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ORNL/NUREG/TM-2

Project Description
ORNL PWR Blowdown Heat Transfer Separate-
Effects Program—Thermal-Hydraulic
Test Facility (THTF)

OAK RIDGE NATIONAL LABORATORY

OPERATED BY OAK RIDGE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT DIVISION

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Reactor Division

PROJECT DESCRIPTION

ORNL PWR BLOWDOWN HEAT TRANSFER SEPARATE-
EFFECTS PROGRAM - THERMAL-HYDRAULIC
TEST FACILITY (THTF)

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PREFACE

The original Thermal-Hydraulic Test Facility (THTF) was designed to permit critical heat flux testing with high-pressure, high-temperature water in single tubes and rods and in small rod bundles up to 8 ft in length at steady-state conditions. Plans for modifying the THTF, at that time incomplete, to permit transient and blowdown heat transfer tests on full-length (12-ft) heater rods in a 7×7 array were begun in January 1972 under the leadership of H. W. Hoffman, C. G. Lawson, and R. H. Chapman working in close collaboration with R. M. Scroggins and E. H. Davidson of the U.S. Atomic Energy Commission. Mechanical and electrical design, under the overall supervision of M. I. Lundin and L. V. Wilson, was carried out by J. L. Crowley, C. J. Claffey, C. W. Collins, W. K. Furlong, S. Malang,^{*} H. R. Payne, F. C. Zapp, W. M. Brown, and E. D. Stulting. The instrumentation and controls design, under the overall supervision of R. L. Moore and B. G. Eads, was carried out by A. H. Anderson, C. Brashear, J. W. Cunningham, D. G. Davis, D. E. Gray, W. R. Hamel, C. S. Meadors, W. Ragan, E. R. Rohrer, R. L. Shipp, Jr., and E. C. Keith. Specifications for the data-acquisition system were developed by C. D. Martin, J. L. Redford, N. E. Clapp, and A. F. Johnson. Analysis effort included contributions by J. P. Sanders, S. Malang,^{*} R. F. Bennett, and R. S. Stone. THTF modification and operation, heater rod procurement, and bundle assembly were under the overall supervision of R. E. MacPherson. R. E. Helms, THTF Project Engineer, participated in all design meetings and supervised THTF modifications, assisted in the latter stages by R. E. Bohanan, C. A. Gifford, and J. E. Wolfe. Heater rod development was initially under the direction of D. L. Clark and subsequently R. W. McCulloch and W. E. Baucum. Bundle 1 was assembled under the direction of A. M. Smith.

^{*}Assigned to Oak Ridge National Laboratory from Nuclear Research Center, Karlsruhe, Federal Republic of Germany.

SUMMARY

The ORNL Pressurized-Water Reactor Blowdown Heat Transfer (PWR-BDHT) Program is an experimental separate-effects study of the relations among the principal variables that can alter the rate of blowdown, the presence of flow reversal and rereversal, time delay to critical heat flux, the rate at which dryout progresses, and similar time-related functions that are important to LOCA analysis. Primary test results will be obtained from the Thermal-Hydraulic Test Facility (THTF), a large nonnuclear pressurized-water loop that incorporates a 49-rod electrically heated bundle. Supporting experiments are carried out in two additional test loops — the Forced Convection Test Facility (FCTF), a small high-pressure facility in which single heater rods can be tested in annular geometry; and an air-water loop which is used to evaluate two-phase flow-measuring instrumentation.

The THTF is an all stainless steel recirculating loop fabricated from 4-in. pipe. The principal components are the test section (~19 ft of 10-in. sched-140 pipe and flanges); three Graham "Heliflow" heat exchangers with a total heat removal capability of 7.5 MW; a pressurizer (~11 ft of 12-in. sched-140 pipe); a two-stage Bingham pump that develops ~1940 ft of fluid head at a flow rate of 700 gpm; four instrumented spool pieces containing drag disks, gamma densitometers, turbine meters, and transient pressure and temperature sensors; and appropriate flow control valves and bypass lines. The pressure-suppression system, although not a part of the primary recirculating loop, is an essential part of the THTF. The pressure-suppression tank is connected to the primary recirculation loop by 8-in.-diam pipes. The 1160-gal pressure-suppression tank contains three spray nozzle manifolds (each containing 24 nozzles) installed parallel to the tank axis. A 1500-gpm pump recirculates water at an initial temperature of less than 100°F through these nozzles. The tank is vented to the atmosphere through an 8-in.-diam pipe.

The rod bundle consists of forty-nine 0.422-in.-diam indirect electrically heated rods spaced on 0.563-in. centers contained in a 4-in. square shroud box. Based on an estimate of the conditions required for equal enthalpy rise in wall channels and interior channels, the centers

of the heater rods adjacent to the shroud box wall were spaced 0.312 in. from the side walls. Low-pressure-drop grid spacers are provided at ~12-in. intervals along the shroud box, and a subchannel thermocouple flange at the shroud box outlet permits temperature measurement to be made in the fluid in each flow subchannel between heater rods. Steady-state temperatures and pressures are monitored at four different levels along the shroud box.

Although the heater rod length varies from 18.5 to 21.5 ft, the active heated section consists of 12 ft of Inconel 600 or cupronickel heating elements on the interior of the rod arranged to give a stepped power profile with a local-to-average power ratio varying from 0.422 to 1.67. The integrated power distribution of the heater rod closely matches that of a symmetrical chopped-cosine profile typical of a nuclear fuel rod. Each heater rod contains 5 to 17 thermocouples; 1 to 5 of these are at various levels along the center of the rod and 4 to 12 are at various levels imbedded in grooves in the dual-walled sheath. Bundle 1 contains a total of 347 sheath thermocouples and 73 center thermocouples.

With the pressurizer half full, the total system volume is 21.4 ft³. Based on a peak heater rod power of 17 kW/ft and a peak-to-average power ratio of 1.67, the power requirements for a single rod are 122 kW, or a total of 5.98 MW for the 49-rod bundle. Thus, the volume-to-power ratio is 3.58 ft³/MW, a value typical of PWR reactors. At a power level of 122 kW/rod and an inlet temperature of 547°F, the outlet temperature is 640°F when the mass flow rate is $2.5 \times 10^6 \text{ lb}_m \text{ hr}^{-1} \text{ ft}^{-2}$. System pressure is 2250 psi. At blowdown, the system will be vented to atmospheric pressure through either or both of the rupture disks; the contents of the loop (~160 gal) will then be transferred to the pressure-suppression system within 20 to 100 sec, depending on the size of the blowdown nozzle. From immediately before until immediately after blowdown, over 500 sensors will be scanned at a rate of 20 times per second, resulting in over 3×10^6 readings per test.

1. OBJECTIVES

The ORNL Pressurized-Water Reactor Blowdown Heat Transfer (PWR-BDHT) Separate-Effects Program is part of the overall light-water reactor safety research program of the Nuclear Regulatory Commission (NRC). Other parts of the NRC program cover a wide range of experimental and analytical efforts from laboratory-scale experiments to small-scale experimental nuclear plants. Separate-effects studies fall in scale between laboratory-scale experiments and small-scale nuclear plants and are designed to answer specific questions relevant to the hypothetical loss-of-coolant accident (LOCA). Some of the different separate-effects studies sponsored by NRC are (1) evaluations of pump behavior during transients with two-phase flow, (2) studies of two-phase flow in downcomers, (3) experiments on the reflood characteristics of rod bundles, (4) tests of alternate emergency core-cooling systems (ECCS), (5) evaluations of fuel rod behavior under extreme conditions that might occur during a LOCA, and (6) determination of heat transfer characteristics of rod bundles under transient conditions postulated for a LOCA. All the separate-effects studies are intimately related to the larger scale integral studies such as Semiscale and LOFT as well as to the analysis programs that are developing improved computer codes to model both components and systems.

Specific objectives of the ORNL-PWR-BDHT Separate-Effects Program are (1) to concurrently determine, for a wide range of parameters, pre-CHF (critical heat flux) heat fluxes, ΔT , heat transfer coefficients, and local fluid properties; time to CHF; and post-CHF heat fluxes, ΔT , heat transfer coefficients, and local fluid properties; and (2) to test the ability of existing codes, such as RELAP, to predict the behavior of the single-rod and 49-rod loops under blowdown conditions.

The parameters to be studied include:

1. single- and double-ended coolant line breaks of varying area ratio,
2. depressurization rates varying from "fast" to "slow,"
3. different combinations of system power and pressure to obtain different values of departure from nuclear boiling ratio (DNBR),
4. a range of power cutoff delays,

5. a range of power decay rates,
6. a range of power to system volume ratios.

Secondary objectives are (1) to obtain CHF data under steady-state conditions over a range of coolant pressures, inlet and exit subcooling, and inlet flow rate appropriate to PWR interests; (2) to evaluate the thermal-hydraulic behavior of the test loops during simulated operational upsets that include variations in local power, system pressure, or coolant flow using the anticipated transient without scram (ATWS), as described in WASH-1270,¹ as a guide; and (3) to determine the effect of different spacer grids and power distribution profiles on both transient and steady-state CHF.

¹*Anticipated Transients without Scram for Water-Cooled Power Reactors*, WASH-1270 (September 1973).

2. OVERALL PROJECT DESCRIPTION

The Program is divided into 8 different tasks:

- Task 1. FCTF Operations
- Task 2. Analysis
- Task 3. THTF Operation
- Task 4. Two-Phase Flow Instrumentation
- Task 5. Bundle Fabrication
- Task 6. Heater Procurement and Evaluation
- Task 7. Bundle Hydraulics
- Task 8. Program Planning

Tasks 1, 2, and 4 to 8 are all in support of the primary program objective of obtaining experimental results in task 3 on the phenomena occurring during the transient blowdown of the 49-rod THTF.

2.1 Task 1. FCTF Operations

The primary purpose of this task is to qualify prototype heaters for use in the THTF and to obtain blowdown heat transfer and steady-state CHF results for single rods in an annular geometry. Tests are conducted in the FCTF, which at present is limited to 1500 psi operating pressure with a temperature at the inlet to the test section of 550°F and an outlet temperature of 592°F when the rod power is 144 kW. The test section is a concentric annulus formed by a 1 1/2-in.-OD, 1 1/4-in.-ID core barrel inside a pressure housing fabricated from 2-in. sched-80 pipe (ID = 1.939 in.). A schematic view of the test section cross section is shown as Fig. 1, and the principal loop components are illustrated in Fig. 2. In its present configuration, the FCTF has a volume-to-power ratio of 10 MW/ft³, and only single-ended break tests are possible.

2.2 Task 2. Analysis

The primary purpose of this task is to provide pre- and posttest predictions for all THTF blowdowns; to determine local transient heat transfer coefficients for all blowdown tests; to calculate "best-estimate" local

Fig. 1. Cross-sectional view of FCTF test section.

fluid conditions in the rod bundle; to perform error analyses for all THTF instrumentation; and, perhaps most important, to evaluate results of all blowdown tests and, based on these evaluations, develop plans for required future tests.

2.3. Task 3. THTF Operation

This task is responsible for the day to day operation of the THTF, for accomplishing modifications required to meet program objectives, and for assuring that all instrumentation is functioning for blowdown and steady-state CHF tests.

Fig. 2. Forced Convection Test Facility.

2.4 Task 4. Two-Phase Flow Instrumentation

The objective of this task is to develop procedures for improving the accuracy of two-phase flow instrumentation. The current test series utilizes a duplicate of a THTF spool piece with a turbine meter, a drag disk, and a gamma densitometer identical to those used in the THTF. Air and water are metered separately into 4-in. glass pipe connected to the THTF spool piece; maximum air and water flow rates are 1000 scfm and 500 gpm respectively. Techniques currently under investigation for improving the accuracy of two-phase flow measurements are (1) screen dispersers to produce uniformly dispersed flow upstream of flow-measuring stations, (2) measurement of ΔP across screens as an indication of mass flow rate, and (3) use of pressure-drop measurement across elbows as a means for determining mass flow rate.

2.5 Task 5. Bundle Fabrication

The function of this task is to procure all components of heater rod bundles, assembly them into a unit, and verify location and functionality of thermocouples, as well as verify that moisture has not been introduced into either the boron nitride or magnesium oxide portions of the heater rod during bundle assembly.

2.6 Task 6. Heater Procurement and Evaluation

The purpose of this task is to procure prototype THTF heaters and to test and evaluate them in the single-rod test facility, FCTF.

2.7 Task 7. Bundle Hydraulics

The primary purpose of this task is to model the THTF heater rod bundle with COBRA/SCORE, to develop subchannel analyses relating local fluid conditions to spool piece measurements, and to experimentally determine mixing and pressure-drop characteristics of the 49-rod bundle.

2.8 Task 8. Program Planning

The primary purpose of this task is to coordinate the activities of tasks 1 through 7 with NRC program objectives and to provide budgetary guidance to all tasks.

2.9 Accomplishments in Previous Years

A production heater rod (No. 150-74) sealed at the top with Viton O-rings was operated for over 99 hr in the FCTF before retirement with no operational problems. During this period, the rod was at 144 kW power for over 35 hr; it experienced 20 blowdowns and 34 on-off cycles. During these evaluation tests, results from the FCTF showed that under repeated blowdowns no gap developed between the BN and the inner stainless steel sheath. However, extensive tests under blowdown conditions showed that the gap resistance between the inner and outer sheaths may increase during the first few blowdowns but probably stabilizes thereafter. Based on these results, which were obtained as a by-product of the heater evaluation tests, a special series of tests was conducted to aid in the development of ORTCAL (sheath thermocouple calibration code).

The THTF was completed. Hydrostatic tests of key components were made at pressures greater than 4000 psi, over 8 miles of thermocouple cable were installed to connect heater rod thermocouples to the data-acquisition system, and 40 yd³ of concrete were required to buttress the pressure-suppression tank. The first isothermal blowdown was conducted on Feb. 21, 1975.

On Apr. 18, 1975, the second blowdown was attempted. After 6.9 hr of operation, the outboard seal failed at a system pressure of 1920 psi and a fluid temperature of ~381°F. The entire contents of the loop were vented (as steam) into the basement through the seal cavity. Posttest inspection showed heavy scoring on the faces of both the rotating tungsten carbide and stationary bronze seal rings; there was also an indication that a secondary O-ring seal failed. Analysis of a blackish deposit on the face of the bronze seal ring showed primarily lead and tin. None of the components of the seal were cracked or broken. Apparently, the seal failure was due to dynamic instability of seal components. After

intensive effort, including replacement of one of the original Bingham seals with one manufactured by the Durametallic Corporation, a blowdown was completed on Sept. 30, 1975, with no seal leakage problems.

The THTF isothermal blowdown tests series was completed on Oct. 17, 1975. The results of the test series are summarized in Table 1. Pressures at the inlet plenum of the test section are shown in Fig. 3 for these blowdowns.

One of the major results in this series was obtained in test 002, a test in which the pressurizer was isolated from the remainder of the loop by a 1/4-in. orifice. As can be seen from Fig. 3, the slow release of fluid from the pressurizer completely dominated the depressurization of the remainder of the loop.

Another significant result was obtained in test 002R. In this test, leaking pressure taps forced blowdown at a temperature of $\sim 400^{\circ}\text{F}$ instead of the planned 547°F . Since the pressurizer fluid was at 650°F , it was clearly identifiable as it passed various temperature sensors around the loop (Fig. 4).

Finally, tests 021 and 023 (the two double-ended breaks in the isothermal test series) demonstrated that both flow reversal and rereversal could be obtained with the THTF. This is illustrated in Fig. 5, which shows the mass flow rate as measured by the instrumentation in the spool piece at the outlet of the test section in test 023.

Results of two-phase flow instrumentation studies in the air-water loop show that flow-dispersing screens are effective for conditioning two-phase flow impinging on a drag disk and can be utilized as a resistance flowmeter in conjunction with mixture density measurements. Calibration of the instrumented spool pieces in steady-state two-phase (air-water) flow has shown a distinct advantage in using a two-velocity model in calculating mass flow instead of homogeneous flow models. Current studies include (1) the comparison of the performance of photomultiplier tubes and ionization chambers as radiation detectors in the gamma densitometers and (2) the design of a capacitance void meter.

Table 1. Isothermal tests - ORNL-PWR-BDHT Separate-Effects Program

Test No.	Date	Test conditions				Significant results
		Temp. (°F)	Pressure (psig)	Area (ft ²)	Location	
001	2/21/75	~450	1300	0.0034	Outlet	Blowdown; first successful test of pump seal; loop inventory control problems
002	4/18/75	~380	1920	0.0067	Inlet	No blowdown; major failure of pump seal
002	6/13/75	~520	2055	0.0067	Inlet	Blowdown; failed to achieve test conditions of 547°F and 2250 psig because of excessive seal leakage. Results demonstrate effect of isolation of pressurizer by 1/4-in. orifice
002R	8/16/75	~400	2250	0.0067	Inlet	Blowdown; failed to achieve test conditions because of leakage at pressure taps. No orifice in pressurizer. <u>Major result.</u> Pressurizer fluid clearly identifiable as it passed temperature sensors
002R2	8/28/75	547	2250	0.0067	Inlet	Blowdown; test conditions achieved, completed scheduled flow calibration tests; seal leakage controlled by injecting high-pressure makeup fluid
021	9/30/75	547	2250	0.0135	Inlet Outlet (50:50 split)	Blowdown; test conditions achieved, completed scheduled flow calibration tests; no seal leakage. <u>Major result.</u> Demonstrated capability for flow reversal and rereversal
023	10/17/75	547	2250	0.0135	Inlet Outlet (30:70 split)	Blowdown; test conditions achieved, completed flow calibrations; no seal leakage. Flow reversal and rereversal occurred

Fig. 3. Pressures at inlet plenum of test section.

Fig. 4. Pressurizer fluid temperature spike at different locations in test 002R.

ORNL DWG 75-17180

Fig. 5. Mass flow from vertical outlet spool piece during isothermal blowdown 023 (positive flow is in same direction as flow prior to blowdown and toward exit break).

3. TECHNICAL APPROACH

Emphasis in the ORNL-PWR-BDHT Program is on the separate-effects approach. This approach provides a key link between large-scale experiments (such as LOFT and Semiscale), whose measurements are largely integral, and bench-scale tests which provide point information. The separate-effects approach has several important consequences:

1. The 7×7 heater rod bundle with a 12-ft-long heated section is sufficiently large that wall effects on central rods may be minimized while still maintaining a link to bench-scale experiments.
2. Some measurements, such as heater rod sheath thermocouple measurements, are made in detail, thus approaching bench-scale experiments.
3. Flow measurements, at the present state of the art, are only possible in spool pieces exterior to the heater rod bundle test section, as in the larger-scale integral tests.
4. The operating characteristics of the THTF must encompass a sufficiently wide range of operating conditions to permit generation of experimental results which will provide a severe test of phenomenological theories as well as calculation procedures developed for PWR safety analysis.
5. There is no attempt to make a 1:1 scaling of any PWR components or test effects; instead, test conditions will bracket those of interest in PWR safety analysis. This means that although many characteristics of a PWR are not modeled (i.e., downcomer volumes, inlet and outlet plenums, multiple pumps, steam generators, etc.), other characteristics such as heated rod length, integrated axial power profile, ratio of system volume to rod power, total rod power, test section inlet temperature, system pressure channel temperature rises, and test section mass velocities are all similar to design values of PWRs.

It is anticipated that the separate-effects test results will be used in a variety of ways. Among these are validation of presently available correlations for pre- and post-CHF heat transfer with special attention to their applicability to rod bundles; identification of important phenomena governing the time to CHF; and provision of data for assessment of the amount of conservatism in computational models used in safety analysis.

In the latter case, the assessment will be made by modeling the THTF and comparing predicted test results with actual test results.

The advantage of the separate-effects approach is that it can provide fundamental information on the transient response of heater rod bundles and single rods in annular geometry to controlled variation of loss-of-coolant parameters. Only by such procedures can the phenomena be determined that govern the time to DNB and the effect of cross-channel flows, interchannel mixing, vapor binding, flow reversals, system volumes, power distribution, etc., on pre- and post-CHF heat transfer. As such, separate-effects studies complement integral studies that attempt to simulate a particular reactor system. The separate-effects tests also bridge the gap between integral studies (which are closely analogous to reactor systems) and small-scale experiments specifically designed to provide quantitative results on the different phenomena involved.

4. FACILITY DESCRIPTION

The Thermal-Hydraulic Test Facility (THTF) is a large nonnuclear experimental loop with a test section that contains a 7×7 array of 12-ft stepped, chopped-cosine heater rods with an outside diameter of 0.422 in. Peak rod power is 7.0 kW/ft, and the peak-to-average power ratio is 1.67; the average mass velocity coolant flow is 2.50×10^6 lb hr⁻¹ ft⁻², and the ratio of system volume to power may be varied from 3.58 to 4.44 ft³/MW. Other THTF design data are summarized in Table 2.

A schematic view of the THTF is shown in Fig. 6, and a simplified flowsheet is shown in Fig. 7. Fluid discharged from the pump flows through two control valves, where excess pump head is dissipated and flow adjusted to the desired level by diverting a portion through the bypass line. Heat generated in the fluid by the pump is removed in the small Graham "Heliflow" heat exchanger in the bypass line. The primary flow then passes through inlet instrumented spool pieces 1 and 2, where flow conditions are monitored by a combination of drag disk, gamma densitometer, turbine meter, and temperature and pressure sensors in each spool piece. Flow enters the test section at the top of the rectangular shroud box, flows down along its length, and then enters the bottom of the rod bundle at a base-line pressure of 2250 psi and a temperature of 547°F. With a base-line rod power of 122 kW (total bundle power of 5.98 MW), the fluid temperature rise is 93°F through the 49-rod bundle. The fluid exits the rod bundle past 64 subchannel thermocouples through outlet spool pieces 1 and 2, which are identical to those on the inlet. Then the enthalpy added by the test section heater rods is removed by Graham "Heliflow" heat exchangers A, B, and C, each with a rated capacity of 2.5 MW. Finally, the fluid returns to the pump section past the line from the pressurizer, which, with its 24 kW of independent heat, provides the primary pressure control for the loop and at the same time serves as a surge tank with 3.8 ft³ of vapor volume when the pressurizer is half full.

At the instant of blowdown, the contents of the primary loop may be discharged through either of two rupture disk assemblies and appropriately sized orifices into the pressure-suppression system, which consists of a 1500-gpm pump that continuously recirculates the 520-gal water inventory

Table 2. Summary of THTF design data

Test section

Heater rods

Number	49
Diameter, in.	0.422
Center spacing, in.	0.563
Center to side wall, in.	0.312
Base-line maximum power, kW/ft	17
Maximum/average power	1.67
Base-line total rod power, kW	122
Sheath thermocouples	347
Center thermocouples	73

Shroud box

Inside dimensions, in.	4 x 4
Outside dimensions, in.	6 x 5 1/2
Grid spacing, in.	~12
Steady-state thermocouples	4 at 4 levels
Steady-state pressure sensors	1 at 3 levels
Subchannel fluid thermocouples (top of heater rod heated zone)	64

Pressure housing

Inside diameter, in.	8.75
Outside diameter, in.	10.75
Length, ft	15

Primary loop

Nominal pipe diameter, in.

4

Graham "Heliflow" heat exchangers

Number	3
Heat removal capacity, each, MW	2.5
Maximum ΔP , each, psi	10

Bypass Graham "Heliflow" heat exchanger

Number	1
Heat-removal capacity, MW	0.38
Maximum ΔP , psi	5

Pressurizer

Inside diameter, in.	10.50
Length, ft	11
Heat input, kW	
Steady state	24
Heatup	43

Pump

Type	Bingham 3 x 6 x 17 CJM
Number of stages	2
Capacity, gpm	700
Head, feet of fluid	~1940
Maximum pressure rating, psi	3000
Maximum operating temperature, °F	600
Pump power, kW	450

Table 2. (continued)

Instrumented spool pieces	
Number	4
Flow instrumentation	
Turbine meter	Flow Technology (full flow) Ramapo
Drag disk	
Densitometer	
¹³⁷ Cs source strength, Ci	25
Beam diameter, in.	1
Temperature sensor	18-msec response
Pressure sensor	
Inside diameter, in.	3.458
Length, in.	36
System volumes, ft³	
Main heat exchangers and associated outlet piping to valves	1.23
Piping downstream of main heat exchanger valves and bypass valves to pump inlet	3.92
Pump	1.49
Pump outlet, bypass line to test section inlet	3.55
Test section inlet, barrel, lower plenum, and inlet blowdown	3.34
Test section bundle and upper plenum	1.69
Test section outlet blowdown line and outlet line to main heat exchanger	2.52
Pressurizer at midpoint between high- and low-level alarms	<u>3.70</u>
	21.44

of the 1160-gal pressure-suppression tank through three tubular spray lines, each containing 24 nozzles. The pressure-suppression tank is vented to the atmosphere through an 8-in. pipe.

4.1 Test Section

The test section pressure housing (Fig. 8) consists of two flanged sections of 10-in., sched-140, 316 stainless steel pipes with an overall length of about 19 ft. Support brackets are attached to the lower spool section, which is about 15 ft long. The upper spool piece, about 4 ft long, is removable with the test bundle. The heater rods protrude another

Fig. 6. Thermal-Hydraulic Test Facility—ORNL-PWR-BDHT Separate-Effects Program.

3 ft through seal flanges at the upper end of the removable spool piece to make the overall test section assembly about 21 ft long.

There are two inlet nozzles located on the lower container. Grayloc flanges are used to permit quick coupling and uncoupling. The upper of the two inlet nozzles will be used for the initial operation. This arrangement more closely resembles the inlet annulus and plenum of the PWR reactor. The lower inlet will be capped until needed for possible future tests in which the shorter annulus is desired. In this event, filler plugs will be installed to reduce the volume of water available in the stagnant annulus. Other nozzle connections are also provided for possible use in the future.

Fig. 7. Thermal-Hydraulic Test Facility flowsheet.

ORNL DWG 73-1184OR1

Fig. 8. Test section using indirect heater rod in 49-rod bundle.

for additional shroud instrumentation, but they are capped for initial operation.

The heater rods penetrate the upper end of the test section, and each rod is sealed with a Viton and an ethylene propylene O-ring in each of two seal plates that form an intermediate pressure chamber between the high pressure of the test section and the atmosphere. The O-ring heater seal must provide a sliding seal that allows differential expansion between the heater rods and the test section container. The seal plates themselves are sealed by conventional static O-ring seals.

The upper and lower test section container closures are fabricated from bolted blind flanges and sealed with conventional flexitallic gaskets. The nickel flange that is sandwiched between the lower weld-neck flange and the blind flange serves both as the anchor for the heater rods and as the conductor of heater rod current. A total heater current of almost 30,000 A in the nickel electrode requires that it contain coolant passages. Holes drilled in the external portion of the electrode share cooling water with the eight water-cooled generator cables connected to the electrode. Loop water has access to both upper and lower internal surfaces of the nickel flange to provide internal cooling.

4.2 Test Bundle Instrument Flanges and Shroud

The upper portion of the test section (consisting of the top container closure, the 33-in.-long outlet spool piece, the subchannel thermocouple flange, and the shroud box instrument flange) is attached to the shroud box which contains the heater rod bundle and spacer grids. Figure 9 is a schematic drawing of the low-pressure-drop spacer grid assembly used in the THTF. Thirteen of these grids are spaced at 12-in. intervals along the shroud box; the grids are positioned in the shroud box by 0.062-in.-deep slots into which the grid and integral spring spacer slide.

The shroud box supports the spacer grids and forms the bundle flow channel. Thus, the dimensions of this portion of the bundle are very important to the thermodynamic and hydraulic analysis of the rod bundle behavior. The shroud inside dimensions are nominally 4 in. square. The

ORNL-DWG 74-5776R

Fig. 9. Low-pressure-drop spacer grid assembly.

thicknesses of the plates forming the shroud (1 and 3/4 in.), the interlocking of the shroud plates, plus the close spacing of shroud plate fasteners (1 1/2 in. center to center for a total of 418 fasteners) are specified to minimize deflection during blowdown.

The heater rod diameter (0.422 in.) and center-to-center spacing (0.563 in.) were chosen as representative of typical PWRs. However, a compromise had to be made in choosing the distance from rod center to shroud box walls; two conflicting criteria bracket the design specification for this distance. First, it would be desirable for the flow channels bounded by two rods and the channel wall (or wall channels) to behave in a manner similar to the interior channels (bounded by four rods) during the blowdown transient. To accomplish this, the equivalent hydraulic diameter of the wall channels should be the same as that of the interior channels. Calculations based on this criterion indicate that the distance from the center of the outer row of rods to the wall should be 0.420 in.

The other, and more important, criterion is that the enthalpy rise in the wall channels during the heating phase be the same as that of the fluid in the interior channels. To meet this criterion, the mass flow of fluid in the wall channels must be one-fourth the flow in the interior channels when the same pressure gradient exists over all subchannels. This criterion assumes that all the heat generated in the rods is transferred directly into the adjacent coolant and neglects the effects of circumferential or axial conduction and the effect of fluid crossflow between subchannels. All the aspects that are neglected will tend to promote uniform enthalpy rise in all subchannels. The dimension from the shroud wall to the outer row of fuel pin simulators was calculated for full, 60%, and 20% design flow using two calculational procedures. One method uses the Kays' correlation² to determine the pressure loss at the grid spacer plus a multiplier on the friction loss in the bundle recommended

²W. M. Kays and A. L. London, Compact Heat Exchangers, National Press, Inc., Palo Alto, Calif., 1955.

by Tong.³ The second method uses a correlation for the spacer loss developed by deStordeur⁴ plus normal frictional losses. The value of 0.312 was chosen from calculated results, which ranged from 0.308 to 0.320 in., to best meet the constant enthalpy rise condition for all flow rates. Sixteen thermocouples project $\sim 1/8$ in. into the fluid stream from the shroud at four different levels (20.5, 54.5, 87.5, and 121.5 in. from lower end of heated zone) to monitor the increase in fluid enthalpy along the test section. Subchannel thermocouples (64 total) are located at the top of the heated rod zone to monitor fluid enthalpy at the exit from each subchannel. Also located along the shroud box walls are pressure taps located 5 1/2, 73, and 121 1/5 in. above the bottom of the heated rod zone.

The shroud box is supported from the upper end by a special flange that is gasketed between test section container flanges. Sixteen thermocouple sheaths and three pressure instrument tubes from the shroud are routed through seven nozzle fittings extending radially from this support flange. An additional nozzle is supplied for use by the operator to vent trapped air from the flow annulus between the container and the shroud during the filling operation.

A subchannel thermocouple flange is provided at the shroud outlet to allow a temperature measurement to be made at each flow subchannel (64 each) between heater rods. These thermocouples will be positioned near the termination of the rod heater length, which is located about 8 in. below the shroud outlet. The thermocouple sheaths will be supported by stiffening tubes that are anchored in the subchannel thermocouple flange and positioned in the shroud by a support grid. The sheaths are then routed to one of eight exit seal nozzles via eight covered troughs that form spokes in the flange. Flow from the test bundle is thus routed around the spokes and enters the test section outlet plenum formed by the upper spool piece. A photograph of this assembly is shown in Fig. 10.

³L. S. Tong, Pressure Drop Performance of a Rod Bundle, pp. 57-69 in Proceedings of a Symposium on Heat Transfer in Rod Bundles, American Society of Mechanical Engineers, New York, Dec. 3, 1968.

⁴A. N. deStordeur, Nucleonics 19(6), 74 (1961).

PHOTO 4408-74

Fig. 10. Subchannel thermocouple flange.

4.3 Heater Rods

The indirect heater rod used in the THTF test bundle is a 0.422-in.-OD rod with a 12-ft-long, stepped, chopped-cosine profile and an overall length of 18 to 21 ft depending on its location in the rod bundle (Fig. 11). The heater rod is double ended, with the sheath and ground-lead extension welded together at the lower end and with the power lead in insulated from the sheath at the upper end. Heat generated by the tubular heating element on the interior of the heater rod is conducted through boron nitride insulation to the dual-walled outside sheath of the rod. Thermocouples are located on the center line of the rod as well as in grooves in the inner layer of the dual-walled outer sheath.

The heater element consists of a series of oversleeves swaged over a central heater tube to provide a series of heat-generation zones. The center 36 in. consists of only the basic Inconel 600 heater tube, thus giving the highest resistance to provide a maximum heat-generation rate of 19.8 kW/ft at 600 A. Successive oversleeves of Inconel 600 or cupronickel of appropriate wall thicknesses and lengths are swaged over the appropriate length of the heater element. Each of these oversleeves extends to the end of the heater element, thus eliminating any butt joints within the heater element itself. As successive sleeves are added between the center zone and the ends, the resistance — and thus the heat generation rate — of that particular zone decreases so that the series of step changes bracket the desired chopped-cosine power profile as shown in Fig. 12. The lengths of the steps for different power levels were chosen to match the integrated power profile of the chopped-cosine power profile (Fig. 13). Nominal heated zone lengths, power ratios, and local powers for THTF heater rods are given in Table 3.

Heaters for bundles 1 and 2 were purchased with four different totals for thermocouples per rod and five different nominal locations for thermocouples. These are summarized in Table 4. Thermocouples both on the rod center and in the rod sheath are 0.020-in.-OD sheathed Chromel-Alumel thermocouples with MgO insulation between the thermocouple and the stainless steel thermocouple sheath. The central rod thermocouple sheaths are insulated from the Inconel heater element by MgO. The sheath thermocouples are

Fig. 11. Indirect heater rod assembly.

Fig. 12. Power profile of prototype heater.

Table 3. Nominal power profile for the THTF indirect heater with average power of 12 kW/ft

Length of heated zone from beginning (in.)	Power ratio, local/average	Local power rate (kW/ft)
0-18	0.422	5.06
18-31.5	0.597	7.16
31.5-42	1.065	12.78
42-54	1.285	15.42
54-90	1.67	20.0
90-102	1.285	15.42
102-112.5	1.065	12.78
112.5-126	0.597	7.16
126-144	0.422	5.06

Fig. 13. Integrated power profile of stepped, chopped-cosine heater rod compared to the integrated power profile of a smooth chopped-cosine curve.

Table 4. Summary of heater rod designation and total number of thermocouples

Type	Number of thermocouples		
	Center	Sheath	Total
H	5	10	15
J	5	12	17
K	5	12	17
M	2	10	12
P	1	4	5

located, two to a groove, in axial grooves machined in the 0.030-in.-thick inner sheath. After the tips of the thermocouple sheath are spot welded at the proper location in the groove, stainless steel filler rod is added to the remainder of the groove and the 0.010-in.-thick outer sheath swaged over the inner sheath. Cross sections of the different heater rod designs are shown in Fig. 14.

One of the important characteristics of the heater rod is the time constant of the sheath thermocouples. First-order theory suggests the time constant is given by

$$\tau = \rho V c_p / hA$$

where

τ = heater rod time constant,

ρ = mean density,

V = volume of thermocouple assembly,

c_p = mean specific heat,

h = surface heat transfer coefficient,

A = heat transfer area.

A variety of tests have been conducted to determine the sheath thermocouple time constant: heatups and cooldowns of a heater rod suspended horizontally in air, quench test in which the heater rod is heated from 1200 to 1500°F in air and then dropped into water, and forced convection cooldown tests

Fig. 14. Heater rod cross section (0.422 in. diam).

at different flow rates in the FCTR. Typical results for heatup and cool-down tests in air are shown in Fig. 15; these results are of particular interest since an external thermocouple was tack welded to the external sheath in close proximity to a sheath thermocouple. As can be seen from Fig. 15, the sheath thermocouple reading followed the external thermocouple reading very closely throughout the heating and cooling transients. A more quantitative measure of the sheath thermocouple time constant is shown in Fig. 16, which is a plot of measured values of τ vs estimated values of the heat transfer coefficient for a wide range of conditions. The significance of these time constants is illustrated in Fig. 17, which shows the estimated response time for a sheath thermocouple to indicate a change of 15°F in an

Fig. 15. Response of heater rod thermocouple to a step change in rod power.

initial surface temperature of 600°F for a range of final surface temperatures.

It seemed desirable to locate the thermocouples in the heater sheath as near as possible to the end of a power section because DNB has been predicted to occur first at this location. Since the heat flux on the heater rod surface near a power step is different from that in the undisturbed region, the distance between power step and thermocouple location should not be too small.

To find the best position, the temperature field and the heat flux at the rod surface have been calculated for a wide range of parameters, the

FIG. 16. Dependence of heater rod sheath thermocouple time constant on heat transfer coefficient at rod surface.

Fig. 17. Response time for sheath thermocouple to indicate 15°F change from initial temperature of 600°F.

most important of which is the heat transfer coefficient. The higher the heat transfer coefficient, the smaller will be the transition zone between two heat flux regions. This can be seen in Fig. 18, which shows the steady-state heat flux distribution vs length for a large range of heat transfer coefficients. The lowest value for h (5 Btu ft⁻² hr⁻¹ °F⁻¹) corresponds to the nondestructive infrared test in open air with about 200°F surface temperature. The lowest coefficient observed in blowdown experiments in the single-rod loop was about 100 Btu ft⁻² °F⁻¹. However, it can be shown that the transition zone between the two heat flux regions is always smaller in a transient case than in the steady-state case with the same coefficient. If, for example, the coefficient drops suddenly from 10,000 to 100 Btu ft⁻² °F⁻¹ and the power goes to zero at the same time, then, even

Fig. 18. Surface heat flux near a step change in heater rod power as a function of surface heat transfer coefficient.

after 7 sec, the heat flux 0.5 in. from the step change in power would be only about 1% lower than that in the undisturbed region. Figure 18 gives about 3% deviation for the steady-state case with the same coefficient.

As an overall result of these calculations, the 0.5-in. distance between power step and thermocouple location appears to be enough to make the influence of the power step on the readings of the sheath and center thermocouples negligibly small for conditions typical of the early stages of a blowdown test.

The nominal locations of thermocouples in the different heater rods are summarized in Table 5 together with location of power steps and spacer grids. Of course, accurate locations of the heater rods cannot be determined until after the heater rod bundle is installed in the THTF.

4.4 Heater Rod Bundle

Type H, J, M, and P heater rods (with 15, 17, 12, and 5 thermocouples, respectively) were used in the fabrication of bundle 1. Figure 19 is a closeup photograph of the shroud box, a spacer grid, and the subchannel thermocouple array with approximately half of the heater rods inserted. The upper end of the heater rod bundle is shown in Fig. 20; this photograph was taken after completion of bundle fabrication with protective wraps on the heater rod thermocouple leads.

After the assembly of THTF bundle 1 was completed, all thermocouples were tested for open circuits; 347 of 351 sheath thermocouples and 73 of 103 center thermocouples were still in good condition. The distribution of heater rods (with nominal 5, 12, 15, and 17 thermocouples) in the rod bundle is shown in Fig. 21, where open thermocouples are identified under each rod position. The locations of thermocouples at different levels in bundle 1 are shown schematically in Fig. 22.

4.5 Instrumented Spool Pieces

The four instrumented spool pieces (Fig. 23) for the THTF were fabricated from 4-in. sched-160 pipe machined to an inside diameter of 3.50 in. A Flow Technology, Inc., full-flow bidirectional turbine meter (Fig. 24) is located with the turbine blade center line 6.27 in. from one end. A Ramapo Instrument Company bidirectional drag disk was located with the drag disk positioned on the center line of the spool piece 5 1/2 in. from the end of the spool piece opposite the turbine meter. A pressure transducer with an air-cooled standoff and a thermocouple station are located 9 in. from the drag disk end of the spool piece. A horizontal gamma densitometer with a 25-Ci ^{137}Cs source and a beam diameter of 1 in. is positioned at the middle of the spool piece.

Table 5. Nominal location of thermocouples in different type heater rods relative to power zone steps and grid spacer

Distance from lower end of heated zone ^a	Grid spacer location	Nominal power kW/m	Thermocouple level	Heater rod type					
				Type A Center	Type J Sheath	Type K Center	Type M Sheath	Type P Center	Type P Sheath
-3/4 to +3/4	X	↑							
11 1/2 to 12 5/8	X	14.12	A					AA	
13 1/8		↑	B					AB	
18		↑	C					BC	
23 to 24 1/2	X	19.95							
31 1/2		↑							
34 7/8 to 36 3/8	X	35.56	D		AD		AD	BD	AD
36 7/8		↑							
42		↑							
45 1/2 to 47	X	42.91	E	ME	AE	ME	CE	AE	
54		↑							
58 5/8 to 60 1/8	X	↑	F	MF	BF	MF	CF	BF	
70 1/2 to 72	X	55.77	G	MG	BG	MG	CG	CG	BC
82 3/8 to 83 7/8	X	↑	H	MH	CH	MH	DH	CH	CH
90		↑							
93 1/2 to 95	X	42.91	I	MI	CI	MI	EI	CI	AI
101		↑	J	MJ	DJ	MJ	EJ	DJ	CJ
102		↑							
105 5/8		↑	K	DK	DK	DK	FK	DK	
106 1/8 to 107 5/8	X	35.56	L						
111 1/2		↑	L	EL	EL	EL	FL	FL	CL
112 1/2		↑							
118 to 119 1/2	X	19.55	M						
125		↑							
126		↑							
129 7/8 to 131 3/8	X	↑	N						
141 1/4		14.12							
141 3/4 to 143 1/4	X	↑							
144		↑							
145 1/4		1.21	O	BO	PO			EO	

^aDistances in most cases are nominal and ±1/4 in. Accurate locations of thermocouples can only be established after the rod bundle is installed in the TRTF.

Fig. 19. Partially assembled THTF heater rod bundle.

Fig. 20. THTF heater rod bundle after being completely assembled.

Fig. 21. Distribution of thermocouples in THTF test bundle 1.

Fig. 23. Instrumented spool piece for THTF.

Calibration tests were performed on the flowmeters in the calibration flow loop at Daniel Industries, Inc. (Houston, Tex.), using water, at approximately ambient conditions, as the flowing fluid. These calibration tests were performed

1. to determine the calibration equations and associated error bands for each of the five turbine and four drag disk flowmeters tested;
2. to note the differences between the calibration equations for each of the individual flowmeters;

3. to determine the effects on the flowmeter accuracy of the installation geometry and close proximity between the turbine and drag disk flowmeters;
4. to determine the effects of the direction of flow (forward vs reverse) on the accuracy of the flowmeters;
5. to determine the effects of a "worst-case" piping configuration on the accuracy of the meters.

Calibration tests were performed on five turbine flowmeters and four drag disk flowmeters. For all tests, the flowmeters were installed in the THTF instrument spool piece, which was then installed in the test section of the Daniel Industries calibration flow loop. The test section was constructed so as to provide simulation of either an "ideal" flow configuration (i.e., straight entrance and exit piping) or a "worst-case" flow configuration (i.e., closely coupled elbows at the inlet and outlet to the blowdown heat transfer instrument spool). Calibration tests were performed for both configurations with the turbine flowmeter or the drag disk flowmeter, or both, installed in the THTF instrument spool piece. The THTF instrument spool was also reversed in the test section to simulate both directions of flow (i.e., the turbine flowmeter upstream or the drag disk flowmeter upstream). Extensive tests were performed on one turbine and one drag disk flowmeter for all geometrical and flow direction configurations. The balance of the flowmeters were tested primarily in the "ideal" configuration. The reference flow conditions for the calibration tests were obtained from the Daniel reference turbine flowmeter, which was calibrated in place using the Daniel 8-in. ball prover calibrator system, the calibration of which is traceable to the National Bureau of Standards (NBS).

The results of the calibration tests indicate that the turbine flowmeter error (2σ standard deviation: 95.4% confidence level) is better than 0.7% of full scale (1000 gpm) for all conditions and configurations tested and that the error below 0.7% is dependent on the geometric configuration. The drag disk flowmeter error (2σ standard deviation: 95.4% confidence level) is better than 1.2% of full scale ($2.5 \times 10^5 \text{ lb ft}^{-1} \text{ sec}^{-2}$) for any given test configuration, but there was an appreciable effect of flow configuration on the drag disk calibration results.

Typical results for calibration of the turbine meter with water are shown in Fig. 25; the good agreement of the results for different flow configurations is readily apparent. Typical results for calibration of the drag disk with water are shown in Fig. 26. The line shown on the figure is an "eyeball" fit to the high flow rate results for three of the four configurations that were in moderately good agreement. The greatest deviations from this line were observed at low flow rates in the "ideal" configuration, when the turbine meter was upstream of the drag disk. Subsequent analysis showed this deviation to be entirely due to zero shift. Almost all the results for the "worst-case" configuration

Fig. 25. Water calibration results for THTP turbine meter.

Fig. 26. Water calibration results for THTF drag disk.

were above the line by ~35% when the drag disk was upstream of the turbine meter.

For spool piece operation at blowdown conditions, the effects of elevated temperatures on instrument readings must be considered. Two factors must be considered in the calibration of the drag disk. First,

the temperature sensitivity of strain gauge assembly results in zero shift over an extended temperature range. Second, the drag disks are designed for a constant drag coefficient over a normal range of operation. However, heatup from ambient to blowdown conditions reduces the kinematic viscosity by an order of magnitude. The resulting increase in Reynolds number makes a drag crisis possible, with a consequent drastic reduction in drag coefficient.

During the heatup for the isothermal tests, steady-state flow data were taken for a preliminary calibration of the effects of elevated temperatures on the operation of the drag disks. Heatup of the THTF for the isothermal tests proceeded in a stepwise manner, thus permitting steady-state flow tests at temperatures between ambient and blowdown conditions.

Each of the heatup tests included a no-flow condition which provided information on zero shift as a function of temperature. Figure 27, which includes data from different isothermal tests, shows reasonable reproducibility among runs. The drag disks in the two horizontal spool pieces show similar behavior and exhibit the least zero shift, approximately $-1000 \text{ lb}_m \text{ ft}^{-1} \text{ sec}^{-2}$ at the blowdown temperature of 550°F . The zero shifts for the vertical outlet and inlet spool pieces were ~ 1500 and approximately $-5200 \text{ lb}_m \text{ ft}^{-1} \text{ sec}^{-2}$ respectively. The zero shift for the vertical inlet spool piece at 550°F is equivalent to a flow rate of about 350 gpm in a direction opposite steady-state flow.

Preliminary analysis of the drag disk hot calibration results indicates that for Reynolds numbers (based on target diameter) greater than 3×10^5 , the drag coefficient is $0.615 \pm 7\%$ and is ~ 1 for Reynolds numbers less than $\sim 10^5$. This behavior is consistent with data in the literature on the occurrence of a drag crisis in this same Reynolds number range.

4.6 Pump

The pump used in the THTF was designed and fabricated in the period 1965-67 by the Bingham Pump Co., Portland, Ore. The $3 \times 6 \times 17$ CHM pump (Serial No. 250920) is a two-stage, double-volute, horizontal, center-line-mounted, heavy-duty, centrifugal unit suitable for continuous operation at

Fig. 27. Effect of temperature on drag disk reading with no flow in the THTF as determined from loop heatup for isothermal tests.

high system temperatures and pressures. Performance curves are shown in Fig. 28.

This pump was specifically designed for high-pressure service and uses a still shaft to minimize deflection. The volute casing is radially split at each end with removable cover-stuffing box units to enable disassembly without disturbing the connecting piping or the driver unit. The pump has babbitted journal bearings at each end of the shaft and a duplex ball thrust bearing on the outboard end. A self-contained oil-ring-type lubrication system, with oil level maintained by constant level oilers, provides lubrication for the bearings. Shaft seals are patented Bingham high-pressure units isolated from the high-temperature zones by an air gap. Seal cooling is accomplished by a closed internal system utilizing a pumping disk on the pump shaft to circulate cooling water from the seal

Fig. 28. Characteristics of Bingham pump type 3 x 6 x 17 CJM, two stage, Serial No. 250920 (Ref. Bingham curve 24740).

chamber through a heat exchanger and back to the seal. The two seal coolant heat exchangers furnished with the pump are models 8 x 6C-12 Graham "Heliflow" units with a tube-side design pressure of 3000 psig and hydrostatic test pressures of 4500 psig on the tube side and 150 psig on the shell side.

5. INSTRUMENTATION

The THTF is instrumented to measure temperature, flow, fluid density, pressure, differential pressure, heater rod power, and time under both steady-state and transient conditions. Additional instrumentation is provided to assure reliable operation of the facility, including means for detecting out-of-limit and unsafe conditions, annunciators to alert the operators to the existence of such conditions, and interlocks to initiate appropriate protective actions upon detection of such conditions.

5.1 Location

The locations of the principal instruments used to obtain test results are shown schematically in Fig. 29 and listed in Table 6. In addition to the instruments identified in Fig. 29, there are 347 sheath thermocouples and 73 center thermocouples in the heater rods of bundle 1; 64 subchannel thermocouples; 16 thermocouples projecting into the fluid on the inside of the heater rod shroud box; and 3 pressure taps at different locations along the shroud box. The location of all THTF instrumentation is shown on plan and elevation drawings in Appendix C.

5.2 Pressure and Differential Pressure

Line pressure gauges and force-balance transmitters are used for normal monitor and control functions during pretest operations. For steady-state sensing prior to blowdown and for CHF tests, Foxboro and Barton electronic force-balance transmitters, Heise precision bourdon-tube gauges, and strain-gauge transducers are used. For sensing blowdown pressure transients, Precise Sensors, Inc., air-cooled, flush-diaphragm, strain-gauge transducers are used. For sensing transient differential pressure, Baldwin Electronics, Inc., strain-gauge transducers are used. The manufacturer has stated that these transducers have a frequency cutoff at about 500 Hz.

The strain-gauge pressure and differential pressure transducers have a specified static error band of $\pm 0.5\%$. (Static error band is the error band applicable at room conditions in the absence of any vibration, shock,

Table 6. Primary loop instrumentation from which test results are derived

PE-156	Pressure at inlet plenum of test section
PE-106	Pressure of pressurizer vapor
PE-76	Pressure at pump suction
LT-100	Pressurizer level
PE-26	Pressure at spool piece 1 (inlet)
PE-174	Pressure at spool piece 2 (inlet)
PE-224	Pressure at spool piece 1 (outlet)
PE-42	Pressure at spool piece 2 (outlet)
P _d E-46	ΔP across main heat exchangers
P _d E-78	ΔP across pump
FE-18	Turbine meter in spool piece 1 (inlet)
FE-166	Turbine meter in spool piece 2 (inlet)
FE-216	Turbine meter in spool piece 1 (outlet)
FE-24	Turbine meter in spool piece 2 (outlet)
F _{mf} E-22	Drag disk in spool piece 1 (inlet)
F _{mf} E-170	Drag disk in spool piece 2 (inlet)
F _{mf} E-220	Drag disk in spool piece 1 (outlet)
F _{mf} E-38	Drag disk in spool piece 2 (outlet)
TE-24	Temperature spool piece 1 (inlet)
TE-172	Temperature spool piece 2 (inlet)
TE-222	Temperature spool piece 1 (outlet)
TE-40	Temperature spool piece 2 (outlet)
DE-20	Density spool piece 1 (inlet)
DE-168	Density spool piece 2 (inlet)
DE-218	Density spool piece 1 (outlet)
DE-36	Density spool piece 2 (outlet)
TE-162	Temperature test section inlet
TE-212	Temperature test section outlet

Fig. 29. Thermal-Hydraulic Test Facility. ORNL-PWR Blowdown Heat Transfer Separate-Effects Program.

or acceleration.) However, the overall accuracy of these transducers during the blowdown transient may be degraded both by high operating temperatures and by the temperature transients. Typical manufacturer specifications are a compensated temperature range of +75 to 600°F, a thermal zero shift of less than 0.020% of full scale per °F over the compensated temperature range, and a thermal sensitivity shift of less than 0.010% of full scale per °F over the compensated temperature range.

In view of the above, it is evident that in the worst case, overall error for these transducers could be as much as $\pm 18\%$ of full scale under blowdown conditions. To minimize this source of error, air-cooled standoffs with a water-filled pressure tap line are used to isolate the transducer from the loop temperature environment. For pressure measurements, the transducer is mounted on the end of this standoff and thus operates at a temperature considerably below that of the fluid in the system; for ΔP measurements, the transducer is located equidistant between two such taps. The air cooling should also reduce flashing of the water in the ΔP taps.

5.3 Temperature

Chromel-Alumel thermocouples and platinum resistance thermometers (RTDs) are used to measure temperature. The RTDs are used for precision steady-state measurement to establish base temperature conditions in the loop prior to blowdown and during CHF tests. Stainless-steel-sheathed, magnesium-oxide-insulated, Chromel-Alumel thermocouples are used extensively to obtain blowdown and CHF test data. Sheathed couples in the Watlow indirect heater have outside diameters of 20 mils. Exposed-junction thermocouples (Nanmac Corporation) are used in a few locations where very fast temperature transients (>10 Hz) must be measured. For routine monitoring of operation temperatures, 0.125-in.-OD sheathed thermocouples are installed. All thermocouples providing test data are of premium-grade material (error band being the greater of either 2°F or $\pm 3/8\%$ of reading) purchased in accord with appropriate standards. Thermocouple cold-junction compensation is handled by multiterminal 150°F reference junction compensators.

5.4 Flow

Both single-phase (liquid-gas) and two-phase (water-steam) flow measurements are required in the THTF. Liquid flow, where no change of phase is involved, is measured directly using turbine meters or indirectly through pressure drops across orifices or in pipe elbows. Turbine meters

are installed where precision and wide rangeability are required. Orifices (~2% accuracy) and pipe-elbow taps (5 to 10% accuracy) serve where less precision is acceptable.

The sensors for two-phase flow measurement are installed in instrumented spool pieces located in the test section inlet and outlet lines. One sensor, a Ramapo Instrument Company drag disk, develops a signal proportional to ρV^2 (the momentum flux), where ρ and V are the fluid density and velocity, respectively. Fluid density at each drag disk station is measured by means of a gamma densitometer. Since the strain gauges in drag disks are temperature sensitive, a correction factor based on preblowdown calibration tests at different temperatures must be applied to the drag disk data.

Flow Technology, Inc., full-flow bidirectional flowmeters are also installed in the instrument spool pieces. The output of a turbine meter is proportional to fluid velocity and is nearly independent of temperature and density. The performance characteristics and inherent accuracy of the turbine meter are superior to those of the drag disk; however, it is not as rugged as the latter and engenders pressure drops that might be excessive under certain conditions. Flow-homogenizing devices are installed upstream of both flow-measuring devices in order to obtain more reliable results.

The densitometer consists of a 25-Ci ^{137}Cs monoenergetic gamma source with associated collimator, scintillation photomultiplier-type detector, and current amplifier. Depleted uranium is used for the collimator and source shield material in the THTF to avoid cooling problems that would exist with lead.

5.5 Voltage and Current

In the dc power system, currents are sensed by instrument shunts; an amplifier with high common mode tolerance is required to isolate the data-acquisition system from the dc voltage on each shunt. Voltage is measured using resistive voltage dividers.

5.6 Time

The time of blowdown initiation (i.e., the moment at which the rupture disks are broken) is indicated by multiple break wires located just downstream of the rupture disks. These wires are broken by the water rushing into the blowdown lines, and the consequent interruption of the continuity signal defines time $t = 0$.

5.7 Data-Acquisition System

The THTF data-acquisition system consists of (1) data sensors and the associated signal-conditioning equipment, (2) two 14-channel analog magnetic tape recorder/reproducer systems, (3) a timing and tape search subsystem, (4) a 512-channel, high-speed, computer-controlled digital-data-acquisition system (CCDAS), and (5) multichannel analog strip-chart recorders. Test data (from immediately preceding to the end of blowdown) are recorded on the CCDAS and the analog magnetic tape system. Selected parameters not expected to vary widely during blowdown and all process control variables are registered on analog strip-chart recorders.

Fast transient data from pressure transducers, densitometers, etc., are recorded by the analog magnetic tape system, while slower speed (< 2 Hz) data are handled by the CCDAS. The CCDAS also serves for on-site digitization of data on the analog magnetic tapes. The analog strip-chart recorders are used primarily to obtain "quick-look" data during CHF experiments and, possibly, for monitoring key variables during blowdown. In some cases, individual signals may be recorded in parallel on more than one system. Systems were not paralleled where the possibility of interaction existed; however, since all the data-acquisition systems have high input impedance and the output impedance of all signal sources is expected to be low, interaction is not expected to be a problem.

The time code generator-translator is used to supply timing signals to both the magnetic tape and CCDAS during data runs and to decode the time information on the magnetic tape during posttest digitization. The associated tape search unit expedites location of the data to be digitized and initiates and stops digitization of data at preset time limits, thus

minimizing operator involvement and eliminating digitization of extraneous data.

All test data are recorded digitally on IBM-360-compatible magnetic tape. On-site readout of data from the CCDAS is available via the ASR-33 teletype. An on-site "quick look" at digitized data is available through use of software routines which plot the data on the CCDAS display oscilloscope.

5.8 Error Analysis of Critical Instrumentation in the THTF

The error analysis to date is a theoretical analysis of the 99.7% confidence limits on the measurement of density, pressure, differential pressure, flow, and mass flow. The information on which the results are based comes mainly from manufacturer's specifications and calibrations by independent testing. These results should be considered preliminary and primarily applicable to steady-state data. Hopefully, the error bands given are outside limits and can be decreased as more experience and data are gained. The drag disks and gamma densitometers, in particular, will require considerably more scrutiny.

Since the error analysis thus far has been strictly a paper study, the interpretive factors that will be applied to the data are not included. In addition, errors that may occur during the blowdown transient (i.e., frequency response limitations and errors due to thermal gradients) are not included. The temperature shift, drag crisis, or whatever causes the apparent span shift in drag disks is not included and will require considerable analysis (and perhaps further testing) to define quantitatively.

Data from test 021 indicate that the primary pressure transducers are within the error bands specified below during steady state prior to blowdown. Except for PE-106, the pressure transducers appear to be within $\pm 1.2\%$ of full scale during steady state for test 021. To attain this degree of accuracy, the transducers were calibrated in situ at ambient conditions prior to the test. The voltage signals for densitometers DE-36, DE-168, and DE-218 were quite stable at steady state prior to blowdown in test 021; DE-20 was exhibiting variations of about $\pm 1\%$ of full-scale voltage signal.

Some of the errors that were assumed to be unpredictable or random are amenable to calibration techniques and may later prove to be quite systematic and correctable. It should be well understood that these results are preliminary and should be interpreted carefully in light of the information on which they are based and the assumptions made.

5.8.1 Pressure measurement

The pressure-measurement system consists of a pressure transducer, a span and zero adjusting network, an instrumentation amplifier, and either the CCDAS or an analog tape recording system. The components and sources of error are listed below:

Pressure transducer

<u>Source of error</u>	<u>Error</u>
Combined nonlinearity and hysteresis	<0.5% of span
Imprecision	<0.1% of span
Zero shift with temperature	<0.0056% of span/°C
Sensitivity shift with temperature	<0.0056% of span/°C

Notes:

1. The temperature effects were assumed to be completely correlated, that is, the zero and sensitivity shifts produce errors in the same direction at the same rate. This is a "worst-case" assumption.
2. It was assumed that the temperature of the transducer would vary between 69.5 and 200°F under the influence of the loop heat and the cooling air to the transducer and the air-cooled pressure tap.
3. The errors due to sensitivity shift will be a linear function of pressure, making the overall error some function of pressure. However, in this analysis the sensitivity error was assumed constant at its maximum value to simplify calculations and produce a conservative estimate.

Span and zero adjusting network

It was assumed that the errors introduced by environmental effects on this passive network of resistors would be negligibly small, since the

network is in the instrument cabinet in the control room where the temperature is almost constant.

Instrumentation amplifier

<u>Source of error</u>	<u>Error</u>
Gain instability	$\pm 0.001\%/^{\circ}\text{C}$
Output offset (G = gain)	$\pm (10 + 0.5G) \mu\text{V}/^{\circ}\text{C}$

The errors due to bias current drift and equivalent noise voltage and current are extremely small and were neglected. Also, errors due to power supply fluctuation were neglected because of the high power supply rejection capability and the assumption that the power supply is very stable.

CCDAS

According to the manufacturer's specifications, the overall inaccuracy is less than $\pm 0.3\%$ of span on any of the CCDAS ranges.

Analog tape system

According to manufacturer's specifications, the overall accuracy is less than $\pm 1\%$ of span.

Overall system

Considering all sources of error listed above, the 99.7% confidence limits on error in pressure measurement are $\pm 2.7\%$ of span on the CCDAS and $\pm 2.9\%$ of span on the analog tape system.

5.8.2 Flow measurement

The flow-measurement system consists of a turbine flow transducer, a flow rate monitor, and the CCDAS and analog tape system.

Turbine flow transducer and flow rate monitor

The turbine flow transducer and flow rate monitor were calibrated as a unit prior to their installation in the facility. This calibration indicated that the 99.7% confidence limits were $\pm 1.05\%$ of span, considering ± 1

uncertainty factors and assuming a proper calibration against a standard with less than 0.1% of span error.

These confidence limits are applicable only for ambient-temperature water. Further work is required to establish uncertainty for other conditions.

Overall system

The overall system inaccuracy should be less than 1.094% of span, with 99.7% certainty, on the CCDAS. Similarly, it is less than 1.45% of span on the analog tape system.

5.8.3 Mass-flow measurement

The mass-flow-measurement system consists of a drag disk flowmeter, a span and zero adjustment network, an instrumentation amplifier, and the CCDAS and the analog tape system.

Drag disk flowmeter

The drag disk flowmeter was calibrated with ambient-temperature water and found to have a span uncertainty of less than 1.8%, with 99.7% confidence.

Span and zero adjustment network

Errors were assumed to be negligible.

Instrumentation amplifier

Errors were the same as those calculated for the instrumentation amplifier on the pressure-measurement system.

Overall system

The uncertainties in measurement of mass flow (momentum flux) were less than $4565 \text{ lb}_m \text{ ft}^{-1} \text{ sec}^{-2}$ on the CCDAS and less than $5148 \text{ lb}_m \text{ ft}^{-1} \text{ sec}^{-2}$ on the analog tape system, with 99.17% confidence.

5.8.4 Pressure-difference measurement

The pressure-difference-measurement system consists of a differential pressure transducer, a span and zero adjustment network, an instrumentation amplifier, and the CCDAS and the analog tape system.

Differential pressure transducer

<u>Source of error</u>	<u>Error</u>
Calibration inaccuracy	0.5% of span
Nonlinearity	0.25% of span
Nonrepeatability	0.10% of span
Hysteresis	0.10% of span
Zero shift with temperature	0.028% of span/°C
Sensitivity shift with temperature	0.028% of span/°C

Note: It was assumed that the temperature of the transducer would vary between 69.5 and 150.5°F under the influence of ambient air temperature.

Zero and span adjustment network

Errors were assumed to be negligible.

Instrumentation amplifier

Same as on pressure and mass-flow measurement.

Overall system

The uncertainty in pressure-difference measurement is less than 10.7 psi on the CCDAS and less than 14.3 psi on the analog tape system, with spans of 1000 psi. For the systems with spans of 200 and 50 psi, the uncertainties are approximately the same percent of span.

5.8.5 Density-measurement system

The density-measurement system consists of a gamma source (^{137}Cs), a scintillator, a photomultiplier, two signal-conditioning amplifiers, and the CCDAS and analog tape system.

Scintillator and photomultiplier

The scintillator and photomultiplier are estimated to be accurate to within 1%, according to the manufacturer's specifications.

Signal-conditioning amplifiers

The first signal-conditioning amplifier is a current-to-voltage converter with a single-pole low-pass filtering characteristic at a frequency

of ~ 1600 Hz. Its sources of error are as follows:

<u>Source of error</u>	<u>Error</u>
Bias current offset drift	<100 pA over 298 K
Input offset voltage drift	± 50 $\mu\text{V}/^\circ\text{C}$ and ± 100 $\mu\text{V}/\text{V}$ (power supply)
Input noise current:	<0.56 pA rms
Drift of gain resistor	± 50 ppm/ $^\circ\text{C}$

The second signal-conditioning amplifier has the same sources of error as the first, except drift in the gain-setting resistor since it is a unity gain voltage follower.

Overall system accuracy

Because of the exponential relation of density ρ to photomultiplier current, the error in density measurement is a strong function of density. The relation is illustrated graphically in Fig. 30.

Fig. 30. Error in gamma-densitometer density measurement vs fluid density.

6. RESULTS EXPECTED

Current program plans call for fabrication and testing of a minimum of three heater rod bundles, two with a symmetrical, stepped, chopped-cosine power profile and the third bundle with a skewed power profile. Because of limited operating experience with the 12-ft heated length heaters, their lifetime cannot be predicted; as a basis for planning, it has been arbitrarily assumed that the first 49-rod bundle might survive 10 blowdowns or 40 hr of operation with power on the rods, whichever is limiting for heater rod lifetime.

6.1 Isothermal Blowdowns

Isothermal blowdowns with no rod bundle in the loop are part of the loop shakedown tests. During isothermal tests the break area will be varied in order to determine the break area required to obtain a given transient. These tests will also permit determination of an appropriate contraction coefficient to be used in conjunction with the Moody choked-flow model in RELAP.

It is not certain what effect heat transfer from the loop walls will have on the blowdown response of the THTF. It would be expected that this effect increases with increasing initial temperature and that the disparity between calculated and experimental pressure traces would be relatively greater for a run starting at a higher temperature, if wall effects are not included in the calculation. RELAP can model loop walls as slabs or cylinders undergoing both convective and boiling heat transfer. These no-power runs may provide a basis for evaluating this aspect of the RELAP calculation. If this heat transfer is significant, it may be possible to instrument a portion of pipe or the test section and experimentally determine the heat removed. With no bundle, the effect of steam formation in the test section on flows should be easily observed, as the entire test section will be at approximately the same pressure and temperature. These experimental data may be compared to a calculated rate of steam formation from depressurization.

The test sequence envisioned for isothermal blowdowns is summarized in Table 7. Tests 001, 002, and 003 make up the first set of tests. Their primary purpose is to determine the relationship between the break area and the time rate of change of pressure. In these tests the pump will be turned off at the instant of blowdown, since it is believed that this represents the least hazard to the pump.

Tests 011, 012, and 013, which make up the second set of isothermal tests, are identical to the first set of tests except that the pump is to be left on after blowdown initiation. After test 011, a critical review will be made of pump vibration and seal coolant temperatures to determine whether it will be safe to conduct the remaining two tests in this series.

Tests 021 and 024 are double-ended isothermal blowdown tests for exploring depressurization rates with different break area ratios and possibly with the pump both off and on during blowdown. The execution of these four tests depends strongly on analysis of the results of prior tests.

Although ten isothermal tests are outlined in Table 7, only five of these are scheduled for the shakedown phase of operation: 001, 002, 002 repeated with an orifice in the pressurizer to restrict the flow from the pressurizer during the transient, 021, and 023. The remainder of the tests will be performed as the schedule permits.

6.2 Powered-Rod Blowdowns

The controlling feature of the program test philosophy is one of separate-effects studies. This means that there are no plans to demonstrate a 1:1 correspondence between events occurring during a blowdown in the THTF and a postulated LOCA in a PWR. Instead, sufficient versatility has been designed into the THTF that the effect of a wide range of operating parameters on LOCA events can be investigated.

The test matrix for the first heater rod bundle is given in Table 8. Nominal rod power of 122 kW was chosen as typical of current power level in PWRs with a peak power of 17 kW/ft and a value of peak-to-average power of 1.67.

Table 7. Isothermal blowdown test matrix (no test bundle in loop)

Variable	Test No.									
	001	002	003	011	012	013	021	022	023	024
Rod power, kW/rod	0	0	0	0	0	0	0	0	0	0
Coolant mass flow rate, ^a $\text{lb}_m \text{ hr}^{-1} \text{ ft}^{-2} \times 10^{-6}$	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Break location (and area ratio where applicable)	Inlet	Inlet	Inlet	Inlet	Inlet	Inlet	Inlet (0.5A) Outlet (0.5A)	Inlet (0.5A) Outlet (0.5A)	Inlet (0.3A) Outlet (0.7A)	Inlet (0.3A) Outlet (0.7A)
Break size, $\text{ft}^2 = A$	0.0034	0.0067	0.0135	0.0034	0.0067	0.0135	0.0135	0.0135	0.0135	0.0135
Time heater rod power on after blowdown initiation	0	0	0	0	0	0	0	0	0	0
Coolant inlet temperature, °F	500	547	547	547	547	547	547	547	547	547
Coolant temperature rise, °F	0	0	0	0	0	0	0	0	0	0
System pressure, psi	1000	2250	2250	2250	2250	2250	2250	2250	2250	2250
Pump condition during blowdown	Off	Off	Off	On	On	On	Off	On	Off	On
Assess prior test results before proceeding with next test	No	Yes	No	Yes ^b	Yes ^{b,c}	Yes ^d			Yes ^e	

^aThe volumetric flow from the pump to the test section will be set at the value required to give this mass flow rate if the bundle were installed in the test section.

^bBefore proceeding with test 012, check to determine for possibility of damage to pump if it is kept on during blowdown. If damage possibility exists, scrub tests 012, 013, 022, and 024.

^cBefore proceeding with test 013, check to determine if blowdown pipe snubber loadings will be exceeded. If they will be, use break area of 0.0067 ft^2 in test 013.

^dBefore proceeding with tests 021 to 024, check to determine if a break area of 0.0135 ft^2 will result in a depressurization curve similar to that for PWR calculations. If not, adjust break area based on results of prior isothermal tests.

^eBefore proceeding with test 024, review the results of tests 023 and 011 to 013 to determine if the combination of asymmetric break and pump on during blowdown poses undue hazard to the pump.

Table 8. ORNL-BDHT Separate-Effects Program test matrix - first 43-rod bundle

Variable	Test No.					
	100	101	102	103	104	105
Rod power ^a						
kW/rod	0	30.5	122	122	122	Power reactor case
Btu hr ⁻¹ /rod	0	0.0089	0.0357	0.0357	0.0357	
Coolant mass flow rate						
kg m ⁻² hr ⁻¹ × 10 ⁻⁶	12.2	12.2	12.2	12.2	12.2	
lb m ⁻² hr ⁻¹ ft ⁻² × 10 ⁻⁶	2.5	2.5	2.5	2.5	2.5	
Break location (and area ratio where applicable) ^b	In (0.5A) Out (0.5A)	Out	In (0.5A) Out (0.5A)	??	In (0.5A) Out (0.5A)	
Break size = A						
cm ²	12.54	6.27	12.54	?	12.54	
ft ²	0.0135	0.0067	0.0135	?	0.0135	
Time heater rod power on after blowdown initiation, sec	NA ^c	d	0	0	?	
Coolant inlet temperature ^e						
°C	286	286	286	286	286	
°F	547	547	547	547	547	
Coolant temperature rise						
°C	0	~13	~52	~52	~52	
°F	0	~24	~93	~93	~93	
System pressure						
MPa	15.51	15.51	15.51	15.51	15.51	
psi	2250	2250	2250	2250	2250	
Pump condition during blowdown	Off	Off	Off	Off	Off	
Sheath thermocouple upper set point ^f						
°C	NA ^c	T _{max} + 27.8				
°F	NA ^c	T _{max} + 50				

^aBased on a peak power of 51.8 kW/m (17 kW/ft) and a peak-to-average power of 1.67.

^bOut = outlet; In = inlet.

^cNA = Not applicable.

^dPossibility of checking power time delay trip.

^eCoolant inlet temperatures are tentative. Final values will be selected after operational experience provides information on conditions required to prevent flashing in control valves.

^fPower trip circuit shutoff is tentatively to be set at a temperature 27.8°C (50°F) greater than the maximum temperature of any sheath thermocouple at steady state, but this set point may be altered based on future calculations.

Test 100 is an isothermal blowdown test with the heater rod bundle in place to obtain information on the pressure drop characteristics of the rod bundle during blowdown for use in tuning the RELAP model. Test 101 is the first blowdown to be conducted with power on the heater rods. The total power will be one-fourth of nominal, and the heater rod power will be turned off at the instant of blowdown. The primary purpose of test 101 is to develop operational experience with the THTF with power on the heater rod bundle. Test 102 will be a full-power double-ended break in which the heater rod power is turned off at the instant of blowdown. The primary purpose of this test is to gain additional operational experience with the THTF with power on the heater rods and to obtain results on the effect of the split between orifice area ratios on the system flow rates. Test 103 will be a full-power double-ended break in which the heater rod power is turned off at the instant of blowdown. Break area ratios will be selected based on the results of test 102. Test 104 will be a full-power double-ended break in which the heater rod power remains on sufficiently long to insure that transient CHF occurs. Test 105 will be a blowdown which, based on results of all previous tests, attempts to match depressurization rates, flow rates, etc., of a typical calculated PWR cold-leg guillotine-break LOCA.

A heater rod power programmer is scheduled to be available for test 108. As soon as the characteristics of this device are known, the decay power profile for tests 108 to 110 will be determined in consultation with NRC.

A key feature of this program will be the determination of steady-state CHF for all initial conditions used in blowdown tests. Since a steady-state CHF test may be equivalent to a blowdown test with regard to bundle lifetime, only a limited number of steady-state CHF tests can be performed. Should the test bundle still be operational at the end of test 110, a series of steady-state CHF tests will be performed covering a range of test variables.

The test matrix outlined above presumes that as the test sequence progresses there is no indication of operational difficulties which could endanger the rod bundle. Should there be an indication of operational difficulties, they will either be corrected or the test matrix variables will be altered.

Appendix A

DESIGN OF THE MECHANICAL AND ELECTRICAL SYSTEMS
FOR THE THERMAL-HYDRAULIC TEST FACILITY (THTF)

ABSTRACT

The Thermal-Hydraulic Test Facility (THTF) is a 7.5-MW nonnuclear test facility designed to permit testing of full-length, multirod bundles under typical PWR core conditions of power level, power profile, coolant temperatures, pressures, and flow rates. Capability is provided for a wide range of conditions, including steady-state critical heat flux (CHF) determinations, operational upsets, and loss-of-coolant (LOCA) tests.

The all stainless steel primary system is designed for pressures up to 2500 psig and for temperatures up to 650°F. The system is designed to accommodate a 49-heater-rod bundle, with blowdown capability over a metered flow range of 100 to 600 gpm. A pump, specially designed for blowdown service and operating with a bypass flow control system, provides more than adequate flow and head for the expected range of test conditions. A pressure-suppression system absorbs the thermal energy during loss-of-coolant tests.

Rupture disk assemblies of the inlet and outlet of the test section, with two-phase flow instrumentation measuring separately the loop and test section blowdown flows, simulate coolant-line breaks. Indirectly heated rods (i.e., rods in which heat is generated by an internal element and transferred through boron nitride insulation to the sheath) are used to simulate nuclear fuel rods in both power level and axial profile.

Power is supplied to the electrically heated test bundle from four dc generators, each rated at 7140 A at 350 V. Heat removal capability of 7.5 MW is provided by three heat exchangers, which reject heat to a large building-wide recirculating demineralized cooling-water system.

1. FUNCTIONS AND DESIGN REQUIREMENTS

1.1 Functions

The Thermal-Hydraulic Test Facility (THTF) serves as a vehicle for studying experimentally the thermal-hydraulic response of heater-rod bundles under operating conditions that are of interest in analysis of PWR loss-of-coolant accidents (LOCAs) as well as transients associated with more normal operating modes. The test section is a 7×7 array of 12-ft-heated-length heater rods geometrically modeling (except for solid bounding walls) a section of a PWR core; this pressurized-water-cooled test section will bracket expected PWR conditions in respect to heater element power level and distribution, rod surface temperatures, and coolant temperatures and pressures during both steady-state and blowdown periods.

The experimental program utilizing this facility concentrates on two areas of transient heat transfer — with priority on the first — in which existing uncertainties influence PWR accident analyses:

1. Heat transfer during the early stages of a LOCA (i.e., prior to emergency coolant injection). Initially, the effects of combined power, flow, and pressure transients and later the separate influences of each of these variables will be examined.

2. Heat transfer during the pre- and post-CHF (critical heat flux) phases of operational transients with the primary variables of power, flow, and pressure spanning ranges anticipated with PWRs. Tests and analyses will emphasize development of understanding and accurate descriptions of thermal-hydraulic processes within the rod bundle.

1.2 Operational Requirements

Design requirements for the facility are dictated primarily by the desire to vary the test parameters independently over ranges spanning that of current PWR designs. Test section operating conditions of interest are shown in Table A.1. System pressures at the test section outlet vary from saturation to normal reactor operating pressure (2250 psia). Maximum mass velocity is consistent with current PWR coolant flow rates; the lower limit

Table A.1. THTF test section operating conditions

Variable	Range of Interest
Coolant pressure, psia	To 2250
Coolant inlet temperature, °F	520 to 560
Coolant temperature rise, °F	60 to 90
Coolant mass velocity, $\text{lb}_m \text{ hr}^{-1} \text{ ft}^{-2}$	$0.6 \text{ to } 3.0 \times 10^6$
Peak rod power, kW/ft	19.8
Average rod power, kW/ft	12
System volume/power ratio, ft^3/MW	>3
Blowdown break area	Single- or double-ended variable area
Break location	Inlet, outlet, varied flow split

on flow is selected to permit determination of CHF over a fivefold span of velocity.

The test section is a full-length, full-scale model of a quarter section of a PWR core fuel assembly using electrically heated rods to simulate fuel rods. Later test bundles may include unheated rods to simulate instrument tubes and control rod thimbles. Power levels for the heater rods will range from average conditions to that of the hot channel in a PWR core; axial and radial power distributions will be characteristic of idealized PWR cores. The large number of tests necessary to fully characterize core behavior and the estimated high cost of the heater-rod bundle require that the facility and test section be capable of repeated steady-state CHF and transient blowdown tests without significant damage and that the time period from system startup to test completion be minimized.

1.3 Structural Requirements

The high-pressure primary circulation system of the THTF is designed for operation with subcooled water at 2500 psig and 650°F except that (1) the pressurizer design is for 2500 psig and 750°F, (2) a section of the pump discharge piping is designed for 3000 psig and 600°F, and (3) the pump is limited to 600°F maximum operating temperature. Further, pump design specifications limit rates of temperature change during normal

operation to 15°F/min during heating and 25°F/min during cooling; very rapid changes of temperature and pressure will occur during the blowdown tests. The pump and other flow components are to be capable of operation throughout the blowdown period under conditions of coolant flash evaporation. All piping and components of the facility shall conform to requirements of the applicable codes and standards listed in Section 1.5.

The circulating test coolant is high-purity demineralized water; the principal factor in material selection for the test facility is avoidance of contamination of the water by corrosion products and/or other impurities. The ability to withstand repeated tests without damage imposes an additional restraint on test section materials, particularly of the heater rods. Rod bundle geometry is to remain fixed throughout the initial test program; this requirement precludes determination of the effects of fuel-rod swelling and bowing.

1.4 System Configuration and Essential Features

The THTF is a complete and independent test facility with no interfacing requirements to other systems other than building or plant-wide utilities. The physical configuration of the facility is primarily determined by the arrangement of major components as required by the available building space, the location of existing components and systems, economics and good practice in piping layouts, and the desired versatility of test section piping connections. The facility includes (1) a closed recirculating primary loop capable of providing a wide range of thermal-hydraulic operating conditions to the electrically heated test sections; (2) instrumentation, controls, and data-acquisition systems necessary for loop operation and test data analysis; (3) test section power supply up to 10 MW; and (4) a primary fluid blowdown system with pressure suppression.

The facility was constructed by upgrading an existing facility built for steady-state or slow transient CHF studies with pressurized water in a single heated tube or annulus. Significant features provided from the original system include building space and utilities, dc test section power up to 5 MW with water-cooled conductors and necessary instrumentation and controls, a recirculating demineralized coolant-water system, a 2.5-MW

primary heat exchange~~r~~ for removal of heat generated in the test section, and certain loop instrumentation and controls.

The new primary loop includes the circulating pump, pressurizer, heat exchangers, and bypass piping and is operable without the test section installed. High-pressure, high-temperature quick-disconnect flanges provide flexibility for flow component rearrangement. The test section housing (containing the multirod bundle and flow shroud) has coolant inlet nozzles at the bottom and top of the housing. Load orifices in the blowdown nozzles will simulate hydraulic resistances of the "second loop."

1.5 Quality Assurance, Codes, and Standards

The THTF was designed, fabricated, and operated as a quality-level III-IV facility. (Quality levels are assigned from I to IV in order of decreasing quality assurance requirements.) Essentially, this means that the electrical, structural, and piping systems are quality level III and come under the jurisdiction of the various appropriate laboratory and industrial codes. Less critical portions, such as the demineralized-cooling-water system, are quality level IV to which different standards apply.

The codes and standards selected for each component and/or subsystem in the THTF pressure boundary, along with major systems outside of the pressure boundary, are summarized in Table A.2. Some of these codes and standards are discussed below.

1.5.1 Codes and Standards for Heat Exchangers

Heat removal capability over a wide range of operating conditions is required in THTF. The method selected involves the use of three identical heat exchangers (A, B, and C) with appropriate valving to control the primary fluid flow rate through the exchangers and the cooling water flow rate. In addition, heat exchanger A has the means for controlling the cooling water temperature to minimize the log-mean temperature difference when operating with low heat removal rates at high primary fluid temperature levels.

Table A.2. Codes and standards applied to the THTF

System or component	Quality level	Code or standard applied
High-pressure primary system		
Piping	III	Power Piping Code B 31.1.0
Valves	III	ASME Sect. III, Class 2, Spec. I-10520-QG-002-S-1
Heat exchangers	III	ASME Sect. VIII, Div. 1, Spec. M-10520-RM-001-X-0
Pump	III	See text
Pressurizer	III	ASME Sect. III, Class 2, Spec. M-10520-RM-005-S-0
Test section container	III	ASME Sect. VIII, Div. 1
Heater rods	III	Spec. E-10520-RM-004-S-0
Pressure-suppression system		
Piping	III	
Tank	III	ASME Sect. VIII, Div. 1
Pump	III	
Demineralized cooling-water system piping	IV	UCC Tech. Spec. P-1.1, Subsection 107
Instrumentation and data-acquisition system	III	ORNL I&C Div. standards and procedures
Power supply system (dc)	III	National Electrical Code, NEMA, IEEE, and Underwriter Laboratories standards, ORNL standards and procedures
Support structure	IV	AISC specifications and standard practices

Some unique features of the Heliflow heat exchangers, manufactured by Graham Manufacturing Company, Inc., are particularly advantageous for applications such as those encountered in the THTF. (See Sect. 1.5.5 for a detailed description of the heat exchanger.) Normally, exchangers designed to operate at high system pressures require rather thick tube sheets to withstand the attendant pressure loadings. If significant temperature levels are involved, serious thermal stress problems may be encountered. These problems are alleviated in the Heliflow exchanger by replacement of the thick tube sheets with relatively thin tubing manifolds,

with the tubes being spirally wrapped around the inner manifold and terminating at a second manifold. Differential expansion resulting from temperature gradients along the tube length is easily accommodated by the spiral tube configuration. Additional benefits are derived from these two basic features. For example, the method of spiraling produces a well-defined secondary flow path so that the exchanger functions with either countercurrent or cocurrent flow without bypassing. Also, the spiral arrangement minimizes the space requirements for installation. This feature is particularly important to the THTF, since it is necessary to install the additional heat removal equipment in a very limited space.

Based on the features discussed above, Graham Heliflow heat exchangers have found wide application in the nuclear industry, and this type of unit was selected for the original THTF construction. Heat exchanger A was purchased in 1969 for that purpose in accordance with an ORNL specification covering design, fabrication, testing, and materials. The specification required the unit to be designed, constructed, and stamped in accordance with Section VIII, Division 1, of the Code. This was considered adequate for the design criteria then applicable to the THTF (i.e., quasi-steady-state critical heat flux research).

Early in the conceptual design of the modifications to increase the capability of the THTF to permit blowdown heat transfer tests on 49-rod bundles operating at typical PWR conditions of power, flow, and temperature levels, sufficient detailed design was performed to ascertain that two heat exchangers (B and C) identical to A would satisfy the requirements and provide adequate flexibility in the test program. Specifications were written, and procurement of these long-delivery items was initiated.

Based on technical and programmatic considerations discussed above, it is concluded that primary system heat exchangers (B and C) procured in accordance with Section VIII, Division 1, of the ASME Code will be fully adequate to satisfy the requirements and goals of the THTF.

In addition to the primary system heat removal equipment, a small heat exchanger is required in a bypass flow loop around the main circulating pump. This exchanger (D) is designed to remove the heat generated by the oversized pump so that the loop temperature level can be maintained at the desired set point. Since the same considerations applicable to

units B and C are appropriate to unit D, a small Heliflow heat exchanger was selected.

Based on a cyclic stress analysis, a modification of the weld joint design of the inlet manifold-baseplate junction was proposed to improve the cyclic lifetime of the Graham heat exchangers. The details of the design modification were then proposed by Graham and accepted by the project management (see Fig. A.1).

ORNL-DWG 75-7044

4384-HC-72
98C8C-14S

4383-HC-72
126C8C-22S

Fig. A.1. Weld joint modification for Graham Heliflow heat exchanger.

Since the previously purchased heat exchanger does not have this modification, one of the new modified heat exchangers will be placed in the A position. The A position heat exchanger will be used for temperature control since it receives more thermal cycles than do positions B and C.

1.5.2 Codes and standards for circulating pump

The number of manufacturers that produce pumps suitable for the pressure, flow, and heat requirements of the THTF is extremely limited. These manufacturers were contacted during the early conceptual design of the modifications to obtain approximate cost and delivery times for a pump having the desired capabilities. It was determined that the cost of such a pump would be in the range of \$100,000 to \$150,000 with delivery in 20 to 30 months from the date of approval of drawings for fabrication. Both cost and delivery were unacceptable, based on project funding and schedule considerations.

A high-head, high-capacity circulating pump, which was originally purchased for an AEC blowdown test program at Battelle Northwest Laboratories (BNWL), was made available to ORNL on an indefinite loan. Except for an excess on the developed head, the pump is well suited for the requirements of the THTF blowdown test program. The pump was designed and fabricated in the period 1965 to 1967 by the Bingham Pump Company of Portland, Ore. Purchase order specifications were developed by BNWL based on their experience with previous pumps in blowdown test loops. Due to cancellation of the BNWL program, the pump was never put into service.

The pump purchase order specifications required that the pump be designed to operate at suction temperatures in the range of 60 to 600°F and at suction pressures in the range of 100 to 2500 psig. Casing design conditions are 3000 psig at 650°F to accommodate the developed head. There is no mention of an applicable code or of design stress values permitted in the structural components. However, Paragraph NC-3410 of Section III of the ASME Code permits the use of any design method of demonstrated adequacy for the service conditions. It is presumed that purchase of the pump from a reliable manufacturer and supplier of reactor-grade pumps would provide a design based on demonstrated adequacy.

Communication with individuals associated with specification and purchase of the pump gives some insight into the philosophy with which the specifications were developed in early 1965 in an era before adoption of detailed quality assurance requirements. The specifications were developed based on previous experience with the performance of pumps in blowdown services. (Note that a detailed idealized blowdown sequence is given as design criteria in the specifications.) The pump was believed to be urgently needed at the time the order was placed, and details of design, fabrication, and inspection were apparently left to the discretion of the manufacturer. The purchaser was of the opinion that faulty design or weaknesses, if present in the pump, would appear quickly under operating conditions. Consequently, the specifications included testing, and acceptance was based on satisfactory performance during a 100-hr test at 2000 psig, 600°F, and 500 gpm. This test, in addition to a 4500-psig hydrostatic test that was performed even though not required by the specifications, was taken as satisfactory evidence of structural integrity. A complete tabulation of materials used in the construction of the pump and most of the fabrication drawings are available. The drawings show weld details and note that the welds are to be liquid-penetrant inspected after the first and final passes and in between as required.

The manufacturer was contacted to determine if his records contained any information that might be used to infer the appropriate level of quality assurance built into the pump. The following quotation is taken from the response to our request.

"There are no quality assurance documents available. Codes were not specifically made applicable except that it is our basic policy to design pumps to meet the requirements of ASME Section VIII. Liquid penetrant examinations were made as well as heat treatments to assure ourselves that pressure parts would pass the 4500 psi hydrostatic test and the 100 hour hot running test at 600°F. BNWL Inspection may have some inspection and test records which, if any, should be available to you with the pumps. Our file dates to the period 1965-1967 and reveals nothing more than the Hydrostatic Test and Performance Testing results possibly given to BNWL aside from the drawings and curves you have."

We believe that structural integrity of the pump has been adequately demonstrated for steady-state operation at THTF design conditions. We know of no method that will provide assurance of its adequacy under blowdown

operation short of experience with the pump under those conditions, and this cannot be accomplished until checkout operation with THTF. A standby set of spare parts, as recommended by the manufacturer, have been purchased to facilitate maintenance. The manufacturer provides service engineering contractual assistance in pump installation and startup operation, and we plan to utilize this service. The pump will have been in storage approximately seven years when the startup operation gets under way. To minimize difficulties during startup, bearings and seals will be replaced. Nevertheless, it is entirely possible that difficulties with bearings and seals will be encountered during the shakedown period. We have no indication of expected performance and life expectancy of the shaft seals under blowdown service. Since the seals can be readily replaced (in approximately two to three days) and we will maintain a complete replacement set as spare parts, we believe prolonged shutdown for maintenance can be avoided.

1.5.3 Codes and standards for pressurizer

The THTF pressurizer serves the dual function of a pressurizing source for the facility and of an expansion volume to dampen pressure surges resulting from coolant expansion. The volume of the pressurizer is approximately 7 ft³. Clamshell-type electrical heaters arranged on downcomers (see description in Sect. 3.3) provide heat to generator steam for maintaining the system pressure at the desired level. The concept selected for the pressurizer is identical to a pressurizer used successfully at 2500 psi (at saturation temperature) in a large pressurized-water in-pile loop facility at ORNL for a number of years. The major difference is that the length of the THTF pressurizer is increased to provide the necessary volume.

Even though ASME Section VIII would have been a satisfactory code from the standpoint of quality-level III requirements, the pressurizer is being designed and built to satisfy requirements of Section III, Class 2. Project Management agreed to let ORNL fabrication shops use the pressurizer as a demonstration vessel for the purpose of acquiring an ASME nuclear stamp.

1.5.4 Codes and standards for piping system

The piping system in the THTF high-pressure primary system contains pipes in the nominal size range of 1/2 to 6 in., except that the major portion of the piping is nominal 4-in. while 6-in. sched-160 pipe is used for the pump suction and the holdup volume. The exception is in reality a class exception in that it includes 1/8- and 1/4-in. nominal pipe and high-pressure autoclave tubing, used as instrument connections, vent lines, etc. Although this class of service is subject to system pressure, in general, the temperature level is essentially ambient.

A significant quantity of suitable heavy wall piping and fittings was available at ORNL to satisfy the major system requirements, particularly in the larger size range. This material was purchased some years ago under stringent material specifications for highly corrosive service in a now-discontinued aqueous reactor program. The existing loop was constructed from these materials, and we are confident that the quality is in excess of the requirements for piping systems. Material certifications (chemistry and physical properties) are either available in "dead storage" files or can be obtained from the manufacturer.

For the new construction, the use of piping and fittings available from existing stock was specified in those cases where the certification could be located or the material upgraded. Piping and tubing not available from existing stock were purchased in accordance with ASME or ASTM material specifications.

Design, fabrication, installation, examination, and testing of the piping system were in accordance with the rules of the Power Piping Code B 31.1.0. Welding was accomplished in accordance with ORNL welding procedure WPS-302. Weld examination was made in accordance with ORNL inspection procedure MET-WR-201, except that x-ray porosity charts of Appendix IV of ASME Code Section VIII, Division 1, were used.

1.5.5 Codes and standards for secondary coolant systems

Heat is rejected from the THTF primary coolant system to a secondary coolant system via four water-to-water exchangers. The secondary coolant

is supplied to the heat exchangers from a 15,000-gpm, building-wide, recirculating, demineralized water system operating at 250 psig. This system has been in operation for a number of years to provide cooling for a number of large thermonuclear experiments. Based on past experience, this system is considered highly reliable for supplying coolant to the many experimental facilities located within the building.

The new construction portions of the secondary cooling-water system were designed, fabricated, and inspected at quality level IV and in accordance with UCC Technical Specification P-1.1 Subsection 107 for Demineralized and Distilled Water Systems.

1.5.6 Codes and standards for pressure-suppression system

The THTF is designed with rupture disk assemblies located to simulate pipeline breaks. The rupture disk assemblies form the boundary between the high-pressure primary system and an energy-absorbing system (a recirculating spray condenser contained in an 1160-gal tank vented to the atmosphere through an 8-in. line). Blowdown is initiated by causing the rupture disk to fail at a predetermined time.

The piping, valves, etc., in this system meet the ANSI Code for Pressure Piping Systems, B 31.1.0 Power Piping. The spray condenser was designed in accordance with Section VIII, Division 1, of the ASME Code. Materials conform to ASTM material specifications appropriate to the service requirement.

1.5.7 Codes and standards for test section housing

The test bundle array is placed in a pressure housing for test purposes. The housing has a number of penetrations and access ports to accommodate the necessary test bundle instrumentation. Coolant inlet and exit flow nozzles are provided at a number of locations to give flexibility in flow configuration. A number of unique problems were encountered with the requirements for the dc power connections to the individual heater rods at the upper end and the common connection to all heater rods at the lower end. The housing was fabricated in two longitudinal flanged sections to facilitate assembly and disassembly for bundle replacement.

These aspects lead to a rather complicated housing with special considerations in regard to instrument penetrations and individual heater element penetrations necessitated by the experiment requirements.

Although some of these special considerations are outside the scope of the Code, the intent of the Code can provide guidance. The rules and intent of Section VIII were followed with deviations as required to accommodate the particular requirements brought about by the nature of the experiment.

Materials were procured in accordance with appropriate ASME and ASTM material specifications.

1.6 Heater Rods for the Test Section

The heaters used to simulate PWR fuel elements are of the indirect type. An indirect heater is one in which heat is generated in an internal element that is electrically isolated from the heater sheath. The Quality Assurance Program Plan (Q-10520-RH-001-S-0) specifies a quality level of III for the heaters but with "special inspection and assembly procedures to assure its functional operability." A heater specification (E-10520-RB-006-S-0) was written based on RDT standard P 4-4T. Most of the materials to be used in the manufacture of the heaters were procured by ORNL and furnished to the manufacturer. The thermocouples were purchased to specification IS 514, Thermocouple Material and Thermocouple Assembly, Chromel-P vs Alumel, Stainless Steel Sheathed Magnesium Oxide Insulated for Use on Blowdown Heat Transfer Program.

2. SYSTEMS DESCRIPTION

2.1 Summary Description

The THTF is a reasonably large nonnuclear test facility having a wide range of capabilities for thermal-hydraulic tests using electrical heaters in multirod geometries with the same heated length and diameter as nuclear fuel rods.

A simplified flowsheet for the THTF is given in Fig. A.2, and pertinent design data are summarized in Table A.3. A brief discussion of the flowsheet follows.

A high-head, high-capacity pump designed for blowdown conditions operates at a constant output of about 700 gpm with a developed head of ~1940 ft of fluid. Since the available head is in excess of the test requirements, a portion is dissipated in discharge throttling valves and load orifices distributed throughout the system. A large-capacity bypass loop controls the pump at constant output over the full range of test flows. Heat transferred to the coolant by the oversized pump (600 hp) is absorbed in a secondary heat exchanger in the bypass line so as to maintain a fixed loop base temperature.

The heat transferred to the coolant in the electrically heated rod bundle is removed by a heat-rejection system consisting of three water-to-water Heliflow heat exchangers and a bypass line. Heat exchanger A, retained from the original THTF installation, has a wide-range automatic control system; new units B and C have manual control. Overall control involves maintaining zero temperature differential between the fluid entering the test section and the mixed effluent from the heat exchangers and the bypass stream; thus, in principle, all heat added in the test section is removed before the test channel flow rejoins the pump bypass flow.

An electrically heated pressurizer maintains a constant pump suction pressure while providing steam volume to dampen pressure surges.

Instrumented spool pieces are located at the inlet and outlet of the test section housing and upstream of the inlet and exit rupture disk

Table A.3. Summary of THTF design data

Parameter	Capability
dc power to test section (maximum)	10 MW
Heat rejection	7.5 MW
Test section exit quality	≤ 0.1
Operating pressure	250 and 2500 psia
Operating temperature	400 to 650°F
Loop flow (maximum)	900 gpm
Pump developed head (600°F, 2250 psia, 900 gpm)	525 psi
Test section flow	1 to 600 gpm
Metered flow control stations	4
Test section heated length	12 ft
Test section flow direction	Vertical upflow

stations. Each spool piece provides sufficient instrumentation to ascertain the fluid state, the mass velocity, and the direction of flow.

Rupture disks at the inlet and exit of the test section housing are used to simulate inlet and exit pipe breaks. Critical flow orifices installed in these lines control the blowdown rate; these orifices may be changed as desired to cover a range of blowdown times. During blowdown, the loop fluid is discharged to the pressure-suppression system, where cold water introduced through spray nozzles condenses the steam. A 1500-gpm pump recirculates the cold fluid from the storage tank to the spray nozzles.

The dc power supply serving the THTF consists of two double-ended motor-generator sets as indicated schematically in Fig. A.2. These four generators, each rated at 7140 A and 350 V dc, can be controlled either jointly or separately. There is no requirement that the generators be paralleled since the heaters to be used are of the indirect type.

Austenitic stainless steel material is used throughout the system to avoid corrosion and degradation of the quality of the high-purity coolant. A small water purification system is also provided to maintain the water quality. The piping system is assembled with a number of flanged disconnects to facilitate rearrangement of the test loop configuration.

Adequate process instrumentation is provided for control, operational safety, and monitoring purposes, and panel-board-mounted indicators and

Fig. A.2. Thermal-Hydraulic Test Facility.

recorders provide readout for this instrumentation to aid in the operation of the facility. Data-acquisition instrumentation (for experiment analysis) consists of two 14-channel FM recorders for the high-frequency output signals from the pressure transducers and other detectors for which very fast response is desired. A 384-channel, computer-based, digital data logger collects the bulk of the data for subsequent analysis. Time markers, at preselected intervals, are recorded simultaneously with the data signals to provide time correlation between the various data recorders during the blowdown sequence.

The THTF is divided into several functional subsystems to clarify the detailed facility description and to provide a ready reference to subsystem features. The process flowsheet drawings that are used to illustrate detailed descriptions are similarly divided. All utilize a common system of nomenclature to identify components and functions, line sizes, and design conditions of flow, pressure, and temperature. See the legend of drawing symbols shown in Fig. A.3.

2.2 High-Pressure Primary System

The schematic flow diagram of the high-pressure primary system referred to in this description is shown in Fig. A.3. This system consists of a closed loop that includes an electrically heated pressurizer, a circulation pump, and heat exchangers to remove heat generated in the pump and test sections. Primary fluid in the recirculating loop, also referred to as test section coolant, is high-purity demineralized water.

The high-head, high-capacity circulating pump operates at a constant output of about 700 gpm with a developed head of ~1940 ft. Since the available head is significantly larger than that required to make up pressure drop through loop components and piping, a remotely operated discharge throttling valve (HCV 2) and load orifices located throughout the system are provided to dissipate excess head. Flow in excess of test section requirements is routed through line 190 to the parallel paths of the high-capacity bypass piping and back to the pump suction. One bypass leg, lines 192 and 194, contains heat exchanger D, which removes heat generated by the pump and throttling valve. Flow rate of primary fluid through

Fig. A.3. Process flowsheet - primary and pressure-suppression piping systems.

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Process flow sheet - primary and pressure-suppression

2

this heat exchanger is essentially constant at 15,000 lb_m/hr (35 gpm at 400°F to 50 gpm at 650°F) and is controlled by the actions of TRCA 13 and TCV 13 to maintain pump discharge temperature at the set point. Flow rate to the test sections is metered and controlled, so the balance of the pump discharge flows through the other bypass leg (line 190) where control actions of FRCA 1 and FCV 1 maintain pump flow rate at the set point.

Primary fluid, which is used as coolant for the electrically heated rod bundles in the test section, flows through lines 102 and 108, upward through the test section, lines 109 and 112, through the holdup volume and line 121, through any or all of the three heat exchangers (A, B, or C) and bypass lines in parallel, and back to the pump suction. Flow rate to the test section is metered and controlled by a fourth flow control station of nominal 100 to 600 gpm capacity consisting of a turbine meter with output to FRC 18 and the flow control valve FCV 18.

The test section is connected to the primary piping and the pressure-suppression system, so that two instrument spools are in series for both the test section inlet and outlet while the junction with the pressure-suppression system is located between the instrument spools (see Figs. A.2 and A.3). Two-phase flow measurements during blowdown will thus be obtained directly for both the loop and the test section. One of the flow stations for both the test section inlet and outlet must be bidirectional since the normal flow direction will reverse during blowdown. A plenum is formed at these two junctions (lines 107 and 110) by 6-in. pipe about 1 ft long to reduce hydraulic instability during blowdown. Also incorporated into the plenum design are a double rupture disk assembly to initiate blowdown, fast-response pressure instrumentation, a replaceable nozzle to control blowdown rate, and break wires to provide the timing mark for the instant of blowdown.

The double rupture disk assembly contains provisions to rupture either or both rupture disk assemblies simultaneously. The pressure-suppression system described in Section 2.3 is designed to absorb the thermal and mechanical energy of the high-velocity flashing liquid.

The "holdup volume" shown in the coolant line (line numbers 114 and 117) of the test section permits the total system primary fluid inventory

to be varied from 23 to 28 ft³ and supplies reentrant coolant during flow reversal associated with inlet line rupture. Current design will allow blowdown tests over three values of coolant inventory by operating with one, two, or three piping assemblies fabricated to contain volumes of about 1.8, 3.7, and 5.1 ft³. This water inventory is based nominally on a scaling ratio of 3 ft³/MW(e) in the PWR primary coolant systems. See Table A.4 for a tabulation of loop volumes.

Table A.4. THTF volumes

	ft ³
<u>Cold volumes</u>	
Main heat exchangers and associated outlet piping to valves	1.23
Piping downstream of main heat exchanger valves and bypass valves to pump inlet	3.92
Pump	1.49
Pump outlet, bypass line to test section inlet	3.55
Test section inlet, barrel, and lower plenum, and inlet blowdown	3.34
Total cold volume	13.53
<u>Hot volumes</u>	
Test section hot bundle and upper plenum	1.69
Test section outlet blowdown line, and outlet line to main heat exchanger	2.52
Holdup volumes - add 1.83, 3.66, or 5.11 ft ³	
Pressurizer at high level alarm	5.53
Pressurizer at mid point	3.70
Total hot volume	9.74 (no holdup vol.) 11.57 (1 holdup vol.) 13.4 (2 holdup vol.) 14.85 (3 holdup vol.)

The heat removal section of this system (heat exchangers A, B, and C) is designed to remove heat transferred to the primary fluid from either of the electrically heated test sections. Effluent from the test section can be routed through none, any, or all of the heat exchangers for utmost versatility during system operational checks, startup, shutdown, and operation

over a wide range of conditions. Heat exchanger A, which is equipped with automatic control systems, will always be in service during operation when heat is being generated in a test section, and the other exchangers (B and C) will be used as required. The automatic control system of heat exchanger A, described in Section 2.4, acts to maintain zero temperature difference between the test section inlet and the mixed effluent from the heat removal section. Good control over a wide range of service conditions (temperature, flow, and heat load) is insured by provisions to automatically vary primary and secondary fluid flow rates and secondary fluid inlet temperature. The flow rate of heat exchanger A primary fluid is controlled by the action of TRC 52 and valves TCV 52A and B to maintain secondary fluid effluent temperature at the set point. Flow through heat exchanger A bypass lines 121 and 122 and 220 and 221 is controlled by the action of PRC 32 and back-pressure control valves PCV 32 and HCV 32 to maintain test section pressure (inlet or outlet) at the set point.

Heat exchangers B and C are manually controlled over a range of heat removal by varying primary and secondary fluid flow rates under certain limitations. A bypass line (220 and 221) which has manual flow control is also provided around these heat exchangers. Effluent from the heat removal section mixes with the bypass flow in a mixing tee. The mixing tee provides for absorbing severe temperature gradients and fluctuations in a non-pressure-containing sleeve before the mixed effluent enters the pressure containment piping. The mixed effluent flows through lines 125 and 131 past the pressurizer to the pump suction.

The electrically heated pressurizer is connected into line 128 at the pump suction side with connecting piping which includes a horizontal line and a changeable restriction (orifice plate) to reduce mixing between the circulating fluid and the higher temperature pressurizer fluid. A condenser coil installed in the steam volume will permit rapid pressure reductions as required by the test program. Air, water, or an air-water mixture can be used in the condenser coil to provide a wide variation in condensing rate. Heaters will be automatically controlled to maintain set-point pressure level, and other instrumentation will include temperature, pressure, and liquid level monitors.

2.3 Pressure-Suppression System

The pressure-suppression system functions to contain and condense the steam-water mixture that results from a blowdown of the primary loop. A receiver tank with three spray headers and recirculating water form a direct-contact heat transfer and containment system which accepts the blowdown effluent from either or both of the blowdown lines connecting the primary loop. A bypass loop with a small heat exchanger removes the pump heat to maintain the water temperature at 100°F or less in readiness for blowdown (see Fig. A.3). It is mandatory that the spray system be in operation and ready to receive the loop contents before the primary pressure and temperature are increased.

The pressure-suppression tank is about 5 ft in diameter, 8 ft long, and has a total volume of 1160 gal. The primary loop inventory is estimated at 962 lb and the holdup volume at 192 lb. The maximum heat content of the primary loop and the holdup volume is 603,000 and 133,400 Btu, respectively. With all considerations of density changes, final tank level, etc., the beginning tank inventory is set at 486 gal. Without the holdup volume, which is the condition for initial operation, another 23 gal can be added, bringing the initial tank inventory to 509 gal. The final mixed-water temperatures, neglecting metal heat capacity, will range from 230°F for maximum loop volume to 207°F for normal loop volume. The pressure-suppression tank is connected to the atmosphere through an 8-in.-diam pipe which exits through the west wall of the pit into the subbasement area.

Blowdown reaction forces have been considered, and the necessary bracing and hydraulic snubbers are provided for in the design. The blowdown piping is sloped for drainage to prevent the collection of fluid, which might be propelled into the pressure-suppression tank during blowdown. Slug dispersers, which consist of a pyramid of concentric rings with a 10° dispersion angle, are also provided in each of the blowdown lines.

The connection between the primary system and the blowdown piping between the instrument spool piece and the rupture disk station is made to provide a more accurate flow measurement of the test section effluent

during blowdown. During normal operation, this configuration places two instrument spools in series for both the inlet and outlet of the test section. For blowdown conditions, one spool in both the inlet and outlet lines must reverse flow direction. Thus, for blowdown, the spools reversing direction are the test section inlet blowdown spool and the test section outlet primary spool. A plenum is placed at the junction of the primary system and the blowdown lines to decrease the probability of instabilities during blowdown and to promote mixing of the two streams before entering the blowdown nozzle.

The critical flow nozzle is located immediately before the rupture disks, both of which are contained in the plenum assembly. The double rupture disk assembly must be replaced after each blowdown. The rupture disk assembly can be removed for maintenance by removing half of the flange bolts and loosening the other half. After the rupture disk assembly is removed, the critical flow nozzle insert can be removed for replacement, remachining of throat diameter, etc.

2.4 Heat Exchanger Coolant System

2.4.1 Basic heat removal requirements

A schematic process flow diagram for the cooling water (secondary or shell-side fluid) of heat exchangers A, B, and C, which remove heat from test section effluent, heat exchanger D in the bypass loop, and the pressure-suppression system heat exchanger, is shown on the left-hand side of Fig. A.4. Cooling water for each heat exchanger is supplied from the supply header (line 650) and discharges to the return header (line 651) of an existing building-wide, 15,000-gpm, 250-psig, recirculating demineralized water system which rejects heat to the atmosphere from a large cooling tower.

The four primary system heat exchangers (A, B, C, and D) are all Graham "Heliflow" exchangers which feature a compact spirally wound tube bundle. Heat transfer rate is adjustable over a wide range by variation of cooling-water flow. Heat exchangers A, B, and C remove the test section heat, while a smaller exchanger D will maintain the temperature level of the loop and remove primary pump heat. In all cases, provisions are made

to prevent the boiling of the low-pressure (200 to 250 psig) secondary cooling water in the heat exchanger shell.

2.4.2 Pump bypass heat exchanger D

Heat exchanger D maintains the base temperature level of the loop, which is controlled by TCV 568 on the outlet of the secondary cooling water with a temperature signal from the primary pump discharge. TCV 13 on the primary inlet senses the temperature of the secondary cooling water outlet and will decrease the primary flow to prevent boiling on the secondary shell side.

2.4.3 Main heat exchangers A, B, and C

The test section heat removal is accomplished by three parallel heat exchangers A, B, and C. Heat exchanger A is used to vary heat removal rate automatically by maintaining a zero temperature difference between the test section inlet and the pump inlet. Heat exchangers B and C are manually controlled "shims" for base-load heat removal. During a load increase to full power, heat exchanger A will automatically assume load to its full capacity (about 2.5 MW). Load is then manually transferred to exchanger B or C via FCV 620 or FCV 720 while A automatically reduces its load. For a full test section load (~6 MW), this process of load shifting would continue until both B and C exchangers were fully loaded.

2.4.4 Temperature limitations imposed by secondary coolant system

The shell side outlet temperature of all four heat exchangers is used to vary the primary flow as necessary to prevent boiling of the low-pressure secondary coolant. Control valves TCV 92, TCV 54, TCV 56, and TCV 13 (for heat exchangers A, B, C, and D, respectively) vary the primary flow according to temperature signals from the secondary coolant outlets. TCV 13 is located upstream to provide a lower operating pressure for heat exchanger D.

Additional provisions for the prevention of boiling in the secondary coolant system are made with a bypass flow around the heat exchangers. Bypass flow is manually adjusted to maintain the mixed system effluent temperature subcooled with respect to the return header pressure (line 651).

The shell sides of the heat exchangers are protected by pressure-relief valves from excessive pressure buildup in the event that both inlet and outlet valves are closed inadvertently.

The water coolant system of heat exchanger A is designed to provide manual or automatic control over wide ranges of exchanger heat load and primary fluid temperatures and flows. Control variables are primary and secondary fluid flow rates and secondary fluid inlet and outlet temperatures. Control in the low heat ranges may be accomplished by utilizing condensing steam in a preheater to raise the secondary fluid temperature.

2.4.5 Steady-state operation

Each main heat exchanger must be capable of removing at least 2.5 MW with a primary inlet temperature in the range of 540 to 650°F. For an inlet temperature of 650°F at a duty of 2.5 MW, the flow velocities remain below the recommended 10 fps. Duty could be increased to 3 MW without apparent difficulty.

However, at a test section outlet temperature of 560°F, the velocity must be increased above 10 fps. With combined operational limitations calling for a secondary outlet temperature of below ~350°F (to prevent boiling) and a ΔT limitation of 400°F (to avoid excessive stresses in the primary stream nozzle-end plate intersection), there will be some difficulty in achieving 2.5-MW duty at the lower operating temperatures.

The pump bypass heat exchanger D has been sized to be capable of removing pump heat at loop temperatures from 400 to 650°F. Operation over this large range of inlet temperature and with the same limitations of the main heat exchanger on ΔT and secondary coolant temperatures will require primary flows to be very low at loop temperatures near 600°F. (Isothermal operation will be limited to 600°F due to the limitations on the primary pump.) At this condition, the primary outlet temperature is very low and requires that a mixing tee be installed at the intersection with the main pump bypass flow. This is also true of the main heat exchangers, and a mixing tee is provided at the intersection of primary outlet and bypass flows.

2.5 Pump Coolant System

Each end of the circulating pump has four integral low-pressure cooling channels and a Graham "Reliflow" heat exchanger with high-pressure seal coolant recirculating through the tube side (Section 2.4). The pump coolant system (Fig. A.4) provides coolant to each channel and heat exchanger with parallel connections across the demineralized coolant water supply and return headers. The headers are a part of a building-wide, 15,000-gpm, 250-psig recirculation system which rejects heat to the atmosphere from a large cooling tower.

The 250-psig header supply pressure is reduced to and controlled at 100 psig with PCV 695, and flow through each pump cooling channel is controlled with individual hand-operated control valves downstream of the pump. Each flow channel is monitored with a flow indicator with low alarm and a temperature indicator with high alarm. In addition, each of the high-pressure, recirculating, pump seal coolant streams is monitored with a temperature indicator and high alarm.

In addition to low flow alarms, the system is protected from pressure buildup, in the event of closure of all flow control valves during operation or malfunction of PCV 695, by the pressure-relief valve PSV 697 in the line bypassing the pump.

All piping materials and components are austenitic or nonferritic stainless steel to prevent contamination of the demineralized water system. Line sizes and coolant design flow, pressure, and temperature are indicated on Fig. A.4.

2.6 Electrical (ac) Power System

The ac electrical power system supplies power to equipment heaters, circulating pump motor, pressure-suppression system pump motor, instruments, and controls (see Fig. A.5).

The 600-hp circulating pump motor is fed from 2300 V circuit breaker unit 11A located in the northwest transformer vault. Three No. 2/0 5-kV cables are provided. Thermal relays and overcurrent relays are located at the switchgear to protect the motor. The pressure-suppression system

Fig. A.4. Process flowsheet -- demineralized cooling water system.

4. Process flowsheet - demineralized cooling water system.

Fig. A.5. Schematic diagram of ac power supply.

A.5. Schematic diagram of ac power supply.

pump motor (approximately 60 hp) is fed from the 460-V building power system. A 300-kVA, 3-phase, 480-120/208 V transformer provides power to the heaters and instruments. Control power is fed from a separate 5-kVA 480-120/240 V transformer.

2.7 Electrical (dc) Power System

2.7.1 Basic requirements

The dc electrical power system supplies variable controlled power to the test section heaters. It also supplies power to other non-BDHT experiments. Use of the dc power system is scheduled since a motor-generator unit can supply only one experiment at a time.

A requirement of the dc power system is to permit the test section heaters to be operated at loads up to a maximum of 7 MW. The supply must be capable of operating at either 30,000 A maximum or 257 V maximum to accommodate test section heaters of various resistances. The power-time requirements used for the design of the dc power system are shown in Fig. A.6. The reduction of heat rate following the blowdown must be adjustable from approximately 4 sec time constant to 20 sec time constant.

2.7.2 Description

The dc power system (Fig. A.7) includes two motor-generator units located in the northwest corner of Building 9201-2. Each unit consists of an ac synchronous motor coupled to two dc generators. The motors are rated 7000 hp and are fed from the 13.8-kV area power supply. The generators are rated 7140 A, 350 V, and 2500 kW each and have a load rating of 125% for 2 hr. The units are suitable for supplying 7.056 MW and 30,000 A required by the 49-rod test bundle for durations specified in Fig. A.6 when suitable rest time is included in the duty cycle for cooling. Each of the single-ended indirect heater rods, as presently designed, require a maximum of 144 kW at 248 ± 9 V and 580 ± 20 A. Twelve heaters are fed from each of three generators, and thirteen heaters are fed from the fourth generator. The single-ended indirect heater rods have one lead connected to the heater sheath, which is connected to the experiment housing and to

Fig. A.6. Power-time requirements used for the design of the dc power system.

Fig. A.7. Schematic of dc power system.

2

the building ground grid; thus the generator power system is grounded at this location.

The generator output is connected to a single-pole 10,000-A circuit breaker with an $0.03\text{-}\Omega$ bypass resistor connected in parallel with the breaker. Two 1- by 10-in. aluminum buses are routed to the disconnect switch location near the center of the building. The disconnect switches are interlocked to assign only one experiment to a generator at a time. Four water-cooled 1000 MCM cables connect the switches to the experiment equipment. A single-pole 10,000-A circuit breaker is provided for fast disconnect operation.

A crowbar-type circuit is provided for each heater to minimize the damage to the heater in the event a fault occurs. A fast-acting circuit detects a fault when the current to the heater reaches a preset value, and an SCR is turned on that will short circuit the heater leads. The short circuit path will divert the current from the faulted heater, thus reducing the current through the fault. The fuse limits the short circuit current and isolates the fault from the generator circuit.

The crowbar circuit includes a shunt in each heater circuit to provide an input signal that is proportional to the heater current. An electronic-type detector unit compares the input signal with an adjustable signal that can be preset by the operator. When the heater current exceeds the preset value, a gating signal is produced to turn on the shorting SCR.

The generator outputs are program controlled by a function generator located at the control panels and by voltage feedback signals from the generator leads. Signals from these sources are fed to a regulator that controls the amplidyne output and the generator shunt field excitation.

2.7.3 Controls and interlocks

Controls and interlocks are provided for the dc power system to permit safe operation of the system and to protect the equipment. The major items provided in the existing system are as follows:

1. Generator breaker:
 - a. overcurrent trip,
 - b. companion breaker trip,

- c. trip reset,
- d. manual close-trip switch (trip only when 13.8-kV breaker is open).

2. 13.8-kV synchronous motor breaker:

- a. instantaneous overcurrent trip,
- b. differential current trip,
- c. incomplete sequence trip,
- d. undervoltage trip,
- e. vibration trip,
- f. overspeed trip,
- g. generator breaker opening trip,
- h. remote manual emergency trip switch,
- i. motor field ground detection alarm,
- j. cooling water low-pressure alarm,
- k. thermal alarm.

3. Assignment panel - The assignment panel and disconnect switches provide the main interlocking to permit safe operation of the generators. The panels are located in the generator control room and are arranged for the assignment of any one of three experiments to be fed from one generator.

4. Disconnect switch:

- a. close-open control only when excitation controller (function generator) is at zero,
- b. close-open control only when field breaker is open,
- c. close-open control only when all other disconnect switches are open.

5. Field breaker:

- a. generator breaker opening trip relay,
- b. 13.8-kV-motor breaker opening trip relay 52a,
- c. overvoltage trip relay,
- d. overcurrent trip relay,
- e. rate of rise trip relay,
- f. cable cooling water low flow trip relay,
- g. remote manual emergency trip switch,

h. close control only when excitation controller (function generator) is at zero,

i. close control only when disconnect switch is closed.

Changes required to the existing system include the following:

1. Load breaker - A single-pole circuit breaker provides a fast disconnecting device that can be reclosed from the experiment. The breaker includes the following features:

- a. close control only when the field breaker is open,
- b. close control only when crowbar devices are reset,
- c. trip on overcurrent,
- d. trip from experiment shutdown signals,
- e. remote manual emergency trip switch.

2. Field breaker - The field breaker will have the following additional features:

- a. closed only when load breaker is closed,
- b. closed only when regulator feedback selector switch is in "BDHT" position,
- c. trip on heater overvoltage.

3. Field regulator - The generators will be controlled by voltage feedback to insure that the loss of one heater will not cause the power level on the other heaters to increase. Changes are as follows:

- a. the voltage feedback signal will be obtained from a voltage divider connected across the generator leads and will be fed into the existing amplifier,
- b. a regulator control switch will be used to switch from the present 100-mV shunt current signal to the new voltage divider signal,
- c. a relatively fast-responding adjustable input signal must be provided to obtain the required 4- to 20-sec time constant power decay operation,
- d. a direct voltage signal programmed through the use of a function generator provided with switches and four isolation amplifiers provides the input signals,
- e. the field breaker cannot be in the closed position unless the regulator controls are in the correct position.

2.8 Cable Coolant System

Power is supplied to the THIF bus from the generator distribution bus (see Sect. 2.7) by water-cooled conductors. The length of cable run is such that excessive voltage drop (and cable heating) would result if the coolant were not provided. Each generator is provided with two water-cooled conductors for the supply and two for the return. Since the design for this system is standardized for the entire building dc power distribution system and has been in operation several years, it is considered suitable for the intended purpose.

Demineralized water from the 15,000-gpm, building-wide, recirculating cooling system is used for this purpose. Flow control valves, flow indicators, etc., are provided with interlocks and alarms to insure that the cable coolant is circulating before the dc power can be turned on. Loss of coolant initiates automatic shutdown of the power supply.

2.9 Test Section Seal Cooling Systems

The heater rods are anchored inside the pressure containment at the lower end of the test section. The upper heater ends extend out the top of the test section, where electrical connections to the dc power system are made. The heater rods must be sealed while also allowing for expansion when heating current is applied. The provision for individual heater rod movement is necessary to allow for some expected test conditions calling for certain rods to be unheated or for radial power profiles where all rods will not operate at equal temperatures. The sealing is accomplished with dual elastomer O-rings in two seal plates. The seal plates form a chamber that is maintained at a pressure between that of the test section and atmospheric.

The seal rings, made of Viton E 60 or of ethylene propylene material, must be maintained at temperatures less than 400°F for necessary reliability. Due to the small copper cross section available in the lead-in conductor at this point, a considerable amount of heat is generated in the "unheated" portion of the rods extending through the seal area. Cooling is provided on all seal plate faces by three separate systems

(see Fig. A.8). Cooling above the top seal plate is provided by ducted air flowing across the rods. The chamber between the two seal plates is cooled by a small recirculating water system. The area below the lower seal plate is cooled by primary loop water obtained upstream of the test section and cooled by a small U-tube heat exchanger. The total heat generated by the heater lead-ins is about 1.5 kW per inch of rod bundle (based on 0.022 in.² of copper and current of 580 A).

The air cooling for the top seal plate is provided by a New York N 23P-15 blower with a capacity of 1500 cfm at 42 in. H₂O. More than 50 ft of 6-in.-diam flexible duct and sched-10 pipe are used to supply air to the special air shroud around the 49-rod bundle and to exhaust the hot air to the subbasement area. The flow is split so that about two-thirds crosses the rod bundle and the remaining one-third exits parallel to the heater rods through slightly enlarged openings around the rods. This leakage air flow exiting the top of the air shroud provides cooling for the heater rod moisture barrier located just above the shroud. The heat generation in this part of the bundle is about 11 kW, and the air flow is calculated to maintain the outer seal temperature at 350°F or below.

Cooling water is circulated through the chamber between the seal plates by a low-pressure recirculating seal cooling system. This system consists of a small canned-rotor 1/4-hp pump, a 10-kW Borg-Warner heat exchanger (model CU 7254), a small pressurizer, and connecting tubing. A flow of about 5 gpm is circulated through the seal chamber at about 150°F and 1000 psig. Cooling water for the heat exchanger is provided by the demineralized cooling-water system. This cooling system removes the heat generated in this portion of the rod bundle plus that conducted by the rods and the inner seal plate from the 450°F temperature area below this plate.

The lower surface of the inner seal plate is cooled by a small flow (about 2 gpm) of high-pressure water from the primary loop obtained upstream of PCV-18. This primary loop water, which can run as high as 600°F during isothermal test operation, is cooled by a small jacketed U-tube heat exchanger to 350°F or less before entering the test section at the upper flange. The flow is directed to a small plenum formed by the lower seal plate and a flow restrictor plate. A small clearance between the

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Fig. A.8. Instrument application diagram for indirect heated test section.

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SEAL COOLING SYSTEMS

ent application diagram for indirect heated test

heater rods and the flow restrictor plate ensures an even flow distribution around all 49 rods. After exiting the flow restrictor plate, the water rejoins the test section flow in the test bundle outlet plenum. This flow, in conjunction with the cooling water on the upper surface of this seal plate, is regulated so as to maintain the seal temperature below 400°F.

2.10 Facility Arrangement

The THTF and associated work areas occupy ~2000 ft² on the basement level and ~3600 ft² on the first floor level of Building 9201-2 in the Y-12 Plant area. A plan view of the first floor area showing a general layout of equipment and work areas is shown in Fig. A.9. The control room on the first floor level contains all instrumentation and controls necessary for normal loop operation. Primary system piping is located southwest of the control panels. Piping layouts are compact, vertically oriented to extend almost to the ceiling, and enclosed by removable sheet metal shielding. The motor-generator and some associated switch gear, interlocks, and controls are located in other parts of the building outside the THTF area and are maintained by others as a part of building utilities.

The multirod test section is mounted vertically through the first-level floor. The assembled test section pressure housing is ~19 ft long and requires vertical clearances of ~5 ft from floor to bottom closure for instrumentation and high-voltage power bus connections and ~33 ft from the housing bottom closure to the overhead hoist hook for test section assembly. Required clearances were obtained by constructing a basement pit under the first-level floor openings with pit floor level 4 ft below the basement floor level and by constructing an access opening in the first-floor ceiling above the test section area. The ceiling access, and the hoist mounted above it, is used only during test section assembly to lower the rod bundle and flow shroud subassembly into the fixed lower spool piece of the housing. Near column P-7 is another opening in the first-level floor through which primary piping is routed to equipment in the basement.

Fig. A.9. Equipment layout - floor plan.

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A.9. Equipment layout - floor plan.

Equipment located in the basement includes the primary circulation pump, components of the bypass loop (lines 190 and 195 in Fig. A.3), the demineralized cooling water distribution station, pressure-suppression system components (for test section coolant blowdown), test section seal cooling systems, and the lower end of the multirod test section.

The test section bundle components are assembled in the capsule area of Building 9201-3 (adjacent to Building 9201-2). Since the test bundle assembly procedure requires that the upper spool piece (pressure container) be assembled with the bundle, a dummy spool piece is provided to allow operation of the primary loop without the test bundle.

After primary loop shakedown, the assembled test section bundle is transported into the area through the double doors at the east end as shown in Fig. A.9. The railing around the stairwell is removed and the test section transported across the opening and to the monorails at the south end of the loop enclosure. The bundle is lifted to a vertical position above the open test section container and lowered into position.

3. COMPONENT DESIGN DESCRIPTIONS

3.1 Piping and Valves

Most of the piping to be used in the high-pressure portion of the facility is special, heavy-wall, type 347 stainless steel available from ORNL unused stock originally purchased (in the period 1955-1958) for the discontinued Homogeneous Reactor Program. This material was purchased under very restrictive specifications and was carefully inspected for assurance of reactor-grade quality. Since this material was not purchased to an appropriate ASTM or ASME specification, special tests were conducted to meet quality assurance requirements. Samples have been removed from each length of pipe for chemical spectrographic analysis. A tensile test specimen was removed from one section to satisfy the tensile property requirements of ASTM A376. Materials required to supplement this stock are purchased in accordance with appropriate ASTM specifications to satisfy Code requirements. Predominant pipe sizes are 1-in. sched-80, 2-in. sched-80, and special 4-in. nominal pipe having 0.500 in. wall thickness. The piping is sized to limit the steady-state flow velocity to less than 30 fps.

Most of the piping is joined by welding, but numerous mechanical connections are included to permit removal of valves, components, load orifices, and special instrumentation for maintenance and to facilitate modifications to the system configuration. Grayloc flange connections, which are less massive than ring joint flanges and lend themselves to quick assembly and disassembly, are utilized.

The high-pressure primary piping system is designed, fabricated, and inspected in conformance with the requirements of the USAS Code for Power Piping B 31.1.0. The low-pressure secondary coolant systems are in accordance with UCC Technical Specification P-1.1, Subsection 107, for Demineralized and Distilled Water Systems. Control valves were purchased in accordance with Specification I-10520-QG-002-S-1 and ASME Section III Class 2 for the pressure range of interest.

Welding is in conformance with ORNL weld procedure WPS-302, with inspection according to ORNL Met-WR series of procedures.

The final piping layout has been analyzed to confirm adequate flexibility as incorporated in the design. Analysis has also been performed to determine reaction forces and deflections during blowdown. Appropriate pipe shock suppressors and pipe bracing have been located accordingly. Insulation is provided as required to minimize heat losses.

3.2 Circulation Pump

The high-head, high-capacity circulation pump was originally purchased as a backup unit for an AEC program at Battelle Northwest Laboratories (BNWL) and was made available to ORNL on an indefinite loan. It was intended for use in blowdown tests at BNWL and, except for excess discharge head, was well suited for the requirements of this program. The pump was designed and fabricated in the period 1965 to 1967 by the Bingham Pump Company, Portland, Ore. A full-range cold hydraulic performance test and a 100-hr hot test at 2000 psig, 600°F, and 500 gpm followed by disassembly and inspection were completed by Bingham before delivery to BNWL, but the pump has not seen experimental service.

The Bingham 3 x 6 x 17 C/M pump (Serial No. 250920) is a two-stage, double-volute, horizontal, center-line-mounted, heavy-duty, centrifugal unit suitable for continuous operation at high system temperatures and pressures. Performance curves are shown in Fig. A.10, and a photograph of the pump is shown in Fig. A.11.

This pump was specifically designed for high-pressure service and uses a stiff shaft to minimize deflection. The volute casing is radially split at each end with removable cover stuffing box units to enable disassembly without disturbing the connecting piping or the driver unit. All parts are machined to close tolerances, and rotating parts are dynamically balanced for smooth operation. The pump has babbitted journal bearings at each end of the shaft and a duplex ball thrust bearing on the outboard end. A self-contained oil-ring-type lubrication system, with oil level maintained by constant-level oilers, provides lubrication for the bearings.

Shaft seals are patented Bingham high-pressure units isolated from the high-temperature zones by an air gap. Seal cooling is accomplished by

Fig. A.10. Bingham pump characteristics.

a closed internal system utilizing a pumping disk on the pump shaft to circulate cooling water from the seal chamber, through a heat exchanger, and back to the seal. The two seal coolant heat exchangers furnished with the pump are models 8 x 6C-12 Graham "Heliflow" units with a tube-side design pressure of 3000 psig and hydrostatic test pressures of 4500 psig on the tube side and 150 psig on the shell side. Basic construction of the heat exchangers is the same as the system primary heat exchangers described in Section 3.5. Water jackets are also located around the stuffing boxes, around the bearing mounts, in the bearing housing, and around the pump pedestal; these cooling jackets are served by an external water supply (see Section 2.5) with the following recommended conditions:

Heat exchanger flow	5 gpm each
Pump pedestal flow	5 gpm each
Bearing housing flow	3 gpm each
Bearing bracket flow	2 gpm each
Stuffing box flow	5 gpm each

Fig. A.11. The THTF two-stage Ringham pump.

Maximum temperature rise	10 to 15°F
Maximum inlet temperature	90 to 95°F
Maximum pressure	150 psig

Protective and surveillance instrumentation recommended by the manufacturer included vibration monitors on bearing housings and temperature indication of pump bearings, process fluid at the pump suction, inlet and outlet seal recirculation fluid, and inlet and outlet cooling water. In general, correct capacities and pressures indicate normal operation; unusual noise, vibration, or heat is a sign of developing trouble. Symptoms of seal deterioration would include increased seal leakage and increased temperature of the seal recirculation fluid, the seal heat exchanger cooling water, and the stuffing box cooling water.

3.3 Pressurizer

The pressurizer (Fig. A.12) serves to control the base pressure in the primary system. It is designed and installed so as to provide a degree of thermal isolation of its contents from the primary loop so that it may operate at a temperature higher than that of the primary loop. This permits saturation temperature and pressure to be maintained in the pressurizer while water in the primary system is at a subcooled temperature.

The pressurizer also serves as a surge tank; that is, its steam volume is sufficient to accommodate operational changes in specific volume of the water in the loop. These changes in specific volume result from temperature transients that occur during operation. However, the steam volume in the pressurizer is not sufficient to accommodate the very substantial increase in specific volume of water during startup. For instance, based on an initial filling of 23 ft³ of water into the primary system at 14.7 psia and 70°F, this volume will expand by about 34.5% or about 8 ft³ when heated and pressurized to the base-line operating condition of 560°F. This 8 ft³ exceeds the normal working volume range of the pressurizer; thus it will be necessary to let down excess inventory during the course of initial system heatup.

From the base-line operating condition (isothermal at 547°F), the increase to full test section power will raise the temperature of that

Fig. A.12. Schematic of pressurizer.

portion of the loop between the test section and the main heat exchangers to 640°F. This temperature change of 93°F will increase the volume about 22%. Since from 42 to 52% of the loop inventory is heated (depending on the amount of holdup volume included), the loop volume increases from 2.2 to 3.35 ft³. See Table A.4 for a complete list of THTF loop volumes.

The main body of the pressurizer is of 12-in., sched-140, type 316 stainless steel pipe about 11 ft long. It has four outboard heater legs at a lower elevation, so that these legs are always full of water except during a blowdown. Each of these four 2-in. pipe legs has a 6-kW clamshell electric heater for a total capacity of 24 kW. These heater legs connect to the 12-in. pipe at their top and to a 4-in. pipe downcomer at the bottom. Natural convection of water through the heater legs and main vessel is assured with this arrangement. To assist in startup, 19 kW of manually controlled heat is provided for on the pressurizer vessel walls. Once the pressurizer contents are at the desired temperature and pressure, these heaters will be shut off.

The heat flux across the boiling film at the pressurizer heater is 24,200 Btu hr⁻¹ ft⁻² at maximum heat input of 24 kW. Of the 24 kW heat input at the pressurizer, it is calculated that approximately 2 kW will be lost through the insulation at the pressurizer, resulting in a net heat input of 22 kW. Conservatively neglecting heat loss through insulation, the 24 kW of heater capacity at the pressurizer will produce 227 lb/hr of steam at 2475 psi, the pressure at which the relief valve is set to open, with heater controls failed "full-on." The relief valve is capable of relieving in excess of this amount.

The four electric heaters are of the split clamshell type and use Calrod-type heaters that are cast into an iron matrix. The heater casing is 20 in. long and 5 in. in outside diameter. This heater design was used successfully on a similar pressurizer for an earlier ORNL project.

The heated legs of the pressurizer are made of 2-in., sched-80, type 347 stainless steel pipe. The outside surfaces of these pipes are turned down to a less-than-nominal OD for a close fit and good thermal conduction with the clamshell heaters. Hand selection of pipe is necessary to ensure that the calculated minimum wall thickness of 0.188 in. required by the

Code is maintained after the outside of the pipe is machined. Pipe heavier than sched 80 was ruled out in the design because excess wall thickness would impair rapid thermal response.

Instrumentation will cause a low-water-level scram, turning off pressurizer heater power, when the water level drops to the elevation of the upper heater leg nozzles on the 12-in. pipe. However, a low-level alarm will be actuated at an elevation 20 in. above these nozzles, thus providing a 1-ft³ volumetric margin between alarm and scram. The high-level-alarm point is at an elevation about 73 in. above the low-level-alarm point. This 73 in. of 12-in. sched-140 pipe has an internal volume of 3.7 ft³, which is the normal working volume range of the pressurizer. Above the high-water-level alarm point is a reserve volume of 2 ft³ of steam. The steam volume above the low-level-alarm point is thus 5.7 ft³, and above the scram level it is 6.7 ft³. Volumes and relative elevations at the pressurizer are shown in Fig. A.12.

Degasification of water in the main loop, when needed, is effected by injecting a small stream of water from the loop into the top region of the pressurizer. A perforated internal tube is used to spray this injected water inside a thermal sleeve. The sleeve protects the outer wall of the pressurizer against thermal shock, which would result if the cooler injected water were allowed to impinge on the hotter wall. Noncondensable gases are evolved and accumulated in the steam volume at the pressurizer. These gases are manually vented from the pressurizer when the temperature in the steam volume is observed to vary from the saturation temperature at the prevailing pressure.

For reducing the pressure, when desired, a cooling coil is provided in the steam space at the top of the pressurizer. The coil is formed of 3/8-in.-OD by 0.065-in.-wall tubing to a diameter of 8 in. with 1-in. center-to-center spacing and has a developed length of about 23 ft. Air or water may be used as the coolant inside the tubes. Using water, steam may be condensed at a heat transfer rate of at least 40 kW. Additionally, depressurization may be accomplished by means of the water-injection method described above for degasification. By this latter means, cooler water from the main loop is injected directly into the pressurizer.

Connections are provided at the pressurizer for liquid-level instrument taps at top and bottom of the vessel, along with connections for gas venting, relief valve, pressure instrumentation tap, water sampling, and letdown.

The 4-in. downcomer pipe continues at the 4-in. size to the point where it tees into the main 4-in. circulating loop. This 4-in. pipe is larger than necessary for the pressurizer to serve its normal pressurizing and surge-tank functions. It is sized sufficiently large that it will offer little restriction, except for an orifice, to the flow of steam-water mixture during blowdown. This line, however, has two features which aid in thermal isolation of the pressurizer: the restricting orifice just below the lower heater leg connections and a horizontal run of about 4 ft to keep main line turbulence and diffusion relatively remote with respect to the pressurizer.

The pressurizer is designed for 2500 psig at 750°F. It will operate at pressures up to 2300 psia, at which the saturation temperature is 656°F. The highest metal temperature will be experienced at the heated legs, where the pipe wall temperature will not exceed 700°F at maximum heat flux. The pressurizer is designed to meet the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Class 2.

In addition to the requirements of Section III of the Code, the combination of hoop stress and thermal stress due to radial thermal gradient in the heated legs was evaluated. The sum of hoop and thermal stresses was found to be less than half of the permissible $3S_m$ limit of Section III of the Code.

The flexibility of the redundant heater leg loops was considered. It was established that the flexibility criterion of ANSI B31.1.0-1967, Par. 119.7(a)(3), is not exceeded in the design, thus indicating that inherent flexibility is adequate. Supporting lugs are provided on the 12-in. IPS body of the pressurizer. Final analysis of the piping system flexibility established that it is possible to rigidly anchor the pressurizer at these support points.

3.4 Pressure-Suppression System Components

The system consists of a tank, a pump, piping for circulating spray water, and connecting lines to the test bundle housing. The tank serves the dual purpose of a receiver and condenser for the blowdown flow and a storage reservoir for water to be utilized as a spray. The pump circulates the water through spray nozzles in the tank. The spray provides the contacting necessary for condensation of the steam.

3.4.1 Receiver/reservoir tank

This tank serves two functions: as a storage volume for cool water to be utilized for spray and as a condenser with vapor space into which water is sprayed. The storage and vapor spaces are separated by horizontal baffles to minimize the tendency for hot condensate to reach the pump suction. Three spray manifolds, each containing 24 nozzles, are installed parallel to the tank axis in the upper half of the horizontal tank. The manifolds are as close to the wall as possible (limited by knuckle in tank head), and the nozzles are aimed to direct spray horizontally or upward in an overlapping pattern.

The blowdown lines enter the end of the pressure-suppression tank in the spray area above the water level. A disperser is provided on each of the blowdown lines in the unlikely event that a liquid slug is propelled into the tank by high-pressure vapor. The disperser is inserted into the tank at the blowdown line inlet so that it is replaceable should it become damaged. The disperser consists of a series of five concentric rings, each of smaller diameter than the previous ring and each having a 10° dispersion angle.

In the event of a failure of the spray system during blowdown, an 8-in. relief pipe extends through the wall adjacent to the tank and into an exclusion area. A resultant reaction force of up to 6600 lb is possible if saturated steam at 100 psia and sonic velocity were to be relieved through this line. Appropriate anchors are provided for the relief pipe and the tank to withstand these forces.

The tank has three blind flange openings for inspection and cleaning in the event that some debris is carried over during blowdown. A 1-in.

drain connection is in the bottom, and a sight gauge is provided for level indication. The main characteristics of the tank are summarized in Table A.5.

3.4.2 Spray circulation pump

The function of the pump is to circulate water from the receiver/reservoir tank and deliver it under pressure to the nozzles. This pump will be energized whenever the test facility is pressurized, so that steam-condensing capability is provided should a blowdown rupture disk assembly accidentally rupture. The requirements of the pump, as contained in the purchasing specification, are summarized in Table A.6.

Table A.5. Pressure-suppression tank characteristics

Design pressure, psig	-15 to +150
Design temperature, °F	650 ^a
Operating pressure range, psig	-14.7 to +100
Operating temperature range, °F	80 to 303
Test pressure (hydro), psig	225
Internal volume, gal	1160
Approximate size, in.	60 OD by 106 long
Maximum water inventory (100°F), gal	522
Empty weight, lb	3500
Material and grade	Carbon steel, ASTM A285 grade C
Shell thickness, in.	1/2
Heads	ASME flanged and dished (torispherical) 5/8 in. minimum thickness
Design code	ASME Section VIII, Division 1
Connections	Bolted and gasketed flange
Spray manifolds	3 1/2 in. sched-40S pipe
Nozzle features	20.8 gpm at 30 psi, 24.0 gpm at 40 psi 90° hollow cone pattern 23/32-in. orifice diameter ~2200-μ median droplet diameter at 30 psi, 1900 μ at 40 psi

^aDesign temperature of 650°F is listed even though operating temperature is only 300°F because allowable stress for this material does not change up to 650°F.

Table A.6. Spray circulation pump characteristics

Design capacity, gpm	1500
Total head at design capacity, ft	100
Pumped liquid	Demineralized water
Elevation of free surface above pump suction, ft	~5
Suction conditions	Flooded
Pump NPSH ^a at design capacity, ft	6
Available NPSH at design capacity and saturated, ft	~6.5
Pump speed, rpm	1150
Pump rotation viewed from driven end	Counterclockwise
Maximum water temperature at inlet, °F	303
Minimum water temperature at inlet, °F	80

^aNet pump suction head.

All wetted parts of the pump are of cast iron, and the horizontal split casing has 125-lb ASA flanged connections. The electric motor driving the pump is of a totally enclosed design because the pump is located in a pit where flooding could occur.

To protect the pump from damage by debris (e.g., pieces of a rupture disk), a coarse (1/4-in.-square mesh) screen is installed on the suction line end inside the receiver/reservoir tank. The screen can be cleaned easily from an adjacent flanged opening in the tank.

3.4.3 Piping

The piping for spray circulation is 6 in. sched 40S, except that between the pump suction and the reservoir, which is 10 in. sched 40S. The head loss is proportioned approximately as follows: pipe and fittings, 3.3 psi; spray manifold, 3 psi; nozzles, 37 psi; total, 43.3 psi (100 ft).

The blowdown piping and relief valve vent piping are considered as part of the pressure-suppression system since they operate at the same pressure. There are two blowdown lines of 6-in. sched-40 carbon steel, one from the test section inlet and one from the outlet, each beginning at the blowdown rupture disk assembly. The inlet blowdown line is about

15 ft long and the outlet about 18 ft long. The blowdown lines are supported by their attachment to the plenum flange at one end and to the pressure-suppression tank at the other. Since the reaction forces during blowdown will be in the upward direction, the plenum lower flanges are supported from below by pinned rods that allow horizontal movement. Analysis of blowdown forces indicated the need for shock suppression on the lower (test section inlet) of the two blowdown lines. A 12,500-lb 5-in.-stroke hydraulic shock suppressor and a cross member are installed between the two tie rods and the main structural support.

The vent side of the two relief valves on the pressurizer and test section outlet are tied into the pressure-suppression system via the blowdown lines. The test section relief valve is located just above the outlet blowdown connection, and its vent line (3 in., sched 40) bypasses the blowdown rupture disk station. Since this vent line will operate in a relatively cold condition, a bellows is provided to accommodate differential expansion between it and the test section outlet. Piping flexibility analysis indicated also that an expansion joint was needed on the inlet of the pressure-suppression system circulating pump. This pump is short coupled to the pressure-suppression tank by 10-in. sched-40 pipe and, during blowdown, must accommodate the temperature increase of the recirculating spray water.

3.4.4 Critical flow nozzle and blowdown rupture disk assembly

The blowdown rate is controlled by the critical flow nozzles located in the base of the plenum at the intersection between the loop and test section piping. The double-diaphragm blowdown rupture disks are located just below the critical flow nozzle. To simulate the ratio of the pipe flow area to total core flow area of the PWRs, the total break size area required is 0.0135 ft^2 . The tests include test section inlet-outlet flow splits of 100 to 0%, 50 to 50%, and 80 to 20%. Thus, in order to cover the range of desired flow splits between the two blowdown lines, the flow nozzle diameters range between 1.57 in. (100%) and 0.70 in. (20%). The nozzles are replaceable along with the rupture disk assembly to minimize the downtime between tests.

The blowdown rupture disk assembly is located just below the critical flow nozzle. Both the nozzle and the disk assemblies are positioned between 6-in. weld-neck flanges which form the coupling between the primary system and the blowdown lines.

3.4.5 Pressure-suppression-system (PSS) heat exchanger

The pump will supply energy to the water at the rate of about 45 kW. In order to keep the spray water cool during pump operation prior to blowdown, a heat exchanger is required. This unit, a Young Radiator Company No. SSR-606-ER-1P, is installed in a small bypass line between the discharge and suction of the spray circulation pump. The characteristics of the heat exchanger are summarized in Table A.7.

Table A.7. PSS heat exchanger characteristics

Thermal duty, kW	45
Coolant and loop water rates, gpm	50
Available cooling water temperature, °F	80
Spray loop water temperature, °F	100
Area required for 80°F loop water, ft ²	41
Area required for 100°F loop water, ft ²	16
Minimum pressure rating, psig	150
Minimum temperature rating, °F	350
Young No. SSF-606-ER-1P	
Surface area, ft ²	55.8
Material	316 SS
Tube size, in. (OD × wall)	3/8 × 0.025
Effective length, in.	54

The design value for spray water was 100°F, but it was desirable to have the capability of using cooler spray to accommodate, for example, more rapid future blowdowns. Hence, the Young heat exchanger selected has an area of about 55 ft² when only 16 ft² is required for 100°F loop water.

3.5 Heat Exchangers

3.5.1 Primary heat exchangers

Heat generated in the test section will be extracted from the recirculating primary fluid by three identical Graham "Heliflow" heat exchangers* connected in parallel. The unique design features of this type of exchanger make it well suited for use in the THTF. Compactness and high performance characteristics derive from the closely packed, spirally coiled tube bundle. The construction details of heat exchanger A are given in Fig. A.13.

Primary fluid, at high temperature and pressure, flows inside the tubes, and cooling water (secondary fluid) flows through the shell outside the tubes. The bundle of tubes is slightly compressed between the shell base plate and casing to form a positive spiral circuit for shell-side fluid flow countercurrent to the direction of tube-side flow. The ends of the coiled tubes terminate in manifolds, which project through the base plate for system piping connections. Pipe stubs for inlet and outlet shell-side flow are also attached to the casing end. The units are of all-welded construction except for the flanged connection joining the casing to the base plate. With the exception of bolts, gasket, and support bracket, all component parts of the heat exchangers are type 316 stainless steel. Figure A.13 shows heat exchanger dimensions and construction details. Specified operating and design characteristics are listed in Table A.8.

The most stringent heat transfer requirement corresponds to one of the expected test conditions, which requires full-heat-load operation at a heat exchanger primary inlet temperature of 500°F. The manufacturer does not recommend continuous operation at fluid velocities exceeding 10 fps. At this velocity, the primary heat exchangers will be adequate only if 100% clean. Although fouling is not expected with the demineralized coolants, fluid velocities above 10 fps may be required for 500°F operation.

*Denoted heat exchanger A, B, and C on the process flowsheet of Fig. A.3.

Fig. A.13. Graham Heliflow heat exchanger.

Table A.8. Specified operating and design characteristics of primary heat exchangers (total duty, 8,540,000 Btu/hr; total surface area, 35.5 ft²; manufacturer's size number, 12-6C6C-22S; tube size, 5/8 in. OD x 0.049 in. wall)

Parameter	Conditions	
	Tube side (primary fluid)	Shell side (secondary fluid)
Fluid	Demineralized water, liquid phase	Demineralized water, liquid phase
Flow rate, lb _m /hr	35,000	45,000
Maximum inlet temperature, °F	650	80
Maximum outlet temperature, °F	406	270
Maximum pressure drop, psi	10	12
Operating pressure, psia	250-2300	200-250
Design pressure, psig	2500	250
Hydrostatic test pressure, psig	4400	475
Design temperature, °F	650	400
Nozzle pipe size	2 in. sched 80	2 in. sched 40

Heat exchanger A was purchased in 1969 under ORNL specifications covering design, fabrication, materials, and inspection. The purchase specification required the unit to be designed, constructed, and stamped in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1.

Heat exchangers B and C, identical in size and construction to heat exchanger A, were procured under ORNL specifications covering design, fabrication, materials, and inspection. These specifications require the units to be designed, constructed, and stamped in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1.

3.5.2 Bypass heat exchanger

The bypass heat exchanger, denoted heat exchanger D on the process flowsheet of Fig. A.3, is required to remove heat generated by the oversized pump and the throttling valve to maintain the base loop temperatures at the desired set point. A small Graham "Heliflow" heat exchanger, having the same basic construction as the primary heat exchangers described in Section 3.5.1, is used for this purpose. Operating and design characteristics are listed in Table A.9. Note that two sets of design conditions are given for the tube sides.

Table A.9. Specified operating and design characteristics of the pump bypass heat exchanger (total duty, 1,300,000 Btu/hr; total surface area, 16 ft²; manufacturer's size number, 9-6C6C-14S; tube size, 1/2 in. OD × 0.049 in. wall)

Parameter	Conditions	
	Tube side (primary fluid)	Shell side (secondary fluid)
Fluid	Demineralized water, liquid phase	Demineralized water, liquid phase
Flow rate, lb _m /hr	15,000	15,000
Maximum inlet temperature, °F	500	80
Maximum outlet temperature, °F	313	167
Maximum pressure drop, psi	5	28
Operating pressure, psia	2500	200-250
Design pressure, psig	2500	250
Hydrostatic test pressure, psig	4400	475
Design temperature, °F	650	
Nozzle pipe size	1 in. sched 80	1 in. sched 40

Heat exchanger D was procured under ORNL specifications covering design fabrication, materials, and inspection. These specifications require that the unit be designed, constructed, and stamped in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII, Division I.

3.6 Volume Holdup Assembly

A variable volume holdup assembly is desired at the exit of the test section to permit a small variation in loop volume and to provide a means to vary the quantity of exit temperature coolant available (between the test section and the heat exchangers) for reverse flow through the test section during the blowdown event. Obviously, the holdup assembly must be designed to prevent stagnation of the coolant.

The holdup volume assembly consists of three U-bends of 6-in. sched-160 pipe and elbows connected in parallel between two manifolds via eccentric reducers and Grayloc flanges. The three parallel assemblies provide a multiple choice of net volume increases of 1.4, 3.3, and 5.1 ft³ which can be added downstream of the test section. See Table A.4 for loop volumes.

Design, fabrication, and inspection of the variable volume holdup assembly are in accordance with the USAS Code for Power Piping B31.1.0 as is the primary loop piping.

3.7 Test Section

The test section consists of a pressure container housing and the test bundle within the housing. The container incorporates the flanges, support nozzles, and instrument taps necessary to accommodate the pressure boundary penetrations. The test bundle consists of the 49 heater rods, a square-cross-section shroud to contain the heater rods, the spacer grids, and the necessary internal instrumentation. The container is in two sections as shown in Fig. A.14. The lower container has support brackets attached and is a permanent part of the loop piping; the upper portion or spool piece is removable and is considered as part of the test bundle assembly. A dummy test section representing this upper spool and outlet nozzle will be available for loop shakedown operation without risking the test bundle.

The heater rod assembly consists of a 7×7 array of electrically heated rods which are instrumented both in the sheath and in the center of the rod. The indirect heater rods with appropriate low-pressure-drop spacer grids closely model a section of a contemporary PWR fuel rod sub-assembly with respect to spacing, dimensions, axial power profile, power level, and coolant conditions.

3.7.1 Test section container

The test section container consists of two flanged sections of 10-in. sched-140, type 316 stainless steel pipes with an overall length of about 19 ft. Support brackets are attached to the lower spool section, which is about 15 ft long. The upper spool piece is about 4 ft long and is removable with the test bundle. The heater rods protrude another 3 ft through seal flanges at the upper end of the removable spool piece to make the overall test section assembly about 21 ft long.

There are two inlet nozzles located on the lower container. Weldolets are utilized to provide the nozzle weld reinforcement required by Section VIII of the Code. Grayloc flanges are used to permit quick coupling and uncoupling. The Graylocs are used not only for simplification of assembly but also for ease of maintenance or replacement of instrument spools positioned near the test section. The upper of the two inlet nozzles are for

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Fig. A.14. Test section using indirect heater rods in 49-rod bundle.

the initial operation. The lower inlet will remain capped until needed for possible future tests in which the shorter annulus may be desired. Other nozzle connections that may be needed in the future for additional shroud instrumentation but that will be capped for initial operation are also provided.

Other test section penetrations are associated with pressure measurements, temperature measurements, heater rod sliding seal, and conventional flange joints. Steady-state pressure measurements are made with weld-on autoclave-type adapters. For fast-response pressure measurements during the blowdown transient, a special air-cooled pressure tap is designed that will prevent the interference of flashing steam in the instrument connection. These special connections use adaptations of the autoclave-type seal that allow the easy removal or replacement of the special air-cooled attachment.

Penetrations for temperature measurements include wells for resistance thermometers, autoclave seals for sheath thermocouples, and Conax fittings for sealing around the 16 thermocouple sheaths for measurements inside the test bundle shroud. Both pressure sensor tubing and thermocouple sheaths for the internal measurements of the shroud exit through a special instrumentation flange which also supports the shroud.

The heater rods penetrate the upper end of the test section and are sealed with special O-rings in two seal plates that form an intermediate pressure chamber between the pressures of the test section and atmosphere. These seals and the cooling required are discussed in more detail in Section 2.9. The O-ring heater seal must provide a sliding seal which allows differential expansion between the heater rods and the test section container. The seal plates themselves are sealed by conventional static O-ring seals.

The upper and lower test section container closures are fabricated from bolted blind flanges and sealed with conventional flexitallic gaskets. A total of six flexitallic gaskets are provided between surfaces of the dummy subflow channel thermocouple flange, the instrument and shroud flange, and the nickel current-carrying flange. The 1500-lb weld-neck flanges are purchased oversized and underdrilled so that there is sufficient material to accommodate the various recesses for seal plates.

Finish machining is done after welding to obtain the close alignment of mating surfaces required.

The nickel flange that is sandwiched between the lower weld-neck flange and the blind flange serves both as the anchor for the heater rods and as the conductor of heater rod current. A total heater current of almost 30,000 A in the nickel flange requires that it be cooled external to the test section container. Passages drilled in the external portion of the plate share cooling with the eight water-cooled generator cables connected to this plate. Loop water has access to both upper and lower internal surfaces of the nickel flange to provide internal cooling. Calculations show that the relatively stagnant water on the lower surface will not boil during steady-state operation. The portion of the dc generator circuit consisting of the heater anchor and the nickel flange is maintained at ground potential, and thus electrical isolation between the nickel flange and test section flanges is not required. The electrical connection between the heater rod and the nickel flange is provided by a tapered end closure and socket. The heater end closure is held in contact with the matching tapered socket in the nickel flange with a threaded fastener. This threaded fastener and the nickel flange must also support the force of about 350 lb on each rod due to pressure tending to push it from the test section.

3.7.2 Indirect heater rod

The PWR fuel pin simulator is an electrically heated rod with the same general geometry and axial power profile as a PWR fuel rod. Heaters for this purpose are characterized as either direct or indirect. The THTF heater is an indirect heater in which heat is generated by passing current through an internal heater element that is insulated from the outer sheath. In a direct heater, heat is generated by current flowing through the heater sheath itself.

The indirect heater rod used in the THTF test bundle is double ended with the sheath and the ground-lead extension electrically common at the lower end and with the lead-in insulated from the sheath at the upper end. The heat is conducted from the heater element (tubular in this case) through the boron nitride insulation to the sheath of the indirect heater.

Thermocouples located both in the dual wall of the heater sheath and in the center of the tubular heater element provide the information necessary to calculate heat flux, heat storage, and heat transfer coefficients during both steady-state conditions and blowdown transients. See Table A.10 for some test bundle parameters.

Table A.10. Some parameters of test section using 49 indirect heater rods

Coolant pressure, psia	To 2250
Coolant inlet temperature, °F	540 to 560
Coolant temperature rise, °F	60 to 90
Coolant mass velocity, $\text{lb}_m \text{ hr}^{-1} \text{ ft}^{-2}$	$0.6 \text{ to } 3.0 \times 10^6$
Peak rod power, kW/ft	19.8
Peak-to-average power ratio	1.65
Heater rod diameter, in.	0.422
Heater rod square pitch, in.	0.563
Heater rod current, each, A	580 ± 20
Heater rod dc voltage	248 ± 9
Number of internal thermocouples, each rod	1 to 5
Number of sheath thermocouples, each rod	4 to 12

The heater rod assembly consists of four major subassemblies: (1) the active component assembly, (2) the dual sheath assembly, (3) the heater cable lug attachment, and (4) the end closure (see Fig. A.15). The structural anchor and the electrical current collector at the closed end (the heater end closure) consists of a 2-in.-thick nickel flange at the lower end of the test section. The heater sheath, the end closure that couples the sheath to the heater ground lead extension, and this nickel flange are all at ground potential and do not require electrical isolation. Extensions on either end of the heater element make up the heater lead-in and the ground-lead conductors. The lead-in conductor is tubular and contains the extensions of the internal thermocouple leads. The major subassemblies are described in more detail below.

Active component assembly

The active component assembly consists of the heater element, the ground lead extension, the heater lead-in conductor, and the internal thermocouples.

Fig. A.15. Indirect heater rod assembly.

The heater element consists of a series of oversleeves swaged over a central heater tube to provide a series of heat generation zones. The center 36 in. consists of only the basic Inconel 600 heater tube, thus giving the highest resistance to provide a maximum heat generation rate of 19.8 kW/ft at 600 A. Successive oversleeves of Inconel 600 or cupronickel of appropriate wall thicknesses and lengths are swaged over the appropriate length of the heater element. Each of these oversleeves extends to the end of the heater element, thus eliminating any butt joints within the heater element itself. As successive sleeves are added between the center zone and the ends, the resistance — and thus the heat generation rate — of that particular zone decreases so that the series of step changes bracket the desired cosine power profile shown in Fig. A.16. The local-to-average power ratio varies from 0.422 at either end to 1.65 at the center heat zone with the average power rate being about 12 kW/ft. See Table A.11 and Fig. A.17 for further information on heat zones.

Table A.11. Power profile for the prototype indirect heater with average power of 12 kW/ft

Heat zone length from beginning (in.)	Power ratio, local/average	Local power rate (kW/ft)
0-18	0.422	5.06
18-31.5	0.597	7.16
31.5-42	1.065	12.78
42-54	1.285	15.42
54-90	1.65	19.8
90-102	1.285	15.42
102-112.5	1.065	12.78
112.5-126	0.597	7.16
126-144	0.422	5.06

Instrumentation for the active elements consists of 0.020-in.-OD sheathed Chromel-Alumel thermocouples located in the center of the tubular heat element. Heater rods for the first bundle have four levels of instrumentation (see Figs. A.15 and A.16). The H, J, M, and P type heaters each

Fig. A.16. Indirect heater rod details.

Fig. A.17. Relationship of heater thermocouples, spacer grids, and heat flux zones.

17. Relationship of heater thermocouples, spacer grids, and
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have center thermocouples numbering 5, 5, 2, and 1 respectively. The thermocouple sheaths are insulated from the heater element by MgO insulation and have insulated measuring junctions. The sheathed thermocouple extends upward through the unheated portion of the lead-in conductor to exit at the top of the heater assembly. The active element is insulated from the sheath by compacted boron nitride powder, which provides a high electrical insulation with a good thermal conductivity coefficient ($K \approx 12 \text{ Btu hr}^{-1} \text{ ft}^{-1} \text{ }^{\circ}\text{F}^{-1}$). Compaction of the powder is achieved by subsequent swaging of the sheath.

Dual-wall heater sheath

The heater rod sheath consists of a double wall with 0.020-in.-OD sheathed thermocouples located in axial grooves between the two walls. The grooves are machined longitudinally in the inner sheath to contain two sheathed thermocouples. The H, J, M, and P type heaters have sheath thermocouples numbering 10, 12, 10, and 4 respectively. Cross sections of three of the heater types with the azimuthal relationship of the sheath thermocouples are shown in Fig. A.16, while the axial locations of the junctions are shown in Fig. A.17.

Cable attachment

The portion of the heater rod above the heated zone is devoted to the following needs: to sheath the lead-in conductor and internal instrumentation until they exit the test section housing, to provide a sealing surface for the pressure containment seals of the container, and to provide for the attachment of electrical connection to the dc power supply system. The outer 0.010-in. layer of the sheath is terminated above the test section about 2 in. before the inner layer of the sheath to allow the thermocouple sheaths to exit and to be collected at this point without damage and without hazard of coming into contact with the lead-in conductor. The grounded sheath terminates about 8 in. above the top of the test section. A moisture barrier is provided to cover the exposed boron nitride insulation at this point. An oversleeve of copper is added to the electrical lead-in beyond this point to decrease conductor resistance. (The total heat generation in the "unheated" portion of the 49-rod bundle

is approximately 18 kW/ft of bundle, which requires that cooling be provided for the seals and the moisture barrier. Cooling of the seals is discussed in Section 2.9.) This exposed lead-in conductor has a potential of about 250 V during power operation and requires care in the placement of supports, thermocouple sheaths, cable connectors, etc. The cable connectors must be staggered and pyramided to provide space for the attachment of electrical cables that are many times the size of the heater rods. Although all four dc generators will operate normally at or near the same voltage, provisions are made to prevent adjacent heater connectors from contacting for three reasons. First, if an individual heater circuit were to open or "crowbar" for some reason (see Section 2.7 for explanation of "crowbar"), that heater lead would be at ground potential. Second, some tests will be performed with "cold" rods by disconnecting cables from certain heater rods. Third, provisions for power skew are "built-in" characteristics of the power supply, and the ability to utilize these characteristics is desirable. For these reasons also, it is necessary that individual heaters be allowed to expand independently. The pyramid of heater connectors provides seven tiers for attachments to the 49 heater rods. A lattice work of Micarta insulation board is provided at each tier, above and below the cable connector lugs, to provide lateral support of the heater lead-in conductors. The seven lengths of heater rods required vary from approximately 18 1/2 to 21 1/2 ft and are tabulated in Fig. A.16. The cable lug attachment device is brazed to the heater rod as shown in Fig. A.15. The size 4/0 welding cable as shown is stripped of insulation for a short distance to provide flexibility and to improve cooling.

End closure

The end closure (Fig. A.16) serves three purposes: (1) to provide the seal between the heater ground-lead extension and the heater sheath, (2) to anchor the heater rod in the test bundle, and (3) to serve as the conductor from the heater ground lead to the nickel current-collector flange. The seal is formed by the weld attachment between both of the sheath layers and the end closure. The threaded fasteners serve as the anchor to retain the heater rod within the test section. The heater rod

is free to expand, except for the forces of support-grid friction and seal friction, upward from the anchor and out the top of the test section. The threaded end closure is also utilized to pull the rod through the test bundle during the assembly of the bundle. The current flows from the copper ground lead to the end closure via a threaded connection and then to the nickel current-collector plate via direct contact with a matching tapered socket. The threaded end fastener establishes contact pressure between the surfaces formed by the American Standard self-holding taper of a nominal rate of 1/2 in./ft.

3.7.3 Test bundle instrument flanges and shroud

The shroud supports the spacer grids and forms the bundle flow channel. Thus, the dimensions of this portion of the bundle are very important to the thermodynamic and hydraulic analysis of the rod bundle behavior. The ability of interior rods and subchannels in a 7×7 array to respond to test conditions and blowdown in a manner directly comparable to that in the very large arrays of PWR cores depends on the effect of the flow channel boundary on interior flow and temperature distributions. A very important design parameter is the dimension from the outer row of rods to the adjacent channel wall. Two conflicting criteria bracket the design specification for this dimension. First, it would be desirable for the flow channels bounded by two rods and the channel wall (or wall channels) to behave during the blowdown transient in a manner similar to the interior channels which are bounded by four rods. To accomplish this aim, the equivalent hydraulic diameter of the wall channels should be the same as that of the interior channels. Calculations based on this criterion indicate that the distance from the center of the outer row of rods to the wall should be 0.420 in.

The other, and more important, criterion is that the enthalpy rise in the wall channels during the heating phase be the same as the enthalpy rise of the fluid in the interior channels. To meet this criterion, the mass flow of fluid in the wall channels must be one-fourth the flow in the interior channels when the same pressure gradient exists over all subchannels. This criterion assumes that all the heat generated in the rods is transferred directly into the adjacent coolant and neglects the

effects of circumferential or axial conduction and the effect of fluid crossflow between subchannels. All of the aspects that are neglected will tend to promote uniform enthalpy rise in all subchannels. The dimension from the shroud wall to the outer row of fuel pin simulators was calculated for full, 60%, and 20% design flow using two calculational procedures. One method uses the Kays¹ correlations to determine the pressure loss at the grid spacer plus a multiplier on the friction loss in the bundle recommended by Tong.² The second method uses a correlation for the spacer loss developed by deStordeur³ plus normal frictional losses. The value of 0.312 was chosen from the results ranging from 0.308 to 0.320 in. to best meet all flow conditions. See Fig. A.18 for details of the spacer-grid assembly.

The thickness of the plates forming the shroud (1 in. and 3/4 in.), the interlocking of the shroud plates, plus the close spacing of shroud plate fasteners (1 1/2 in. center to center for a total of 418 fasteners) are specified to minimize deflection during blowdown. Analysis of the blowdown transient indicates that about 1000 psi differential pressure could exist momentarily between the shroud and the test section container. The shroud is supported from the upper end by a special support flange that is gasketed between test section container flanges (see Fig. A.14). This support flange also serves as the means by which instrumentation from the shroud leaves the test section container. Sixteen thermocouple sheaths and three pressure instrument tubes from the shroud are routed through seven nozzle fittings extending radially from this support flange. An additional nozzle is supplied for use by the operator to vent trapped air from the flow annulus between the container and the shroud during the filling operation.

¹W. M. Kays and A. L. London, Compact Heat Exchangers, National Press, Inc., Palo Alto, Calif., 1955.

²L. S. Tong, Pressure Drop Performance of a Rod Bundle, pp. 57-69 in Proceedings of a Symposium on Heat Transfer in Rod Bundles, American Society of Mechanical Engineers, New York, Dec. 3, 1968.

³A. N. deStordeur, Nucleonics 19(6), 74 (1961).

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Fig. A.18. Low-pressure-drop spacer grid assembly.

The shroud is centered in the test section container by a shroud spacer plate at the lower end and by tabs at two locations along its length which allow thermal growth of the shroud relative to the container.

A subchannel thermocouple flange is provided at the shroud outlet which allows a temperature measurement to be made at each flow subchannel (64 each) between heater rods. These thermocouples are positioned near the termination of the rod heated length, which is located about 8 in. below the shroud outlet. The thermocouple sheaths are supported by stiffening tubes that are anchored in the subchannel thermocouple flange and positioned in the shroud by a support grid. The sheaths are then routed to one of eight exit seal nozzles via eight covered troughs that form spokes in the flange. Flow from the test bundle is thus routed around the spokes and enters the test section outlet plenum formed by the upper spool piece. This assembly is shown in Fig. A.19.

PHOTO 4408-74

Fig. A.19. Subchannel thermocouple flange.

Appendix B

INSTRUMENTATION AND DATA-ACQUISITION SYSTEM

i. INSTRUMENTATION

The THTF instrumentation system is designed to assure the reliable and safe operation of the experimental facility. Instrument channels monitoring critical test parameters provide data needed for the determination of system behavior under steady-state and transient conditions. Additional instruments are installed in the test loop and associated secondary systems to provide the operators confidence that the facility is operating normally. The instrumentation system includes means for detecting out-of-limit and unsafe conditions, alerting the operators that such conditions exist, and initiating appropriate protective actions on detection of such conditions.

1.1 Parameters Measured

The THTF is instrumented to measure temperature, flow, pressure, power, and time under both steady-state and transient conditions. Instrument applications and locations for the primary piping system and for the test section are shown in Figs. B.1 to B.3 and Fig. B.4 respectively. Temperature, pressure, and flow measurements are of primary interest to the operators, with measurements of other parameters secondary.

1.1.1 Temperature

Temperature measurements are required to (1) detect the onset of CHF and film boiling and permit calculation of heat transfer coefficients in the test bundle, (2) determine the subchannel coolant temperature distribution and the relation of flow to energy input during steady-state operation, (3) establish heat balances in the test section and heat exchangers, (4) monitor the coolant and steam space in the pressurizer, (5) detect pressurizer voiding during a transient, and (6) determine mass, energy, and momentum balances during a transient. Primary temperature measurements

B.1. Primary piping instrumentation, sheet 1.

2

Fig. B.3. Pressure-suppression instrumentation.

B.3. Pressure-suppression instrumentation.

2

are taken to provide the following data:

1. cladding temperature of heater rods in test bundle,
2. subchannel coolant outlet temperature,
3. coolant temperatures at the inlet and outlet to the test section,
4. coolant temperatures at four levels in the fluid adjacent to the heater rod shroud,
5. coolant temperature in the primary loop at the inlet and outlet of the heat exchangers,
6. temperature in the steam space of the pressurizer,
7. coolant temperature at the bottom of the pressurizer,
8. coolant temperature near each flow detection station,
9. temperature on the secondary side of the primary loop heat exchangers,
10. coolant temperature in the test section inlet plenum.

1.1.2 Pressure

Transient pressure measurements are required to (1) detect the presence (or absence) of shock waves that may influence the test results, (2) determine the thermodynamic state of the liquid, (3) detect the presence of any unusual pressure difference condition across the test section, and (4) compare with calculated results derived from analytical models describing the flow-pressure drop relationship of the loop and test section.

Primary pressure measurements are made to obtain the following information:

1. bundle differential pressure,
2. test bundle inlet and outlet pressure,
3. heat exchanger inlet pressure,
4. heat exchanger differential pressure,
5. pump suction inlet pressure,
6. pump differential pressure,
7. pressurizer liquid level and steam pressure,
8. pressure at each flow measuring station.

1.1.3 Flow

Transient flow measurements are required to determine the mass, energy, and momentum balance of the fluid entering and leaving the test section.

This requires a measure of steam quality, temperature, density, and the mass flux density (ρV^2). Critical measurement points utilize bidirectional sensors since flow may be toward or from the test section during the transient. Flow measurements are taken to provide the following information:

1. primary coolant flow at entry to inlet blowdown rupture disk assembly,
2. primary coolant flow at test section inlet,
3. primary coolant flow at test section outlet,
4. primary coolant flow in return line to pump,
5. pump discharge flow,
6. heat exchanger secondary coolant flow,
7. pressure suppression system spray supply flow,
8. flow of coolant to primary pump bearings and seals,
9. flow of coolant to test bundle seals.

1.1.4 Miscellaneous parameters

Measurements of system fluid levels, primary coolant density, dc voltage and current applied to the test bundle heater rods, and time of blowdown initiation are taken to fulfill data requirements for the facility. The primary coolant level in the system pressurizer is monitored to set initial conditions and assure adequate level during operations, the density of coolant in the primary loop is measured to determine fluid phase and provide data for calculation of mass flux density; and dc voltage and current measurements are taken for the determination of power available to the test bundle. Blowdown transient testing is timed from the initiation of the blowdown sequence.

1.2 Sensors

The process variables important to facility operation are monitored by conventional-type instruments suited to the operating conditions. Most of the test variables are monitored by conventional-type instruments, except the gamma densitometers, bidirectional drag disks, bidirectional turbine meters, and fast-response pressure transducers.

Table B.1 details the type of measurements, the sensor error, and required sensor response for all classes of primary measuring devices in the THTF. In the table, the "Type" column gives the class or principle of operation of the sensors, and the "Error" column gives the error band for each type of sensor either as a percentage of full scale (% FS), percentage of reading (% Rdg), or an absolute value (such as $\pm 2^\circ\text{F}$). The "Required response" column defines the maximum time constant (time required for output to change 63.2% in response to a step change in the measured variable) and minimum frequency acceptable for obtaining the desired data. Each type of sensor has an assigned code, as indicated in the "Designation" column; these codes are used in Table B.2 as a shorthand notation for the type of sensor used at each location.

Table B.2 lists the measurements made in the THTF, the type, and the location. Many of the more routine operational measurements involved in assuring reliable operation are not enumerated. Only those logged by the data-acquisition system and those necessary to establish base conditions in the facility at the beginning of a test are listed. The intended use of the data derived from each measurement is defined by a Roman numeral in the "Purpose" column; the code for the application is (I) blowdown test data, (II) steady-state data prior to blowdown, (III) critical heat flux test data, and (IV) operational and base conditions data.

The next entries indicate the number of instruments associated with each measurement and the type of sensor used. The range, error, and required response are given for each measurement system (defined as the combination of a sensor, signal-conditioning equipment, and a readout of data-logging device). The "Error" column gives the total error band for each system either as a percentage of full scale (% FS), percentage of reading (% Rdg), or an absolute value (such as $\pm 4^\circ\text{F}$). The "Required response" column is based on the assumption that each system, from sensor to readout, responds as a first-order system. This column defines the maximum time constant (time required for readout to indicate 63.2% change in response to a step change in the measured variable) and minimum frequency response acceptable for obtaining the desired data. The frequency f is defined by $f = 1/(2\pi\tau)$, where τ is the system time constant. The

Table B.1. Sensor description

Measurement	Designation	Type	Error ^a	Required response
Fluid temperature	TF1	Chromel/Alumel, 0.090-in.-OD metal-sheathed thermocouple	<527°F, ±2°F >527°F, ±3/8% Rdg	50 msec (3 Hz)
	TF2	Platinum RTD	±1°F	10 sec (0.016 Hz)
	TF3	Chromel/Alumel, 0.125 in. OD	<527°F, ±2°F >527°F ±3/8% Rdg	2 sec (0.08 Hz)
	TF4	Fast-response, exposed-junction Chromel/Alumel thermocouple ^b	±2°F from 0 to 600°F	18 msec (8.8 Hz)
Fuel-pin simulator	TP	Chromel/Alumel, 0.020-in.-OD metal-sheathed, insulated-junction thermocouple	<527°F, ±2°F >527°F, ±3/8% Rdg	50 msec (3 Hz)
Pressure	P1	Strain gauge ^c	±0.5% FS	0.16 msec (1000 Hz)
	P2	Bourdon tube gauge	0.1% FS	0.3 sec (0.5 Hz)
	P3	Force balance pressure transmitter	±0.5% FS	0.3 sec (0.5 Hz)
Differential pressure	DP1	Strain gauge ^c	±0.5% FS	0.32 msec (500 Hz)
	DP2	Force balance DP cell	±0.75% FS	0.3 sec (0.5 Hz)
Fluid flow	F1	Turbine meter	±0.5% Rdg	50 msec (3 Hz)
	F2	Orifice	±1% FS	0.1 sec (1.6 Hz)
	F3	Pipe elbow taps	±7% FS	0.1 sec (1.6 Hz)
Momentum flux	MF	Strain gauge cantilever beam (drag disk), bidirectional	±1% FS at constant density and temperature	16 msec (10 Hz)

Table B.1. (continued)

Measurement	Designation	Type	Error ^a	Required response
Density	D	Gamma attenuation/ photomultiplier tube		16 msec (10 Hz)
Voltage	E	Voltage divider	±0.25% FS	50 msec (3 Hz)
Current	I	Shunt	±0.2% FS	50 msec (3 Hz)
Initiation of blowdown	BW	To detect when rupture disks have broken (blowdown initiated) ^d	±0.1 msec	0.1 msec
Liquid level	L	Force balance DP cell	±1% at constant temperature	0.3 sec (0.5 Hz)
Velocity	V	Turbine meter, bidirectional	±0.5% Rdg at con- stant density	8 msec (20 Hz)

^aFS — full scale; Rdg — reading.

^bResponse in H₂O at 5 fps.

^cError at static conditions.

^dUsed for t = 0 reference.

Table B.2. Data sensor locations and systems characteristics

Location and measurement	Purpose	Instrument application No.	Sensor designation ^a	System			Logging system
				Range	Error	Required response	
Main pump							
Inlet pressure ^{b,c}	I	PE-76	P1	0-3000 psig	±1% FS	0.16 msec (1000 Hz)	MT
Inlet fluid temperature	IV	TE-74	TF3	0-800°F	±2% FS	2 sec (0.08 Hz)	P1
Differential pressure ^{b,c}	I,II	PdE-78	DP1	0-1000 psid		0.52 msec (500 Hz)	MT
Pump flow	IV	FE-1	F2	0-800 gpm	±3% FS	1 sec (0.16 Hz)	CCDAS, PR
Discharge fluid temperature	II,III,IV	TE-4B, TE-56B	TF2	0-800°F	±0.5% FS	10 sec (0.016 Hz)	CCDAS, PR
Pressurizer							
Vapor space pressure ^{b,c,d}	I	PE-106	P1	0-3000 psig	±1% FS	0.16 msec (1000 Hz)	MT
Vapor space pressure	IV	PT-102	P3	500-2500 psig	±20 psi	1 sec (0.16 Hz)	CCDAS, PR
Vapor space temperature	I	TE-1	TF4	0-1800°F	±1% FS	50 msec (3 Hz)	CCDAS
Vapor space temperature	II	TE-101	TF2	0-800°F	±0.35% FS	10 sec (0.016 Hz)	CCDAS
Bottom outlet liquid temperature	I	TE-3	TF4	0-1800°F	±1% FS	50 msec (3 Hz)	CCDAS
Liquid level ^{b,e}	IV	LT-100	L	0-150 in.	±1% FS	0.5 sec (0.3 Hz)	PR
Pump bypass heat exchanger							
Secondary outlet temperature	II,III,IV	TE-13, TE-557	TF2	0-400°F	±0.35% FS	10 sec (0.016 Hz)	CCDAS, PR
Secondary flow	IV	FE-550	F1	6.2-50 gpm	±0.6% FS	50 msec (3 Hz)	CCDAS, PR
Primary outlet temperature	IV	TE-5B	TF1	0-1800°F	±1% FS	10 sec (0.016 Hz)	CCDAS
Three main heat exchangers							
Primary upstream pressure of all ^{b,c}	I	PE-44	P1	0-3000 psig	±1% FS	0.16 msec (1000 Hz)	MT
Primary ΔP of all ^{b,c}	II	PdE-46	DP1	0-200 psid		0.32 msec (500 Hz)	MT
Primary ΔP of each	IV	PdT-48	DP2	0-24 psid	±1% FS	1 sec (0.16 Hz)	CCDAS, PR
Primary outlet temperature	IV	TE-30B, TE-32B, TE-34B	TF1	0-1800°F	±1% FS	10 sec (0.016 Hz)	CCDAS
Secondary outlet temperature	II,III,IV	TE-52/-525, TE-54/-627, TE-56/-727	TF2	0-400°F	±0.35% FS	10 sec (0.016 Hz)	CCDAS, PR
Secondary flow of each	III,IV	FE-522A, FE-620, FE-720	F1	14-150 gpm	±0.4% FS	50 msec (3 Hz)	CCDAS, PR
Primary downstream temperature of all	IV	TE-28B	TF3	0-800°F	±0.5% FS	10 sec (0.016 Hz)	CCDAS
Test section							
Test bundle inlet pressure ^{b,c,d}	I	PE-156	P1	0-3000 psig	±1% FS	0.16 msec (1000 Hz)	MT
Test bundle outlet pressure ^{b,c}	I	PE-201	P1	0-3000 psig	±1% FS	0.16 msec (1000 Hz)	MT
Test bundle ΔP ^{b,c}	I,II,III	PdE-200	DP1	0-50 psid		0.32 msec (500 Hz)	MT
Miscellaneous bundle ΔP ^f	III	PdT-199	DP2	0-50 psid	±1% FS	1 sec (0.16 Hz)	CCDAS
Fuel pin temperatures ^{g,h}	II,III	TE-301-TE-349 (460 max) ⁱ	TF	0-1800°F	±1% FS	50 msec (3 Hz)	CCDAS, TS
Inlet line fluid temperature	I	TE-162	TF4	0-1800°F	±1% FS	50 msec (3 Hz)	CCDAS
Inlet line fluid temperature	II,III,IV	TE-160	TF2	0-1800°F	±0.35% FS	10 sec (0.016 Hz)	P1
Outlet line fluid temperature	I	TE-212	TF4	0-1800°F	±1% FS	50 msec (3 Hz)	CCDAS
Outlet line fluid temperature	II,III,IV	TE-210A, TE-210B	TF2	0-800°F	±0.5% FS	10 sec (0.016 Hz)	CCDAS, P1
Bundle inlet temperature ^g	I	TE-150-153	TF4	0-1800°F	±1% FS	18 msec (8.8 Hz)	CCDAS
Inlet to outlet fluid ΔP	II,III	PdT-30	DP2	0-50 psid	±1% FS	1 sec (0.16 Hz)	CCDAS, PR
Voltage across bundle	I,II,III,IV		V	0-285 V dc	±0.4% FS	50 msec (3 Hz)	CCDAS
Individual rod current	I,II,III	(49 max)	I	0-800 A	±0.5% FS	50 msec (3 Hz)	CCDAS
Outlet subchannel fluid temperature	I,III	(64 max)	TF1	0-1800°F	±1% FS	50 msec (3 Hz)	CCDAS
Miscellaneous fluid temperature	I,III	(36 max)	TF4	0-1800°F	±1% FS	50 msec (3 Hz)	CCDAS
Outlet line pressure ^d	II,III	PT-32	P3	500-2500 psig	±20 psi	1 sec (0.16 Hz)	CCDAS
Individual generator currents ^j	IV	(4 max)	I	0-10,000 A	±0.4% FS	50 msec (3 Hz)	CCDAS

Table B.2. (continued)

Location and measurement	Purpose	Instrument application No.	Sensor designation ^a	System			Logging system
				Range	Error	Required response	
<u>Inlet-line spool pieces^k</u>							
Fluid density ^b	I	DE-20, DE-14 ^h	D	0-62.4 lb/ft ³	tbd ⁱ	16 msec (10 Hz)	MT
Pressure ^c	I	PE-26, PE-174	P1	0-3000 psig	±1% FS	0.15 msec (1000 Hz)	CCDAS
Fluid temperature	I	TE-24, TE-172	TF4	0-1800°F	±1% FS	18 msec (8.8 Hz)	CCDAS
Momentum flux ^b	I	PmfE-22, PmfE-170	MP	2.5×10^5 pV ²	tbd ⁱ	16 msec (10 Hz)	MT
Velocity ^b	I	VE-19, VE-166	V	100-1000 gpm	±1.5% FS (water only)	8 msec (20 Hz)	MT
<u>Outlet-line spool pieces^k</u>							
Fluid density ^b	I	DE-16, DE-218	D	0-62.4 lb/ft ³	tbd ⁱ	16 msec (10 Hz)	MT
Pressure ^c	I	PE-42, PE-224	P1	0-3000 psig	±1% FS	0.16 msec (1000 Hz)	CCDAS
Fluid temperature	I	TE-40, TE-222	TF4	0-1800°F	±1% FS	18 msec (8.8 Hz)	CCDAS
Momentum flux ^b	I	PmfE-38, PmfE-220	MP	2.5×10^5 pV ²	tbd ⁱ	16 msec (10 Hz)	MT
Velocity ^b	I	VE-34, VE-216	V	100-1000 gpm	±1.5% FS (water only)	8 msec (20 Hz)	MT
<u>Pressure-suppression system</u>							
Receiver pressure ^b	I, IV	PE-412	P1	0-200 psig	±3% FS	0.34 msec (500 Hz)	MT, PI
Recirculating water temperature	IV	TE-408B	TF3	32-350°F	±9°F	2 sec (0.08 Hz)	CCDAS
Recirculating water flow	IV	FT-406	F1	0-1500 gpm	±8% FS	1 sec (0.16 Hz)	PI
<u>Blowdown lines</u>							
Initiation of blowdown	I	XE-420-XE-423	BW	0-5 V dc	±0.1 msec	0.1 msec	MT
Rupture disk buffer pressure ^b	IV	PE-979, PE-989	P2	0-1500 psig	±0.5% FS		PI

^aSee Table B.1.^bAlso monitored by CCDAS with 50-msec (3-Hz) response.^cSee Sect. 1.2.2 for discussion of error.^dAlso monitored by precision bourdon pressure gauge.^eError at constant temperature.^fApproximately three total possibly; only one monitored at any one time.^gA selected number of these temperatures, not exceeding eight, may be recorded on an oscillographic strip-chart recorder to obtain "quick-look" data.^h325 selected fuel pin temperatures will be recorded on CCDAS, and 50 selected fuel pin temperatures will be displayed on a multichannel temperature monitor (TM), which will also initiate removal of fuel pin power if any of the 50 selected temperatures exceed a preset value.ⁱNumbers in parentheses indicate quantity of sensors for that measurement.^jAlso monitored on main panel.^kThere are two spool pieces in the test section inlet line and two in the test section outlet line with the blowdown lines connected between the spool pieces in each line.^lTo be determined.

column labeled "Logging system" gives the data logger or final readout device for each measurement; the code used in this column is (MT) analog magnetic tape recorder/reproducer, (CCDAS) computer-controlled data-acquisition system, (PR) main control panel recorder, (PI) main control panel indicator, and (TS) multichannel temperature monitor. More detailed descriptions of the various sensors, along with some considerations on their application in the THTF, are given below.

1.2.1 Temperature

Chromel-Alumel thermocouples and platinum resistance thermometers (RTDs) are used in this facility to measure temperature. The RTDs are used for precision steady-state measurement to establish base temperature conditions in the loop prior to blowdown and during CHF tests. Associated with each RTD is the excitation and signal conditioning equipment necessary to sense the resistance change with temperature. This auxiliary equipment consists either of a constant current source and readout of the emf across the RTD for data signals or of a Wheatstone bridge instrument with a current output proportional to the resistance change (temperature for process control signals).

Stainless-steel-sheathed, magnesium-oxide-insulated, Chromel-Alumel thermocouples are used extensively to obtain blowdown and CHF test data. Sheathed couples in the Watlow indirect heaters have outside diameters of 20 mils. Exposed-junction thermocouples (Nanmac Corporation) are used in a few locations where very fast temperature transients (>10 Hz) must be measured. For very fast temperature transients in the coolant streams, consideration may also be given to unsealed, exposed-junction, sheathed, magnesium-oxide-insulated thermocouples of the type used in 1 1/2-loop Semiscale experiments. For routine monitoring of operation temperatures, 0.125-in.-OD sheathed thermocouples are installed. All thermocouples providing test data are of premium-grade material (error band being the greater of either 2°F or $\pm 3/8\%$ of reading) purchased in accord with appropriate standards. Thermocouple cold-junction compensation is handled by multi-terminal 150°F reference junction compensators.

1.2.2 Pressure and differential pressure

Line pressure gauges and force-balance transmitters are used for normal monitor and control functions during pretest operations. For steady-state sensing prior to blowdown and for CHF tests, Foxboro and Barton electronic force-balance transmitters, Heise precision bourdon-tube gauges, and strain-gauge transducers are used. For sensing blowdown pressure transients, Precise Sensors, Inc., air-cooled, flush-diaphragm, strain-gauge transducers are used. While these latter transducers have a frequency response cutoff at about 100,000 Hz, frequency information above 1000 Hz is not needed; and no special effort is made to record data in the higher range. For sensing transient differential pressure, Baldwin Electronics, Inc., strain-gauge transducers are used. The manufacturer has stated that these transducers have a frequency cutoff at about 500 Hz. Pressure gauges are complete in themselves and, as such, require no signal conditioning. Strain-gauge transducers require a source of excitation, a bridge completion network, and signal amplification; commercially available equipment will satisfy all three of these needs.

The strain gauge pressure and differential pressure transducers have a specified static error band of $\pm 0.5\%$. (Static error band is the error band applicable at room conditions in the absence of any vibration, shock, or acceleration.) However, the overall accuracy of these transducers during the blowdown transient is degraded both by high operating temperatures and by the temperature transients. Typical manufacturer specifications for environmental conditions are a compensated temperature range of $+75$ to 600°F , a thermal zero shift of less than 0.01% FS/ $^\circ\text{F}$ over the compensated range, and a thermal sensitivity shift of less than 0.010% FS/ $^\circ\text{F}$ over the compensated temperature range. In view of the above, it is evident that, in the worst case, the overall error for these transducers could be as much as $\pm 11\%$ of full scale under blowdown conditions. Care in installation and operation is exercised to minimize this error; for example, air-cooled standoffs (water-filled pressure tap line) are used to isolate the transducer from the loop temperature environment. For pressure measurements, the transducer is mounted on the end of this standoff, thus operating at a temperature considerably below the temperature of the fluid in the system;

for ΔP measurements, the transducer is located equidistant between two such taps. The air cooling should also reduce flashing of the water in the ΔP taps. As experience is gained in the use of these transducers, their overall error can be better defined and, perhaps, reduced well below $\pm 11\%$. Some method for compensating the transducer output signals for environmental conditions will also be sought.

1.2.3 Flow

Both single-phase (liquid-gas) and two-phase (water-steam) flow measurements are required in the THTF.

Liquid flow, where no change of phase is involved, is measured directly using turbine meters or indirectly through pressure drops across orifices or in pipe elbows. Turbine meters are installed where precision and wide rangeability are required. Orifices ($\sim 2\%$ accuracy) and pipe-elbow taps (5 to 10% accuracy) serve where less precision is acceptable.

The sensors for two-phase flow measurement are installed in instrumented spool pieces located in the test section inlet and outlet lines and in the blowdown lines. One sensor is a drag disk that develops a signal proportional to ρV^2 (the momentum flux), where ρ and V are the fluid density and velocity respectively. Fluid density at each drag disk station is measured by means of a gamma densitometer. The density and momentum flux are then combined to compute the mass flow, ρVA (lb_m/min), where A is the pipe cross-sectional area. It has been found that drag disks are temperature sensitive; the offset due to temperature is a function of the temperature of the cantilevered beam at the strain gauges, in turn related to the fluid temperature, which varies during blowdown. Therefore, a correction factor based on post-blowdown zero shift must be applied to the drag disk data.

Turbine meters, which are velocity-measuring devices, are also used to obtain two-phase flow data. The output of this type of meter (directly proportional to fluid velocity and nearly independent of temperature and density) can be combined with density and cross-sectional area to obtain mass flow. The performance characteristics and inherent accuracy of the turbine meter are superior to those of the drag disk; however, the turbine

meter is not as rugged as the drag disk and engenders pressure drops that under certain conditions might be excessive. Screens or other flow-homogenizing devices are installed upstream and downstream of the drag disk in order to obtain more reliable results.

The densitometer, designed and constructed at ORNL, consists of a 25-Ci ^{137}Cs monoenergetic, gamma source with associated collimator, scintillation photomultiplier-type detector, and current amplifier. Depleted uranium is used for the collimator and source shield material in the THTF application to avoid cooling problems that would exist with lead.

The fluid state during blowdown is established from temperature and pressures logged at each two-phase flow-metering station as a function of time.

1.2.4 Miscellaneous

Voltage and current

In the dc power system, currents are sensed by instrument shunts; an amplifier with high common mode tolerance is required to isolate the data-acquisition system from the dc voltage on each shunt. Voltage is measured using resistive voltage dividers.

Time

The time of blowdown initiation (i.e., the moment at which the rupture disks are broken) is perceived by break wires located just downstream of the rupture disks. These wires are broken by the downward openings of the rupture disks, and the consequent interruption of the continuity signal defines time $t = 0$.

Liquid level

Sight glasses are suitable for local indication of liquid levels in low-pressure applications where levels change only during drain or fill operations; positive shutoff valves may then be required if the vessels subsequently operate at high pressures. In high-pressure applications involving frequent changes in liquid level or where automatic or manual level control is required, electronic differential pressure transmitters are used to provide a continuous panel-board readout and/or a signal for controlling liquid level.

1.3 Protective Features

For protection of personnel and equipment, the instrumentation and controls for this facility include means for detecting out-of-limit and unsafe conditions, annunciators to alert the operators to the existence of such conditions, and interlocks to initiate appropriate protective actions on detection of such conditions.

1.3.1 General description

Many of the off-limit conditions have dual protective functions, both alerting the operator and shutting down the subsystem in which the condition exists. Where possible, two triggering levels are established. The primary level sets off the alarm bell and alerts the operator. In response to the alarm, the operator may initiate corrective action to return the system to normal operating range. A secondary level produces automatic shutdown in the event the condition progresses further off limit. Some circuits have only a single triggering device. In these cases, one set point applies for both operator alert and system trip. This occurs where contacts of a control relay open the annunciator and shutdown circuits simultaneously.

The remaining protective circuits are single purpose, actuating either the operator alert or system trip. Sensors monitoring heat exchangers and the rod seal cooling system provide signals to operate the annunciator circuit. In circuits of primary safety significance, a second shutdown interlock is included to assure system trip.

The automatic shutdown system is designed to be fail safe. Safety action is initiated by the interruption of control circuit power to the appropriate relays. In this way, loss of electrical control power will result in system shutdown. The facility air supply is interlocked with the system so that loss of air pressure will produce shutdown. Failure of the coolant systems to provide adequate cooling will initiate safety action.

1.3.2 Automatic shutdown systems

When a serious abnormal condition develops, prompt action is initiated automatically to trip the system involved, thus providing protection against damage to equipment. Interlocks are arranged in series so that shutdown will be actuated by any single off-limit condition.

Primary circulation pump

This device is heavily instrumented. Before pump startup is permissible, the instrument air supply system must be up to normal pressure, valve controllers must be powered, the primary system pressurizer must have reached a minimum pressure level, secondary cooling water flow must be adequate, and the pressure-suppression system must be functioning normally. In addition to preventing pump startup, loss of instrument air pressure or controller power will trip the pump breaker. Overtemperature of the primary cooling system and pump bearings, overpressure in the primary pip⁴ 3, excessive pump vibration, or abnormal pump power will also initiate pump shutdown.

Primary system pressurizer

The pressurizer establishes and maintains the pressure of the primary system at the designed operating level. Power to heaters which are part of the automatic control circuit is interrupted under certain conditions. Low instrument air supply pressure, lack of controller power, excessive pressurizer pressure, inadequate cooling water volume, high heater temperature, or the sensing of a blowdown will deenergize the heater breakers.

Test section power

For powered blowdown operations, the heater rod bundle will be in place in the test section. Protection of this assembly is accomplished by deenergizing the load breakers in the dc power supply when one of the following conditions is sensed:

1. low instrument air supply pressure,
2. loss of instrument power,
3. high primary-coolant temperature,
4. low primary-coolant flow into test section,
5. low differential pressure across test section,

6. insufficient pressurizer pressure,
7. primary pump deenergized,
8. low coolant flow in rod seal cooling system,
9. high rod seal cooling system temperature,
10. test section heater sheath high temperature.

Blowdown initiate circuit

The blowdown initiation circuit contains interlocks which prevent blowdown until system operating conditions are satisfactory. Blowdown inhibit is in effect as long as primary coolant flow through the test section is low, rupture disk accumulator pressure is below the level required for successful blowdown, control valve actuators are unlocked, or the pressure-suppression system is not operating properly.

2. DATA-ACQUISITION SYSTEM

2.1 General Description

As shown in Fig. B.5, the THTF data-acquisition system consists of (1) the data sensors and associated signal-conditioning equipment, (2) a 512-channel, high-speed, computer-controlled digital data-acquisition system (CCDAS), (3) two 14-channel analog magnetic tape recorder/reproducer system, (4) a timing and tape search subsystem, (5) a 50-channel thermocouple display and alarm system, and (6) multichannel analog strip-chart recorders.

Test data (steady-state and blowdown transient) are recorded on the CCDAS and the analog magnetic tape system. Selected parameters not expected to vary widely during blowdown, and all process control variables are registered on analog strip-chart recorders. In some cases, individual signals may be recorded in parallel on more than one system. Systems are not paralleled where the possibility of interaction exists; however, since all the data-acquisition systems have high input impedance and the output impedance of all signal sources is expected to be low, interaction is not expected to be a problem.

Fast transient data (from 10 to 1000 Hz) from pressure and differential pressure transducers, spool piece instrumentation, etc., are recorded by the analog magnetic tape system. The data on the analog magnetic tapes are digitized onto industry-compatible magnetic tape by the CCDAS after a test run. An on-site "quick look" at analog data on magnetic tape may also be obtained by recording the reproduced output of the magnetic tape system on multichannel strip-chart recorders.

Slower response data (<2 Hz) are handled by the CCDAS. In addition, the fast-response signals are monitored in parallel with the analog tape system for steady-state calculations and logs as well as redundancy. All test data are recorded digitally on industry-compatible computer magnetic tape. On-site readout of data from the CCDAS is available via the teletype. The CCDAS assists in pre- and posttest checkout and calibration of process and signal-conditioning instrumentation. During a test, the CCDAS records and logs loop conditions for operator information. The CCDAS also

Fig. B.5. Data-acquisition block diagram.

serves as an element of the safety system by performing overtemperature checks of approximately 325 bundle thermocouples during approach to full power and the blowdown transient. An on-site "quick look" at recorded data is available through use of software routines which plot the data on the storage display unit.

The time code generator-translator is used to supply timing signals to both the analog tapes and CCDAS during data runs and to decode the time information on the analog tape during posttest digitization. The associated tape search unit expedites location of the data to be digitized and initiates and stops digitization of data at preset time limits, thus minimizing operator involvement and eliminating digitization of extraneous data.

The analog strip-chart recorders are used primarily to obtain "quick look" data during CHF experiments and, possibly, for monitoring key variables during blowdown.

Additional details of components of this system are discussed in the following sections.

2.1.1 Signal conditioning

Much signal-conditioning equipment is required with the data-acquisition systems; the types of conditioners required include (1) temperature reference ovens, (2) strain-gauge bridge completion and conditioning circuits, (3) voltage-isolation amplifiers, (4) frequency converters, (5) resistance converters, and (6) signal amplifiers.

The temperature reference ovens provide a cold junction reference temperature for thermocouples. Since thermocouples constitute the bulk of the data sensors, most of the signal-conditioning equipment is of this type.

The strain-gauge bridge completion and conditioning equipment is associated with the strain-gauge-type transducers used for pressure, differential pressure, and drag disk measurements.

The voltage-isolation amplifiers isolate the data equipment from sensors having an excessively high common mode voltage on the signal leads, such as the heater rod current shunts.

The frequency converters alter the pulse output frequency of turbine meters to a proportional dc voltage signal.

The resistance converters are used with the resistance-type temperature sensors to convert resistance to a proportional dc signal.

Signal amplifiers provide conversion of low-level to high-level signals.

2.1.2 Computer-controlled data-acquisition system

The CCDAS consists of a Digital Equipment Corporation (DEC) PDP8/E computer and various peripheral devices and interfaces as listed in Table B.3. The nucleus of the software is the FOCAL* interpreter with modifications as made by the ORNL Instrumentation and Controls Division. Application programs are written in FOCAL, which is a high-level, scientific, interactive language.

*FOCAL is a registered trademark of DIGITAL Equipment Corporation.

Table B.3. Components of the CCDAS

Item	Description	Vendor
1	Computer, including 8K core memory and teletype control, PDP-8/E-AE	DEC
2	Additional 24K core memory	Fabritek
3	Programmable, real-time clock, DK8-EP	DEC
4	Power failure detector and auto restart, DP8-E	DEC
5	12-bit buffered digital I/O, DR8-EA (used to interface to timing and tape search subsystem and for alarm outputs)	DEC, ORNL
6	Magnetic tape controller and 1 transport, model 5091	Datum, Pertec
7	Cartridge disk controller and 1 drive, 1.6M word, model 3010	System Industries, Diablo
8	512-channel, analog input system and controller, model 120	Datum
9	Storage, display unit and interface, model 611	Tektronix, ORNL
10	Teletype, ASR-33	Teletype
11	Cabinets, 3 each	DEC

The number of process and data signals required to monitor and provide data from the THTF primary and secondary loops necessitated a computer-based data-acquisition system. These signals must be recorded in digital form to facilitate analysis of tests, to monitor loop conditions prior to each test, and to effect on-site conversion of critical data to engineering units. In general, the highest frequency component of these signals does not exceed 2 Hz; therefore, the acquisition speed of the CCDAS (20 samples/sec for 500 channels) is adequate. Most inputs are temperature signals from thermocouples located in the heater rods and in the test section coolant streams; the remainder of the signals come from sensing of flows, pressures, differential pressures, temperatures, amperages, voltages, etc., within the test bundle and in the coolant inlet and exit lines. Table B.4 lists the signals recorded by this system.

The analog input system for the THTF is capable of scanning, digitizing, and recording signals from 512 dc voltage sources in the ranges of 5 mV to 10.24 V. The system has a resolution of one part in ± 2048 , an accuracy of 0.3% of full scale, and a scanning rate of 10,000 samples (channels) per second. The input signal multiplexer is easily field expandable in eight-channel increments to a total of 1024 channels. Data are recorded in real time on industry-compatible seven-track magnetic tape, along with time code information for correlation purposes.

To achieve the high scanning rate demanded on the system, field effect transistors (FETs) are used to switch the input signals. Since the FETs will not tolerate input signals with common mode voltages greater than 10 V above ground peak to peak without degradation of accuracy and can be damaged by a higher voltage, protection is provided in the form of fuses that, when blown, preclude the acquisition of data from that input until the fuse is replaced. However, an effort is made to insure that the common mode voltages on signals from the sensors does not exceed 10 V peak to peak. Thus, isolation amplifiers are included in channels where signals have common mode voltages that cannot be reduced below 10 V, such as those monitoring generator current.

In addition to data acquisition and recording, the CCDAS serves as a primary safety system. Simultaneously with data acquisition, the CCDAS

Table B.4. Summary of measurement requirements in the THTF

Measurement location	Transient functions	Steady-state functions
<u>Temperature</u>		
1. Heater rod, interior and cladding	Thermal history of heater rod; onset of CHF	Operational control and initial conditions
2. Coolant, flow subchannels at bundle exit	Local enthalpy rise (vs bundle); radial uniformity in coolant distribution	Monitor coolant condition
3. Coolant, test section inlet and outlet	Bulk enthalpy conditions (flow reversals and rereversals)	Operational control and initial conditions; bundle enthalpy rise (heat balance)
4. Coolant, test section blowdown lines	Thermal history during blowdown	
5. Coolant, subchannels along flow shroud wall	Boundary-coolant thermal interaction	Monitor coolant condition; heat balance
6. Flow shroud and pressure housing	Boundary-coolant thermal interaction	Monitor test section; heat balance
7. Coolant, flow measurement stations	Thermodynamic state of coolant	Operational control
8. Coolant, heat exchanger inlet and outlet		Operational control and initial conditions; heat balance
9. Pressurizer, steam volume	Correlate with calculated response	Operational control
10. Pressurizer, exit line	Detect pressurizer voiding	Operational control
11. Secondary coolant, heat exchangers		Operational control; heat balance

Table B.4. (continued)

Measurement location	Transient functions	Steady-state functions
<u>Flow</u>		
1. Coolant, test section inlet and exit	Flow velocity; flow direction	Operational control and initial conditions; heat balance
2. Coolant, test section blowdown lines	Flow velocity	
3. Coolant, heat exchangers (primary and secondary flows)		Operational control; heat balance
<u>Pressure</u>		
1. Test section, inlet (flow stations)	Pressure history; thermodynamic state	Operational control and initial conditions
2. Test section, blowdown lines (flow stations)	Pressure history; thermodynamic state	
3. Test section, overall ΔP	Pressure history; thermodynamic state	Operational control and initial conditions
4. Test section, ΔP along flow shroud wall	Pressure history; thermodynamic state	
5. Heat exchanger, inlet and ΔP	Pressure history	Operational control
6. Pump suction, inlet and ΔP	Pressure history	Operational control
7. Pressurizer, steam volume	Pressure history	Operational control and initial conditions

Table B.4. (continued)

Measurement location	Transient functions	Steady-state functions
	<u>Power</u>	
1. Test section, overall and individual rod	Transient history	Initial conditions; heat balance
	<u>Time</u>	
1. Test section, blowdown lines	Blowdown history	

performs high-limit checking on all analog channels and actuates alarm relays in the event of out-of-limit conditions. Approximately 325 bundle thermocouples are connected to the CCDAS which are continuously checked for overtemperature conditions during powered operation. The maximum delay between the occurrence of an out-of-limit condition and the actuation of the appropriate alarm relays will be 350 msec for approach to power and 200 msec for the blowdown transient. In order to minimize the possibility of trips from noise, the alarm criteria is two successive samples out of limits during approach to full power and three successive samples during blowdown. Initially, the system will give an alarm and trip bundle power when any one signal exceeds the designated limit. However, with a minor software patch, the system can activate an alarm when "X" signals are out of limits and activate the trip when "Y" signals are out of limits. The high-limit set point for any channel is individually assigned via a simple FOCAL command. A watchdog timer contact is also incorporated to monitor the integrity of the CCDAS and give an alarm if the computer should fail.

2.1.3 Analog, magnetic tape recorder/reproducer system

Two, 14-channel, magnetic tape, recorder/reproducer systems are provided to record the extremely important high-frequency signals from the transient pressure and two-phase flow instrumentation during blowdown. These systems have an overall (record/reproduce) accuracy of 1% or better, multiple tape speeds covering the range of 15/16 to 60 in./sec, wide bandwidth electronics, tape servo and tachometer speed control, and the capability of recording in either direct or FM mode. Tape speeds are electronically switchable to record at any of the seven available tape speeds and to reproduce at any two speeds preselected from the available seven speeds.

Time-code and break-wire signals are recorded in the direct mode and use 4 of the available 28 channels. One channel on each system is used to record a reference signal in direct mode when operating with tape speed servo control. The remaining 22 channels are available for data. These channels are used in the FM mode to record signals during blowdown from fast-response (1000-Hz) pressure and differential pressure transducers, drag-disk flow elements, turbine meters, and gamma densitometers.

After completion of the test, the tape is played back and digitized via the on-site CCDAS discussed in the preceding section. All data and time-code information in one system is reproduced and digitized in parallel, or one data channel at a time may be reproduced and digitized along with the time-code information. The required record/reproduce speed ratio needed for digitizing the data is a function of both the number of channels played back and the highest frequency content required in the digitized data. In general, data are recorded at 30 ips and reproduced at 3 3/4 ips. By allocating an appropriate mix of fast and slower response signals on each tape unit, this 8-to-1 speed reduction allows all channels from a single tape unit to be digitized in parallel while still maintaining the required sampling rate.

2.1.4 Timing and tape search system

A time-code generator and tape-search unit is provided for data correlation purposes. An IRIG-A time-code signal superimposed on a 10-kHz carrier is recorded on one track of each analog tape unit and signals obtained from break wires below the rupture disks are registered on another track of each to establish the time of blowdown ($t = 0$). Together, these signals permit time correlation to within ± 0.1 msec between all data channels throughout the blowdown period.

The tape-search unit uses the reproduced time-code information to locate the desired data, to initiate digitization at the selected time, and to stop it after a preselected period, thus increasing the efficiency of the digitization operation.

2.1.5 50-channel thermocouple display and alarm system

A 50-channel Metrascope is used to provide additional display and overtemperature monitoring of bundle thermocouples. The Metrascope consists of type K thermocouple reference junction compensation, a high-speed solid-state (FET) multiplexer, adjustable high and low limits for each channel, a cathode-ray tube (CRT) display of thermocouple temperatures and alarms, and associated control electronics. The Metrascope provides an alarm relay each for high- and low-temperature conditions occurring on any

one channel. The high alarm relay causes an alarm and trip of bundle power; the low alarm relay is used only for indication of an open thermocouple and causes no control action.

The Metrascope, in conjunction with the CCDAS, will provide over-temperature monitoring of approximately 375 of the 420 to 460 total bundle thermocouples.

2.1.6 Multichannel analog strip-chart recorders

One or more multichannel strip-chart recorders are provided for trend recording of key parameters during test operations. These recorders are used primarily for obtaining a "quick look" at, and observing trends in, selected parameters during CHF experiments. A variety of instruments of this type (including 2, 4, 6, and 8 channel Sanborn recorders) is available at ORNL. The data recorded will vary from test to test.

2.2 Application

The PDP8E computer is a valuable tool for obtaining information required by the operator for loop operation. In addition, the computer is used for post-blowdown evaluation of data that will be used as input into the decision about the conditions for the next blowdown. The bulk of the data analysis and reduction is to be done by the IBM computers. In order to minimize the processing time of the raw data tapes written by the PDP8E computer for the IBM computers, the software development for both computers has to be treated as a unit. As shown below, the software requirements have been divided into three general areas.

2.2.1 Loop operation

This section describes a set of tasks that has been programmed on the PDP8E computer to be run before and after a blowdown test. This set of tasks is called the operation log program; a simplified flow diagram is shown in Fig. B.6. The tasks performed by this program are described below.

Fig. B.6. Operation log program flow diagram.

Initialize

This task is divided into two classes: initial setup and run setup. In the initial setup, all the information regarding the channel designation and the engineering unit conversion factors is requested by the computer program, and this information is stored in computer memory for use by the program. In the run setup mode, two inputs are required: the time interval between scans and the scan table number.

Fast scan 3 sec

This will cause the CCDAS to scan and record at high speed (10,000 channels/sec) 3 sec of data in accordance with the selected scan table.

Rewind and verify

This will cause the tape to rewind to the beginning of the last recorded file and to read the recorded data, to verify that data are being recorded, and to calculate a sampled average of the data recorded. If data are not being recorded properly, a message is typed out on the teletype indicating a recording error and the execution of the program is terminated.

Rod T/C check

This task examines the heater rod thermocouple data using the sampled average values previously determined. The average value for each level is determined and each thermocouple signal at that level compared to the average value for that level. If the thermocouple signal differs from the average value by an amount greater than the allowed error tolerance, the computer program causes an output message to be printed on the teletype indicating the error in the thermocouple signal.

Loop pressure drop check

This task uses the sampled average data and converts the millivolt signals into engineering units using calibration data. Loop pressure drop calculations are made using flow rate and density information, and these results are compared with measured signals. If the error exceeds the allowed error band, an output message is written on the teletype indicating which pressure transducer reading is exceeding the error band.

Bundle subcooling calculation

This task uses the sampled average data for temperature and pressure in the test bundle. A thermocouple conversion correlation is used to convert the millivolt signals into engineering units. Where more than one thermocouple is used to measure the temperature, an average of the reading is used. Pressure readings are used when available; when pressure readings are not available, an interpolation scheme is used to calculate the pressure. The teletype output for this task consists of the measured temperature, saturated temperature, and the amount of subcooling for each measurement point from test section inlet to test section outlet.

Flow-measurement check

This task compares the spool piece turbine meters to determine the value of loop flow and to verify each turbine meter. Spool piece temperatures are used to provide density corrections to the flow readings. A teletype output indicates if any turbine meter is outside an error tolerance.

Densitometer check

This task calculates the density based on temperature and pressure measurements and compares the calculated value with the measured density. A teletype output is provided if the comparison exceeds a preselected error tolerance.

Heat balance

This task calculates and compares the heat balances for the test section, heat exchangers, and other loop sections. A teletype output is provided to display the results of the heat balance calculation.

Assess loop conditions

This task scans data a given number of times with a selected time interval between scans. An output is printed on the teletype showing the average value and the drift rate for ten preselected variables.

TTY summary

This task provides a teletype output describing the loop conditions as defined by the last 3-sec data scan.

2.2.2 Preliminary evaluation of blowdown data using the PDP8E

The first question to be answered by the computer is whether there were any instrumentation failures in the measurement of important parameters. This answer would be one of the inputs required in making the decision about what conditions will be set for the next blowdown. Additional "quick-look" information could be provided by the computer as indicated in the following list:

1. Compare the instrumentation of pre-blowdown and post-blowdown to determine if any zero shift has occurred.
2. Check the power trace of all four generators by using the CRT display to verify that test conditions were met.
3. Verify the time at which the rupture disk ruptured. This is also important in the double-ended break to verify that both occurred at the same time or with a given time delay.
4. Determine from data the time to DNB for selected rod zones.
5. Verify spool piece instrumentation by using a mass balance calculation using flow rate and density data.
6. Compare measured coolant temperature with saturation temperature calculated from pressure measurements.

This list should not be considered as being complete but only to indicate what can be done using the computer.

2.2.3 Evaluation and analysis of data using IBM computers

The tape of recorded data produced by the PDP8E computer is sent to the IBM computer as soon as possible after a blowdown. The first process code will convert the raw data into engineering units and place the converted data on a disk file. The rest of the analysis codes will use this disk file as a data source; therefore, after a period of code testing, all the analysis results should be available about three days after a blowdown. We believe that the main analysis areas should be heat transfer calculations, time to DNB, heat transfer coefficient comparisons, and projections of fuel rod behavior. An optional task would be to obtain an improved power trace.

Heat transfer calculations for selected bundle locations

Determine the coolant temperature at the selected bundle location by using an appropriate calculation. If two-phase coolant is present at the selected location, the saturation temperature is to be obtained from pressure measurement. If the coolant is subcooled water or superheated steam and if subchannels have equal flow and all rods have equal power, the coolant temperature can be calculated from the enthalpy rise. In all other cases the use of a computer code such as COBRA will be necessary to determine coolant temperature. By using this coolant temperature and measured rod temperature, calculate the heat transfer coefficient and the heat flux between rod and coolant.

Time to DNB

Using measured rod temperatures, determine the time and location for the first DNB and determine how it spreads over the bundle.

Comparison of measured and predicted heat transfer coefficients

By using standard heat transfer correlations, calculate heat transfer coefficients and compare them with the one determined above. Codes such as RELAP and THETA would not be needed for this calculation since every region can be calculated separately. After a number of blowdowns have been made, the data can be used as a basis for obtaining an improved heat transfer correlation if required.

Projection of the experimental results to the temperature of a fuel rod

Since the thermal behavior of an electrically heated rod is different from a fuel rod, a translation code is needed to account for these differences in making projections of fuel rod behavior.

Improved power trace

Theoretically, it should be possible by using a different power trace to take into account the differences in the thermal behavior between heated rods and fuel rods. Practically, this is possible only to a certain degree and only for one axial level of the rod. The main problem is that the heat transfer to the coolant has an influence on the required power trace to match surface temperature of the heated rod and the fuel rod. A second problem is that for blowdowns with a short time to DNB, a very high rod

power would be required during the first few seconds of blowdown to match the surface temperature of a fuel rod. However, using iterative procedures, some compromise could be made to obtain the best power trace to obtain some agreement.

Appendix C

**PLAN AND ELEVATION DRAWINGS OF THE THTF SHOWING SIGNAL
INSTRUMENTATION LOCATIONS**

T-10000 06-309-D

LEGEND

ASTERISK INDICATES THAT BLOCK ONLY SHOWS A CONNECTION POINT FOR THE FIELD DEVICE AND NOT THE ACTUAL MOUNTING LOCATION OF THE DEVICE. IF ASTERISK DOES NOT APPEAR THEN THE BLOCK INDICATES THE ACTUAL MOUNTING LOCATION OF FIELD DEVICE.

FIELD DEVICE NO. (N - INSTRUMENT OR SENSOR).

DRAWING NO. - IF ASTERISK IS PRESENT BY BLOCK IT IS THE DWG. THAT SHOWS ACTUAL MOUNTING LOCATION OF FIELD DEVICE. IF ASTERISK DOES NOT APPEAR THEN IT IS THE DWG. THAT SHOWS TYPICAL INSTALLATION DET'S.

FIELD DEVICE NO. (N - INSTRUMENT OR SENSOR). THIS TYPE OF BLOCK INDICATES THAT SPECIAL DWG. DET'S. OF MOUNTING OR INSTALLATION ARE NOT REQ'D.

REFERENCE DRAWINGS

PLAN & ELEV. VIEWS OF CABLE TRAY, WIREWAY, CONDUIT DROPS & A.C. & SIGNAL PULL BOXES - LAYOUTS.

INSTRUMENT ROOM & FACILITIES, CABLE TRAY & WIREWAY - PLAN LAYOUT.

PLAN & ELEV. VIEWS OF SIGNAL INSTRUMENTATION LOCATIONS.

WIRE DRY & CABLE TABULATIONS.

PLAN & ELEV. VIEWS OF A.C. INSTRUMENTATION LOCATIONS.

INSTRUMENT INSTALLATION DETAILS.

INSTRUMENT LOCATION & MOUNTING DETAILS.

MISCELLANEOUS FIELD WIRING DETAILS.

CONDUIT & JUNCTION OR PULL BOX BILL OF MATERIAL.

INSTRUMENTED SPOOL PIECE ASSEMBLY & DETAILS.

06-300-D

= THRU

06-308-D

= 06-309-D THRU

06-315-D

= 06-316-A

SHEETS 1 THRU 97

= 06-317-D THRU

06-323-D

= 06-324-D THRU

06-331-D

= 06-332-D THRU

06-336-D

= 06-337-D THRU

06-340-D

= 06-307-D

= P-1000-100-E

= AND - 101-E

PLAN VIEW A-A AT 945'-0" ELEV.
SHOWS FROM 945'-0" ELEV. DOWN TO 930'-0" ELEV.

REVISIONS

Figure C.1

Figure C.2

Figure C.2

Figure C.3

Figure C.4

Figure C.5

Figure C.6

Figure C.7

FOR QA REQUIREMENTS
SEE QA-100-0

Figure C.7