.

Table 3-3

ECCS TEST LOOP FLOW AREAS

Description	Area (in.^{2})	
Upper Tie Plate - Net Flow Area at Upper Bundle Exit	Stages 1 and 3 Stage 2	10.08 10.52
Top of Bypass - Flow Area at Elevation of Upper Tie Plate	Stages 1 and 2 Stage 3	9.45 9.06
Bypass - Flow Area Between Inner and Outer Channels	Stages 1 and 2 Stage 3	10.10 9.68
Guide Tube - Bypass Connection - Minimum Area Where GT is Connected to the Bypass		2.41 for each hose
	2 hoses =	4.81 Total
Side Entry Orifice		
d = 2.43 in.		4.64
d = 1.257 in.		1.25
Upper Plenum		39.28
Standpipe		11.11
Jet Pump		
Maximum		4.79
Minimum		0.86
Core - Rod Region Between Spacers		15.81
Annulus		
• Below Jet Pump		
• Maximum		30.38
• Minimum		25.25
• Above Jet Pump		8.35
Steam Dome		434
Guide Tube		180
Lower Plenum		
• Below Jet Pump Entry		244
• Above Jet Pump Entry		182

have deformed to a degree which makes them unsuitable for separate effect heat transfer testing. However, they are adequate for use in the Stage 1 system performance tests. Each of the simulated fuel rods has a double peaked axial profile, as shown in Figure 3-2. The power for the heated bundle is supplied by a 277-volt silicon controlled rectifier (SCR) d-c power supply. The individual heater rods are rated at 9 kW at 277 volts. The power is controlled by an automatic control system which can hold the bundle power constant or vary it by a preprogrammed power transient. A Piping and Instrumentation Diagram (P&ID) of the facility, as set up for the Stage 1 tests, is shown in Figure 3-3.

System performance tests will be conducted by establishing a set of steady-state initial conditions, and then initiating a transient refill-reflood test. Independent parameters are spray and/or LPCI flow and temperature, steam injection into the LP and/or GT, and bundle power and stored heat. The values for these parameters will be selected using the scaling approach to simulate the reference LOCA from the point when the pressure has reached 150 psia. Tests with variations of these parameters are also planned.

Stage 2 Tests will be performed with an adiabatic bundle of the same design as bundles in the 30-deg SSTF to be used for Task 4.4 testing. Both the Stage 1 heated bundle and the outer channel, which forms the bypass region around the bundle, will be removed and replaced with components designed to meet the requirements of Stage 2. The adiabatic bundle has been fabricated with a steam injection tube, weir assembly, and other components from the 30-deg SSTF bundles.[2] The inner and outer channel sections were fabricated to match the length and end flange dimensions of the ECCS Test Loop. This results in a bundle that is 61.742 inches longer than the Lynn bundle with the additional length accounted for in the lower rods. All other facility components and regional volumes are the same as used in the Stage 1 tests.

Stage 3 Tests will be performed with a new bundle which is made up of an 8x8 array of electrically heated simulated fuel rods including two water rods. Each of the heater rods will have a center peaked chopped cosine axial power profile. All other components are the same as for the Stage 1 tests.

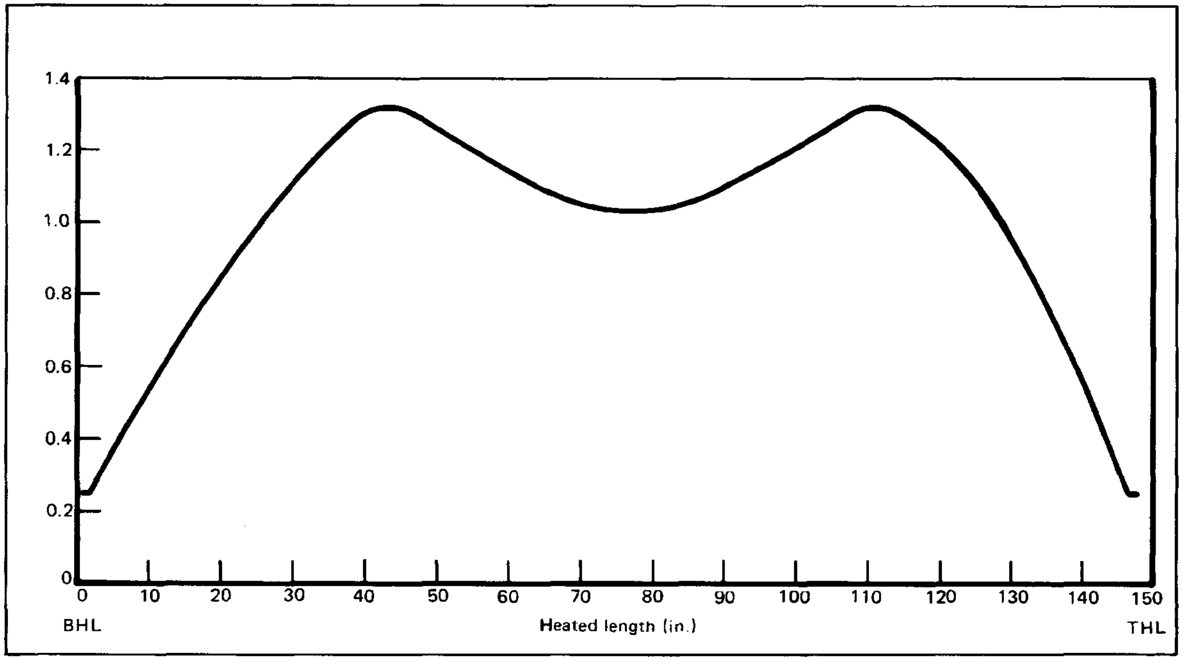


Figure 3-2. Stage 1 Heated Bundle Double Peak Axial Power Bundle

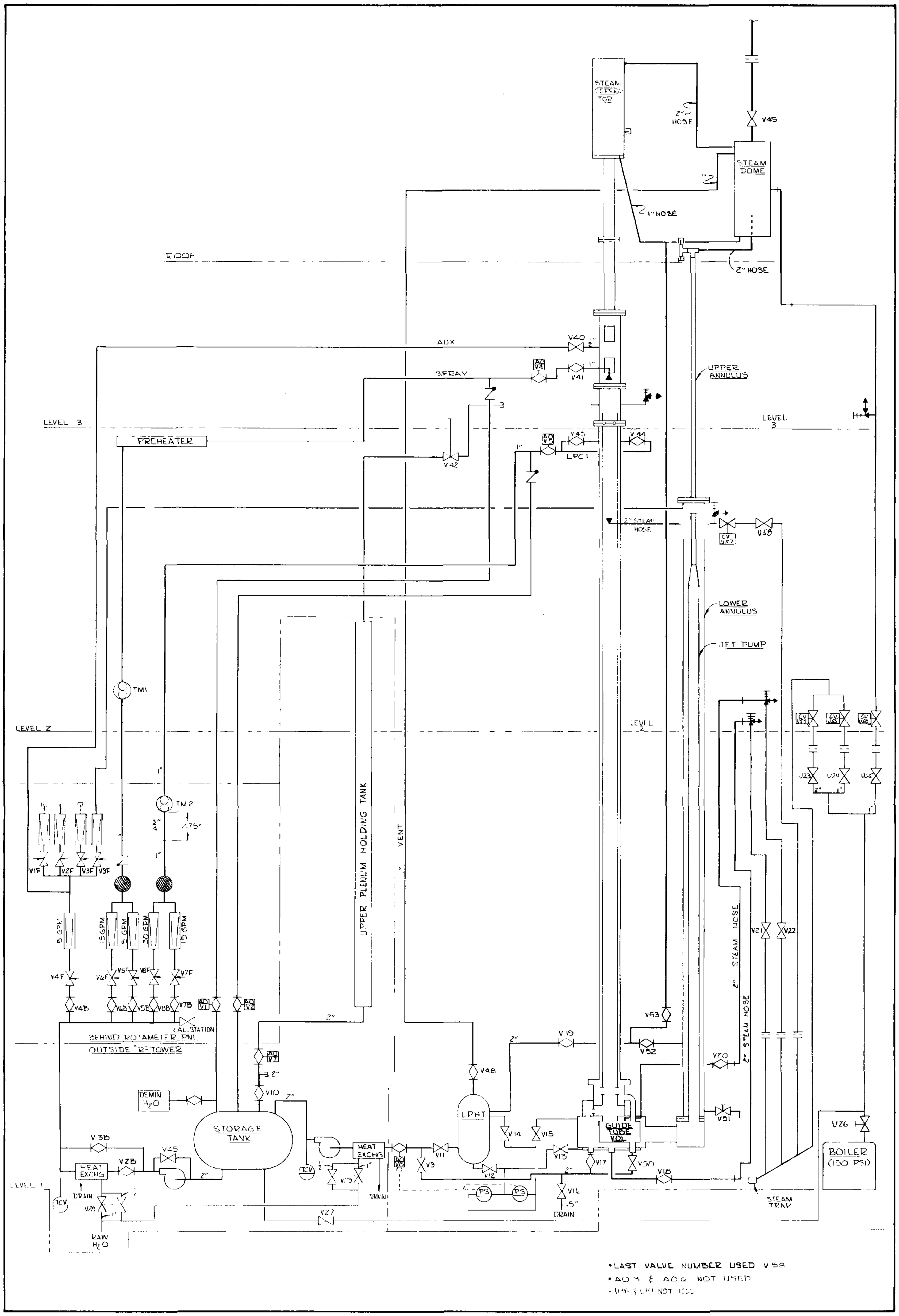


Figure 3-3. Stage 1 Heated Bundle Facility P&ID

Section 4

ADIABATIC INJECTION TECHNIQUE AND PRESSURE SCALING VERIFICATION

The approach for verifying that adiabatic channel steam injection can be used to simulate heated bundles for LOCA system testing is as follows:

1. To conduct a low pressure transient typical of the BWR/6 design basis accident (DBA) LOCA transient using a single electrically heated bundle (SHB) and record the experimental results of the simulation.

2. Replace the heated bundle with a Lynn adiabatic bundle (LAB) mock-up and repeat the same LOCA experiments with steam injection rates determined from SHB results.

3. Evaluate the results of these two experiments and, if the systems have the same response with both the adiabatic and the heated bundles, the adiabatic simulation is qualified as adequate. This comparison will take into account experimental uncertainty, as well as mechanical differences between the two bundles. Acceptance is based on the refill response of the two systems, ensuring that important phenomena are included in the comparison.

Since the ECCS Test Loop operates at or near atmospheric pressure, two pressure scaling parameters must be determined. First, the depressurization flashing must be simulated with steam injection. Second, compensation must be made for the difference in fluid properties (such as ρ_g and T_{sat}) between atmospheric pressure and the elevated pressures of the BWR/6 LOCA transient. The basis for the scaling has been determined and a detailed procedure for scaling from LOCA pressures to atmospheric pressure experiments has been developed (see Appendix A). The pressure scaling is verified by a direct comparison of TLTA LOCA refill and reflood with that of the SHB facility for a comparable test.

The objective of the pressure scaling is to simulate, in a constant pressure atmospheric test facility, the same liquid refilling transient that would occur at prototypical BWR LOCA pressures and depressurization rates. The pressure scaling basis used for the SHB atmospheric tests focuses on the sensitive CCFL controlled liquid flow rates. Therefore, the steam production rates due to the net effects of heat transfer, depressurization flashing and subcooled injection condensation were scaled to give the same CCFL water flow rates in the SHB LOCA simulation as in the TLTA depressurization LOCA transient. The TLTA test is used as the reference case.

A schematic of a BWR LOCA simulation facility, such as the SHB or TLTA, is given in Figure 4-1. This figure shows the leakage flow paths and heat transfer sources. Mass, energy and momentum balances were written for each of the regions shown in Figure 4-1. The pressure scaling basis, as discussed in detail in Appendix A, was arrived at by evaluating the effects of pressure on the phenomena governing the LOCA refill transient. The governing phenomena are the steam production due to heat transfer and depressurization flashing, the CCFL controlled liquid flow rates, the void fractions (static heads and region masses), and the jet pump flow losses (dominated by the local loss in the throat).

These phenomena do not all scale with pressure in exactly the same proportions. The scaling is based on the most sensitive of the phenomena, the CCFL controlled liquid flows. This results in some compromise in the other phenomena. These differences must be taken into account when comparing the SHB test results with the TLTA data for scaling verification.

Verification of the pressure scaling for simulating LOCA transients using atmospheric tests (SHB), is based on the following procedure: (a) Identify a reference TLTA depressurization LOCA test; (b) apply the pressure scaling to this test to obtain SHB test conditions (steam injection, bundle power and stored heat, ECCS subcooling, initial mass distribution); (c) perform an SHB test using these conditions; and (d) compare the SHB test results (region refilling versus time) with the TLTA reference data, evaluating the facility differences and scaling compromises using current LOCA methods.

Steps (a) and (b) of this procedure are given in Appendix B. The reference tests are TLTA-5A Test 6422 Run 3 and Test 6423 Run 3. The SHB scaled test inputs are given as well as the equations, assumptions and procedure for calculating them.

The pressure scaling, based on CCFL controlled liquid flow rates, was derived by applying mass and energy balances to each region of the test facility, starting with the liquid filling rates, which is the response to be simulated,

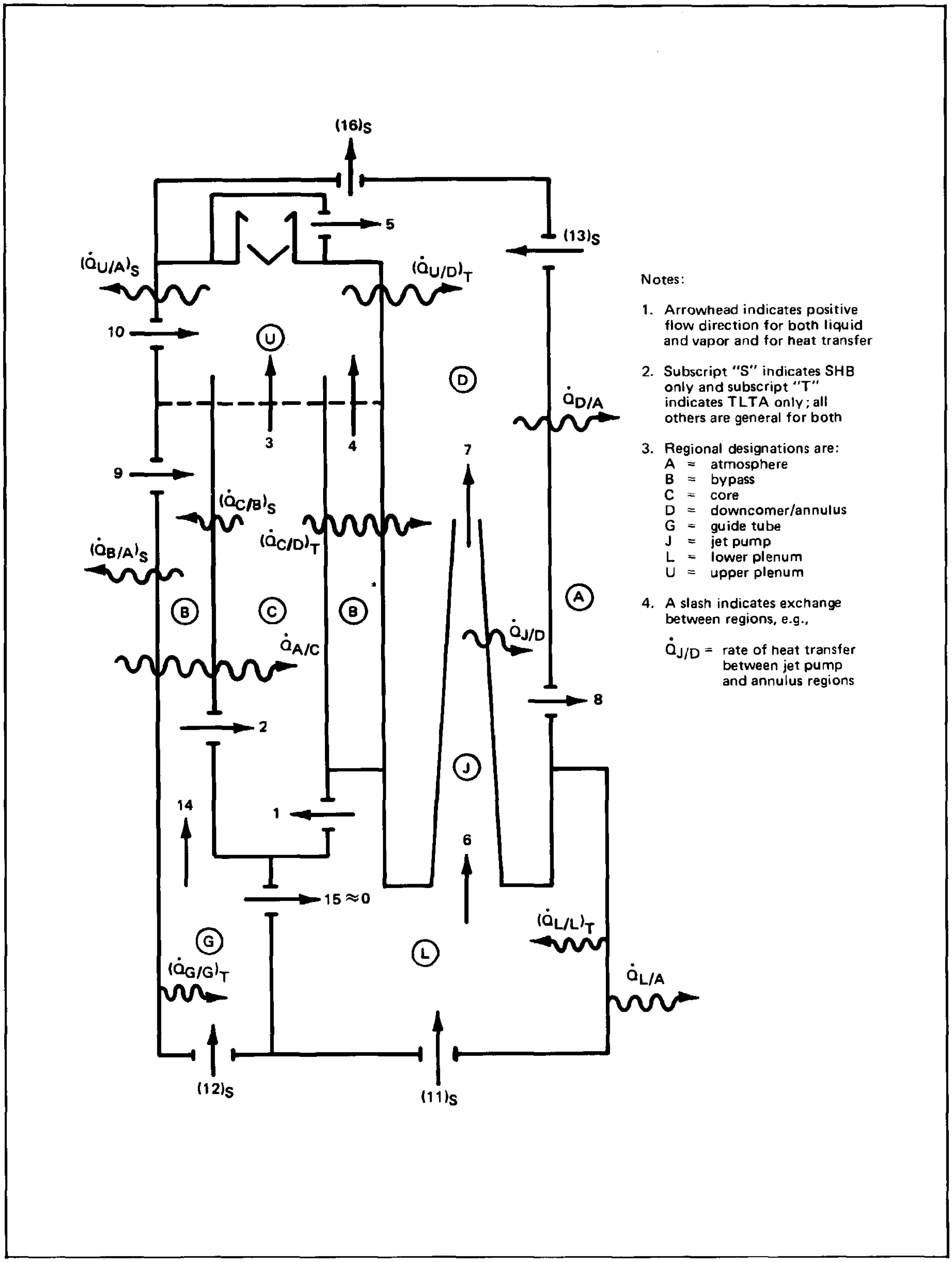


Figure 4-1. System Diagram

$$\dot{M}_f = \Sigma(W_f)_{in} - \Sigma(W_f)_{out} - W_{fg}$$

$$\approx \Sigma(W_f)_{in} - \Sigma(W_f)_{out} \quad . \qquad (1)$$

For several of the regions (LP, channel, bypass, and possibly the GT) one of the dominant liquid inflows is controlled by CCFL. Thus, using a typical modified-Wallis-type correlation, for m = 1 and where C includes the characteristic dimension,

$$W_{f_{CCFL}} = A_{CCFL}\, \rho_f^{1/2} \left[C\, (g\Delta\rho)^{1/4} - \left(\frac{W_{g_{CCFL}}}{A_{CCFL}\, \rho_g^{1/2}} \right)^{1/2} \right]^2$$

$$= f_{CCFL}\left(W_{g_{CCFL}}\right) \quad . \qquad (2)$$

where f_{CCFL} is used to represent a particular functional relationship or dependence between $W_{f_{CCFL}}$ and $W_{g_{CCFL}}$.

The objective of the pressure scaling is to make the liquid flow rates in the SHB equal to those in the TLTA. Therefore,

$$\left(W_{f_{CCFL}}\right)_S = \left(W_{f_{CCFL}}\right)_T \quad . \qquad (3)$$

To accomplish this, the steam flow, $W_{g_{CCFL}}$, must be adjusted in the SHB to account for differences in pressure and CCFL areas. The required adjustment in steam flow is found by combining Eq. 2 and Eq. 3.

The steam flow, W_{gCCFL}, is not a test parameter but is a result of the test. It is a function of the steam generated in the saturated region, as given by the conservation of steam mass,

$$W_{g_{CCFL}} = -\dot{M}_g + W_{fg} + \Sigma W_{g_{in}} - \Sigma W_{g_{out}} + W_{g_{injection}}$$

$$\approx W_{fg} + \Sigma W_{g_{in}} - \Sigma W_{g_{out}} + W_{g_{injection}} \qquad (4)$$

and the energy equation for the region,

$$W_{fg} \approx \frac{1}{h_{fg}} \left[\Sigma\dot{Q} - M_f \frac{dh_f}{dP} \dot{P} - \Sigma W_{f_{in}} \Delta h_{sub_{in}} \right] . \tag{5}$$

The CCFL scaling is applied to all terms in the steam generation equation including the subcooled condensation term. In this way, all of the steam flows will be scaled and the correct liquid flows should result.

The procedure for obtaining the SHB steam injection rates for simulating the TLTA depressurization flashing and any non-simulated heat transfer rates starts with first determining the steam generation rate in the TLTA,

$$\left(W_{fg_{Flash}}\right)_T = \frac{1}{h_{fg_T}} \left[\dot{Q} - M_f \frac{dh_f}{dP} \dot{P} \right]_T . \tag{6}$$

Next, the CCFL controlled liquid flow for this steam rate is found using Eq. 2,

$$\left(W_{f_{CCFL}}\right)_T = f_{CCFL} \left(W_{fg_{Flash}}\right)_T . \tag{7}$$

Since the scaling objective is to have equal liquid flows in the SHB and TLTA,

$$(W_{f_{CCFL}})_S = (W_{f_{CCFL}})_T . \tag{8}$$

The SHB steam rate that is equivalent to this liquid flow is,

$$\left(W_{g_{injection}}\right)_S = f^{-1}_{CCFL} \, (W_{f_{CCFL}})_S \tag{9}$$

where f^{-1}_{CCFL} is the inverse of the functional relationship in Eq. 7.

Since the SHB has no depressurization flashing, this steam must be injected into the appropriate region of the SHB. For scaling the bundle power a similar procedure is used. The steam produced by the TLTA electrically heated bundle is determined first,

$$\left(W_{fg_{elec}}\right)_T = \frac{1}{h_{fg_T}} (\dot{Q}_{elec})_T , \tag{10}$$

Then the same steps as in Eq. 7 and Eq. 8 are followed. Finally, the SHB scaled steam rate bundle power is calculated,

$$\left(W_{fg_{elec}}\right)_S = f^{-1}_{CCFL} \left(W_{f_{CCFL}}\right)_S \tag{11}$$

$$(\dot{Q}_{elec})_S = h_{fg_S} \left(W_{fg_{elec}}\right)_S \quad . \tag{12}$$

The ECCS scaled temperature is obtained by maintaining the same condensation capacity ratio in the SHB as in the TLTA. The condensation capacity ratio is defined as,

$$K_T = \left[\frac{W_{f_{spray}} C_p \left(T_{sat} - T_{spray}\right)}{\Sigma W_{g_{in}} h_{fg}}\right]_T \quad , \tag{13}$$

then for CCFL breakdown scaling, this capacity ratio should be matched,[3]

$$K_S = K_T \quad . \tag{14}$$

Imposing the condition of matched input ECCS flows,

$$(W_{spray})_S = (W_{spray})_T \quad , \tag{15}$$

and the definition of K_S,

$$(T_{spray})_S = (T_{sat})_S - K_S \left(\frac{\Sigma W_{g_{in}} h_{fg}}{W_{f_{spray}} C_p}\right)_S \tag{16}$$

This scaled ECCS temperature gives a steam condensation rate that is scaled in the same ratio as the steam energy injection rates, $W_g h_{fg}$. Thus, all the resultant steam flows are scaled to give the same CCFL controlled liquid flows in the SHB as in the TLTA at BWR prototypical pressures.

Section 5

DATA REQUIREMENTS AND MEASUREMENT PLAN

5.1 STAGE 1 AND STAGE 2 TESTS

A primary purpose of these tests is to determine if heated bundle conditions representative of a LOCA can be simulated in tests (such as the 30-deg SSTF) with adiabatic steam injection. The adequacy of this simulation will be judged on comparisons of data obtained from electrically heated bundle tests in Stage 1 and adiabatic bundle tests in Stage 2. These facilities are single channel simulations of a BWR/6 reactor system, and the comparison tests are simulations of a representative BWR/6 LOCA during the refill phase of the transient. Adiabatic simulation will be judged successful if the refill responses of the two sets of tests are the same within experimental repeatability and accuracy.

The measurement objectives for the Stage 1 and Stage 2 tests are:

1. To assure that the initial conditions specified for each test have been established. Initial conditions will include ECC flows and temperatures, inlet steam flows, liquid level in the LP and GT, and bundle power and temperatures. (Initial liquid levels are not established in the core and UP due to difficulty in assuring a controlled value; the UP level is accounted for by increasing the initial GT level; the core level is considered negligible.)

2. To determine the refill response of the LP, UP, GT, bypass, and core regions. The parameters include the regional liquid mass, temperature, and pressure.

3. To determine the refill-reflood system interaction performance and core steaming rate. The parameters include ECC flows and temperatures, break flow, inlet steam flows, internal steam flow splits, regional inventories (including collapsed level, mass amount of subcooling, temperature stratification, and void fraction), core power, and heat loss.

4. To provide sufficient auxiliary measurements to ensure efficient operation of the test loop, determine heater rod and channel wall temperatures, complete continuous strings of pressure differentials, and provide checks on the measurement system and verification of the data.

The data requirements are the same for both the Stage 1 SHB tests and the Stage 2 LAB tests. The rates of mass change, $\dot{m}$, for the fluid in each region are the dependent variables of interest. It is also necessary to measure a number of independent variables, summarized in Table 5-1 and shown schematically on Figure 5-1.

The mass and rates of mass change for the LP, GT, bypass, UP, and core regions are measured from differential pressure transducers. The initial test conditions are set up by providing a specified mass, m_o, of saturated liquid in the LP and GT and establishing steam flows, W_g, into each region. Control of these variables provides simulation of the proper inventory and flashing rate at the point in the depressurization transient at which the test is started. A steam flow is also established into the steam dome and out the stack to assure that a slight overpressure is maintained in the system to prevent the drawing of air into the system during the test. The mass values are determined by the same measurements made for rates of mass change, i.e., differential pressure, pressure, and temperature. The steam flows are determined by orifice differential pressure measurements and the associated pressures and temperatures.

Measurements of bundle mass and/or energy input are required to properly simulate the addition of both stored and decay heat. In the case of the adiabatic bundle, the rate of steam injection flow to the bundle is measured using an orifice differential pressure, pressure, and temperature. For the heated bundle, it is necessary to establish the initial temperature of the rods in the bundle, T_{oc}, to properly simulate stored heat.

The tests measure the flow of subcooled liquid through the spray and/or LPCI lines with a turbinemeter in each line, and the amount of subcooling is determined by measuring the temperature of the injected liquid, T_{ECC}.

The various absolute and differential pressure measurements may be grouped into three major categories:

(a) measurements of flows which cross the test section system control volume (external flows);

(b) measurements of flows which are within the test section control volume (internal flows); and

(c) measurements of the regional mass inventories.

Table 5-1

DEPENDENT AND INDEPENDENT VARIABLES

Dependent Variables of Interest:

m_U, $\dot{m}_U$	mass and mass rate in UP
m_L, $\dot{m}_L$	mass and mass rate in LP
m_G, $\dot{m}_G$	mass and mass rate in GT
m_B, $\dot{m}_B$	mass and mass rate in bypass
m_C, $\dot{m}_C$	mass and mass rate in core
T_C	bundle temperature

Independent Variables Controlled:

m_{OL}	initial mass in LP
m_{OG}	initial mass in GT
W_{gL}	steam injection rate into LP
W_{gG}	steam injection rate into GT
W_{gD}	steam injection rate into steam dome
W_{gC} [a]	steam injection rate into core
$\dot{Q}_C$ [b]	bundle power rate of change
T_{OC} [b]	initial bundle temperature
Q_{OC} [b]	initial bundle power
W_{spray}	spray injection rate
W_{LPCI}	LPCI injection rate
T_{ECC}	spray and LPCI temperature

---

[a] Adiabatic bundle

[b] Heated bundle

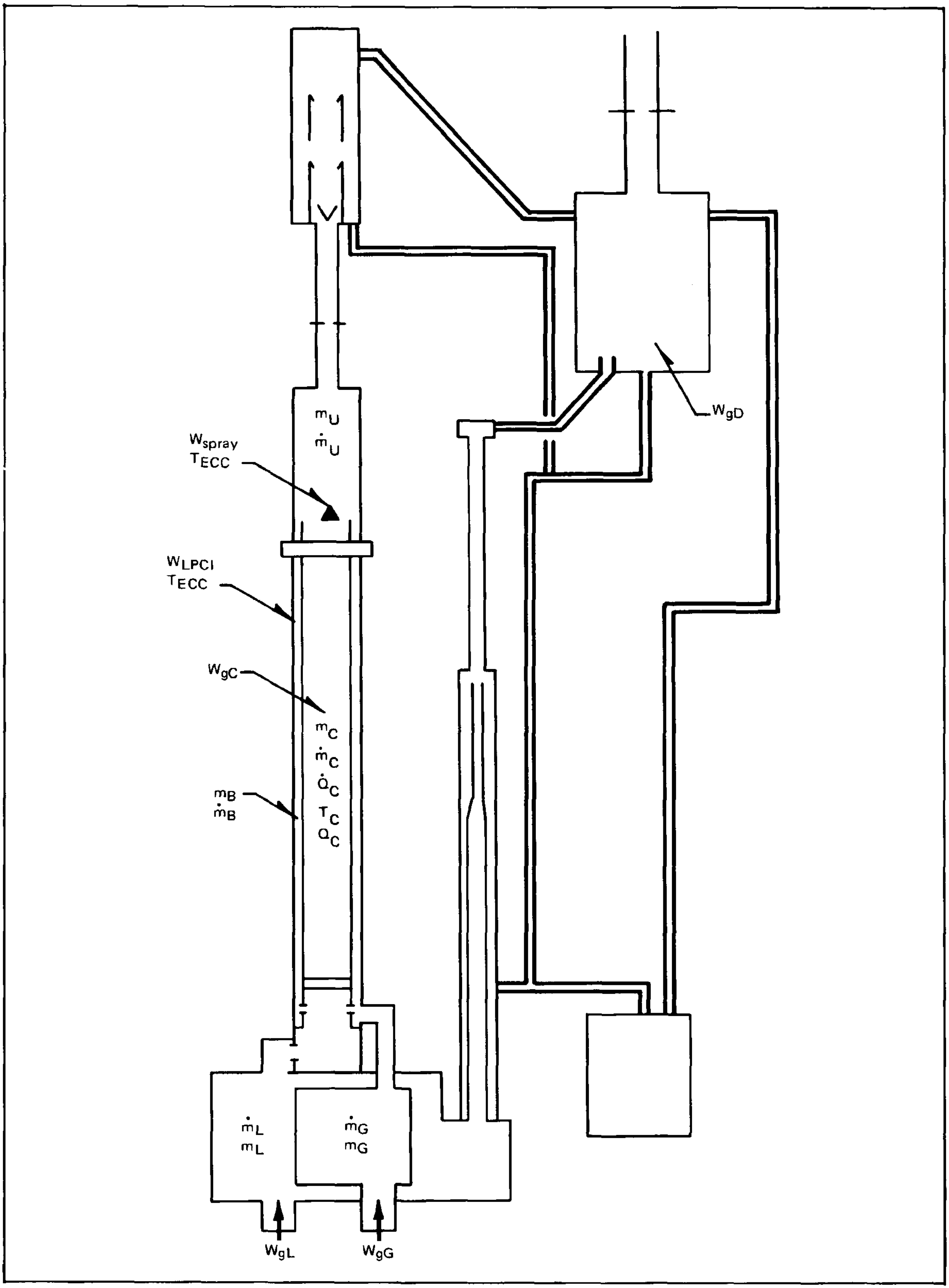


Figure 5-1. Data Requirements for Stage 1 and 2 Tests

Measurements of the internal flows aid in the determination of core vaporization rate and steam flow split between the core and jet pump. The measurement groupings used to determine the external and internal flows are shown in Figure 5-2. The differential pressures shown in Figures 5-3 and 5-4 provide for tracking of the collapsed level within the test section. Secondary measurements are also provided to verify the sum of differential pressure strings. The temperature measurements shown in Figures 5-5 and 5-6 monitor the degree of subcooling in the various regions and provide a means for detecting subcooled CCFL breakdown at flow restrictions, e.g., the side entry orifice (SEO), upper tie plate, and top of the bypass (TOB). The relative locations of the BHL and the ECC injection points are shown for reference on the temperature measurement figures. The locations of temperature measurements for the Stage 1 SHB test relative to the rod power profile are shown on Figures 5-7, 5-8, and 5-9 for the heater rods (10 axial locations), inner channel (8 axial locations plus 3 additional at the lower peak), and outer channel (all 4 sides at 3 axial locations), respectively. Power measurements are made for each of the 62 heater rods individually and for each of the 9 rod groups. The rod groupings are shown in Figure 5-10. Total bundle power is the calculated sum of the nine groups.

5.2 STAGE 3 TESTS

The data requirements and measurement plan for the Stage 3 SETs will be addressed in an addendum to this Experimental Task Plan.

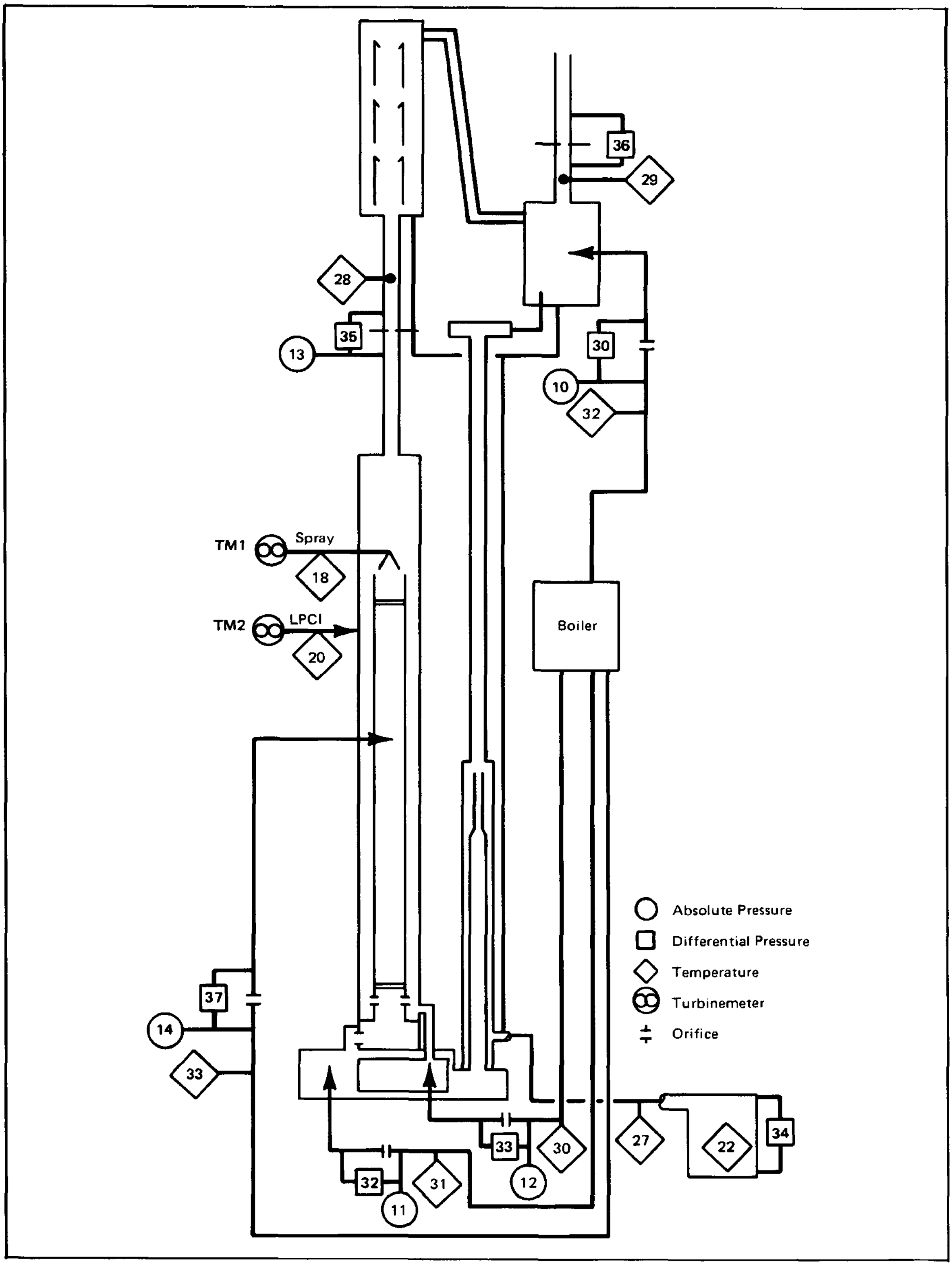


Figure 5-2. Internal and External Flow Measurements

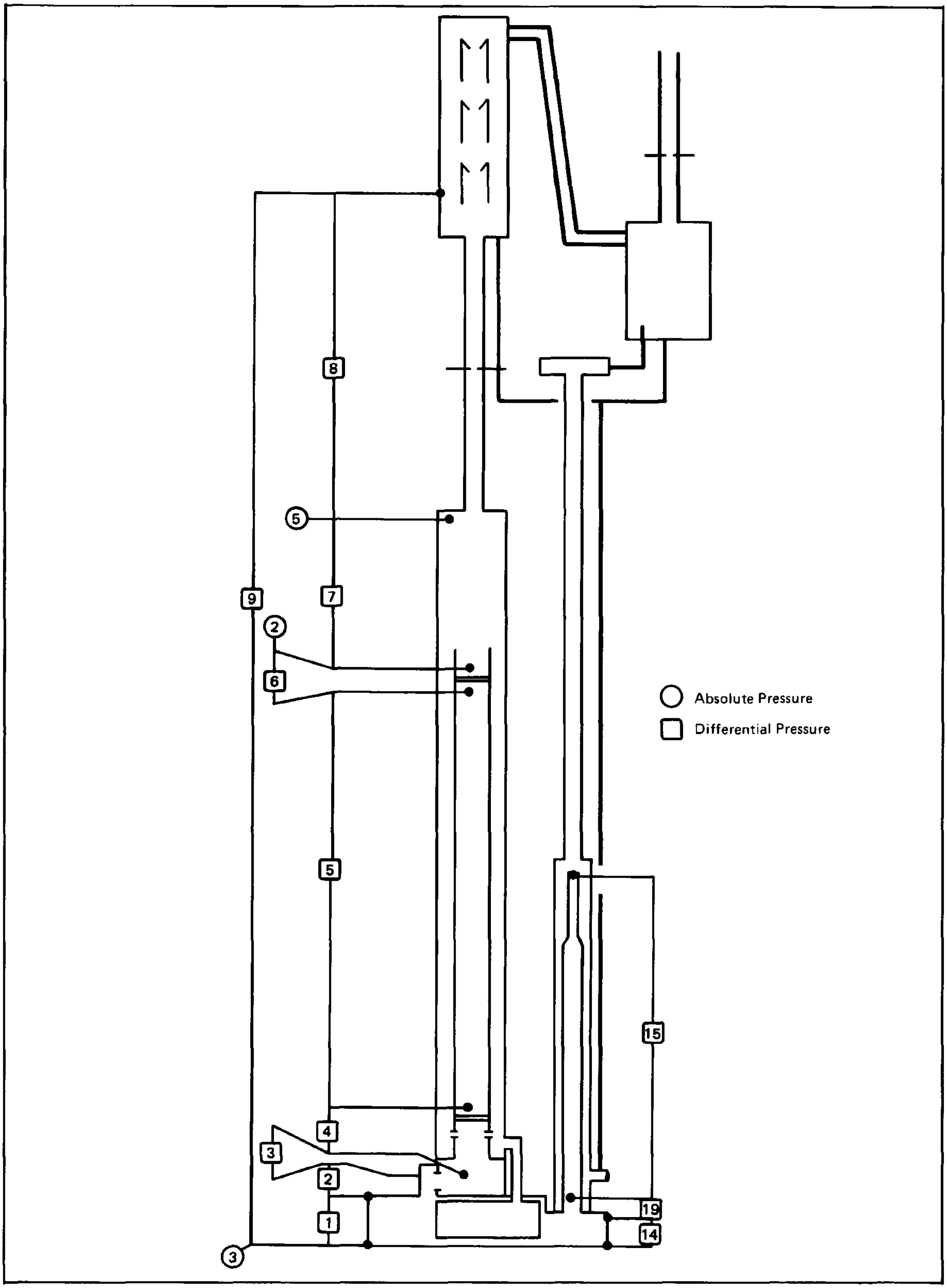


Figure 5-3. Collapsed Level Differential Pressure Measurements
(Lower Plenum and Jet Pump Strings)

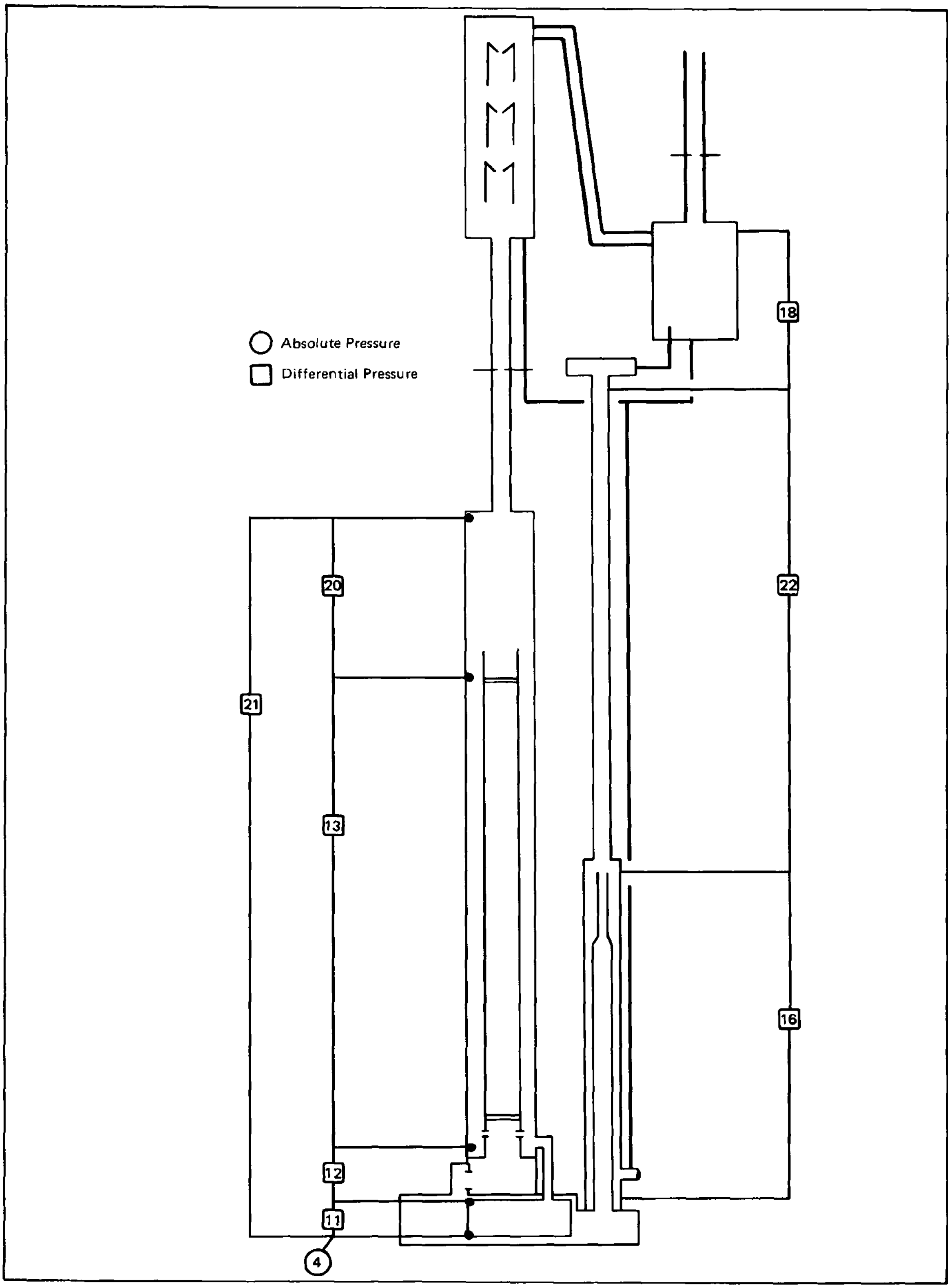


Figure 5-4. Collapsed Level Differential Pressure Measurements (Guide Tube and Annulus Strings)

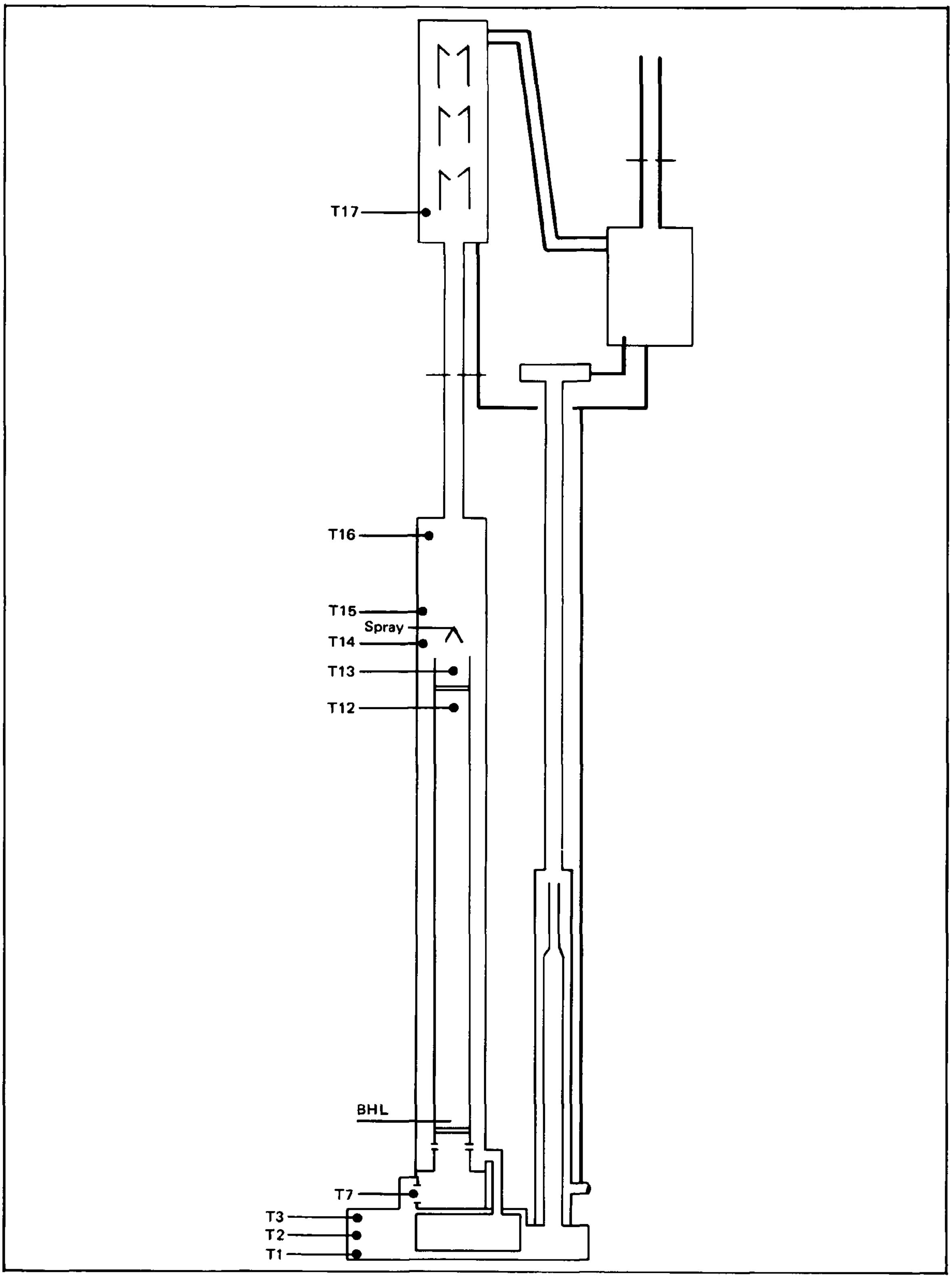
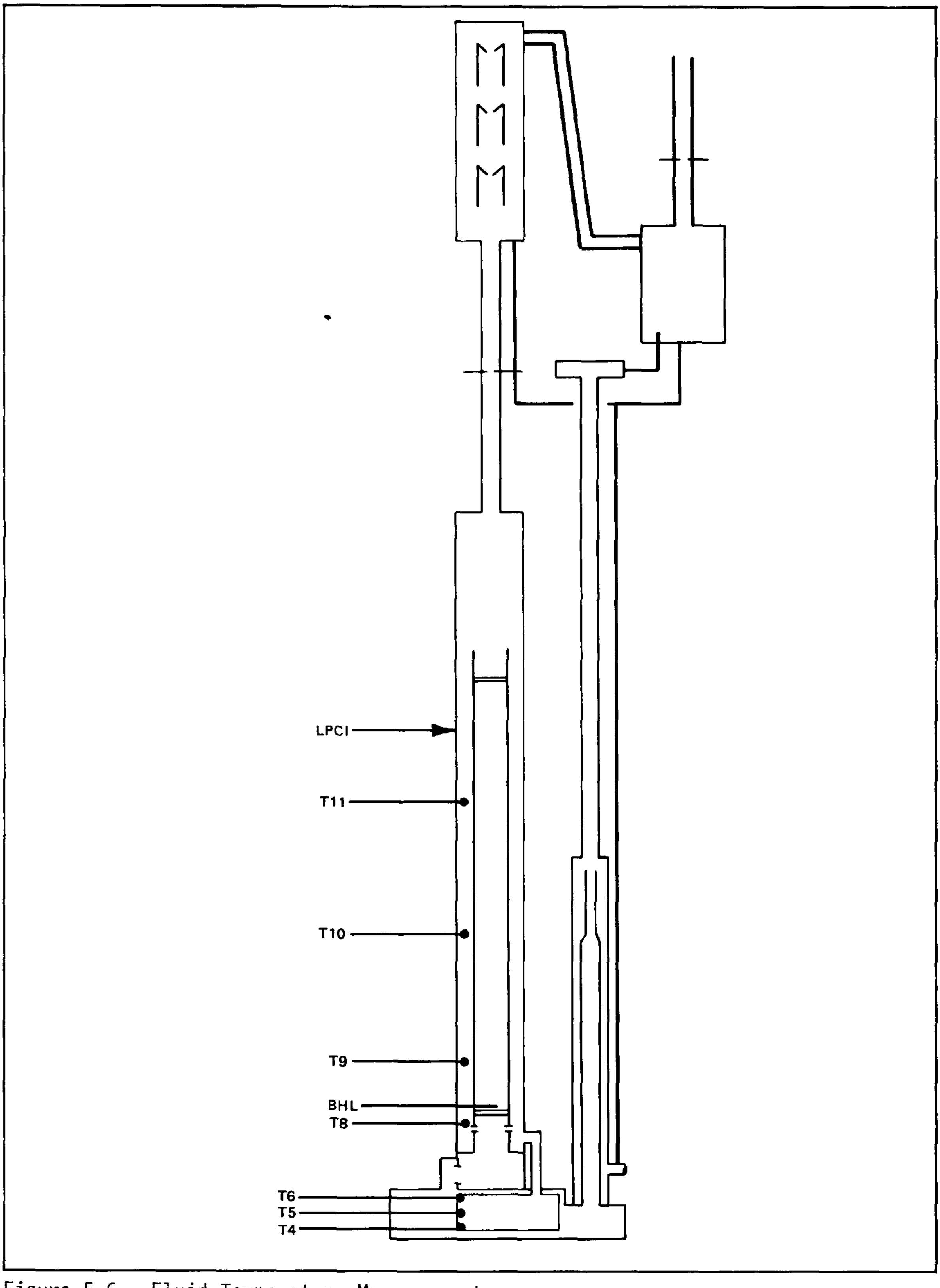


Figure 5-5. Fluid Temperature Measurements (Plena and Bundle String)



Fiqure 5-6. Fluid Temperature Measurements
(Guide Tube and Bypass String)

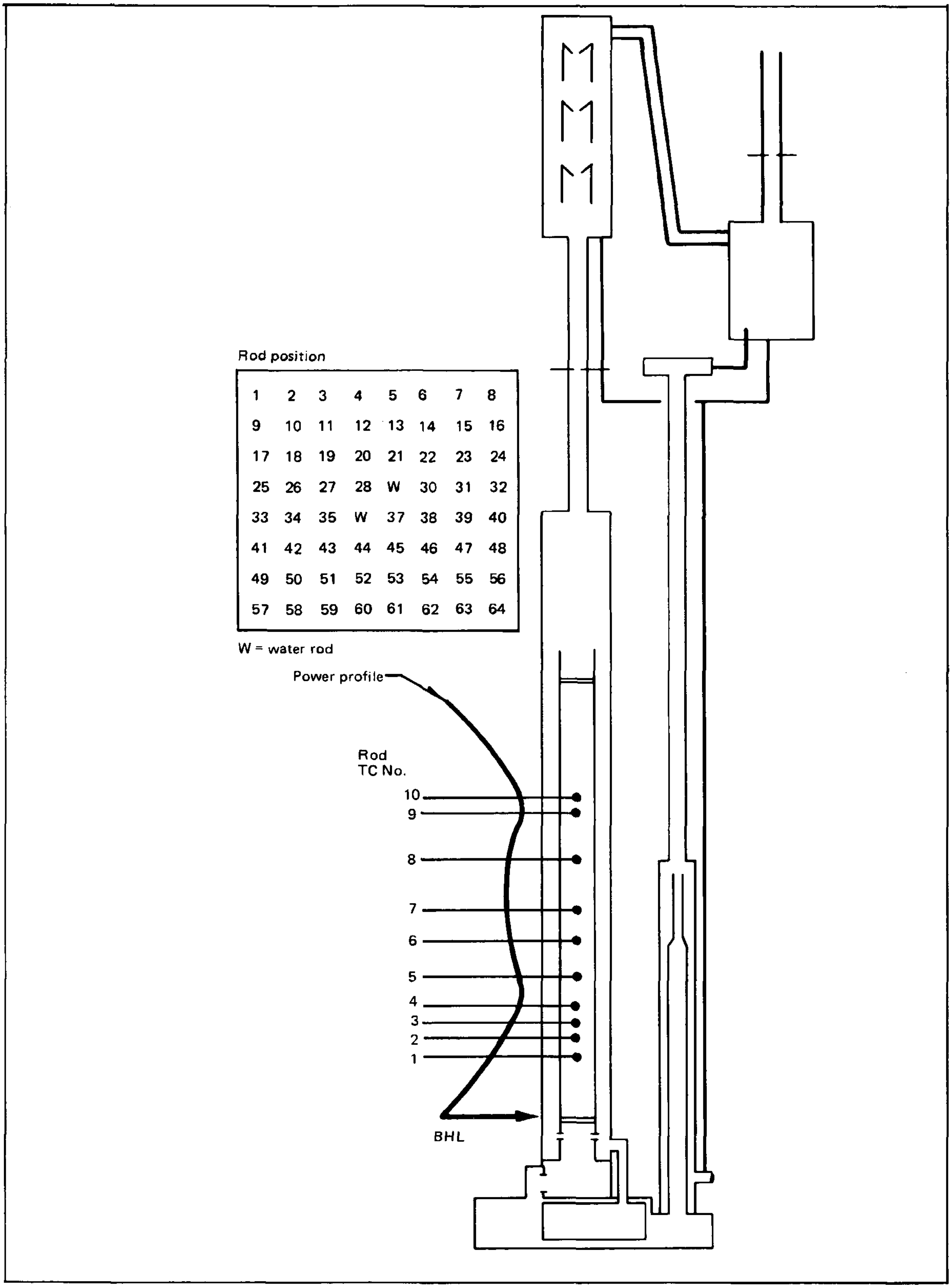
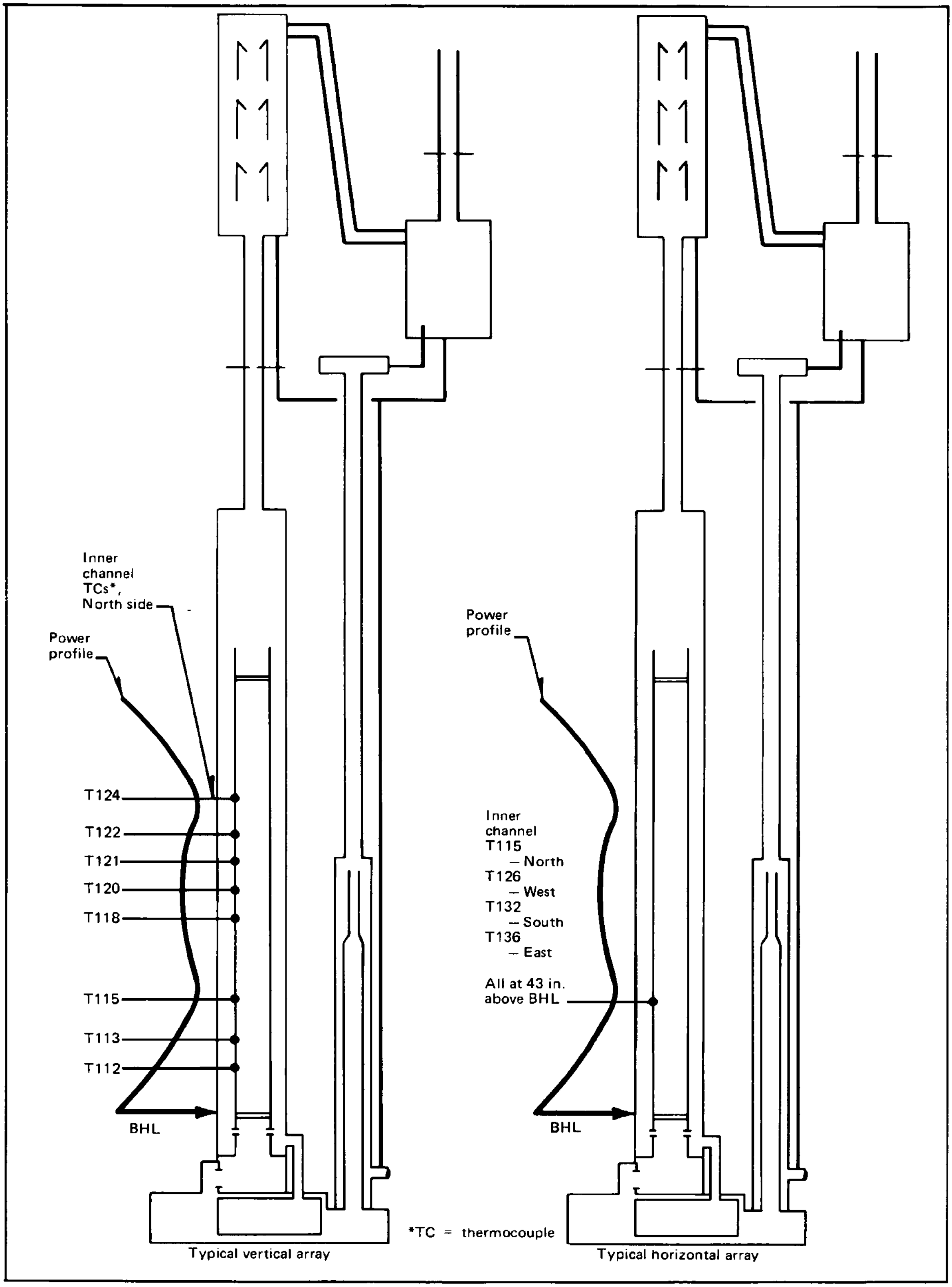


Figure 5-7. Temperature Measurements
(Heater Rods)



Fiqure 5-8. Temperature Measurements (Inner Channel)

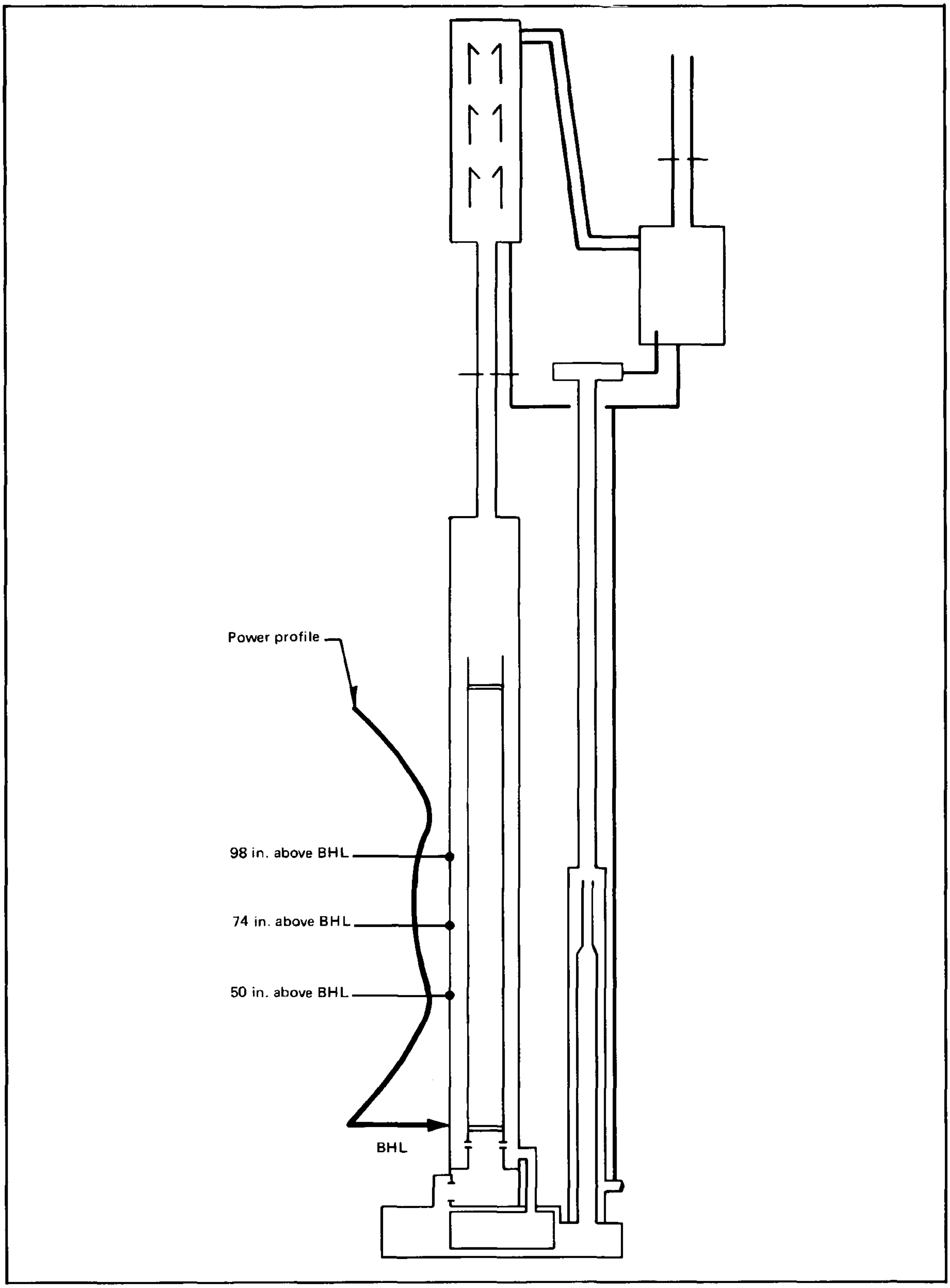


Figure 5-9. Temperature Measurements (Outer Channel)

ROD POSITIONS

GROUP 1 — 10, 15, 50, 55

GROUP 2 — 19, 20, 22, 27, 38, 43, 45, 46

GROUP 3 — 1, 8, 13, 31, 34, 52, 57, 64

GROUP 4 — 3, 17, 21, 28, 30, 35, 37, 48, 62

GROUP 5 — 4, 5, 25, 32, 33, 40, 44, 60, 61

GROUP 6 — 2, 7, 9, 16, 49, 56, 58, 63

GROUP 7 — 6, 12, 24, 26, 39, 41, 53, 59

GROUP 8 — 11, 18, 47, 54

GROUP 9 — 14, 23, 42, 51

ROD POSITIONS

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	W	30	31	32
33	34	35	W	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

W = WATER ROD

Figure 5-10. Heater Rod Power Groupings

Section 6

TEST PARAMETERS AND TEST MATRIX

6.1 STAGE 1 TESTS

The Stage 1 SHB tests are divided into three groups for convenience in discussing the test parameters and utilization of test data.

The first group of 11 tests is designed to evaluate the pressure scaling basis which will be verified in the second series of tests utilizing the TLTA-5A test results. Specified results from this group of tests include:

1. Determination of SHB refill-reflood performance with scaled TLTA-5A parameters to evaluate facility adequacy.
2. Variation of the initial core bulk temperature to investigate the effect of stored energy on the refill-reflood performance.
3. Variation of the LP steam injection rate to assess the effect of the uncertainty in the TLTA-5A LP flashing rate (the major uncertainty is in evaluating the amount of steam generated by the TLTA LP wall heat transfer).
4. Variation of the GT steam injection rate to assess the uncertainty in determining the TLTA GT/bypass flashing rate (uncertainties due to nonprototypicality of the TLTA core to bypass wall heat transfer).

This group of tests is summarized in Table 6-1. The bundle power during each test follows the normalized power decay shown in Figure 6-1. The test parameter values were based on preliminary pressure scaling considerations which were refined for the later tests.

The second group of five tests is designed to confirm the pressure scaling technique discussed in Section 4 and in Appendices A and B. Specifically, the tests provide:

1. The base case for scaling confirmation which is scaled to simulate the average power/average ECC TLTA-5A test 6422 Run 3.

Table 6-1

PRELIMINARY SCALING EVALUATION AND SENSITIVITY TESTS

Run Number	Initial Core Power (kW)	Initial Rod Temperature (°F)	Lower Plenum Steam (lbm/hr)	Guide Tube Steam (lbm/hr)
0200	0	1020	470	85
0301	85	1020	470	85
0400	85	250	470	85
0500	0	310	470	85
0600	85	650	470	85
0700	85	800	470	85
0800	85	800	50	85
0900	85	800	185	85
1000	85	800	325	85
1100	85	800	470	0
1200	85	800	470	185

All tests

- Spray Flow 19.2 gpm
- LPCI Flow 6.6 gpm
- ECC Temp 120°F

Initial masses

- Lower plenum 60 lbm
- Guide tube 90 lbm
- Annulus 12 lbm

Steam Dome Steam - 50 lbm/hr for Run 0200 and 100 lbm/hr for others

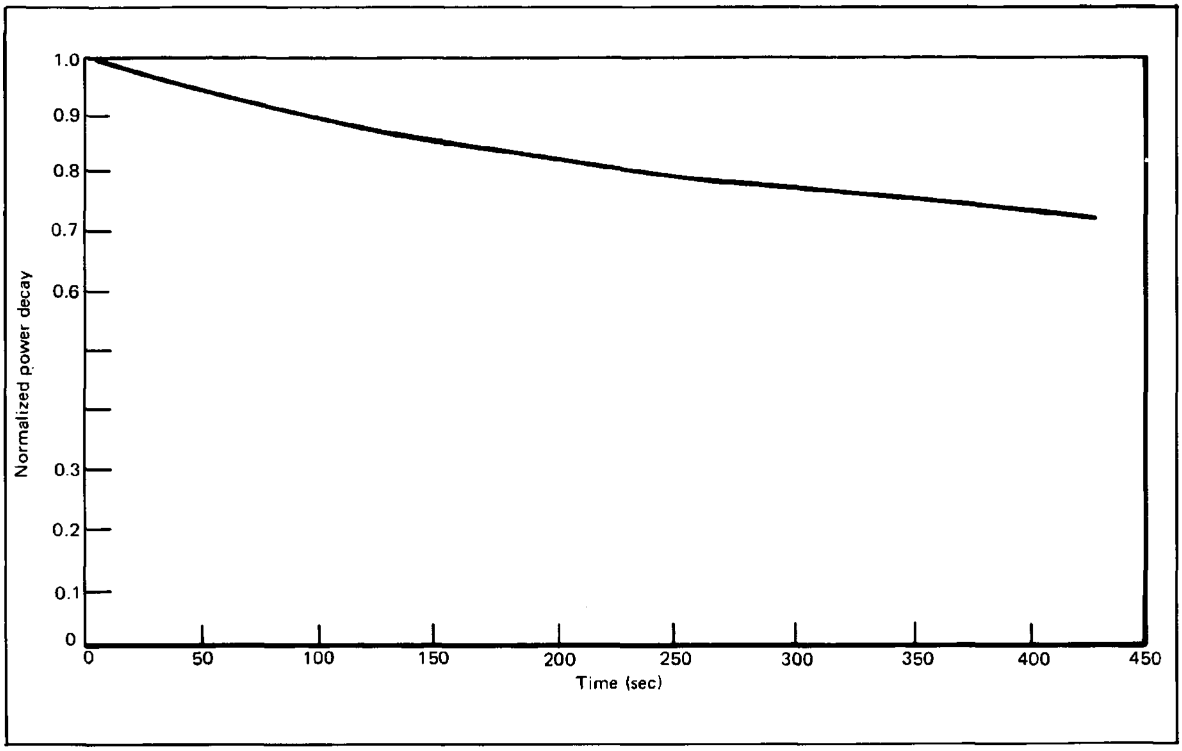


Figure 6-1. Single Heated Bundle Power Decay

2. An increased LP injection case to evaluate the uncertainty in determining TLTA LP wall heat transfer and LP flashing rate.

3. An increased GT injection case to evaluate the uncertainty in determining the TLTA GT flashing rate.

4. A high core power case to evaluate the uncertainty in determining the core steam generation resulting from core heat (the power used for this test approximates the total TLTA-5A power, i.e., power is not scaled).

5. A lower bound case on scaled core power which corresponds to scaled TLTA power with no core-to-bypass heat transfer (bundle power for this case follows the scaled TLTA power transient shown in Figure 6-2).

This group of tests is summarized in Table 6-2.

The third group of seven tests provides the reference heated bundle cases for the Stage 2 adiabatic bundle to evaluate adiabatic steam injection simulation of heated bundle performance. To cover the range of BWR conditions, scaled values for initial bundle power and initial bulk core temperature are included for peak, average, and low power bundles. The low power case is run for the 1.257-in.-diam

Table 6-2

SCALING CONFIRMATION TESTS

	Core		Steam Injection			ECC			Initial Masses		
Run Number	Power (kW)	Initial Core Temp. (°F)	Lower Plenum (lbm/hr)	Guide Tube (lbm/hr)	Steam Dome (lbm/hr)	Spray (gpm)	LPCI (gpm)	Temp. (°F)	Lower Plenum (lbm)	Guide Tube (lbm)	Annulus (lbm)
1302*	100	250	260	86	100	17.1	6.3	130	56	110	12
1400	100	250	378	86	100	17.1	6.3	130	56	110	12
1500	100	250	260	130	100	17.1	6.3	130	56	110	12
1600	145	250	260	86	100	17.1	6.3	130	56	110	12
1700	45 (Transient)	250	260	86	100	17.1	6.3	130	56	110	12

*Corresponds to TLTA-5A Test 6422 Run 3.

SEO located in peripheral fuel support as well as for the 2.43-in. central bundle fuel support size used for the other cases. A hot voided bundle case is included, with initial rod temperatures, GT injection, and ECC flows specified to eliminate downflow in the bypass and provide CCFL at the upper tie plate. For all of the cases the bundle power follows the scaled TLTA transient power* shown in Figure 6-2. The final test runs are adiabatic simulations of the hot voided bundle case, in which steam is injected near the bottom of the rod bundle at a rate approximating the heated bundle steam production. This group of tests is summarized in Table 6-3.

6.2 STAGE 2 TESTS

The first six Stage 2 LAB tests duplicate the conditions of the reference heated bundle tests from Stage 1, except that core steam injection rates will be determined to simulate the decay power and stored energy of the heated bundle. The last two Stage 2 LAB tests represent high power, low ECC flow conditions scaled from TLTA-5A Test 6423 Run 3; the corresponding heated bundle tests will be run during Stage 3. This group of tests is summarized in Table 6-4.

6.3 STAGE 3 TESTS

The test parameters and test matrix for the Stage 3 SETs will be addressed in an addendum to this Experimental Task Plan.

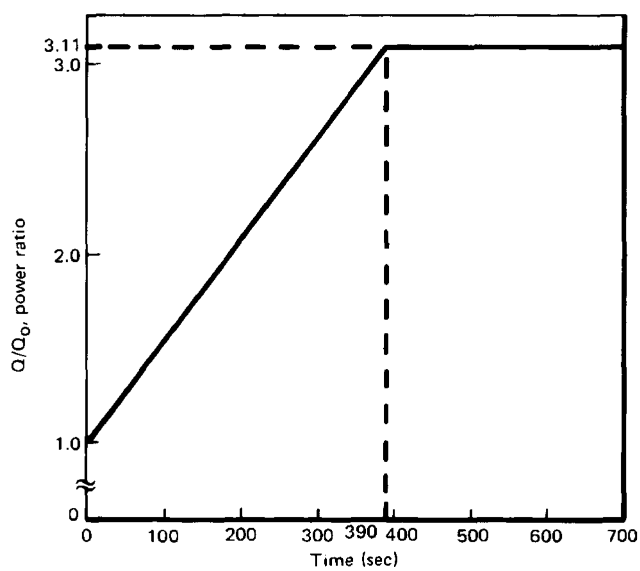


Figure 6-2. Scaled TLTA Power Transient

*See Appendix B for explanation of shape of curve.

Table 6-3

ADIABATIC INJECTION EVALUATION TESTS
(SHB REFERENCE CASES)

Run Number	Test Description	Initial Power (kW)[a]	T_i[b] (°F)	Steam Injection (lb/hr) Lower Plenum	Guide Tube	Steam Dome	Core	ECC Flow (gpm) Spray	LPCI	ECC Temp (°F)	SEO Diam. (in.)	Initial Mass (lbm) Lower Plenum	Guide Tube	Annulus
1800	Average Power Bundle	45	250 (480)	155	86	100	0	17.1	6.3	130	2.43	56	110	12
1901	High Power Bundle	59	400 (620)	155	86	100	0	17.1	6.3	130	2.43	56	110	12
2000	Low Power Bundle	23	220 (370)	155	86	100	0	17.1	6.3	130	2.43	56	110	12
2100	Low Power Bundle	23	220 (370)	155	86	100	0	17.1	6.3	130	1.257	56	110	12
2202	Hot-Dry Bundle	59	1000 (2000)	155	500	100	0	25	0	120	2.43	150	0	12
2300	Adiabatic Simulation of Hot Dry Bundle	0	N/A	155	500	100	*	25	0	120	2.43	150	0	12
2400	Adiabatic Simulation of Hot Dry Bundle	0	N/A	155	500	100	*	25	0	120	2.43	150	0	12

*Bundle steam injection to be determined from results of Test 2202. Test 2300 assumed 50% of LP steam going to the core and Test 2400 assumed 100%.

[a]Bundle power is increased linearly from initial power.

[b]T_i = bulk core temperature at start of power transient. Values in parentheses indicate equivalent TLTA/Reactor temperatures.

Table 6-4

ADIABATIC INJECTION EVALUATION TESTS
(LAB DEMONSTRATION CASES)

Run Number	Test Description	Steam Injection (lbm/hr) Lower Plenum	Guide Tube	Steam Dome	Core	ECC Flow (gpm) Spray	LPCI	ECC Temp (°F)	SEO Diam (in.)	Initial Mass (lbm) Lower Plenum	Guide Tube	Annulus
3900	Adiabatic Simulation of Avg. Power Bundle	155	86	100	*	17.1	6.3	130	2.43	56	110	12
2600	Adiabatic Simulation of High Power Bundle (w/o stored heat)	155	86	100	*	17.1	6.3	130	2.43	56	110	12
4000	Adiabatic Simulation of High Power Bundle (w/stored heat)	155	86	100	*	17.1	6.3	130	2.43	56	110	12
2700	Adiabatic Simulation of Low Power Bundle	155	86	100	*	17.1	6.3	130	2.43	56	110	12
2800	Adiabatic Simulation of Low Power Bundle	155	86	100	*	17.1	6.3	130	1.257	56	110	12
2901	Adiabatic Simulation of Hot-Dry Bundle	155	500	100	*	25	0	120	2.43	150	0	12
4301**	Adiabatic Simulation of High Power, Low ECC Bundle (BWR-like)	187.2	151.2	100	*	7.1	6.9	118	2.43	52	71	12
4400**	Adiabatic Simulation of High Power, Low ECC Bundle (TLTA-like)	399.6	151.2	100	*	7.1	6.9	124	2.43	52	71	12

*Bundle Steam injection to be determined on the basis of results from Run Numbers 1800-2202.
**Correspond to TLTA-5A Test 6423 Run 3.
Note: A limited number of upper tie plate CCFL tests will also be run with the LAB.

Secion 7

DATA UTILIZATION

7.1 STAGE 1 AND STAGE 2 TESTS

Utilization of the data from the Stage 1 and Stage 2 tests follows the same groupings as identified in discussing the test matrix in Section 6.

Results of the 11 tests in the first group will evaluate the refilling characteristics of the various regions to determine if the responses are similar to the TLTA. Refill times for the LP and core regions will be plotted as a function of the initial rod temperature, LP steam injection rate, and GT steam injection rate as indicated on the diagrams presented in Figure 7-1.

The five pressure scaling confirmation tests will be compared with the responses of TLTA-5A Test 6422 Run 3 and Test 6423 Run 3 to evaluate the pressure scaling technique and to determine the sensitivity of the technique to uncertainties in the data. The results will also demonstrate the use of steam injection to represent depressurized flashing in the GT and LP. Specific responses to be compared are indicated on the diagrams presented in Figure 7-2. The schematic TLTA-5A responses are based on those presented and discussed in Appendix B; Figure 7-2 indicates which Stage 1 tests will be compared with each one. The dotted lines on the flashing and power diagrams represent uncertainties in the TLTA data. The parametric Stage 1 tests indicated will help to qualify these uncertainties.

The Stage 1 and Stage 2 tests will be used to evaluate the adiabatic steam injection simulation of heated bundle performance. The heated bundle test results will be used to determine the bundle steam injection rates to be used in the adiabatic bundle tests. The responses of primary interest are the regional masses as depicted in Figure 7-3. Also shown in Figure 7-3 are the individual heated bundle and adiabatic bundle tests which will be compared.

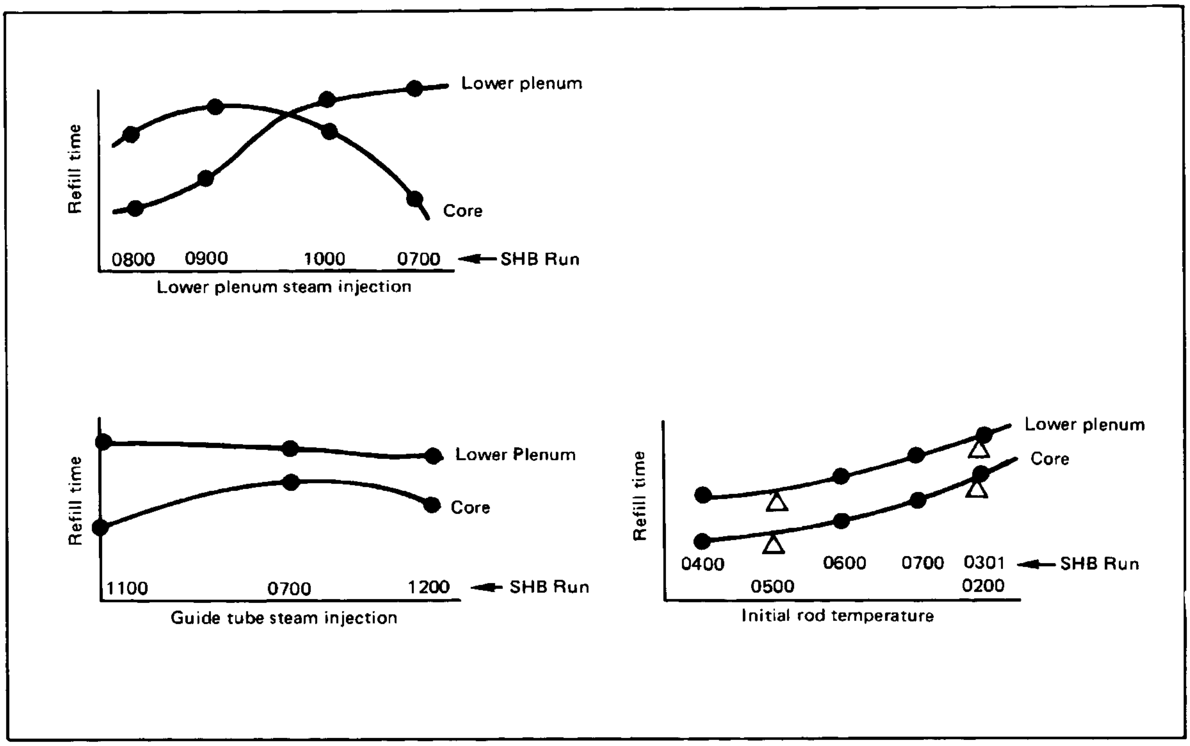


Figure 7-1. Data Utilization - Preliminary Demonstration and Sensitivity Tests

Specification of representative 30-deg SSTF core steam injection rates to simulate the vaporization rates from heated bundles during a representative BWR/6 DBA LOCA transient will be accomplished by:

1. Defining the representative BWR/6 DBA LOCA transient, channel boundary conditions, bundle power and initial rod temperature for average, peak, and low power regions. TLTA data and analytical methods will be used to estimate net steam generation.

2. Converting these net steam generation rates to steam injection rates at the 30-deg SSTF (BWR/6) pressure conditions. Results from the Stage 1 SHB tests and the Stage 2 LAB tests will be considered in converting the vaporization rates to injection rates.

7.2 STAGE 3 TESTS

Data utilization for the Stage 3 SETs will be addressed in an addendum to this Experimental Task Plan.

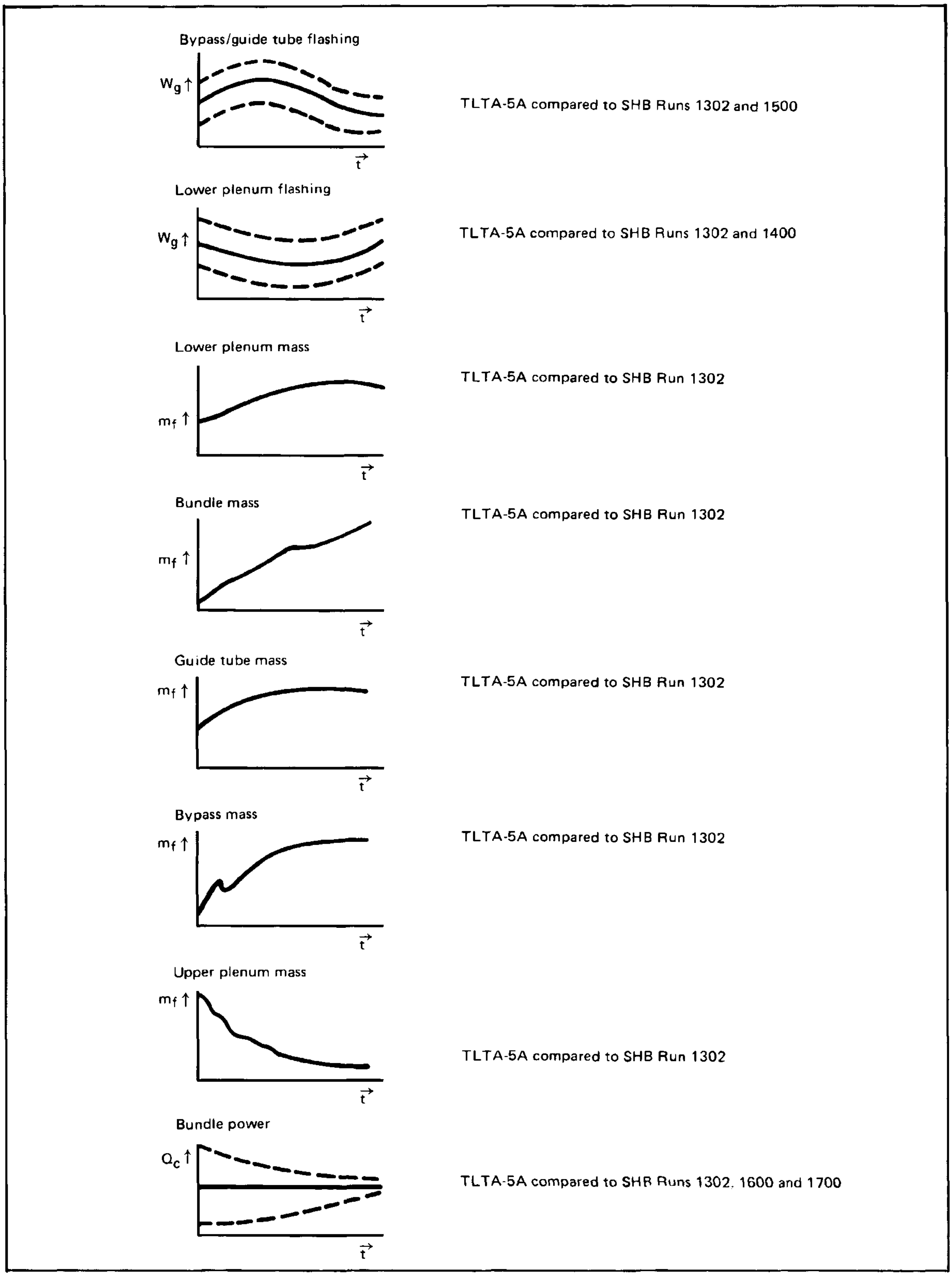
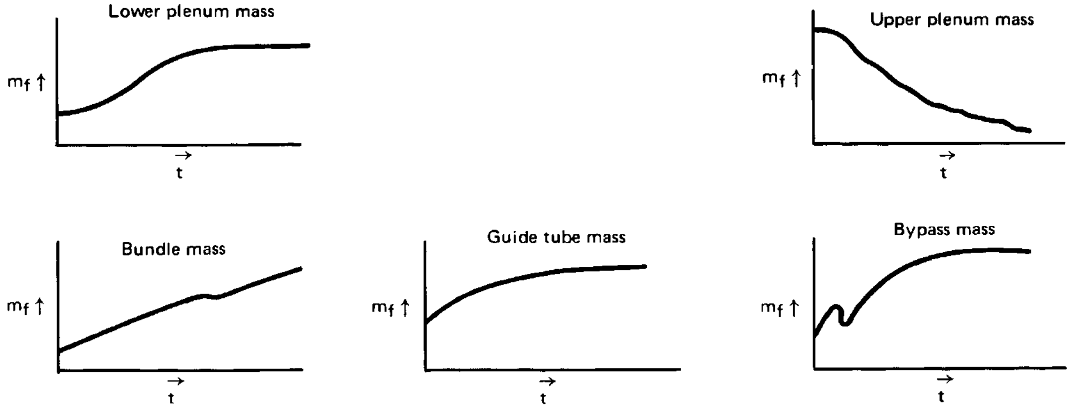


Figure 7-2. Data Utilization - Pressure Scaling Confirmation Tests



Bundle Characteristic	SHB Run	compared to	LAB Run
Average power	1800		3900
High power	1901		2600
Low Power			
Large orifice	2000		2700
Small orifice	2100		2800
Hot-dry			
Heated	2202		2901
Adiabatic	2300		
	2400		

Figure 7-3. Data Utilization - Adiabatic Injection Evaluation Tests

Section 8

SCHEDULE

The schedule for the Task 4.3 testing is shown in bar chart form in Figure 8-1. The Stage 1 tests were initiated in November 1979, and continued into February 1980. The heated bundle will be removed and replaced with the adiabatic bundle for Stage 2 testing to be conducted in April 1980. Hardware for the Stage 3 heated bundle will be procured during the first quarter of 1980, so that bundle assembly and installation can follow the Stage 2 tests, and Stage 3 testing can be performed during the third quarter of 1980.

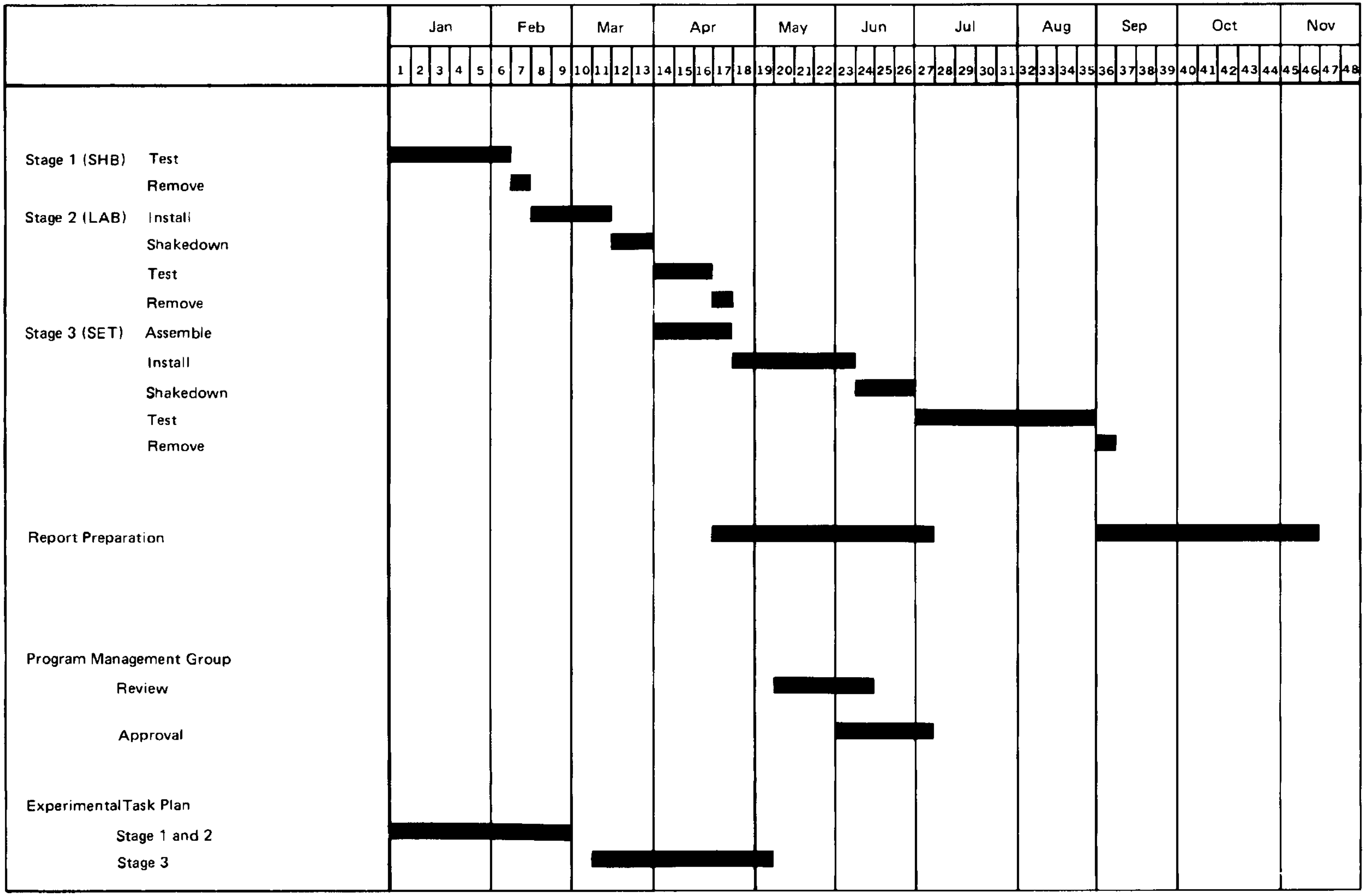


Figure 8-1. Single Heated Bundle Task 4.3 Schedule

Section 9

NOMENCLATURE

BD/ECC	- Blowdown/Emergency Core Cooling
BHL	- Bottom of the Heated Length
BP	- Bypass
BWR	- Boiling Water Reactor
CCFL	- Counter-Current Flow Limiting
DBA	- Design Basis Accident
DRF	- Design Record File
ECCS	- Emergency Core Cooling System(s)
EPRI	- Electric Power Research Institute
ETP	- Experimental Task Plan
GE-NED	- General Electric - Nuclear Engineering Division
GT	- Guide Tube
HPCS	- High Pressure Core Spray
LAB	- Lynn Adiabatic Bundle
LOCA	- Loss-of-Coolant Accident
LP	- Lower Plenum
LPCI	- Low Pressure Coolant Injection
LPCS	- Low Pressure Core Spray
NRC	- Nuclear Regulatory Commission
PMG	- Program Management Group
SCR	- Silicon Controlled Rectifier
SEO	- Side Entry Orifice
SET	- Separate Effects Test
SHB	- Single Heated Bundle

SSTF	=	Sector Steam Test Facility
THL	=	Top of the Heated Length
TLTA	=	Two-Loop Test Apparatus
TOB	=	Top of the Bypass
UP	=	Upper Plenum
A	=	Flow Area
α	=	Void Fraction
C_o	=	Void Fraction Distribution Parameter
$\overline{V}_{gj}$	=	Void Fraction Drift Velocity
C	=	CCFL Correlation Constant
g	=	32.2 ft/sec^2
h	=	Enthalpy
h_{fg}	=	Heat of Vaporization
Δh_{sub}	=	$h_f - h_{liquid}$
$j=j_g+j_f$	=	Total Volumetric Flux
j_g	=	Volumetric Steam Flux
j_f	=	Volumetric Water Flux
(K/A^2)	=	Single Phase Flow Loss Factor
M_f	=	Saturated Water Mass
P	=	Pressure
$\dot{P}$	=	Pressure Rate
Q	=	Wall or Rod Heat Transfer Rate
v_f	=	Specific Volume of Saturated Water
W	=	Mass Flow Rate
W_{fg}	=	Evaporation Rate
X	=	Quality of a Saturated Mixture
ρ	=	Density
$\Delta\rho$	=	$\rho_f - \rho_g$

$W_{fg_{Flash}}$ = Evaporation Rate Due to Flashing

$W_{fg_{elec}}$ = Evaporation Rate Due to Electrical Heating

K = Condensation Capacity Ratio

C_p = Specific Heat

T_{sat} = Saturation Temperature

T_{spray} = ECCS Spray Temperature

SUBSCRIPTS

g = Saturated Steam

g_{in} = Saturated Steam into a Region

f = Saturated Water

f_{in} = Liquid Flow into a Region

f_{out} = Liquid Flow out of a Region

f_{spray} = Liquid Flow from ECCS Spray

fg = Flashing of Liquid to Vapor

CCFL = Counter-Current Flow Limiting

S = Single Heated Bundle Test Facility

T = TLTA

1 = Pressure Condition 1

2 = Pressure Condition 2

injection = Steam Injection to the SHB

elec = Due to Electrical Heating

Section 10

REFERENCES

1. Contract NRC-04-79-184, BWR Refill-Reflood Program (NRC, EPRI, GE-NED); Appendix B - BWR Refill-Reflood Program Workscope, February 12, 1979.

2. D. W. Danielson, "Lynn SSTF Bundle Flow Measurement System Description and Calibration," General Electric Company, August 1979 (NEDO-24706).

3. D. D. Jones, "Subcooled Counter-Current Flow Limiting Characteristics of the Upper Region of a BWR Fuel Bundle," General Electric Company, July 1977 (NEDG-NUREG-23549).

Appendix A

PRESSURE SCALING BASIS FOR EXPERIMENTAL LOCA REFILL TRANSIENT SIMULATIONS

A.1 LOCA REFILL SCENARIO

The first step in developing a pressure scaling basis for loss-of-coolant accident (LOCA) atmospheric pressure testing is to review the LOCA refill scenario. This review is based on BWR/6 predictions using current methods, two-loop test apparatus (TLTA) test results, and engineering evaluation of this information.

The refill phase picks up the LOCA transient near the beginning of the emergency core cooling system (ECCS) injection, Figure A-1. The distribution of mass in the lower plenum and core channel is dominated by the pressure balance between the jet pump and channel/upper plenum. This pressure balance is determined by the static head in the channel and upper plenum, and the pressure drop across the jet pump (static-head plus local flow loss). Liquid flow from the channel to the lower plenum is controlled by counter-current flow limiting (CCFL) at the side entry orifice (SEO). The steam generated in the lower plenum splits between the channel and the jet pump in proportions that yield the required pressure balance.

Subcooled injection of ECCS water into the bypass and upper plenum condenses steam in these regions, changing the static heads, resulting in an adjustment of the lower plenum flow split, and increasing the possibility of subcooled breakdown of CCFL.

The rest of the refill period exhibits refilling of the guide tubes, bypass, channels, upper plenum, and the lower plenum. The refill is governed by the competing effects of condensation and flashing, a shifting lower plenum steam flow split, and possible subcooled CCFL breakdown at the upper tie plate and SEO. The refilling of these various regions is the system response that is important to simulate in a LOCA experiment. The refilling is primarily a function of the liquid flow rates. Therefore, the primary basis in scaling is to duplicate the liquid flow rates to and from each region of the system.

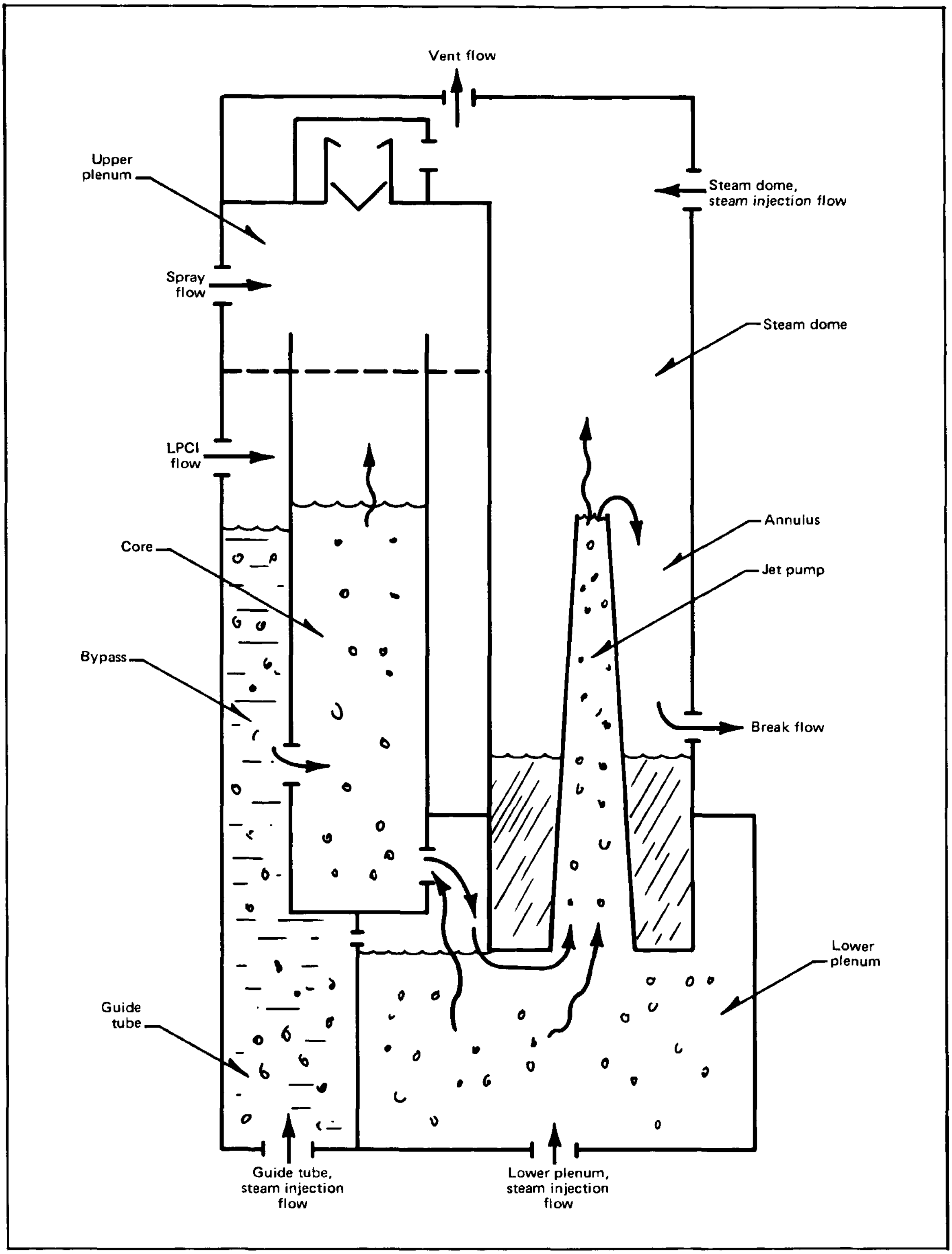


Figure A-1. Schematic of the Early Refill Period of the LOCA Transient

A.2 GOVERNING PHENOMENA

Based on this scenario, the phenomena that govern the LOCA refill transient are:

a. Steam production that is a result of the competing effects of heat transfer, depressurization, and subcooled ECCS condensation.

b. CCFL controlled liquid flow rates at the SEO, UTP (upper tie plate), and possibly at the top guide (bypass) and flow area restriction between the guide tubes and the bypass.

c. Void fraction distribution, which affects the static heads and the regional mass storage.

d. The local pressure loss across the jet pump throat. This will influence the lower plenum flow split.

A.3 EFFECTS OF PRESSURE ON GOVERNING PHENOMENA

The phenomena governing the LOCA refill are not all affected by pressure in the same proportion. It is necessary then to look at each phenomenon individually and examine the effect of pressure on it. Based on this study, a pressure scaling procedure will be selected that most closely simulates in the atmospheric, constant pressure test (SHB), the correct liquid filling rates.

The governing phenomena are represented by the following relationships. The CCFL controlled flows are related by a typical Wallis-type saturated CCFL correlation,

$$j_g^{1/2} \left(\frac{\rho_g}{g\Delta\rho}\right)^{1/4} + m j_f^{1/2} \left(\frac{\rho_f}{g\Delta\rho}\right)^{1/4} = C \ . \qquad \text{(A-1)}$$

The void fractions can be predicted by a drift-flux relationship,

$$\alpha = \frac{j_g}{C_o j + \overline{V}_{gj}} \ . \qquad \text{(A-2)}$$

Finally, the two-phase local pressure drop across the jet pump throat is given by

$$(\Delta P_{2\phi})_{JP} = \left[1 + \left(\frac{\rho_f}{\rho_g} - 1\right) x\right] \left(\frac{K}{A^2}\right)_{JP} \frac{W^2}{2g\rho_f} \ . \qquad \text{(A-3)}$$

Now each of these expressions will be analyzed to see how the system steam rates would have to be scaled with pressure to maintain the phenomenon approximately unchanged when scaled to a lower pressure. In each case, the liquid flow rates will be assumed the same in each facility since this is the ultimate objective of the pressure scaling.

1. Matched CCFL Drain Rate Scaling

Matching the SHB and TLTA CCFL drain rates can be expressed as

$$(W_f)_S = (W_f)_T \quad , \tag{A-4}$$

where these liquid flow rates are determined by the CCFL equation (A-1) for each facility. This leads to the following relationship for scaling the SHB steam flow from the TLTA steam flow,

$$(W_g)_S^{1/2} = (W_g)_T^{1/2} \left(\frac{\rho_g}{\rho_f}\right)_S^{1/4} \left(\frac{\rho_f}{\rho_g}\right)_T^{1/4} + (\rho_g)_S^{1/4} \left[C_S A_S^{1/2} (g\Delta\rho)_S^{1/4} - C_T A_T^{1/2} (g\Delta\rho)_T^{1/4} (\rho_f)_T^{1/4} \Big/ (\rho_f)_S^{1/4}\right] . \tag{A-5}$$

The consequences of this relationship can more easily be studied by noting that

$$C_S \approx C_T \quad , \quad (\rho_f)_S \approx (\rho_f)_T \quad , \quad (\Delta\rho)_S \approx (\Delta\rho)_T \quad , \quad A_S \approx A_T \quad .$$

For these assumptions, Eq. (A-5) reduces to

$$(W_g)_S \approx (W_g)_G (\rho_g)_S^{1/2} \Big/ (\rho_g)_T^{1/2} \tag{A-6}$$

or

$$(j_g)_S (\rho_g)_S^{1/2} = (j_g)_T (\rho_g)_T^{1/2} \quad . \tag{A-7}$$

Thus the steam flows would be scaled approximately by Eq. A-6 or Eq. A-7, and exactly by Eq. A-5. The TLTA-to-SHB scaling for the reference case has the largest ratio at the beginning of the simulation (P = 150 psia for TLTA). Therefore, the maximum scaling ratio would be

$$\frac{(j_g)_S}{(j_g)_T} \approx \frac{(\rho_g)_T^{1/2}}{(\rho_g)_T^{1/2}} \approx \left(\frac{150 \text{ psia}}{15 \text{ psia}}\right)^{1/2} \approx 3 \quad . \tag{A-8}$$

When this CCFL scaling is used, the void fractions, as given by Eq. A-2, will be compromised approximately in the following ratio

$$1.15 \le \frac{\alpha_S}{\alpha_T} \le 1.46 \quad \text{for} \quad 3 \ge (j_g)_T \ge 1 \text{ ft/sec} \quad . \tag{A-9}$$

Although important, this is not a first order effect.

Applying the CCFL scaling Eq. A-8 to Eq. A-3, it can be seen that the jet pump local loss ratio is

$$\frac{(\Delta P_{JP})_S}{(\Delta P_{JP})_T} \approx \frac{(j_g)_S}{(j_g)_T} \approx 3 \quad . \tag{A-10}$$

This relationship was obtained by assuming that

$$(K/A^2)_S \approx (K/A^2)_T \quad , \quad (W_f)_S = (W_f)_T$$

and noting that

$$\left[1 + \left(\frac{\rho_f}{\rho_g} - 1\right) x\right] \approx \frac{\rho_f}{\rho_g} x \quad \text{and} \quad W \approx W_f \quad .$$

With these assumptions, Eq. A-3 simplifies to

$$(\Delta P_{2\phi})_{UP} \approx \left[\left(\frac{K}{A^2}\right) \frac{A}{2g} j_g \, W_f\right]_{JP} \quad . \tag{A-11}$$

These compromises will influence the lower plenum flow split and must be accounted for in the test evaluations.

2. Matched Void Fraction Scaling

The system void fractions, as given by Eq. A-2, are dominated by the steam volumetric flux, j_g, since $j_g >> j_f$. Also $(C_0)_S \approx (C_0)_T$ and $(\overline{V}_{gj})_S \approx (\overline{V}_{gj})_T$. Thus for $\alpha_S \approx \alpha_T$, equal steam flux modeling should be used, i.e.,

$$(j_g)_S \approx (j_g)_T \tag{A-12}$$

Although this scaling would preserve the jet pump pressure drop modeling, Eq. A-10, it has a very significant effect on the CCFL scaling. This can be seen by rewriting Eq. A-1 in the following form,

$$W_f = \rho_f A \left(\frac{\rho_f}{g\Delta\rho}\right)^{-1/2} \left[C - j_g^{1/2}\left(\frac{\rho_g}{g\Delta\rho}\right)^{1/4}\right]^2 \qquad \text{(A-13)}$$

Applying the assumptions used in deriving Eq. A-6, we have,

$$\frac{(W_f)_S}{(W_g)_T} \approx \frac{\left[C - (j_g^{\,2}\rho_g/g\Delta\rho)_S^{1/4}\right]^2}{\left[C - (j_g^{\,2}\rho_g/g\Delta\rho)_T^{1/4}\right]^2} \qquad \text{(A-14)}$$

Substituting Eq. A-12, the void scaling relationship, into Eq. A-14 we have;

$$\frac{(W_f)_S}{(W_f)_T} \approx \left[\frac{C - (j_g^{\,2}/g\Delta\rho)^{1/4}\,(\rho_g)_S^{1/4}}{C - (j_g^{\,2}/g\Delta\rho)^{1/4}\,(\rho_g)_T^{1/4}}\right]^2$$

$$\approx \left[\frac{K - (\rho_g)_S^{1/4}}{K - (\rho_g)_T^{1/4}}\right]^2 \quad ; \quad K = C\,(j_g^{\,2}/g\Delta\rho)^{1/4} \,. \qquad \text{(A-15)}$$

With a maximum density ratio of

$$\frac{(\rho_g)_T}{(\rho_g)_S} \approx 10 \,, \qquad \text{(A-16)}$$

it can be seen that a significant error in the liquid CCFL flows would result from this scaling option.

3. <u>Matched Jet Pump Pressure Drop Scaling</u>

As can be seen from the previous discussion, the $(j_g)_S = (j_g)_T$ scaling preserves the $(\Delta P_{2\phi})_{JP}$ phenomenon as well as the void fraction; this needs no further discussion.

A.4 CCFL SCALING BASIS CHOSEN

Following the evaluation of the various scaling choices, it is obvious that CCFL pressure scaling most closely achieves the objective of preserving the liquid refilling rates. Using this scaling basis, the parameters for the scaled SHB tests can be specified (see Appendix B).

A.5 STEAM INJECTION SIMULATION OF DEPRESSURIZATION FLASHING

For a depressurizing system such as the BWR or the TLTA, the net steam function in any region is determined by,

$$(W_{fg})_T = \frac{1}{(h_{fg})_T} \left[\dot{Q} - M_f \frac{dh_f}{dp} \dot{P} - (W_f)_{in} (\Delta h_{sub})_{in} \right]_T , \qquad \text{(A-17)}$$

where,

$$\frac{\dot{Q}}{h_{fg}} = \text{wall heat transfer steam generation,} \qquad \text{(A-18)}$$

$$\frac{-M_f}{h_{fg}} \frac{dh_f}{dp} \dot{P} = \text{depressurization steam generation; and}$$

$$\frac{(W_f)_{in}}{h_{fg}} (\Delta h_{sub})_{in} = \text{subcooled injection steam condensation.}$$

For a constant pressure LOCA test facility such as the SHB, there is no depressurization steam generation. This steam source must be simulated by injecting steam into the required regions. The net "source" of steam for the SHB is given by,

$$(W_{fg})_S = \frac{1}{(h_{fg})_S} \left[\dot{Q} - (W_f)_{in} (\Delta h_{sub})_{in} \right]_S + \left(W_{g_{injection}} \right)_S . \qquad \text{(A-19)}$$

The steam rates in Eq. A-19 for the SHB must be scaled from the TLTA rates given in Eq. A-17, using the CCFL pressure scaling procedure given in Appendix B.

Appendix B

PRESSURE SCALING VERIFICATION TESTS
(TLTA-5A Reference Test Data and Scaled Inputs for the SHB Confirmation Test)

Since the two-loop test apparatus (TLTA) and single heated bundle (SHB) test facilities do not have exactly equal counter-current flow limiting (CCFL) areas,* the general form of the CCFL scaling is used. The equations used to accomplish such scaling, and the step-by-step process followed are summarized in Table B-1. The assumptions used to derive these equations are summarized in Table B-2. These assumptions apply specifically to the TLTA and SHB facilities.

The TLTA-5A reference test initial conditions are given in Table B-3 and the steam flashing conditions are given in Figure B-1. The mass filling rates of each TLTA region are shown as a function of time in Figures B-2 through B-6. These are the responses that will be compared with the SHB test responses for confirming the pressure scaling basis.

The initial conditions to be used for the SHB tests are summarized in Table B-4 and the steam injection rates in Figure B-7. The spray and LPCI rates (same as TLTA) and the scaled ECCS temperature are given in Figure B-8.

The TLTA power and the scaled SHB power are both given in Figure B-9. The reference power to be used in the SHB test is higher than the scaled value to compensate for the core-to-bypass heat transfer that occurs in the SHB but not in the TLTA. This curve is also shown in Figure B-9.

These test results and inputs are sufficient to make the pressure scaling evaluation once the SHB tests are completed.

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*The top guide (bypass) areas for the two facilities are: $A_{BT} = 0.098\ ft^2$ and $A_{BS} = 0.070\ ft^2$. The upper tie plate areas and side entry orifice (SEO) areas in the TLTA and SHB are equal.

Table B-1

EQUATIONS AND PROCEDURE FOR CALCULATING THE SINGLE HEATED BUNDLE TEST INPUTS FROM THE TLTA REFERENCE TEST

Step	Equation	Comments
1.	$\left(W_{fg_L}\right)_T = \frac{1}{h_{fg_T}}\left[\dot{Q}_{L/L} - M_{fL}\frac{dh_f}{dP}\dot{P}\right]_T$	$\dot{Q}_{L/L}$ = estimated from calculation in GEAP-23592 $M_{fL}, \dot{P}$ = TLTA-5A data Test 6422 Run 3
2.	$(W_{f1})_T = A_{SEO_T}\,\rho_{f_T}^{1/2}\left[C\,(g\Delta\rho)^{1/4} - \left(\frac{W_{fg_L}}{A_{SEO}\rho_g^{1/2}}\right)^{1/2}\right]_T^2$	SEO CCFL correlation (TLTA), C_T = 0.539, A_{SEO_T} = 0.0322 ft^2
3.	$(W_{f1})_S = (W_{f1})_T$	Objective of scaling
*4.	$(W_{g11})_S = A_{SEO_S}\,\rho_{g_S}\left[C\,(g\Delta\rho)^{1/4} - \left(\frac{W_{f1}}{A_{SEO}\rho_f}\right)^{1/2}\right]_S^2$	SHB-LP (lower plenum) Steam Injection; SEO CCFL Correlation (SHB), C_S = 0.539, A_{SEO_S} = 0.0322 ft^2.
5.	$(W_{fgG})_T = \frac{1}{h_{fg_T}}\left[\dot{Q}_{G/G} - M_{fG}\frac{dh_f}{dP}\dot{P}\right]_T$	$\dot{Q}_{G/G}$ estimated from Zeus run, M_{fG}, $\dot{P}$ = TLTA data
6.	$(W_{fgB})_T = \frac{1}{h_{fg_T}}\left[- M_{fB}\frac{dh_f}{dP}\dot{P}\right]$	M_{fB}, $\dot{P}$ = TLTA data

Table B-1

EQUATIONS AND PROCEDURE FOR CALCULATING THE SINGLE HEATED BUNDLE TEST INPUTS FROM THE TLTA REFERENCE TEST (Continued)

Step	Equation	Comments
7.	$(\Sigma W_{fgB})_T = (W_{fgG})_T + (W_{fgB})_T$	Lump guide tubes (GT) and bypass (BP) together.
8.	$(W_{f4}')_T = A_{B_T} \rho_{ft}^{1/2} \left[C\ (g\Delta\rho)^{1/2} - \left(\frac{\Sigma W_{fg_B}}{A_B\ \rho_g^{1/2}} \right)^{1/2} \right]^2$	Neglect GT/BP CCFL, CCFL scaling of lumped GT/BP steam based on bypass area at LPCI, $C = 0.619$, $A_{B_T} = 0.098\ ft^2$.
9.	$(W_{f4}')_S = (W_{f4}')_T$	Objective of scaling
*10.	$(W_{g12})_S = A_{B_S} \rho_{g_S}^{1/2} \left[C\ (g\Delta\rho)^{1/4} - \left(\frac{W_{f4'_S}}{A_{B_S}\ \rho_f^{1/2}} \right)^{1/2} \right]^2_S$	The BP and GT steam injection is lumped into the GT injection; $C = 0.619$, $A_{B_S} = 0.070\ ft^2$.
11.	$(\dot{Q}_{A/C})_T = \dot{Q}_{elec_T} + \dot{Q}_{rods_T}$	Estimated from TLTA data, i.e., all $\dot{Q}_{elec}$ to fluid, $T_{rods} \approx T_{sat}$ for transient.
12.	$\left(W_{fg_{elec}}\right)_T = \frac{\dot{Q}_{elec_T}}{h_{fg_T}} - \left(M_{fL} \frac{dh_f}{dP} \dot{P}\right)_T$	Lump flashing steam in with electrical since there is no SHB core steam injection.

LPCI = low pressure coolant injection

Table B-1

EQUATIONS AND PROCEDURE FOR CALCULATING THE SINGLE HEATED BUNDLE TEST INPUTS FROM THE TLTA REFERENCE TEST (Continued)

Step	Equation	Comments
13.	$\left(W_{\substack{fcore\\elec}}\right)_T = A_{UTP_T}\, \rho_{f_T}^{\ 1/2} \left[C\,(g\Delta\rho)^{1/4} - \left(\frac{W_{fg_{elec}}}{A_{UTP}\, \rho_g^{\ 1/2}}\right)^{1/2}\right]^2$	Referenced to upper tie plate (UTP) CCFL
14.	$\left(W_{\substack{fcore\\elec}}\right)_S = \left(W_{\substack{fcore\\elec}}\right)_T$	Objective of scaling
15.	$\left(W_{fg_{elec}}\right)_S = A_{UTP_S}\, \rho_{g_S}^{\ 1/2} \left[C\,(g\Delta\rho)^{1/4} - \left(\frac{W_{\substack{fcore\\elec}}}{A_{UTP}\, \rho_f^{\ 1/2}}\right)^{1/2}\right]_S^2$	Scaled to UTP CCFL
*16.	$\dot{Q}_{elec_S} = h_{fg_S} \left(W_{fg_{elec}}\right)_S + \dot{Q}_{C/B}$	<u>SHB Bundle Power</u>, $(\dot{Q}_{C/B})_T = 0$; $(\dot{Q}_{C/B})_S \neq 0$; Estimates of $(\dot{Q}_{C/B})_S$ were made from SHB tests.
17.	$\dot{Q}_{rods_T} = \left(M_{rods}\, C_{p_{rods}}\, \frac{\Delta T_{rods}}{\Delta t}\right)_T$	Estimated from TLTA-5A rod temperature data at beginning and end of test.

UTP = upper tie plate

Table B-1

EQUATIONS AND PROCEDURE FOR CALCULATING THE SINGLE HEATED BUNDLE TEST INPUTS FROM THE TLTA REFERENCE TEST (Continued)

Step	Equation	Comments
18.	$\left(W_{fg_{rods}}\right)_T = \frac{1}{h_{fg_T}} \dot{Q}_{rods_T}$	Steam flashing due to stored heat in rods.
19.	$\left(W_{\substack{fcore\\rods}}\right)_T = A_{UTP_T}\, \rho_{f_T}^{1/2} \left[C\, (g\Delta\rho)^{1/4} - \left(\frac{W_{fg_{rods}}}{A_{UTP}\rho_g^{1/2}}\right)^{1/2}\right]^2$	Referred to UTP CCFL
20.	$\left(W_{\substack{fcore\\rods}}\right)_S = \left(W_{\substack{fcore\\rods}}\right)_T$	Objective of scaling
21.	$\left(W_{\substack{fgcore\\rods}}\right)_S = A_{UTP_S}\, \rho_{g_S}^{1/2} \left[C\, (g\Delta\rho)^{1/4} - \left(\frac{W_{\substack{fcore\\rods}}}{A_{UTP}\rho_f^{1/2}}\right)^{1/2}\right]^2$	Scaled to UTP CCFL
22.	$\dot{Q}_{rods_S} = h_{fg_S} \left(W_{fg_{rods}}\right)_S$	Scaled rod stored heat
23.	$\Delta T_{rods_S} = \frac{\dot{Q}_{rods_S}}{\left(M_{rods}\, C_{p\ rods}\right)_S} \cdot \Delta t$	Scaled change in rod temperature
*24.	$\left(T_{rod_S}\right)_{t=0} = \Delta T_{rods_S} + T_{sat_S}$	Scaled initial rod temperature

Table B-1

EQUATIONS AND PROCEDURE FOR CALCULATING THE SINGLE HEATED BUNDLE TEST INPUTS FROM THE TLTA REFERENCE TEST (Continued)

Step	Equation	Comments
25.	$(W_{g3})_T = \left(W_{fgcore\ elec}\right)_T + \left(W_{fgcore\ rods}\right)_T$	Steam to upper plenum (UP); no steam from bypass; $\dot{Q}_{U/A}$ and $\dot{Q}_{U/D}$ small
26.	$(K_U)_T = \left[\frac{W_{fspray}\ C_p\ \Delta T_{spray}}{W_{g3}\ h_{fg}}\right]_T$	$\Delta T_{spray} = T_{sat} - T_{spray}$; Ratio of spray condensing energy to UP steam energy
27.	$(K_U)_S = (K_U)_T$	Same ratio of condensing to steam energy. Scaling basis.
28.	$(W_{fspray})_S = (W_{fspray})_T$	Objective of scaling to have the same liquid flows.
29.	$(W_{g3})_S = \left(W_{fgcore\ elec}\right)_S + \left(W_{fgcore\ rods}\right)_S$	Steam to SHB UP.
30.	$(\Delta T_{spray})_S = (K_U)_S \frac{(W_{g3})_S\ h_{fg_S}}{(W_{fspray})_S\ C_{p_S}}$	Definition of K.
*31.	$(T_{spray})_S = T_{sat_S} - (\Delta T_{spray})_S$	Scaled spray temperature.
32.	$(K_B)_T = \left[\frac{W_{fLPCI}\ C_p\ \Delta T_{LPCI}}{\Sigma W_{fg_B}\ h_{fg}}\right]_T$	Energy ratio for bypass.

Table B-1

EQUATIONS AND PROCEDURE FOR CALCULATING THE SINGLE HEATED BUNDLE TEST INPUTS FROM THE TLTA REFERENCE TEST (Continued)

Step	Equation	Comments
33.	$(K_B)_S = (K_B)_T$	Maintain same ratio.
34.	$(W_{fLPCI})_S = (W_{fLPCI})_T$	Objective of scaling basis.
35.	$(\Delta T_{LPCI})_S = (K_B)_S \dfrac{(W_{g12})_S \, h_{fg_S}}{(W_{fLPCI})_S \, C_{p_S}}$	Definition of K.
*36.	$(T_{LPCI})_S = T_{sat_S} - (\Delta T_{LPCI})_S$	Scaled LPCI temperature

LPCI = low pressure coolant injection

*Starred steps represent inputs to the SHB test.

Table B-2

ASSUMPTIONS FOR OBTAINING EQUATIONS IN TABLE B-1

a. Lower Plenum Flashing

Term	Sign	Nominal Value or At 150 Psia	Range	Basis/Comments
$\dot{Q}_{C/L}$	+	10	0-20	Zeus TLTA Run -
$\dot{Q}_{L/L}$	+	100	30-180	Figure 3-25, GEAP-23592 Zeus TLTA Run
$W_{f11}(h_{f11} - h_{fL})$		0	-	No LP steam injection
$W_{f15}(h_{f15} - h_{fL})$		0	-	LP and GT at saturation $h_{f15} = h_{FL}$
$W_{f1}(h_{f1} - h_{fL})$		0	-	LP and lower core at saturation and $h_{f1} = h_{fL}$
$W_{f6}(h_{f6} - h_{fL})$		0	-	LP and annulus at saturation: $h_{f6} = h_{fL}$
$W_{g11}(h_{g11} - h_{gL})$		0	-	No LP steam injection
$W_{g15}(h_{g15} - h_{gL})$		0	-	LP and GT at saturation cond: $h_{g15} = h_{gL}$
$W_{g1}(h_{g1} - h_{gL})$		0	-	No super heating of LP or core steam: $h_{g1} = h_{gL}$
$W_{g6}(h_{g6} - h_{gL})$		0	-	No super heating of LP steam: $h_{g6} = h_{gL}$
$M_{fL} \frac{dh_{fL}}{dPL} \dot{P}_L$	+	69	20-75	
$M_{gL} \frac{dh_{gL}}{dP_L} \dot{P}_L$	+	0.15	0.02-0.15	Negligible
$\frac{V_L}{J} \dot{P}_L$	-	1.2	0.2-1.4	Negligible

Table B-2

ASSUMPTIONS FOR OBTAINING EQUATIONS IN TABLE B-1 (Continued)

b. Guide Tube Flashing

Term	Sign	Nominal Value or At 150 Psia	Range	Basis/Comments
$\dot{Q}_{G/G}$	+	10	0-20	Zeus TLTA Run
$W_{f12}\ (h_{f12} - h_{f_G})$		0	-	No GT steam injection
$W_{f14}\ (h_{f14} - h_{f_G})$		0	-	During GT filling - BP & GT at sat.; $W_{f14} \approx 0$ after
$W_{f15}\ (h_{f15} - h_{f_G})$		0	-	LP and GT at sat.: $h_{f15} = h_{f_g}$
$W_{g12}\ (h_{g12} - h_{g_G})$		0	-	No GT steam injection
$W_{g14}\ (h_{g14} - h_{g_G})$		0	-	No steam superheating in GT
$W_{g15}\ (h_{g15} - h_{g_G})$		0	-	GT and LP at saturation
$M_{fG} \frac{dh_{fG}}{dP_G}$	+	78	32-78	
$M_{gG} \frac{dh_{gG}}{dP_G}$	+	0.05	0-0.06	Negligible
$\frac{V_G \dot{P}}{J}$	-	0.7	0.1-0.9	Negligible

Table B-2

ASSUMPTIONS FOR OBTAINING EQUATIONS IN TABLE B-1 (Continued)

c. Bypass Flashing

Term	Sign	Nominal Value or At 150 Psia	Range	Basis/Comments
$\dot{Q}_{C/B}$		0	-	BP tubes isolated from bundle
$\dot{Q}_{B/A}$		0	-	BP tubes isolated from test vessel outer wall
$\dot{Q}_{B/D}$		0	-	Heat transfer to BP fluid neglected - W_{fg} overestimated
$W_{fg}\ (h_{fg} - h_{fB})$		0	-	Neglected; $h_{fB} > h_{fg}$ so W_{fg} overestimated
$W_{f14}\ (h_{f14} - h_{fB})$		0	-	BP and GT at sat. condition until GT fills; $W_{f14} \approx 0$ after
$W_{f2}\ (h_{f2} - h_{fB})$		0	-	Initially both region sat. $h_{fg} = h_{fB}$; overestimated W_{fg} when $h_{fg} < H_f$
$W_{f4}\ (h_{f4} - f_{fB})$		0	-	Neglected; $h_{fB} > h_{fg}$ so W_{fg} overestimated
$W_{g9}\ (h_{g9} - h_{gB})$		0	-	Subcooled spray $W_{g9} = 0$
$W_{g14}\ (h_{g14} - h_{gB})$		0	-	No steam superheating in GT
$W_{g2}\ (h_{g2} - h_{gB})$		0	-	W_{g2} negligible
$W_{g4}\ (h_{g4} - h_{gB})$		0	-	$W_{g4} = 0$; all steam condensed in BP - cond capability ≈ 2
$M_{fB} \frac{d\ h_{fB}}{dP} \dot{P}_B$	+	40	0-42	
$M_{gB} \frac{d\ h_{gB}}{dB} \dot{P}_B$	+	0.03	0-0.06	
$\frac{V_B}{J} \dot{P}_B$	-	0.4	0.1-0.5	

Table B-2

ASSUMPTIONS FOR OBTAINING EQUATIONS IN TABLE B-1 (Continued)

d. Core Flashing

Term	Sign	Nominal Value or At 150 Psia	Range	Basis/Comments
$\dot{Q}_{A/C}$		0	-	No direct heat transfer from core to atmosphere
$\dot{Q}_{C/B}$		0	-	BP tubes isolated from core
$\dot{Q}_{C/D}$		0	-	Core channel insulated
$W_{f1} (h_{f1} - h_{fC})$		0	-	Fluid exiting core and in LP both at sat. ($h_{f1} = h_{fC}$)
$W_{f2} (h_{f2} - h_{fC})$		0	-	Initially both regions at sat.; overestimated W_{fg} when $h_{f2} < h_{fC}$
$W_{f3} (h_{f3} - h_{fC})$		0	-	$h_{f3} \leq h_{fC}$; overestimated W_{fg}
$W_{g1} (h_{g1} - h_{gC})$		0	-	No superheating of steam in LP; $h_{g1} = h_{gC}$
$W_{g2} (h_{g2} - h_{gC})$		0	-	W_{g2} Negligible
$W_{g3} (h_{g3} - h_{gC})$		0	-	No superheating in core; $h_{g3} = h_{gC}$
$M_{fC} \frac{dh_{fC}}{dP_C} \dot{P}_C$	+	10	4-26	
$M_{gC} \frac{dh_{gC}}{dP_C} \dot{P}_C$	+	0.26	0-0.26	
$\frac{V_C}{J} \dot{P}_C$	-	0.54	0.11-0.64	

Table B-3

TLTA-5A
TEST 6422 RUN 3
INITIAL CONDITIONS

Masses (lbm)	
Lower Plenum	56
Guide Tube	56
Bypass	5
Bundle	5
Upper Plenum	54
Rod Temperature (°F)	
Bulk Temp.	475

Table B-4

INITIAL CONDITIONS
FOR SHB PRESSURE SCALING TESTS

Masses (lbm)	
Lower Plenum	56
Guide Tube	110
Bypass	0
Bundle	0
Upper Plenum	0
Rod Temperature (°F)	
Bulk Temp.	250

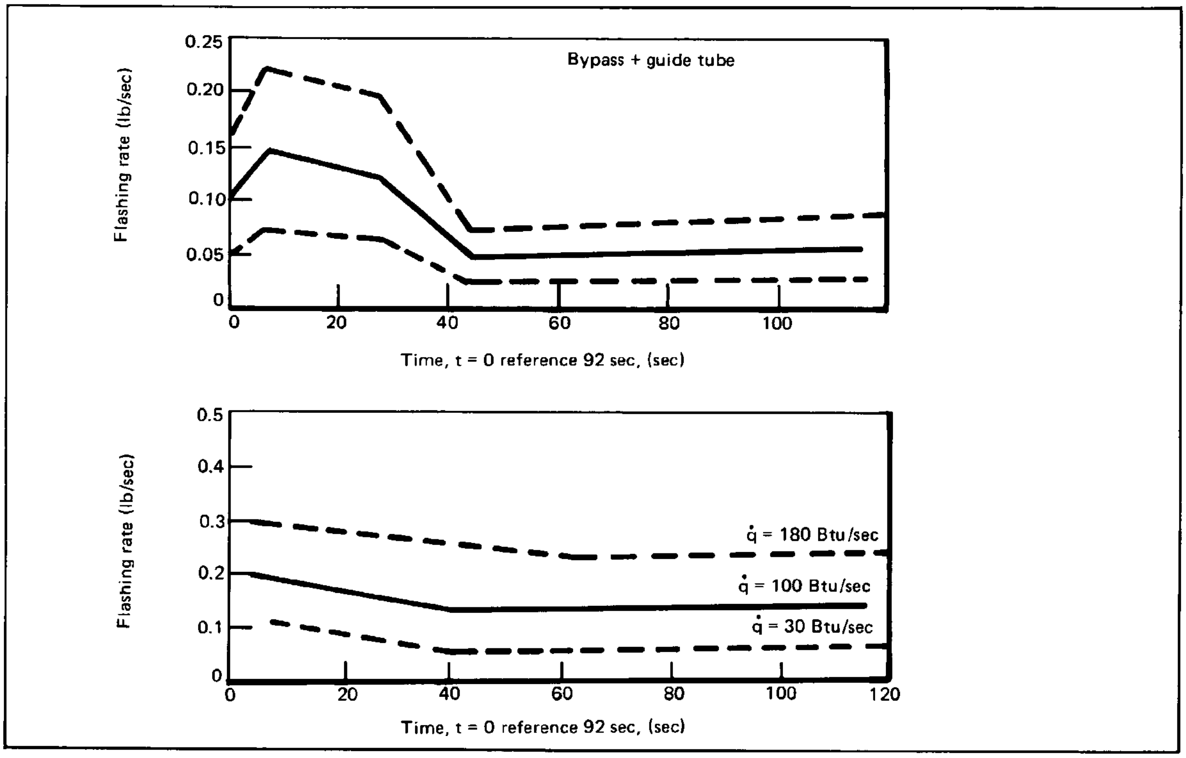

Figure B-1. TLTA-5A Reference, Upper and Lower Bounds for Flashing Rates in Bypass Region and Lower Plenum Region

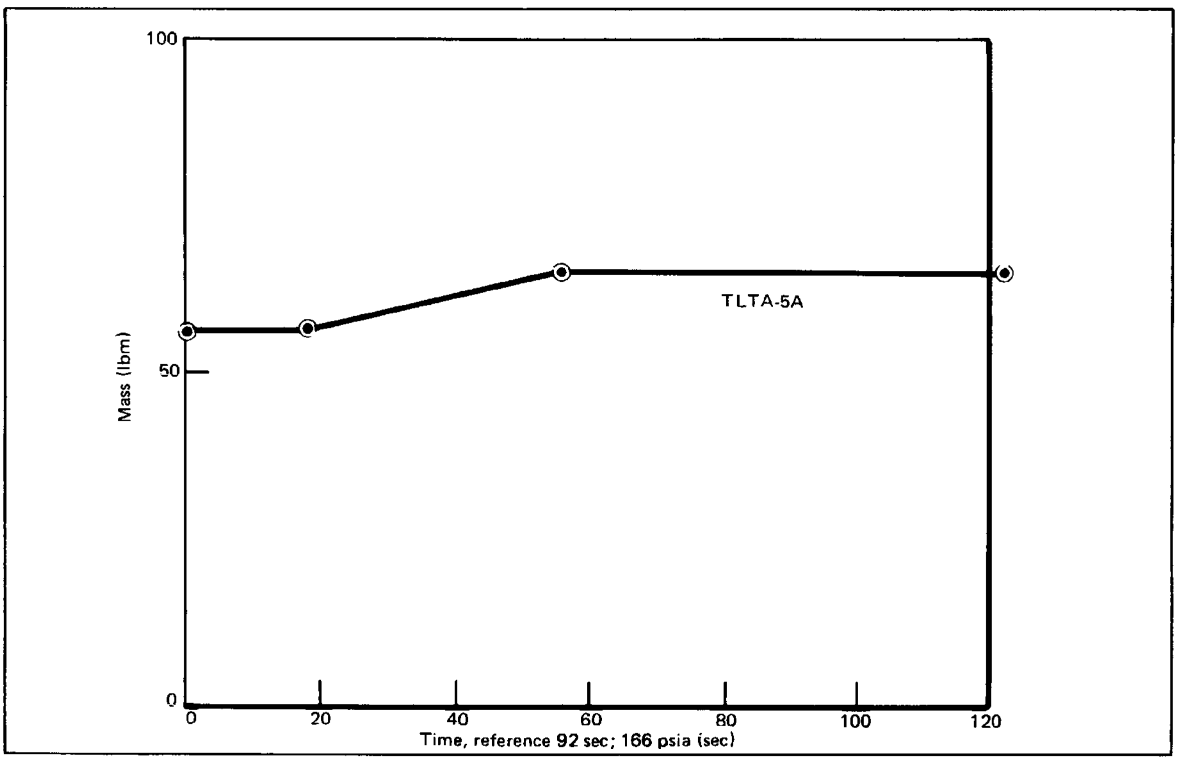

Figure B-2. Lower Plenum Mass Inventory TLTA-5A Test 6422 Run 3

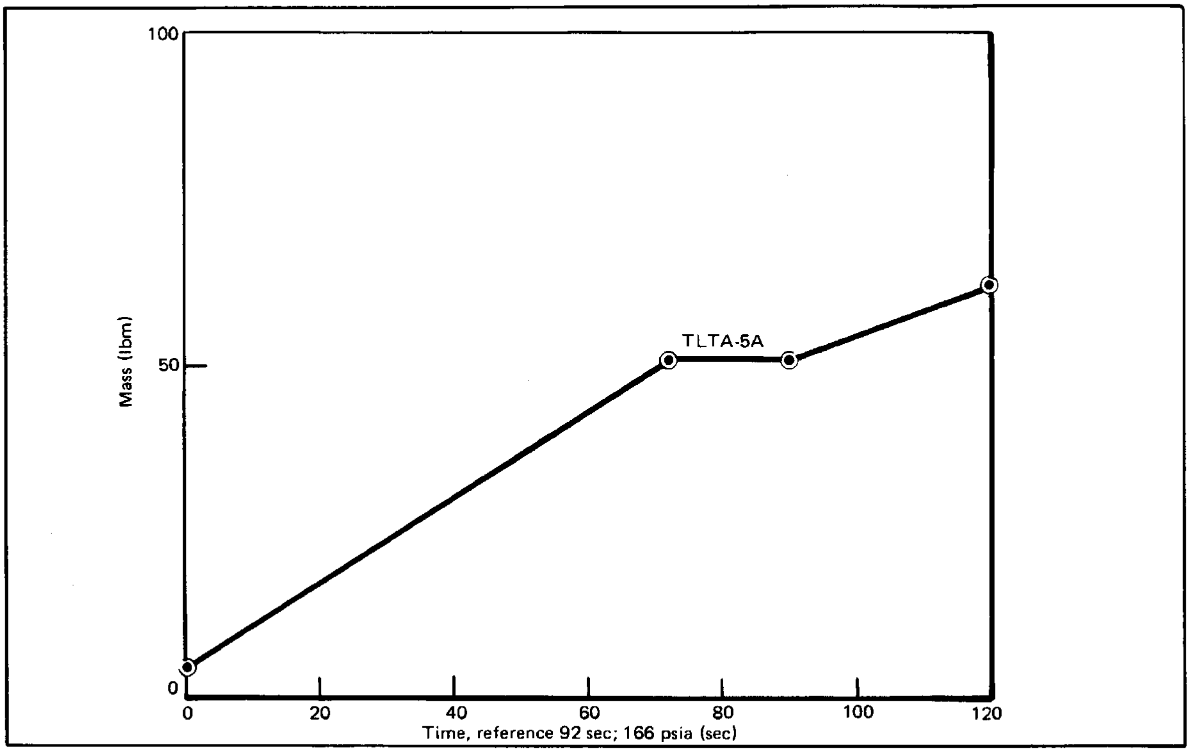

Figure B-3. Bundle Mass Inventory TLTA-5A Test 6422 Run 3

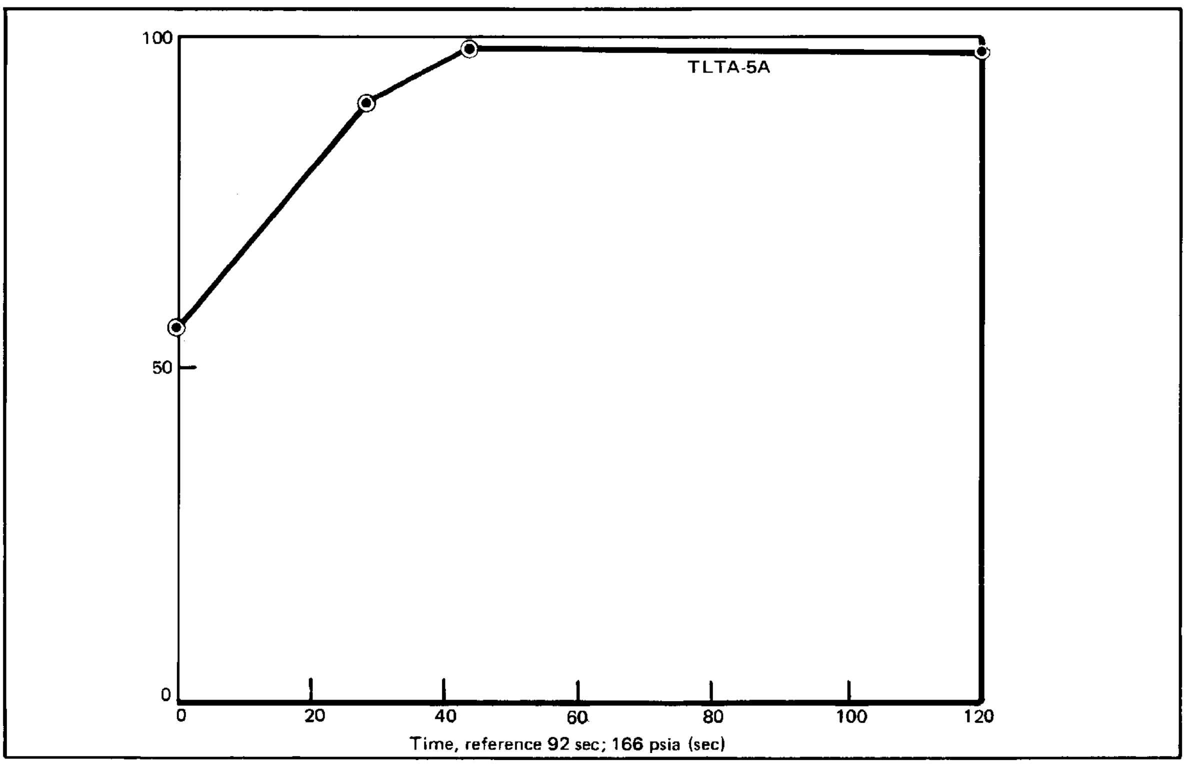

Figure B-4. Guide Tube Mass Inventory TLTA-5A Test 6422 Run 3

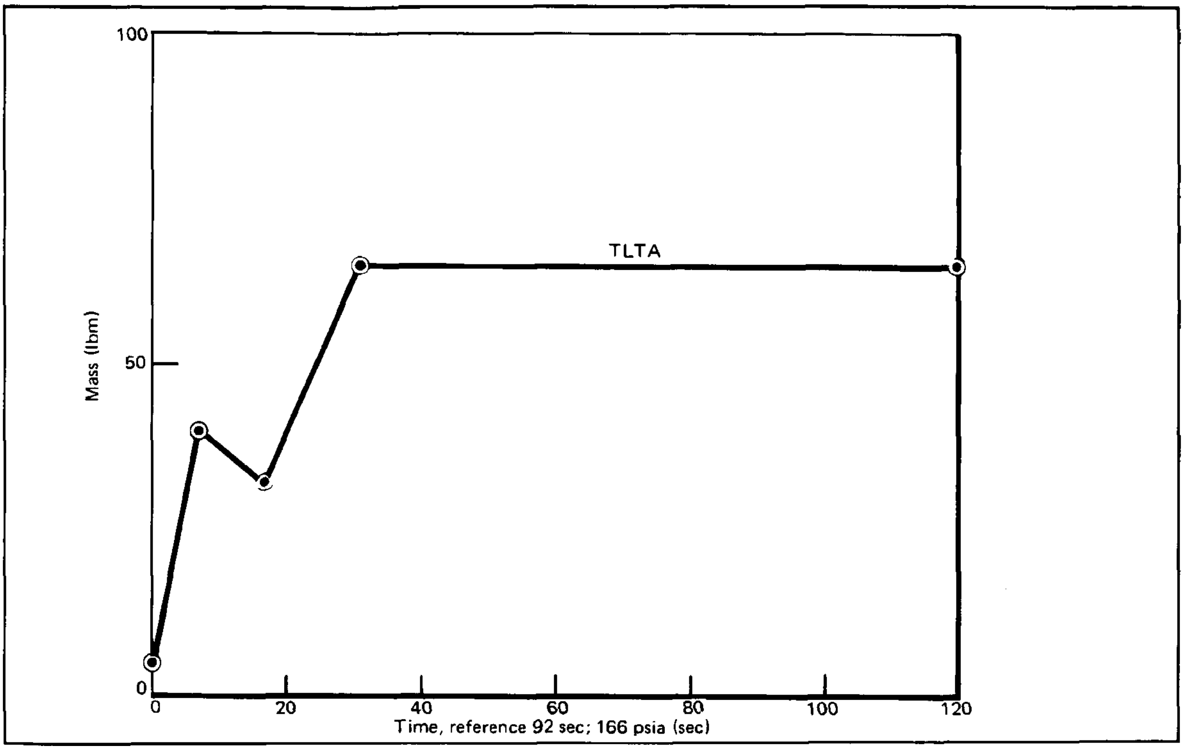

Figure B-5. Bypass Mass Inventory TLTA-5A Test 6422 Run 3

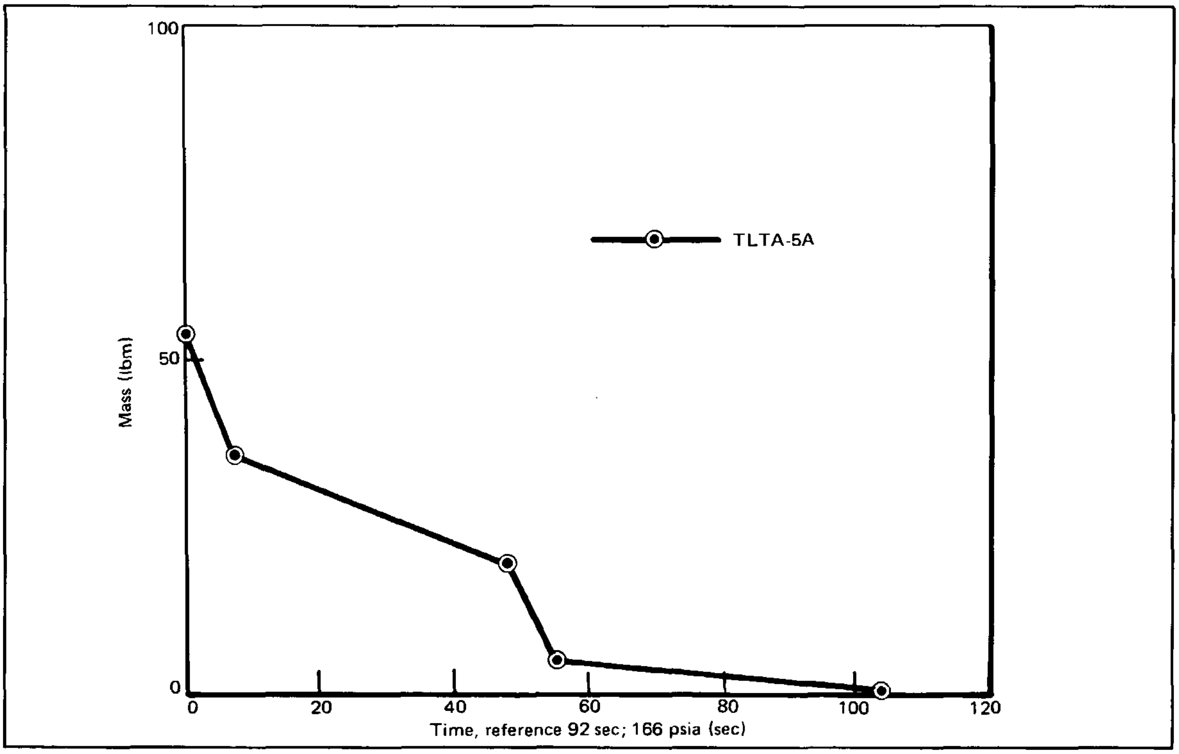

Figure B-6. Upper Plenum Mass Inventory TLTA-5A Test 6422 Run 3

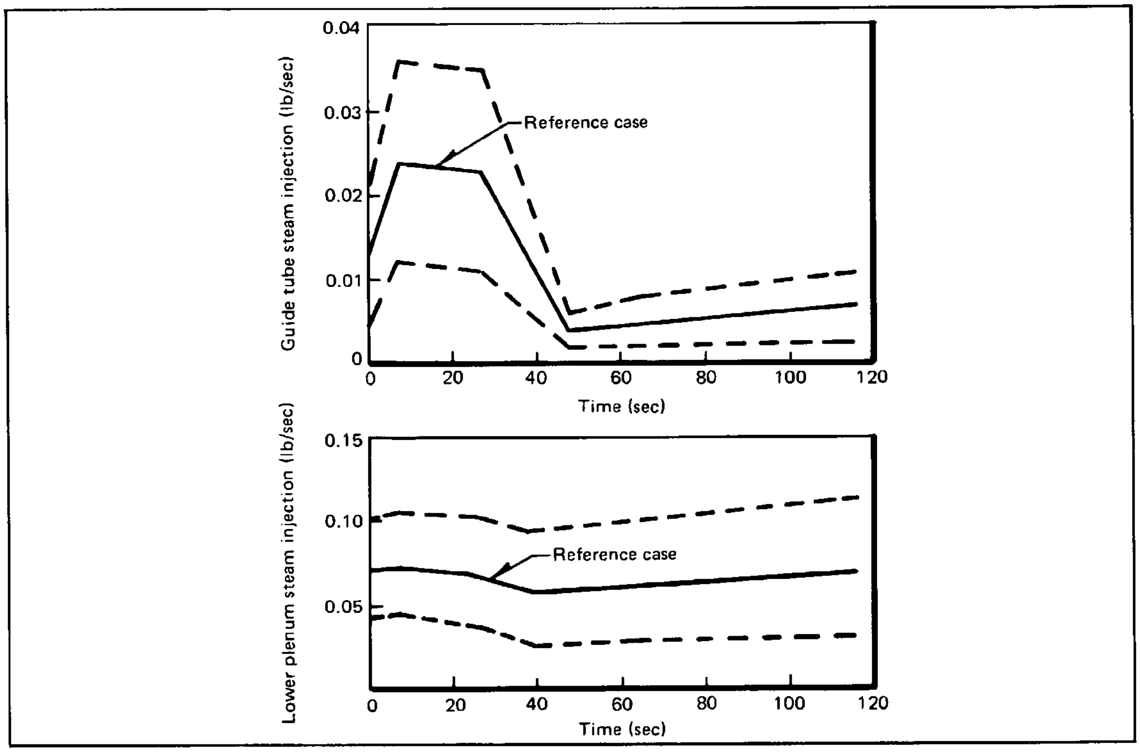

Figure B-7. Scaled Lower Plenum and Guide Tube Steam Injection Rates for SHB Pressure Scaling Tests

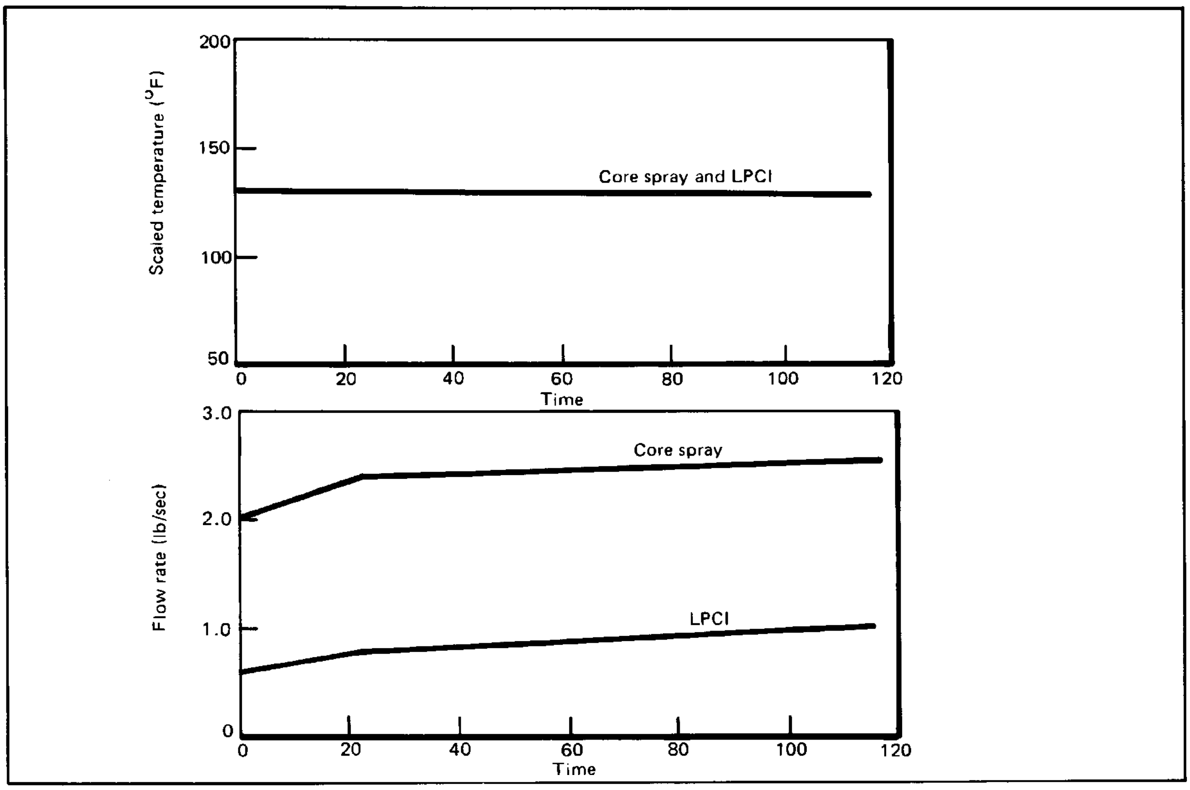

Figure B-8. LPCI and Core Spray Injection Rates and Scaled Fluid Temperatu e for SHB Pressure Scaling Tests

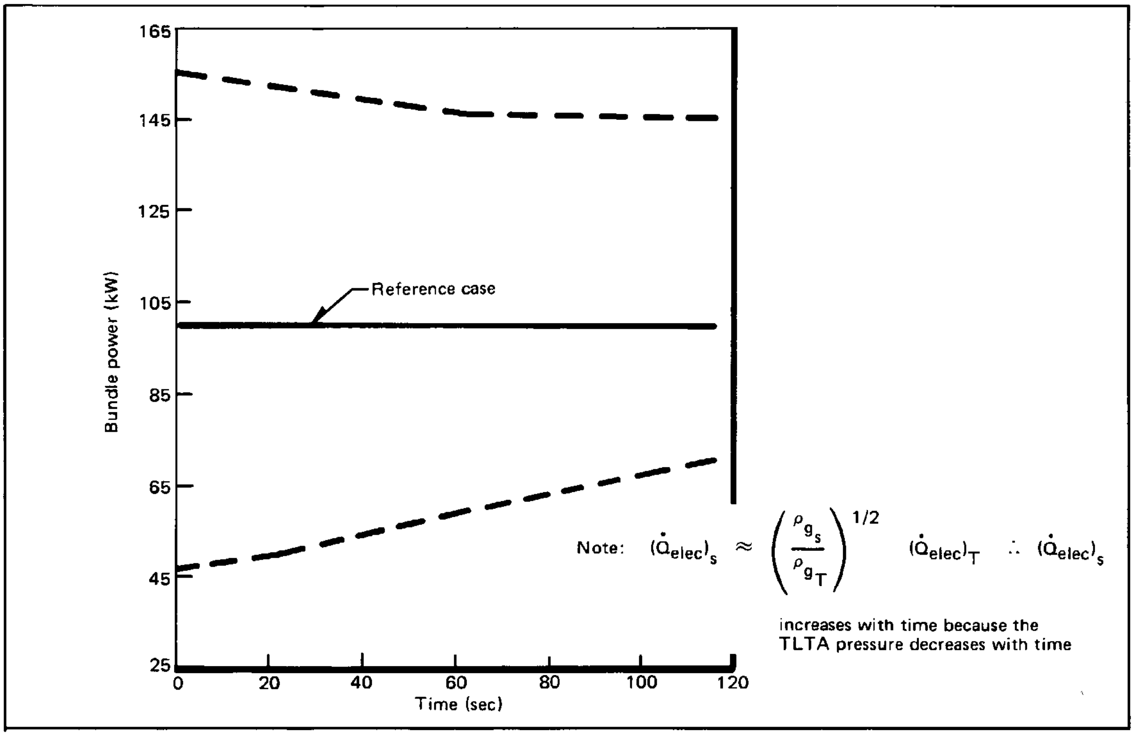

Figure B-9. SHB Bundle Power Based on Scaling of TLTA-5A Data

Volume 2

Addendum 1
Stage 3—Separate-Effects Bundle

ABSTRACT

An experimental task plan for the separate effects bundle tests of the Single Heated Bundle Task in the BWR Refill-Reflood Test Program is presented. The tests will provide core spray and reflood heat transfer data and will investigate BWR refill-reflood controlling phenomena to support model development tasks in the BWR Refill-Reflood Program. Individual test conditions, the measurement plan and data utilization are discussed.

CONTENTS

ILLUSTRATIONS

TABLES

Section 1

OBJECTIVES

The objectives of the separate effects bundle (SEB) tests of the Single Heated Bundle (SHB) Task are to (a) extend the refill-reflood data base, and (b) provide a data base of separate parameters in support of model development and model qualification tasks.

Section 2

TASK ROLE IN PROGRAM

Separate effects bundle tests under Task 4.3 will be performed for model development and qualification. Tasks 4.7 and 4.8 of the BWR Refill-Reflood Program[1] will utilize the data from these tests to develop and qualify loss-of-coolant accident (LOCA) models. The specific models to be addressed are:

1. Core Spray Heat Transfer
2. Reflood Heat Transfer
3. Core to Bypass Heat Transfer
4. Entrainment
5. Core Liquid Carryover
6. Upper Tie Plate Counter-Current Flow Limiting (CCFL)
7. Upper Tie Plate CCFL Breakdown
8. Side Entry Orifice (SEO) CCFL
9. Top of Bypass (TOB) CCFL
10. Core Vaporization
11. Core Void Distribution
12. Condensation Effects of Lower Tie Plate Leakage
13. Refill-Reflood Flow Distribution

This experimental task plan describes the program to obtain these data.

Section 3

FACILITY DESCRIPTION

The SEB will be installed in the Emergency Core Cooling System (ECCS) Test Loop. The ECCS Test Loop is a 1/624-scale mock-up of the BWR/6-218 reactor. The major features of the facility are shown in Figure 3-1. These features include a full-scale simulated fuel bundle and a system mock-up which includes the lower plenum (LP), guide tube (GT), core, bypass, upper plenum (UP), separator, steam dome, annulus, and jet pump.

To conduct separate effects tests, the jet pump, bypass, and GT may be isolated. The ECC systems are simulated with (a) liquid injection 26 inches above the upper tie plate for high pressure core spray (HPCS) and low pressure core spray (LPCS) flows, and (b) liquid injection into the bypass region on all four sides of the fuel channel at 18.7 inches below the upper tie plate for low pressure coolant injection (LPCI) flows. The spray and the LPCI share a common controlled temperature water supply, and thus are injected at the same temperature. The spray and LPCI flows may be individually varied from 0.5 to 30 gpm and 1 to 10 gpm, respectively, at temperatures from ambient to near saturation. Liquid may also be injected directly into the lower plenum (LP). The generation of steam by flashing is simulated by the injection of steam into the GT and LP. Steam may also be injected directly into the core. Each of these flows may be set separately at up to 1000 lbm/hr.

The SEB is a new simulated BWR/6 fuel bundle made up of an 8x8 array of electrically heated simulated fuel rods including two water rods. Each of the heater rods will have a center peaked chopped cosine axial power profile and 10 clad-surface thermocouples (TC), as shown in Figure 3-2. An individual heater rod, of which there are 62 in the SEB test section, is shown in Figure 3-3. All other test section components for these Stage 3 tests are the same as those for the Stage 1 tests.[2]

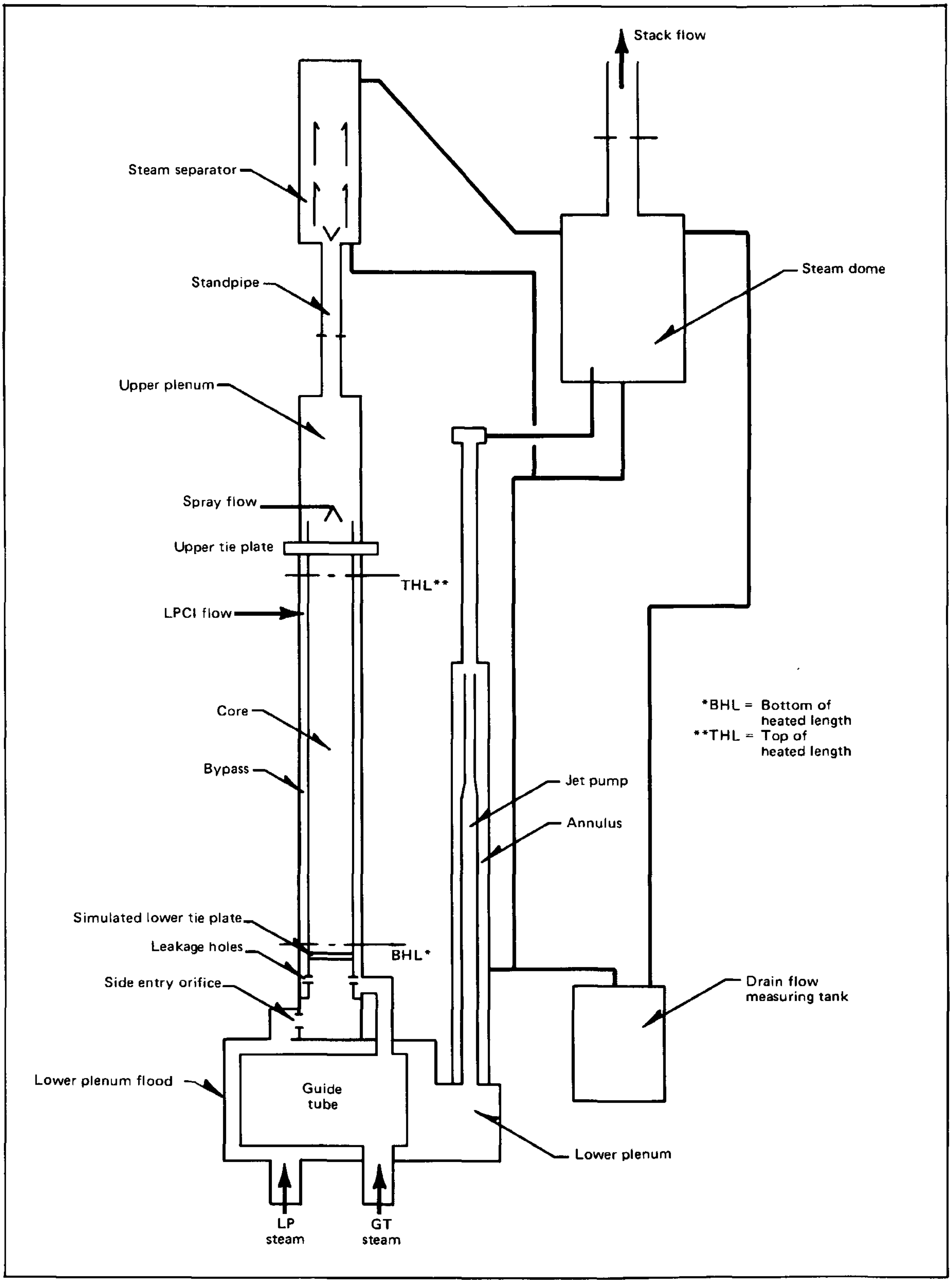

Figure 3-1. ECCS Test Loop

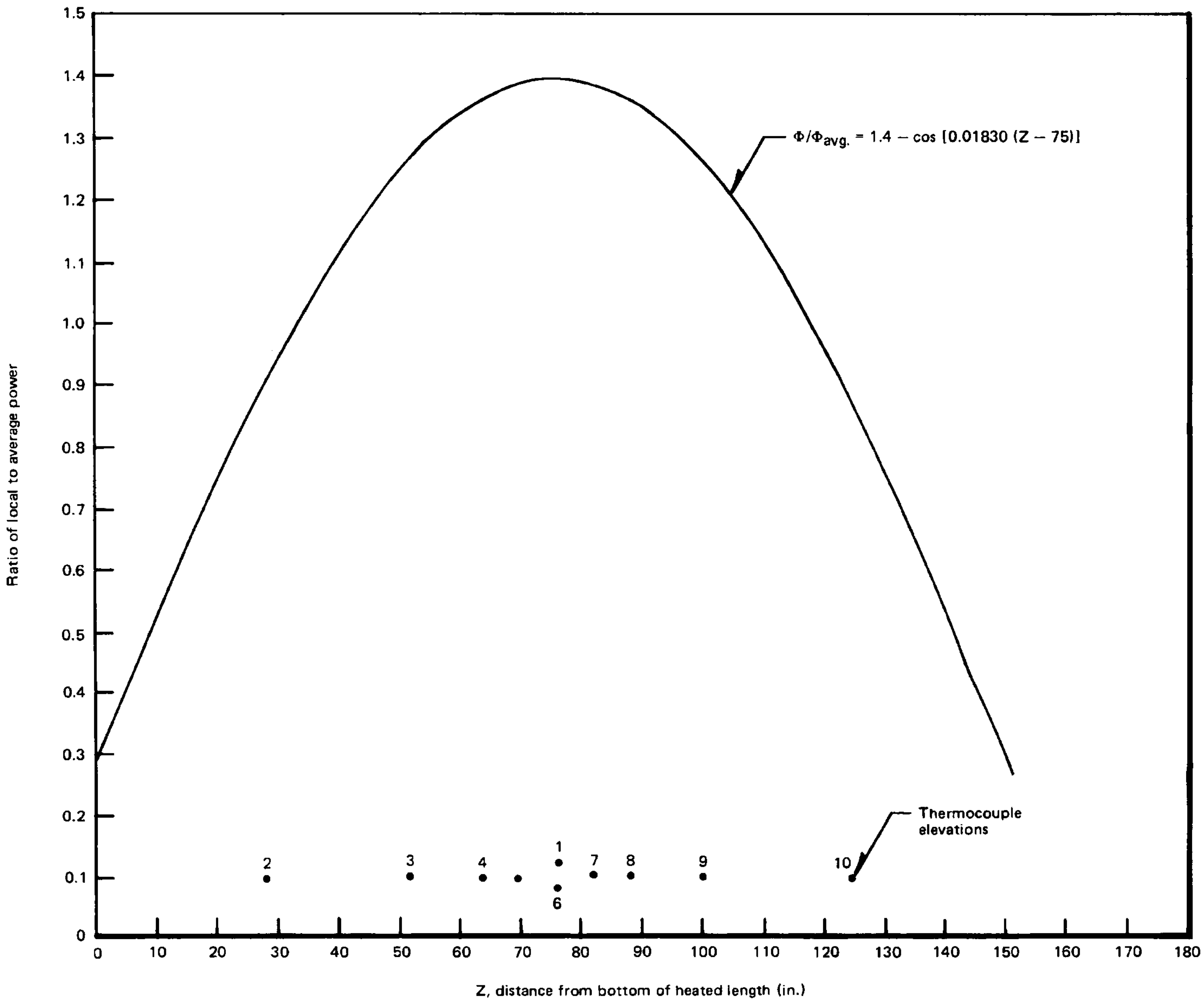

Figure 3-2. Power Profile

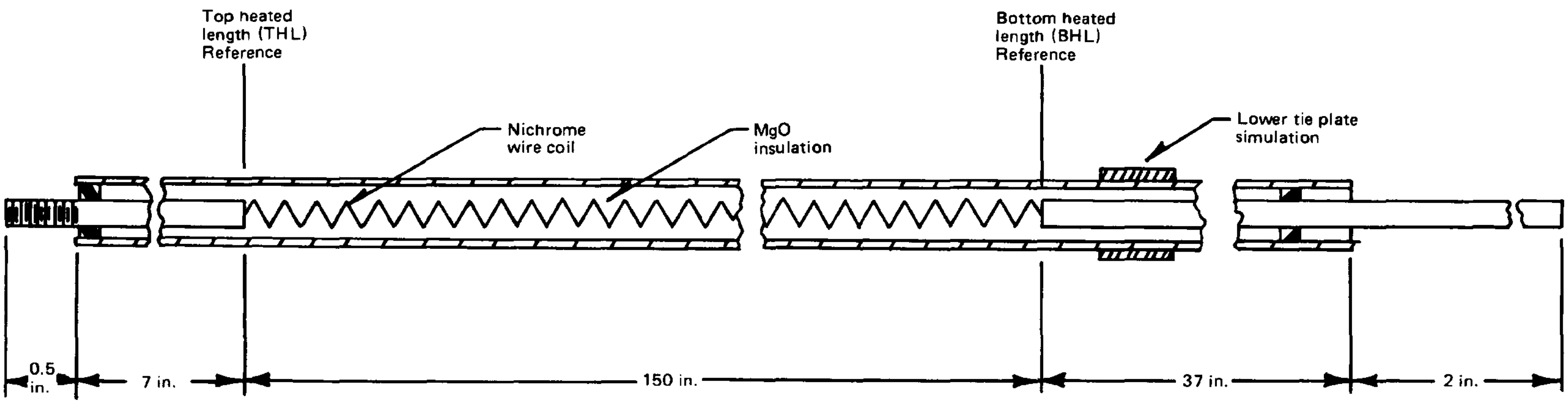

Figure 3-3. Heater Rod Configuration for Separate Effects Bundle Test Series

For the SEB tests, the test section may be configured several ways. These configurations are shown schematically in Figures 3-4 through 3-7 and are described below (system components are identified in Figure 3-1):

1. System Configuration: All flow paths are open, including bypass leakage and jet pump (Figure 3-4).

2. Blocked Jet Pump: A blank flange is installed to isolate the jet pump (Figure 3-5).

3. Blocked jet pump; blocked bypass leakage lower tie plate leakage holes are plugged (Figure 3-6).

4. Blocked jet pump; blocked bypass leakage; isolated GT; top of bypass blocked; continuous bypass leakage - the bypass to GT connecting hoses are removed; the GT opening plugged; and the bypass water (which enters the test section via LPCI) is then drained into a measuring tank (Figure 3-7).

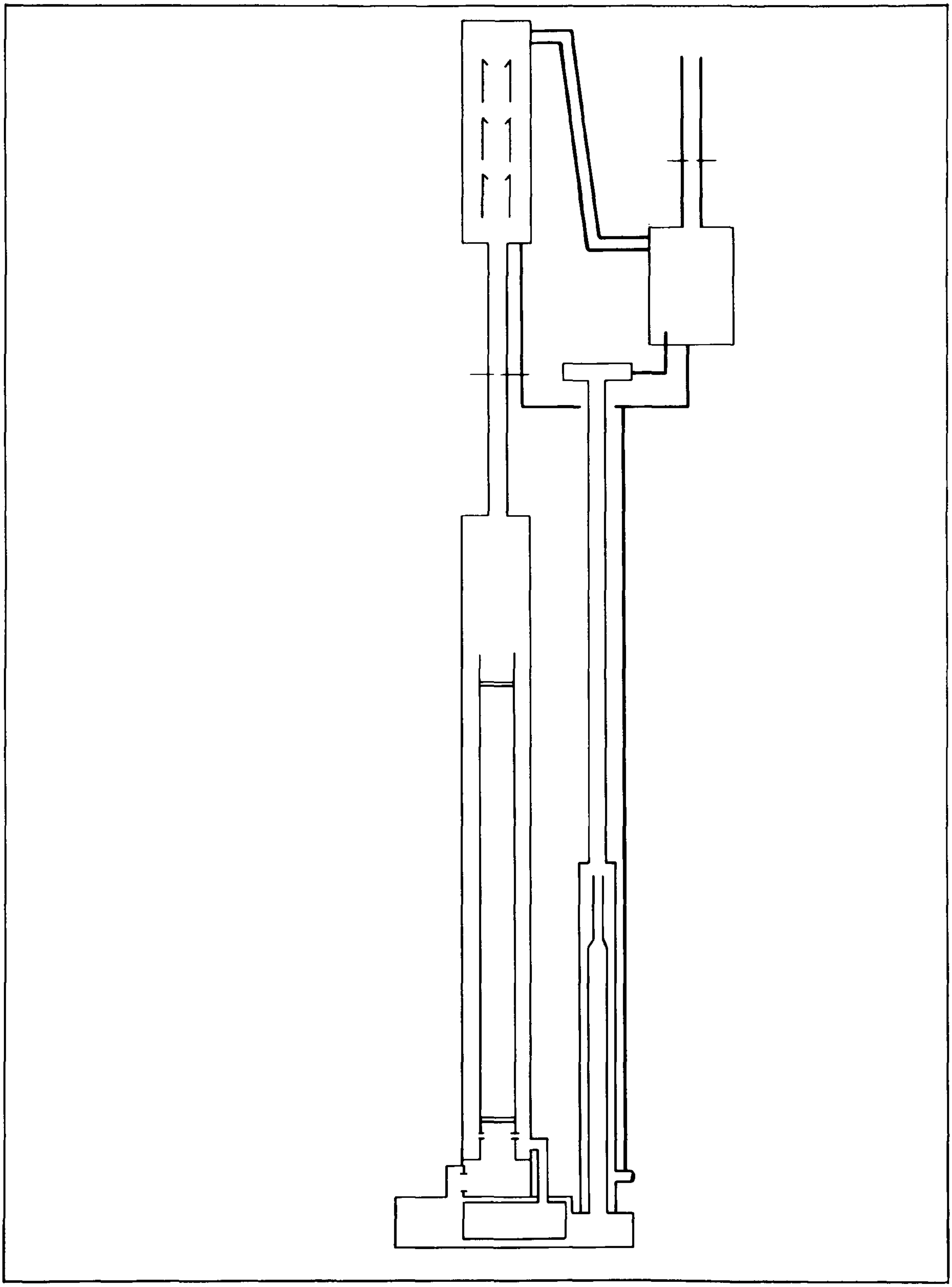

Figure 3-4. System Configuration

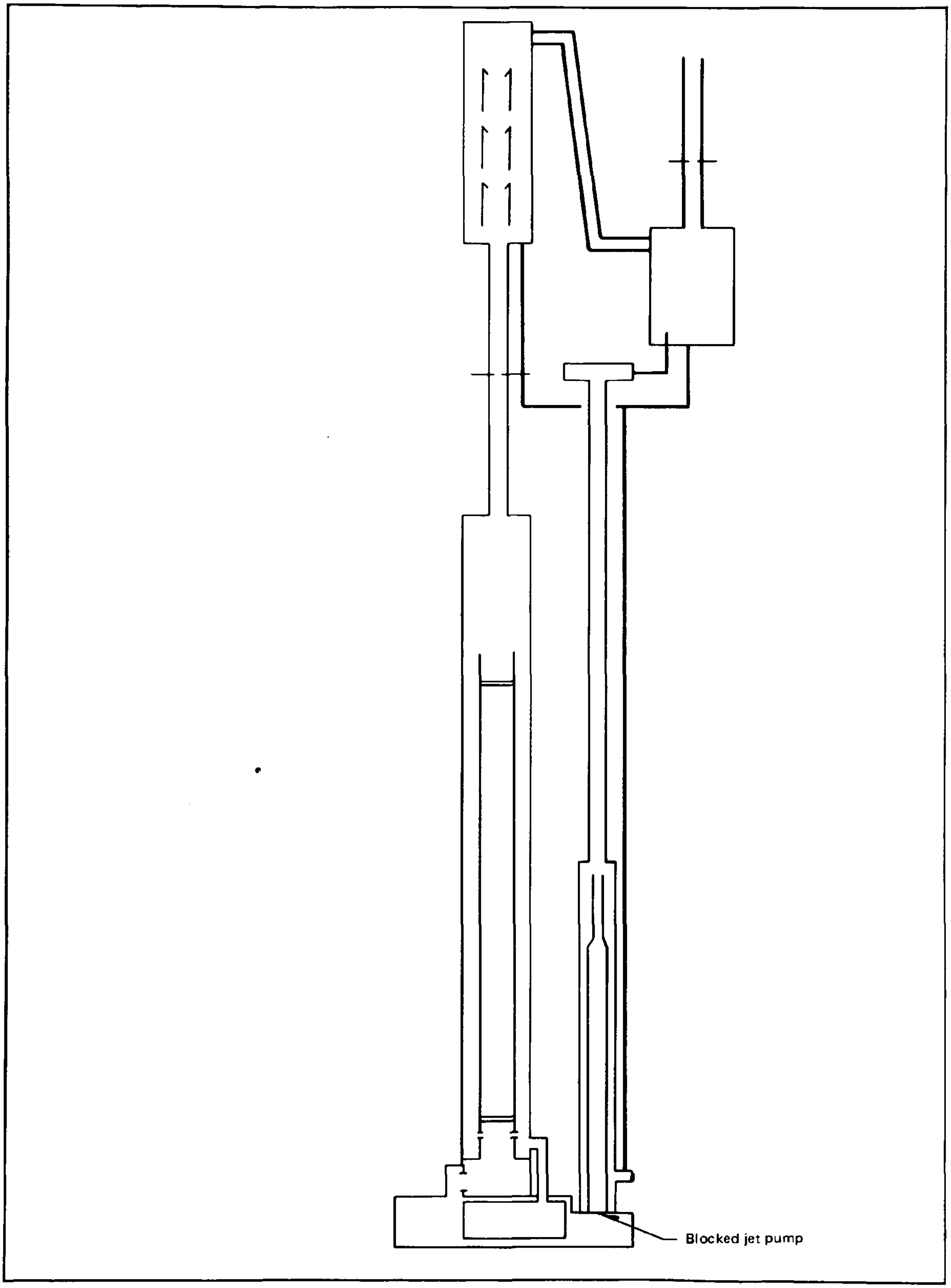

Figure 3-5. Blocked Jet Pump

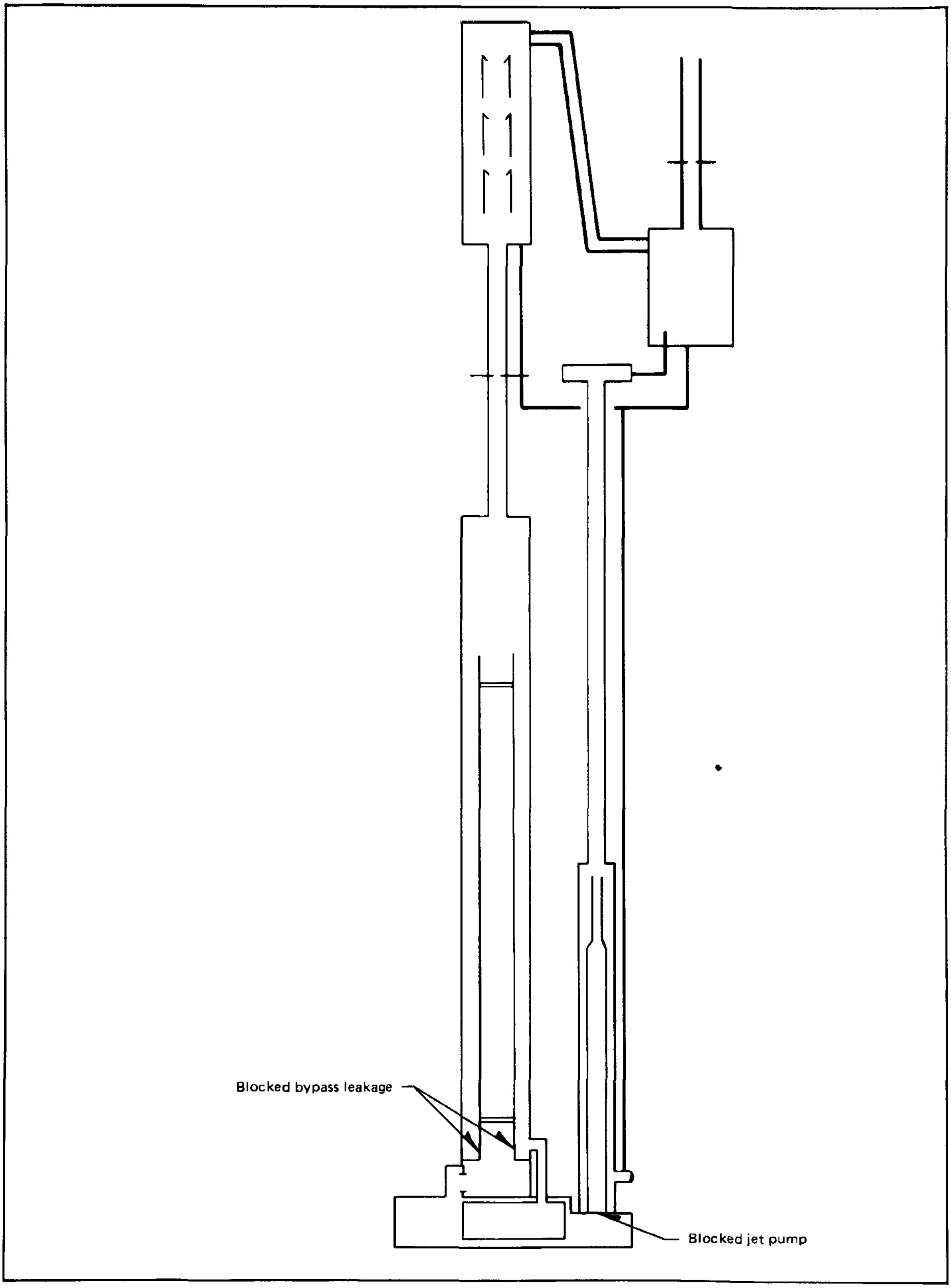

Figure 3-6. Blocked Jet Pump and Blocked Bypass Leakage

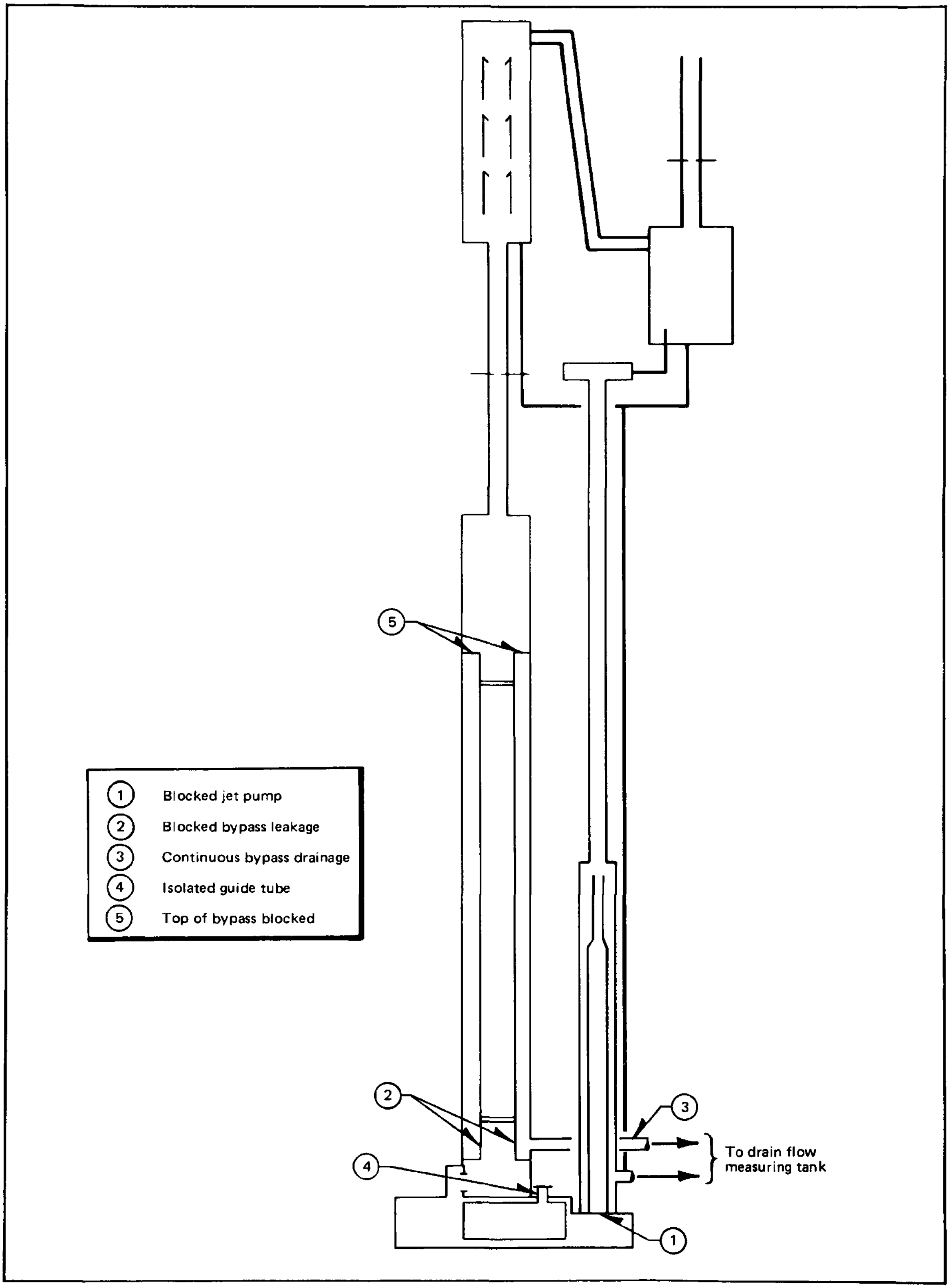

Figure 3-7. Blocked Jet Pump, Blocked Bypass Leakage, Continuous Bypass Drainage, Isolated Guide Tube, and Top of Bypass Blocked

Section 4

DATA REQUIREMENTS AND MEASUREMENT PLAN

The LOCA model requirements are to develop and qualify the following separate effects models:

1. Core Spray Heat Transfer
2. Reflood Heat Transfer
3. Core to Bypass Heat Transfer
4. Entrainment
5. Core Liquid Carryover
6. Upper Tie Plate CCFL
7. Upper Tie Plate CCFL Breakdown
8. Side Entry Orifice CCFL
9. Top of Bypass CCFL
10. Core Vaporization
11. Core Void Distribution
12. Condensation Effects of Lower Tie Plate Leakage
13. Refill-Reflood Flow Distribution

To provide the data to fulfill these requirements, the measurement objectives for the Stage 3 tests are:

1. To assure that the initial conditions specified for each test have been established. Initial conditions will include ECC flows and temperatures, inlet steam flows, liquid level in the LP and GT, and bundle power and temperatures.

2. To provide sufficient auxiliary measurements to ensure efficient operation of the test loop, continuous strings of pressure differentials, and provide checks on the measurement system and verification of the data.

3. To provide sufficient primary measurements to fulfill the data requirements of the various separate effects models. Required measurements will be discussed in the following paragraphs.

4.1 MEASUREMENT PLAN

The SEB measurement plan is designed to provide measurements of (a) controllable test parameters (independent variables), and (b) dependent variables sufficient to meet the measurement plan objectives. The measured independent variables are summarized in Table 4-1 and are shown schematically in Figure 4-1.

Measurements to meet the model development data requirements are made with absolute and differential pressure transducers and thermocouples (TCs). The specific data requirements and measurements designed to meet those requirements are tabulated in Table 4-2. The various absolute and differential pressure measurements may be grouped into three major categories:

1. Measurements of flows which cross the test section system control volume (external flows).

2. Measurements of flows which are within the test section control volume (internal flows).

3. Measurements of the regional mass inventories and two-phase levels.

Measurements of the internal flows aid in determination of the core liquid vaporization rate and the steam flow split between the core and the jet pump. The measurement groupings used to determine the external and internal flows are shown in Figure 4-2. The differential pressures shown in Figures 4-3 and 4-4 provide for tracking of the collapsed level within the test section. Secondary measurements are also provided to verify the sum of differential pressure strings. The temperature measurements shown in Figures 4-5 and 4-6 monitor the degree of subcooling in the various regions and provide a means of detecting subcooled CCFL breakdown at each flow restriction, e.g., the side SEO, upper tie plate, and TOB. The relative locations of the bottom of the heated length (BHL) and the ECC injection points are shown for reference on the temperature measurement figures. The locations of temperature measurements for the Stage 3 SEB test are shown on Tables 4-3, 4-4, and 4-5 for the heater rods (10 axial locations), inner channel (28 TCs) and outer channel (20 TCs), respectively. Power measurements are made for each of the 62 heater rods individually and for each of the nine groups. Total bundle power is the calculated sum of the nine groups.

The simulated fuel assembly consists of 62 heater rods and 2 water rods. As with the heater rods, each water rod is instrumented with 10 TCs, as described in Table 4-6. Of these 10, 8 TCs are welded to the inside surface of the hollow

Table 4-1

INDEPENDENT VARIABLES

Independent Variables Controlled:

m_{OL}	Initial mass of water in LP
m_{OG}	Initial mass of water in GT
W_{gL}	Steam injection rate into LP
W_{gG}	Steam injection rate into GT
W_{gD}	Steam injection rate into steam dome
W_{gC}	Steam injection rate into core
$\dot{Q}_C$	Bundle power rate of change
T_{OC}	Initial bundle temperature
Q_{OC}	Initial bundle power
W_{spray}	Spray injection rate
W_{LPCI}	LPCI injection rate
T_{ECC}	Spray and LPCI temperature
W_{LP}	LP flood rate

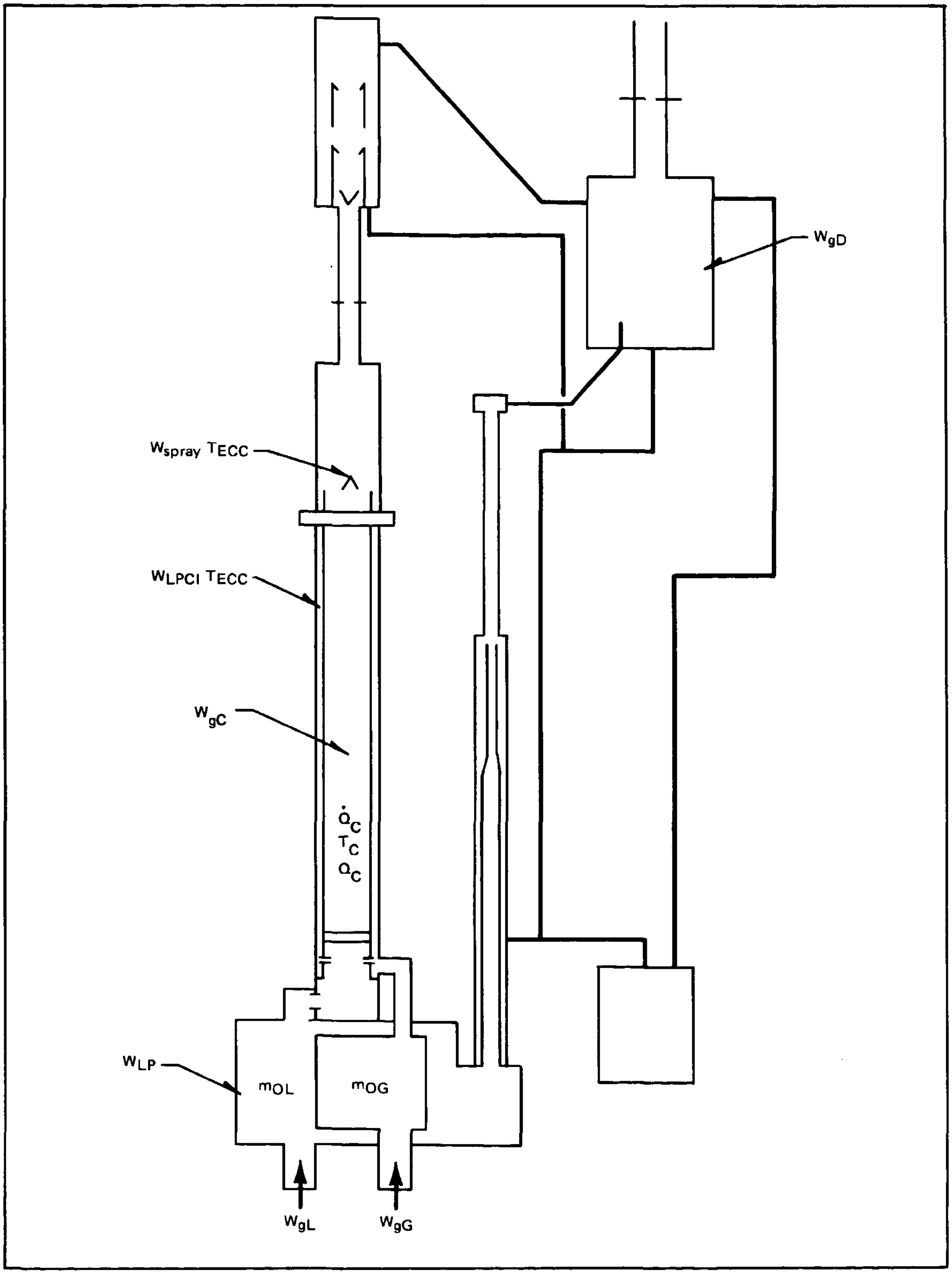

Figure 4-1. Measured Independent Parameters

Table 4-2

SEPARATE EFFECTS BUNDLE MEASUREMENT PLAN

Separate Effects Model	Primary Data Requirements	Primary Measurements
1. Core Spray Heat Transfer	• ECC flow rate and temperature	TM1, TM2, T18, T20
2. Reflood Heat Transfer	• Rod surface temperature	640 Rod TCs
3. Core to Bypass Heat Transfer	• Channel surface temperature	48 Inner/Outer Channel TC
	• Core power	Heater Power, Silicon Controlled Rectifier (SCR) Power
	• Core two-phase level	DP23 through DP29
	• Core single-phase level	DP5
	• Bypass temperature	T8, T9, T10, T11
	• Injected steam flow rate	DP37, P14, T33
	• Core steam superheat	4 TCs on Water Rods
	• LP flooding rate and temperature	TM2, T34
4. Entrainment	• Core ΔP	DP5
	• Bypass ΔP, Guide Tube ΔP	DP13, DP11
5. Core Liquid Carryover	• Core steaming rate	DP35, T28, P13
	• ECC flow rate and temperature	TM1, TM2, T18, T20
	• Injected steam flow rate	DP37, P14, T33
	• Steam separator liquid flow rate	Drain Tank, DP34, Measurement of Separated Liquid Flow

Table 4-2

SEPARATE EFFECTS BUNDLE MEASUREMENT PLAN (Continued)

Separate Effects Model	Primary Data Requirements	Primary Measurements
6. Upper Tie Plate CCFL	• Upper tie plate steam flow	DP35, T28, P13, DP32, P11, T31
7. Upper Tie Plate CCFL Breakdown	• Upper tie plate liquid down flow	TM1
	• ECC flow and temperature	TM1, T18
	• Upper tie plate pressure	P2
	• Fluid temperature below UTP	T12
	• Fluid temperature above upper tie plate	T13
	• UP mass	DP7
8. SEO CCFL	• SEO steam flow	DP32, P11, T31
	• SEO liquid flow	TM2
	• ECC flow and temperature	TM2, T20
	• SEO pressure	P3, DP1, DP2
9. TOB CCFL	• TOB steam flow	DP33, P12, T30
	• TOB liquid flow	TM1
	• ECC flow and temperature	TM1, T18
	• TOB pressure	P5, P2
10. Core Vaporization	• Steam flow exiting from the core	DP35, T28, P13
	• Core rod temperatures	640 Rod Thermocouples
	• Core two-phase level	DP23-DP29
	• ECC flow and temperature	TM1, TM2, T18, T20
	• Core power	Heater Power, SCR Power

Table 4-2

SEPARATE EFFECTS BUNDLE MEASUREMENT PLAN (Continued)

Separate Effects Model	Primary Data Requirements	Primary Measurements
11. Core Void Distribution	• Core pressure drop	DP23-DP29, DP5
12. Condensation Effects of Lower Tie Plate Leakage	• Lower tie plate leakage flow rate	DP13, DP38
	• Lower tie plate leakage flow temperature	T8, T9, T10, T11
	• Core rod temperatures	640 Rod TCs
	• Channel temperatures	48 Inner/ Outer Channel TCs
	• Steam flow exiting the core	DP35, T28, P13
13. Refill-Reflood Flow Distribution	• Core mass	DP5
	• LP mass	DP1, DP2
	• Bypass mass	DP13

water rod, and 2 TCs protrude through the rod surface into the region between adjacent fuel rods. These four TCs (two TCs per each of the two water rods) protrude 0.100 inch and are intended to provide an indication of steam superheat in the core.

In addition to the series of TCs and pressure transducers, one conductivity probe will be installed at the jet pump entrance into the LP to provide an indication of the void fraction of the two-phase mixture flowing through the jet pump.

The orientation of the rods within the inner and outer channel, and also the orientation of the bundle in reference to north, south, east, and west directions are shown in Figure 4-7.

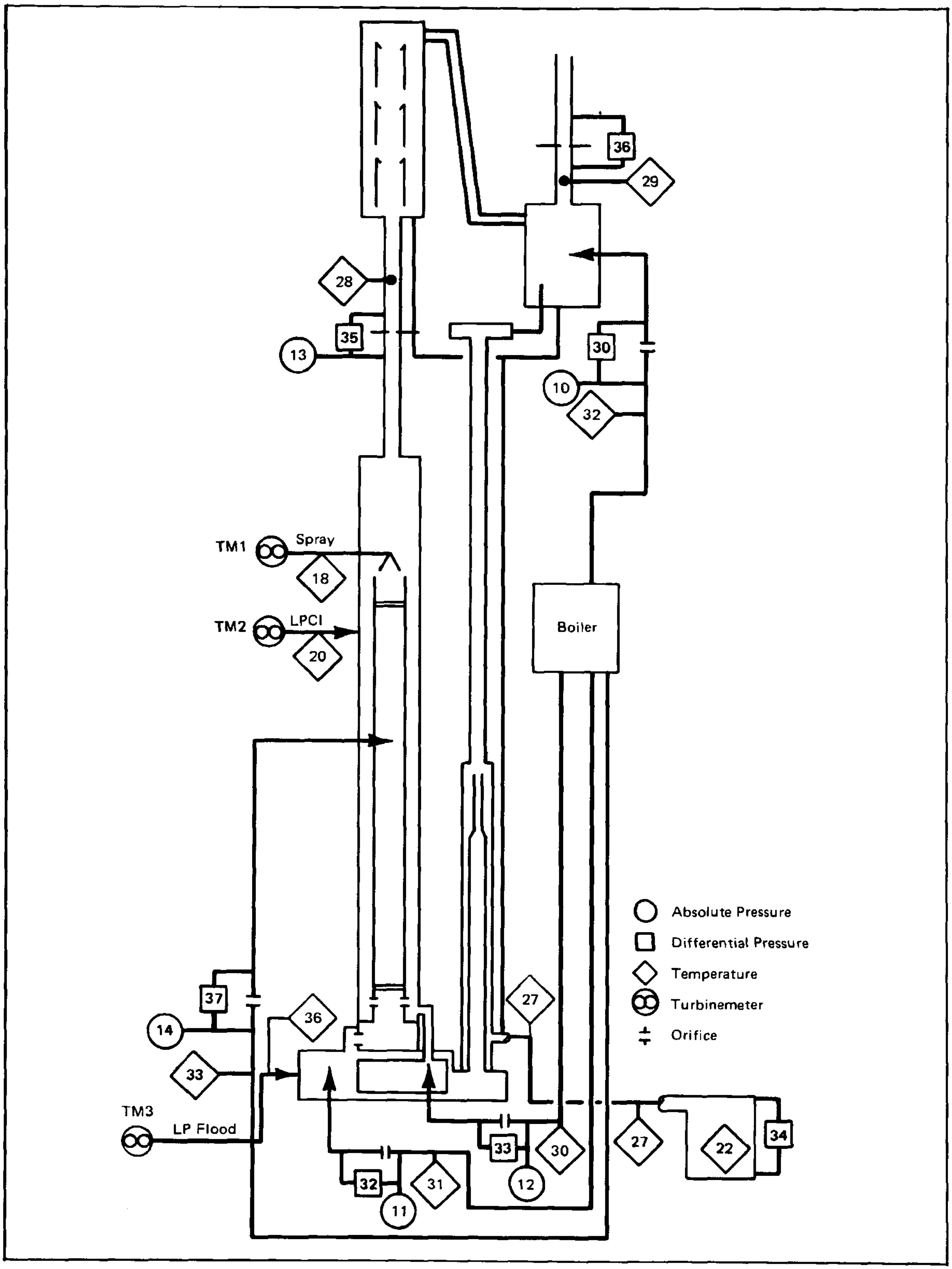

Figure 4-2. Internal and External Flow Measurements

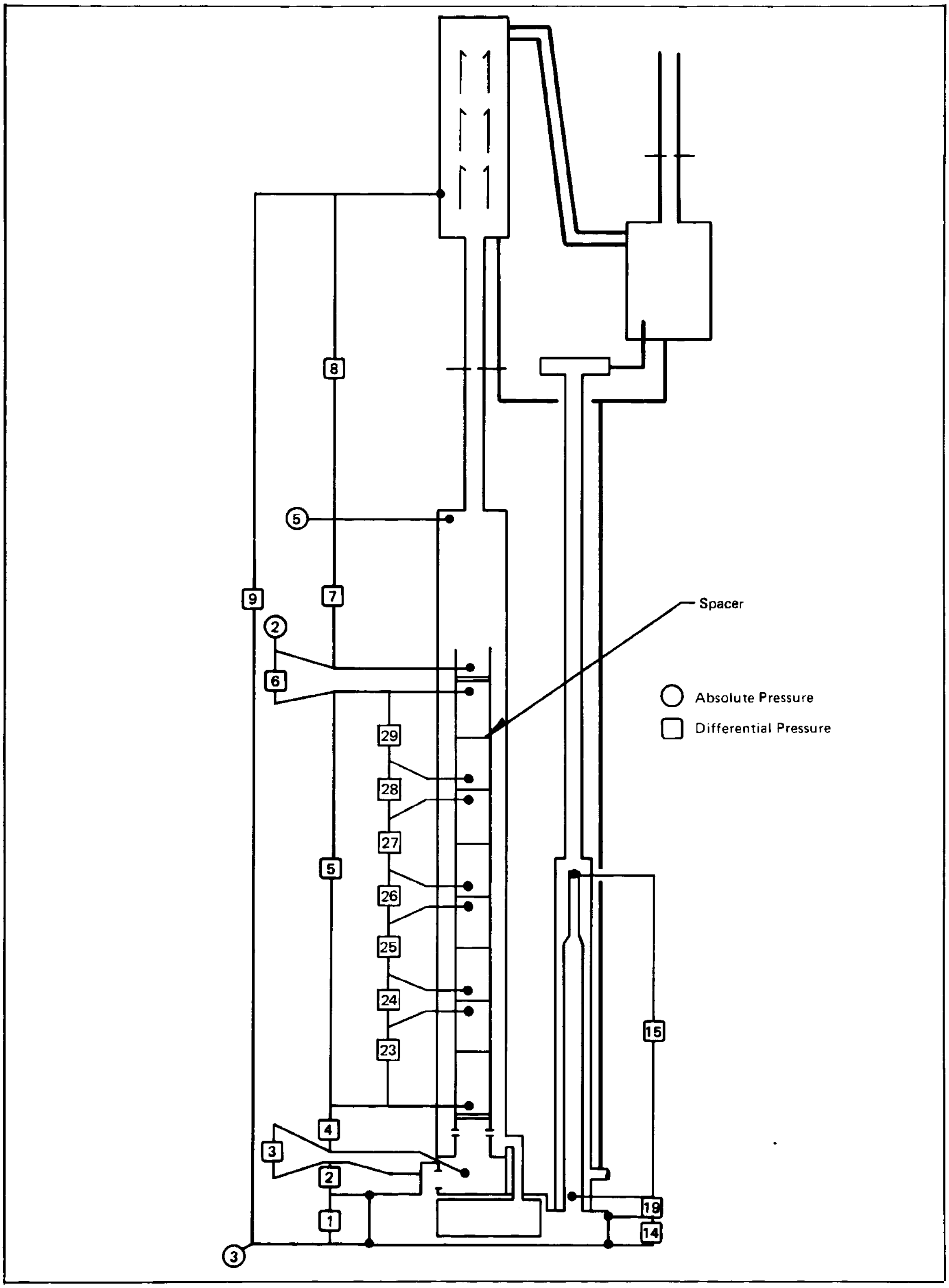

Figure 4-3. Collapsed Level Differential Pressure Measurements
(Lower Plenum and Jet Pump Strings)

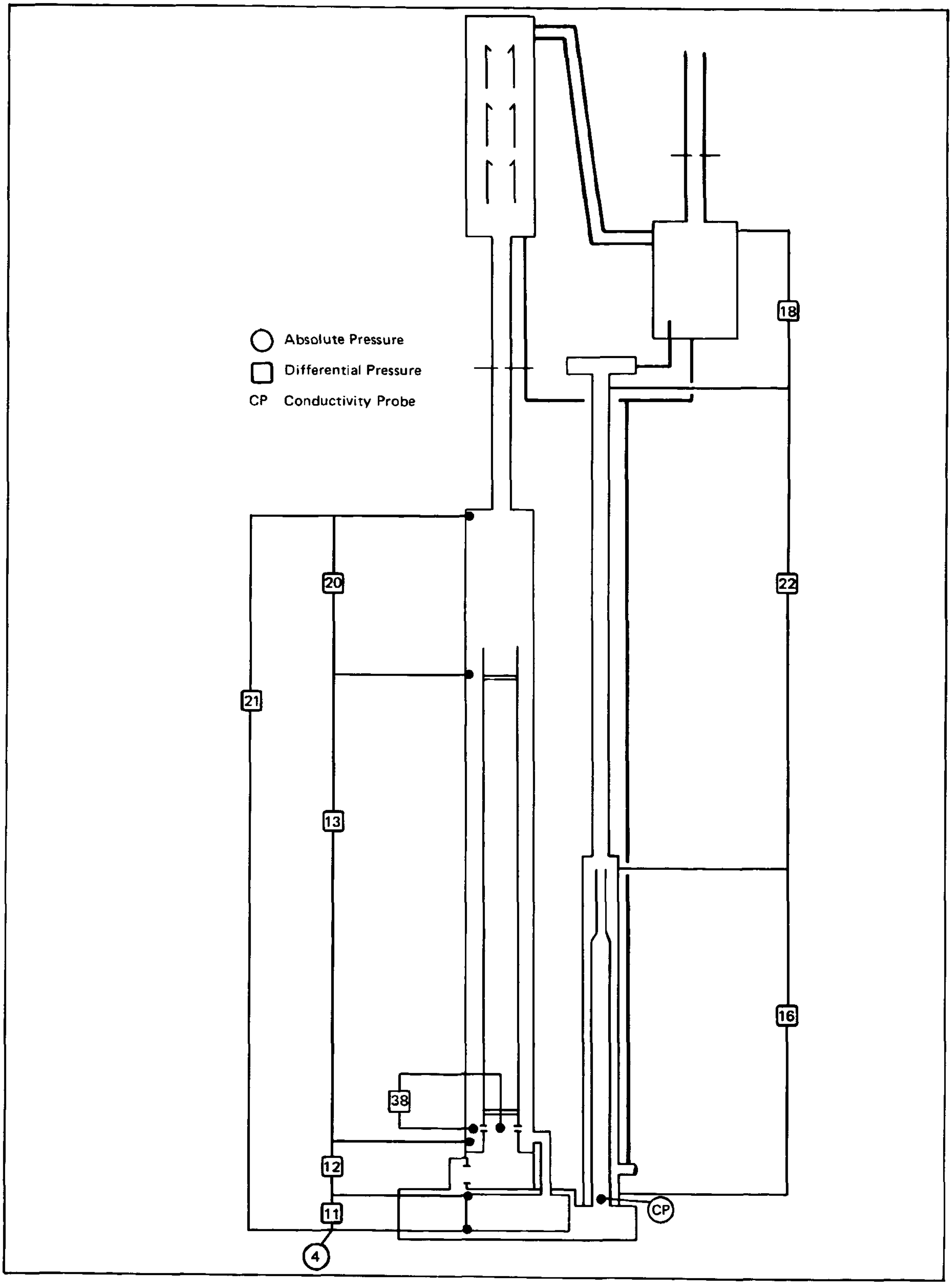

Figure 4-4. Collapsed Level Differential Pressure Measurements
(Guide Tube and Annulus Strings)

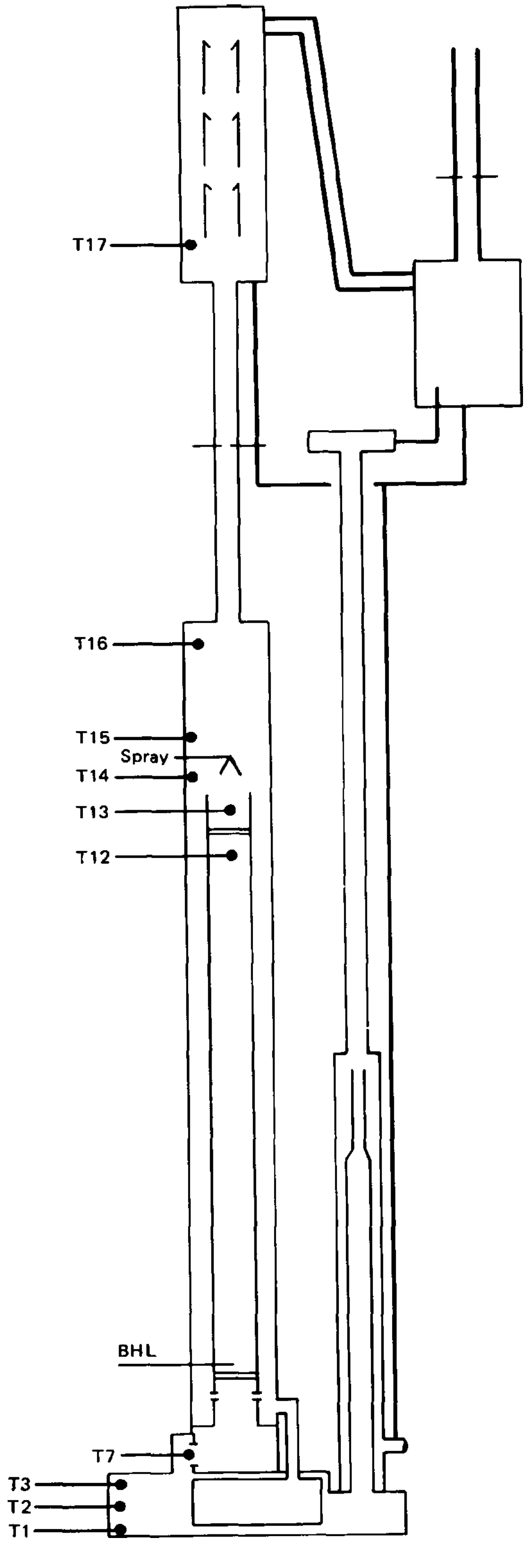

Figure 4-5. Fluid Temperature Measurements (Plena and Bundle String)

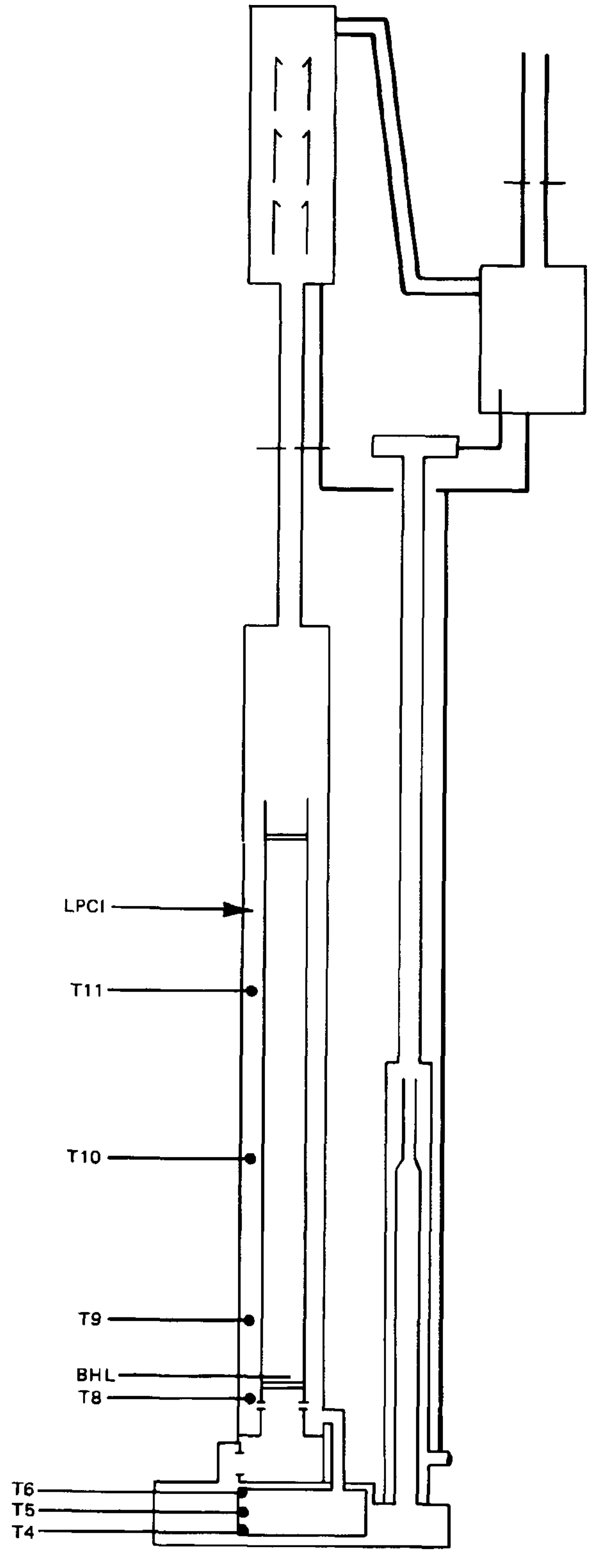

Figure 4-6. Fluid Temperature Measurements (Guide Tube and Bypass Sring)

Table 4-3

HEATER ROD
THERMOCOUPLE LOCATIONS
(10 Thermocouples Per Heater)

Thermocouple	TC Location, Distance Above BHL (in.)
1	75
2	27
3	51
4	63
5	69
6	75
7	81
8	87
9	99
10	123

Table 4-4

INNER CHANNEL THERMOCOUPLE
LOCATIONS
(28 Thermocouples)

Side of Channel	TC Location, Distance Above BHL (in.)
South	27, 48, 60, 69, 75, 81, 90, 102, 123
North	27, 51, 69, 75, 81, 99, 123
East	27, 51, 69, 75, 81, 99
West	27, 51, 69, 75, 81, 99

Table 4-5
OUTER CHANNEL
THERMOCOUPLE LOCATIONS
(20 Thermocouples)

Side of Channel	TC Location, Distance Above BHL (in.)
North	27, 51, 75, 99, 123
South	27, 51, 75, 99, 123
East	27, 51, 75, 99, 123
West	27, 51, 75, 99, 123

Table 4-6
WATER ROD
THERMOCOUPLE LOCATIONS
(10 Thermocouples per Water Rod)

Thermocouple	TC Location, Distance Above BHL (in.)*
1	24
2**	48
3	60
4	66
5**	72
6	72
7***	78
8	84
9	96
10***	120

*Water rod TCs are located 3 inches lower than heater rod TCs due to increased thermal expansion allowance after the TCs were installed.

**Steam superheat TC for first water rod (location 29).

***Steam superheat TC for second water rod (location 36).

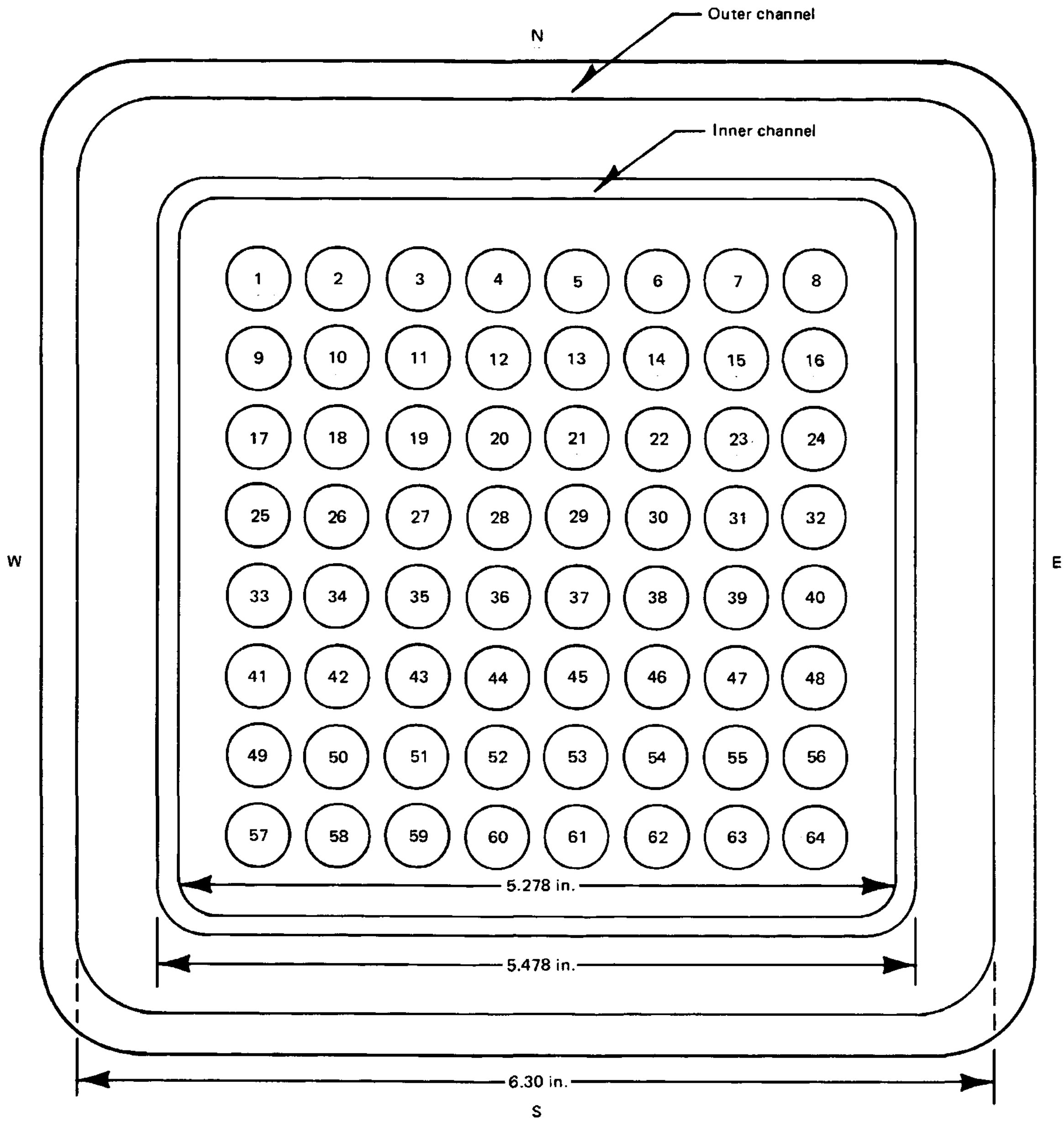

Figure 4-7. Bundle Cross Section Showing Rod Orientation

Section 5

TEST PLAN

The test plan for Stage 3 of Task 4.3 is divided into facility calibration and separate effects tests. Facility calibration tests include facility operational shakedown and calibration of various system components. Separate effects tests will include tests to investigate the following general phenomena:

1. Core Spray Heat Transfer
2. Reflood Heat Transfer
3. Bypass Heat Transfer
4. Refill-Reflood Performance

5.1 FACILITY CALIBRATION TEST PLAN

The objectives of the facility calibration tests are:

1. To debug facility operational problems.
2. To provide test section calibration data to aid in evaluation of the separate effects data.

The test series includes the following types of tests:

1. Single-phase fill
2. SCR Power System Checkout
3. Upper Tie Plate CCFL
4. TOB CCFL
5. SEO CCFL
6. Bypass Leakage Calibration

Each of these tests is described briefly in the following paragraphs.

5.1.1 Single Phase Fill

Configuration: System Configuration (Figure 3-4)

Objective: Checkout operation of facility and the test instrumentation

Procedure: Use saturated LPCI to fill test section

5.1.2 Silicon Controlled Rectifier Power System Checkout

Configuration: System Configuration (Figure 3-4)

Objective: Verify operation of heater rods and the power decay transient system.

Procedure: Initialize core power at 100 kW and then initiate transient. Compare power versus time data against expected transient.

5.1.3 Upper Tie Plate Counter-Current Flow Limiting

Configuration: Blocked jet pump; blocked core to bypass leakage (Figure 3-6)

Objective: Confirm CCFL characteristics of upper tie plate as predicted by current best estimate CCFL correlation.

Procedure: Turn on saturated LPCI and fill the GT and bypass. Inject core steam. Inject saturated spray, as required to maintain a constant level in the UP. Record steam flow and spray flow. Repeat for several steam flows.

5.1.4 Top of Bypass Counter-Current Flow Limiting

Configuration: Blocked jet pump; blocked core to bypass leakage (Figure 3-6)

Objective: Determine CCFL characteristics of the reduced flow area at the TOB.

Procedure: Fill the LP and core, to the top of the inner channel, with saturated liquid. Inject GT steam. Turn on saturated spray and adjust spray rate to maintain a constant level in the UP. Record steam flow and spray rate.

5.1.5 Side Entry Orifice Counter-Current Flow Limiting

Configuration: Blocked jet pump; blocked bypass leakage (Figure 3-6)

Objective: Confirm CCFL characteristics of SEO.

Procedure: Inject LP steam. Inject saturated spray as required to maintain a constant level in the region above the SEO. Record steam flow and spray flow. Repeat for several steam flows.

5.1.6 Bypass Leak Calibration

Configuration: System Configuration (Figure 3-4)

Objectives: Determine bypass leakage as a function of bypass head.

Procedure: Inject saturated LPCI into bypass. Allow bypass level to reach steady state. Record LPCI flow and bypass level. Repeat for several LPCI flows.

5.1.7 Facility Calibration Test Matrix

A complete test matrix for the Stage 3 facility calibration tests is shown in Table 5-1.

Table 5-1

FACILITY CALIBRATION TEST MATRIX - STAGE 3

Run Number Series	Core Power (kW)	ECC Flow (gpm)	ECC Temp (°F)	Steam Injection LP (lb/hr)	Steam Injection GT (lb/hr)	SEO Diam (in.)	Test Section Configuration	Comments
100 (Single-Phase Fill)	0	10	212	0	0	2.43	System	LPCI Only
200 (SCR Checkout)	100	17	120	0	0	2.43	System	Spray Only
300 (Upper Tie Plate CCFL)	0	Vary	212	Vary	0	2.43	Blocked jet pump; blocked bypass leakage	Bypass Full Spray Only
400 (TOB CCFL)	0	Vary	212	0	Vary	2.43	Blocked jet pump; blocked bypass leakage	Core Full Spray Only
500 (SEO CCFL)	0	Vary	212	Vary	0	2.43	Blocked jet pump; blocked bypass leakage	Spray Only
600 (Bypass Leak)	0	Vary	212	0	0	2.43	System	LPCI Only

5.2 SEPARATE EFFECTS TEST PLAN

The separate effects strategy is designed to study LOCA phenomena to support the model development task of the BWR Refill-Reflood Program. The test plan is divided into four types of tests: (a) core spray heat transfer, (b) reflood heat transfer, (c) bypass heat transfer, and (d) refill-reflood performance. The test plan for each of these tests is outlined in the following subsections.

5.2.1 Core Spray Heat Transfer

Configuration:	Blocked jet pump; blocked core to bypass leakage; SEO removed; isolated guide tube; top of bypass blocked (Figure 3-7).
Objective:	Determine bundle core spray heat transfer characteristics at spray flows less than 2.5 gpm. Two types of tests will be performed. The first has a flooded bypass region throughout the test. The other type is to have a bypass flow which is 20% of the spray flow rate.
Procedure:	Establish bypass conditions according to the test matrix. Inject steam into the LP. Set core power to desired value and allow core to heat up to desired temperature. Initiate core spray and power decay and continue until core has cooled (T bulk < 400°F). If the core bulk temperature exceeds 1800°F, terminate core power and allow core to cool. Continually drain the LP to prevent core reflooding.
Test Plan:	The test parameters are based on best estimate values for the BWR. The test plan is to vary the core spray from 3 gpm down to 0. Once these tests are complete, the core steaming rate and the core spray rate are varied. It is necessary to limit the bundle temperature to preserve the test bundle for other separate effects tests. The test matrix is shown in Table 5-2.

5.2.2 Reflood Heat Transfer

The objective of the reflood heat transfer (RHT) tests is to examine the reflood heat transfer performance to provide entrainment, void fraction, spacer differential pressure, quench front propagation, and bundle temperature data. The RHT tests are divided into three categories:

1. RHT with controlled bottom flooding
2. RHT with core-bypass interaction and
3. RHT with core-bypass-jet pump interaction.

The test plan for each of these is outlined in the following pages.

Table 5-2

CORE SPRAY HEAT TRANSFER TEST MATRIX

Run	Spray Rate (gpm)	LP Steam Injection (lbm/hr)	Initial Temp (°F)	Initial Power (kW)	Comments*
1001	2.5	400	1100	250	
1002	2.0	400	1100	250	
1003	1.5	400	1100	250	
1004**	1.0	400	1100	250	
1005	0.5	400	1100	250	
1006**	0	400	1100	250	Dry Bypass
1007**	1.5	0	1100	250	
1008**	2.0	0	1100	250	
1009	2.5	0	1100	250	
1010**	3.0	0	1400	250	Tieback Test
1011**	1.0	1200	1100	250	Dry Bypass
1012**	1.5	0	1100	250	Flooded Bypass
1013**	1.0	0	1100	250	
1014**	1.0	600	1100	250	
1015	0.5	600	1100	250	
1016	0	600	1100	250	
1017	2.0	200	1100	250	
1018**	1.0	200	1100	250	
1019	2.0	200	800	250	
1020	1.0	200	800	250	
1021	0	200	800	250	
1022	0.5	200	1100	250	
1023	0	200	1100	250	
1024**	0.5	0	1100	250	
1025	1.0	400	800	250	Flooded Bypass
1026	0.5	400	800	250	Flooded Bypass
1027**	1.0	400	1100	250	
1028**	2.0	0	1100	250	Flooded Bypass
1029**	0.5	0	1100	250	Flooded Bypass
1030**	1.0	0	1100	250	Flooded Bypass
1031	0	0	N/A	30	Steady-State Radiation Test***

*All tests with bypass flow = 20% of spray rate except those labeled "Flooded Bypass" or "Dry Bypass."

**1st Priority Tests

***Other steady-state radiation tests to monitor bundle condition are included as part of another test.

All Tests:

Configuration:	Blocked jet pump; blocked bypass leakage; isolated GT; top of bypass blocked.
ECC Temperature	= 212°F
Steam Dome Steam Injection	= 100 lbm/hr
GT Steam Injection	= 0 lbm/hr
GT Full of Saturated Water	
Maximum Allowable Bundle Temperature	= 1800°F

5.2.2.1 Reflood Heat Transfer With Controlled Bottom Flood

Configuration: Blocked jet pump; blocked bypass leakage (Figure 3-6).

Objective: Determine reflood heat transfer characteristics with controlled bottom flood. Measure entrainment, core void fraction, spacer ΔP, and bundle temperatures.

Test Procedure: Fill the LP to the bottom of the lower tie plate with saturated water. Initiate steam flow as required. Initiate core power (if required) and allow core bulk temperature to reach desired value. Initiate power transient and LP flood. If core peak temperature exceeds 1800°F, terminate the core power and allow core to cool. Otherwise, allow test to continue until bulk core temperature is less than 400°F.

Test Plan: Conduct this series of tests with three LP flood rates (1, 2, and 3 LPCI) and three core steam flow rates with no core power. Vary the core power and initial bulk temperature to investigate the effect of stored and decay heat. Vary the core steam injection rate to determine its effect on RHT. The test matrix is shown in Table 5-3.

Table 5-3

REFLOOD HEAT TRANSFER WITH CONTROLLED BOTTOM FLOODING TEST MATRIX

Run	Lower Plenum Flood Water Flow (gpm)	Lower Plenum Flood Water Temp. (°F)	Core Power (kW)	Initial Core Temp. (°F)	LP Steam Injection (lbm/hr)
2301*	8	212	0	Saturation	200
2302*	8	212	0	Saturation	400
2303	8	212	0	Saturation	800
2304	16	212	0	Saturation	200
2305	16	212	0	Saturation	400
2306	16	212	0	Saturation	800
2307	24	212	0	Saturation	155
2308	24	212	0	Saturation	400
2309	24	212	0	Saturation	800
2310	8	212	250	1100	0
2311	16	212	250	1100	0
2312	24	212	250	1100	0
2313	8	212	250	800	155
2314*	8	212	250	1100	155
2315	8	212	250	1400	155
2316	8	212	150	800	155
2317	8	212	150	1100	155
2318	8	212	150	1400	155
2319*	8	212	100	1100	155
2320	8	212	100	1400	155

Table 5-3

REFLOOD HEAT TRANSFER WITH CONTROLLED BOTTOM FLOODING TEST MATRIX (Continued)

Run	Lower Plenum Flood Water Flow (gpm)	Lower Plenum Flood Water Temp. (°F)	Core Power (kW)	Initial Core Temp. (°F)	LP Steam Injection (lbm/hr)
2321	8	212	100	800	400
2322	8	212	300	1100	0
2323	8	212	100	1100	0
2324	8	212	250	800	0
2325	8	212	250	1400	0
2326	8	120	250	1100	0
2327	8	160	250	1100	0
2328*	8	212	0	Saturation	155
2329*	8	212	250	1100	0
2330*	8	212	100	1100	0
2331*	4	212	250	1100	155
2332	1	212	250	1100	155
2333	8	212	0	Saturation	800
2334	24	212	0	Saturation	400
2335	16	212	0	Saturation	155

*1st Priority Test.

All Tests:

Configuration: Blocked jet pump; blocked bypass leakage
GT Steam = 0 lbm/hr
Core Steam = 0 lbm/hr
Bypass Continually Drained
SEO Diameter = 2.43 in.
Maximum Allowable Peak Cladding Temperature (PCT) = 1800°F
Lower plenum full of saturated liquid to lower tie plate.

5.2.2.2 Reflood Heat Transfer with Core-Bypass Interaction

Configuration: Blocked Jet Pump (Figure 3-5).

Objective: Determine core heat transfer performance with core-bypass interaction; compare results to controlled bottom flood RHT results.

Procedure: Fill the LP to the level of the lower tie plate with saturated water. Initiate steam flow and core power and allow core bulk temperature to reach desired value. Initiate LPCI and power transient. Allow test to continue until the core temperature exceeds 1800°F, terminate core power and allow core to cool.

Test Plan: Perform this test with three bundle powers and three LPCI subcoolings. The test matrix is shown in Table 5-4.

Table 5-4

REFLOOD HEAT TRANSFER WITH CORE-BYPASS INTERACTION TEST MATRIX

Run	LPCI Temp (°F)	Core Power (kW)
2101*	212	250
2102	160	250
2103*	130	250
2104	212	150
2105	160	150
2106	130	150
2107	212	100
2108	160	100
2109	130	100

*1st Priority Test

All Tests:

Configuration:	Blocked Jet pump
Spray	= 0 gpm
LPCI	= 8 gpm
Initial Core Temperature	= 1100°F
Maximum PCT	= 1800°F
Steam Dome Steam Injection	= 100 lbm/hr
LP Steam	= 155 lbm/hr
GT Steam	= 0 lbm/hr

Lower plenum initially full of saturated liquid to lower tie plate.

5.2.2.3 <u>RHT with Core-Bypass - Jet Pump Interaction</u>

Configuration: System Configuration (Figure 3-4).

Objective: Determine the effect of the jet pump flow path on the RHT performance.

Procedure: Same as RHT with blocked jet pump. For tests with LP steam flow, start the steam flow prior to initializing the core power.

Test Plan: Repeat the high power RHT with core-bypass interaction tests, with and without LP steam injection. The test matrix is shown in Table 5-5.

Table 5-5

REFLOOD HEAT TRANSFER WITH CORE-BYPASS - JET PUMP INTERACTION TEST MATRIX

Run	LPCI Temp (°F)	LP Steam Injection (lbm/hr)
2201*	212	155
2202	160	155
2203	120	155
2204	212	0
2205	160	0
2206	130	0
2207	130	155
2208	130	155
2209	130	155

*1st Priority Test

All Tests:

Configuration:	System (open jet pump)
Core Power	= 250 kW
Spray	= 0 gpm
LPCI	= 8 gpm
Initial Core Temperature	= 1100°F
Maximum Allowable PCT	= 1800°F
Steam Dome Steam Injection	= 100 lb/hr
GT Steam	= 0 lbm/hr

Remove the SEO

Lower plenum initially full of saturated liquid to lower tie plate.

5.2.3 Bypass Heat Transfer

Configuration: Blocked jet pump; blocked bypass leakage; isolated GT; TOB blocked (Figure 3-7).

Objective: Determine the bypass heat transfer rate.

Test Procedure: Initiate lower plenum flow as required. Initiate core power as required and allow core to heat up to desired initial temperature. Initiate LPCI and core power transient. Continue test until core temperature has peaked and is below 400°F. Terminate core power if PCT exceeds 1800°F.

Test Plan: Perform adiabatic (no core power) tests. Vary LPCI flow rate and LPCI temperature to determine bypass heat transfer rate. Perform similar heated tests for three bundle powers with various initial core temperatures. The test matrix is shown in Table 5-6.

Table 5-6

BYPASS HEAT TRANSFER TEST MATRIX

Run	LPCI Temp (°F)	Core Power (kW)	Initial Core Temp (°F)	LP Steam Injection (lbm/hr)	LPCI Flow (gpm)
3001	212	0	Saturation	200	8
3002	212	0	Saturation	800	8
3003	212	0	Saturation	400	8
3004	160	0	Saturation	400	8
3005	160	0	Saturation	800	16
3006	160	0	Saturation	400	24
3007	120	0	Saturation	800	8
3008*	120	0	Saturation	800	16
3009	120	0	Saturation	800	24
3010*	120	250	800	400	16
3011	120	250	1100	400	16
3012*	120	250	1400	400	16
3013	120	250	800	400	16
3014	120	150	1100	400	16
3015	120	150	1400	400	16
3016	120	100	800	400	16
3017	120	100	1100	400	16
3018*	120	100	1400	400	16
3019	120	300	1400	400	16
3020*	120	0	Saturation	400	8
3021*	120	0	Saturation	400	16
3022*	120	0	Saturation	400	24
3023*	160	0	Saturation	400	16

*1st Priority Test

All Tests:

Core Steam	= 0 lbm/hr
GT Steam	= 0 lbm/hr
Steam Dome Steam	= 100 lbm/hr
LP Initial Mass	= 0 lb/hr
Maximum Allowable PCT	= 1800°F

5.2.4 Refill-Reflood Performance

Configuration: System Configuration (Figure 3-4).

Objective: Repeat Stage 1 refill-reflood experiments with the additional instrumentation available for Stage 1 data.

Test Procedure: Establish initial mass levels in the LP and GT. Establish initial steam flows. Initiate core power and bring core to initial bulk temperature. Initiate spray and LPCI and power transient. Terminate test if PCT exceeds 1800°F. Continue test until core level is stabilized at the level of the jet pump.

Test Plan: Repeat "BWR-Like" Stage 1 test for average and high power bundles (run numbers 1800 and 1901). Perform tests to simulate TLTA test 6423 Run 3 (High Power, Low ECC). The test matrix is shown in Table 5-7.

Table 5-7

REFILL-REFLOOD PERFORMANCE TEST MATRIX

Run	ECC			Initial Core		Steam Injection (lbm/hr)			Initial Mass (lbm)		Comments
	LPCI (gpm)	Spray (gpm)	Temp (°F)	Power (kW)	Temp (°F)	Core	Lower Plenum	Guide Tube	Lower Plenum	Guide Tube	
4001	6.3	17.1	130	45	250	0	155	86	56	110	Avg. Power, Avg. ECC
4002	6.3	17.1	130	59	400	0	155	86	56	110	Avg. Power, Avg. ECC
4003*	6.9	7.1	124	130	400	0	400	151	52	71	High Power, Low ECC (TLTA-Like)
4004*	6.9	7.1	118	69	400	0	187	151	52	71	High Power, Low ECC (BWR-Like)

*1st Priority Test

All Tests:

Configuration:	System
Steam Dome Steam	= 100 lbm/hr
SEO Diameter	= 2.43 in.
Maximum Allowable PCT	= 1800°F

Section 6

DATA UTILIZATION

Data from these Stage 3 tests will be used to develop and qualify the separate effects models described in Section 4. The utilization of these Stage 3 data in fulfilling the data requirements is shown diagrammatically in Table 6-1, which indicates the particular models for which the various tests series are designed to provide data.

Note that specific test series are not designated for upper tie plate CCFL breakdown. Test Series 300 establishes saturated conditions and was not designed to include CCFL breakdown. The breakdown phenomena is expected to occur in Test Series 4000, but use of the data for CCFL correlation is not included in the planning.

Table 6-1

SHB STAGE 3 DATA UTILIZATION

Data Requirements	Core Spray Heat Transfer	Reflood Heat Transfer	Core Bypass Heat Transfer	Entrainment	Liquid Carryover	CCFL Upper Tie Plate	Upper Tie Plate CCFL Breakdown	SEO CCFL	Top of Bypass CCFL	Core Vaporization	Void Distribution	Condensation Effects - LTP Leak	Flow Distribution
Core Spray Heat Transfer (Run 1000 Series)	X									X	X		
Reflood Heat Transfer Controlled Bottom Flood (Run 2300 Series)		X		X	X					X	X	X	
Reflood Heat Transfer With Core-Bypass Interaction (Run 2100 Series)		X		X	X					X	X	X	
Reflood Heat Transfer With Core-Bypass-Jet Pump Interaction (Run 2200 Series)		X		X	X					X	X	X	
Bypass Heat Transfer (Run 3000 Series)			X										
Upper Tieplate CCFL (Run 300 Series)						X							
TOB CCFL (Run 400 Series)									X				
SEO CCFL (Run 500 Series)								X					
Refill-Reflood (Run 4000 Series)										X	X		X

Section 7

TEST STRATEGY AND SCHEDULE

The Stage 3 SEB test series will be divided into four sub-series dependent on the test section configuration utilized. The various tests described earlier are presented in Table 7-1 as a summary showing which tests required a particular configuration. Those tests labelled with a first priority in Tables 5-2 through 5-7 will be performed first in each sub-series. The other tests will be performed as necessary to meet the model development data requirements. All testing in Stage 3 is scheduled for completion in mid-September 1980.

The high temperature heat transfer tests typical of this program can damage the heated bundle. To monitor the condition of the test bundle so that the bundle remains in satisfactory condition for all tests series, a program of x-ray inspections will be conducted. These inspections will be performed at the end of each block of testing, and more often as required by the responsible engineer. Thermocouple and heater rod characteristics will also be assessed on a continuing basis.

Table 7-1

TEST CONFIGURATION SUMMARY

Test Configuration	Test Series
System (Figure 3-4)	Series 100, Single-Phase Fill
	Series 200, SCR check
	Series 600, Bypass Leakage
	Series 2200, RHT
	Series 4000, Refill-Reflood
Blocked Jet Pump (Figure 3-5)	Series 2100, RHT
Blocked Jet Pump; Bypass Leakage Blocked (Figure 3-6)	Series 300, UTP CCFL
	Series 400, TOB CCFL
	Series 500, SEO CCFL
	Series 2300, RHT
Blocked Jet Pump; Blocked Bypass Leakage; Isolated GT; TOB Blocked; (Figure 3-7)	Series 3000, Bypass HT
	Series 1000, Core Spray HT

Section 8

REFERENCES

1. Contract NRC-04-79-184, BWR Refill-Reflood Program, NRC, EPRI, GE-NED; Appendix B - BWR Refill-Reflood Program Workscope, February 12, 1979.

2. D. D. Jones, L. L. Myers, J. A. Findlay, "BWR Refill-Reflood Program Task 4.3 - Single Heated Bundle Experimental Task Plan," General Electric Company, January 1980 (NUREG/CR-1708; EPRI NP-1524; GEAP-24865).