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Quarterly Progress Report on Blowdown Heat Transfer Program for October-December 1975

D. G. Thomas
R. A. Hedrick

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OAK RIDGE NATIONAL LABORATORY

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$6.00 ; Microfiche \$2.25

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Contract No. W-7405-eng-26

Reactor Division

QUARTERLY PROGRESS REPORT ON BLOWDOWN HEAT
TRANSFER PROGRAM FOR OCTOBER-DECEMBER 1975

D. G. Thomas
R. A. Hedrick

Work funded by the Nuclear Regulatory
Commission under Interagency Agreement
40-495-75

MARCH 1976

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OAK RIDGE NATIONAL LABORATORY
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ORNL-TM-4655 (Vol. 1)	April-June 1974
ORNL-TM-4729 (Vol. 1)	July-September 1974
ORNL-TM-4805 (Vol. 1)	October-December 1974
ORNL-TM-4914 (Vol. 1)	January-March 1975
ORNL-TM-5021 (Vol. 1)	April-June 1975
ORNL-TM-5117	July-September 1975

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SUMMARY

1. PROGRAM PLANNING AND ADMINISTRATION

A revised test matrix was developed during an NRC Program Review on November 24 and 25. The principal changes are the addition of test 100, an isothermal blowdown with the heater rod bundle installed to permit acquisition of data required for tuning the RELAP core model, and moving the first test with full power on the rod bundle from test 104 to test 102.

2. TWO-PHASE FLOW INSTRUMENTATION STUDIES

Two-phase flow dispersers were designed, fabricated, and installed in the THTF for isothermal test 023. Preliminary calculations of mass flow through the instrumented spool pieces indicate that the screens improved instrument signal quality significantly. The drag disk strain gauge assemblies show an appreciable zero shift over a temperature range from ambient to blowdown conditions. Further, increased Reynolds numbers resulting from system heatup results in a drag crisis and a significantly reduced drag coefficient at elevated temperatures. Isothermal test data were utilized to quantify the extent of zero shift and change in drag coefficient of the THTF drag disk flowmeters. These correction factors were incorporated in preliminary calculation of mass flow in tests 021 and 023.

3. FORCED-CONVECTION TEST FACILITY (FCTF) OPERATION

The second heater taken from the production lot used to assemble THTF bundle 1 is undergoing blowdown testing in the FCTF. After two blowdowns and a total of 15.5 hr of operation, the heater is still in good operating condition. The heater contains 15 thermocouples — 10 in the sheath and 5 in the MgO inner core. One of the inner thermocouples was open before the heater was tested; all the other thermocouples are in good condition.

Measured values of pertinent parameters are presented for several FCTF blowdown experiments. The shortest observed time to CHF was about 4 sec. An investigation of the effect of break area on time to CHF has demonstrated a local maximum in a time-to-CHF vs break area curve. Indications of rewet and subsequent CHF have been observed in some tests. All the blowdowns were single-ended cold-leg break tests with a rapid reversal of flow and no subsequent rereversal.

4. PROGRAM PLANNING AND ANALYSIS

The results from isothermal tests 021 and 023 demonstrate the potential of the THTF for separate-effects tests of the effect of flow reversal and rereversal on events occurring during a hypothetical LOCA.

Multiple improvements have been made in the RELAP4 model of the THTF using the isothermal test data. Dry Run Commitment No. 4 was met on schedule.

The development of the inverse code remains on schedule.

All data-acquisition and -handling codes are being updated to process the powered-rod blowdown data.

5. THERMAL-HYDRAULIC TEST FACILITY (THTF) OPERATION

Isothermal tests 021 and 023 were performed successfully. Calibration data for the flow instrumentation were taken during heatup, and the tests met the planned objectives.

Several modifications have been made to the system in preparation for powered-rod blowdown and to improve the operation of the facility. The 49-rod bundle was installed.

6. THERMAL-HYDRAULIC TEST FACILITY INSTRUMENTATION

Work continues on improving the response of the gamma densitometers, in particular, their sensitivity to magnetic fields. The turbine meter bearing problem has been investigated further, with different bearings and rotors being tested.

Problems with the data-acquisition system have been identified and corrected. The system is being updated to handle the powered-rod blow-down operational and transient data.

The 49-rod bundle thermocouples have been connected, and the wiring has been verified.

The preliminary error analysis of the critical instrumentation in the THTF is complete.

7. HEATER ROD PROCUREMENT AND DEVELOPMENT

Problems continue with thermocouple procurement for bundle 2. Current schedules call for manufacture to begin in January 1976.

Watlow Electric Manufacturing Company is continuing investigation of the sheath gap problem.

1. PROGRAM PLANNING AND ADMINISTRATION

D. G. Thomas

The first phase of isothermal tests with the Thermal-Hydraulic Test Facility (THTF) was completed on Oct. 17, 1975. For these tests, the heater rod bundle was replaced by a 3.96-m-long (13-ft) section of 10.16-cm (4-in.) pipe. The tests conducted in this series are summarized in Table 1.1. The most notable results from the tests are (1) pressurizer could be effectively isolated from the remainder of the loop by placing a 0.635-cm (1/4-in.) orifice in the pipe connecting the pressurizer to the loop (test 002, Fig. 1.1); (2) with sufficient temperature difference between the loop fluid and pressurizer fluid ($\sim 140^{\circ}\text{C}$ or 250°F), the pressurizer fluid was clearly identifiable as it passed different temperature sensors around the loop as illustrated in Fig. 1.2 (test 002R); and (3) it was possible to obtain both flow reversal and rereversal with a double-ended blowdown in the THTF (tests 021 and 023). Further details of test results are given in subsequent sections of this report and in previous quarterly reports.

During an NRC program review on November 24 and 25, the test matrix was revised (Table 1.2). The principal changes are the addition of test 100, an isothermal blowdown with the heater rod bundle installed to permit acquisition of data required for tuning the RELAP core model, and moving the first test with full power on the rod bundle from test 104 to test 102. To provide an additional margin of heater rod safety, the heater rod power will be turned off at the instant of blowdown.

Table 1.1. Isothermal tests conducted in the THTF

Test No.	Date	Test conditions							Significant results
		Temperature		Pressure		Break			
		°C	°F	MPa	psig	Area		Location	
cm ²	ft ²								
001	2/21/75	232	~450	8.96	1300	3.14	0.0034	Outlet	Blowdown; first successful test of pump seal; loop inventory control problems
002	4/18/75	193	~380	13.24	1920	6.27	0.0067	Inlet	No blowdown; major failure of pump seal
002	6/13/75	271	~520	14.17	2055	6.27	0.0067	Inlet	Blowdown; failed to achieve test conditions of 286°C (547°F) and 15.51 MPa (2250 psig) because of excessive seal leakage; results demonstrate effect of isolation of pressurizer by 0.635-cm (1/4-in.) orifice
002R	8/16/75	204	~400	15.51	2250	6.27	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	286	547	15.51	2250	6.27	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	286	547	15.51	2250	12.54	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	286	547	15.51	2250	12.54	0.0135	Inlet, outlet (30:70 split)	Blowdown; test conditions achieved; completed flow calibrations; no seal leakage; flow reversal and rereversal occurred

Fig. 1.1. Pressures at inlet plenum of test section.

Fig. 1.2. Pressurizer fluid temperature spike at different locations in test 002R.

Table 1.2. ORNL Blowdown Heat Transfer (BDHT) Separate-Effects Program
test matrix — first 49-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 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 initia- tion, 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.

2. TWO-PHASE FLOW INSTRUMENTATION STUDIES

J. D. Sheppard

2.1 Flow Dispersers for the THTF

Flow dispersers were designed, fabricated, and installed in the THTF instrumented spool pieces for isothermal test 023. The design was essentially the same as that designated as LS-3+2 and tested in the air-water, two-phase flow facility.¹ These flow dispersion screens consisted of two 30-mesh, 0.3-mm (12-mil) wire screens sandwiched between three 5-mesh 0.89-mm (35-mil) wire screens.

The screen assembly was welded between two stainless steel rings (e.g., see Ref. 2, p. 53) for installation in the spool piece flanges. It has been shown that the principal benefit of flow dispersion screens is to condition the flow impinging on the drag disk. Therefore, as a preliminary test of dispersers under the blowdown conditions of test 023, one disperser was installed on each of the four spool pieces at the flange nearest the drag disk. Examination of all four flow dispersers following test 023 showed no effect of the blowdown.

2.2 Hot Calibration of the THTF Drag Disks

Calibration of two-phase flow monitoring instruments began with water tests at ambient conditions in a system traceable to the National Bureau of Standards (Ref. 3, p. 52) and ambient two-phase tests in the air-water facility.¹

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. Figure 2.1 shows the signal of the drag disk on the horizontal inlet spool piece as a function of temperature for two system heatups. The data include flow rates from 0.8 to 2.3 m³/sec (200 to 600 gpm). Momentum changes over this range of flows were accounted for by dividing the drag disk reading by the velocity head, ρV^2 , where the velocity was given by the turbine reading and density was determined from fluid temperature. Since the drag disk reading, $\overline{\rho V^2}$, is a measure of force on the target, the normalized reading is a drag coefficient. The value of this coefficient varied from ~ 1.0 at ambient conditions to ~ 0.3 to 0.6 at temperatures of 149 to 343°C (300 to 650°F).

Each of the heatup tests included a "no-flow" condition which provided information on zero shift as a function of temperature. Figure 2.2, 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 $-1500 \text{ kg m}^{-1} \text{ sec}^{-2}$ ($-1000 \text{ lb}_m \text{ ft}^{-1} \text{ sec}^{-2}$) at the blowdown temperature of $\sim 287^\circ\text{C}$ (550°F). The zero shift for the vertical outlet spool piece was $+2200 \text{ kg m}^{-1} \text{ sec}^{-2}$ ($\sim 1500 \text{ lb}_m \text{ ft}^{-1} \text{ sec}^{-2}$) and for the vertical inlet spool piece was $-9300 \text{ kg m}^{-1} \text{ sec}^{-2}$ (approximately $-6200 \text{ lb}_m \text{ ft}^{-1} \text{ sec}^{-2}$). The zero shift for the vertical inlet spool piece at 287°C (550°F) is equivalent to a flow rate of about 1.3 m³/sec (350 gpm) in a direction opposite steady-state flow.

Figure 2.3 shows the effect of compensating for the zero shift in the data shown in Fig. 2.1. The scatter of the data was reduced significantly from that in Fig. 2.1, and the drag coefficient $\overline{\rho V^2}/\rho V^2$, was ~ 0.6 at blowdown temperatures.

The data are presented as a function of Reynolds number in Fig. 2.4, using the drag disk target diameter as the characteristic length. At constant velocity, higher Reynolds numbers correspond to higher temperatures because of viscosity effects. For Reynolds numbers greater than

Fig. 2.1. Uncorrected data of drag disk 22 (horizontal inlet) during THTF heatup prior to isothermal tests 021 and 002R2. (Data not corrected for zero shift; normalized to fluid momentum ρV^2 using turbine velocity.)

Fig. 2.2. Effect of temperature on drag disk reading with no flow in THTF as determined from loop heatup for isothermal tests.

Fig. 2.3. Data of drag disk 22 (horizontal inlet) after correction for zero shift of strain gauge (heatup for isothermal tests 021 and 002R2; subcooled water; data normalized to fluid momentum ρV^2 using turbine velocity).

Fig. 2.4. Temperature corrected data of drag disk 22 (horizontal inlet) as a function of Reynolds number during THTF heatup for isothermal tests 021 and 002R2 (drag disk data normalized to fluid momentum ρV^2 using turbine velocity).

3×10^5 , the drag coefficient was $0.615 \pm 7\%$. For comparison, the Reynolds number for 1.6 m³/sec (420 gpm) and 287°C (550°F), typical of THTF operation, is 4.6×10^5 . The data shown in Fig. 2.4 for Reynolds numbers less than 3×10^5 are characteristic of the drag crisis. Szechenyi⁴ has shown that the drag crisis may occur for Reynolds numbers of the order of $\sim 10^5$, depending on surface roughness of the bluff body and fluid turbulence intensity.

2.3 Mass Flow Rate

Utilizing the instrument calibration results discussed above, mass flow rates were calculated for the transient of isothermal test 023.

Figure 2.5 shows mass flow G discharging through the vertical outlet spool piece (No. 1 outlet) calculated by two different one-velocity models, $G = \rho_a V_T$ or $G = \sqrt{\rho_a \rho V^2}$, where ρ_a is the apparent density given by the densitometer, V_T is the characteristic velocity given by the turbine meter, and ρV^2 is fluid momentum given by the drag disk. The good

Fig. 2.5. Mass flow from vertical outlet spool piece during isothermal blowdown 023 (positive flow is in direction of flow prior to blowdown and toward exit break; Dec. 5, 1975).

agreement between these two models shown by the figure indicates that the characteristic velocities of both the turbine and drag disk were similar and flow was relatively uniform. Initial conditions were loop temperature 286°C (547°F), test section outlet pressure $1.55 \times 10^7 \text{ N/m}^2$ (2250 psig), and test section flow $1.6 \text{ m}^3/\text{sec}$ (420 gpm). The total break area of $1.25 \times 10^{-3} \text{ m}^2$ (0.0135 ft^2) was distributed 70% at the outlet leg and 30% at the inlet leg. Mass flow prior to blowdown, designated as the positive direction, was $\sim 3200 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($650 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$); for this spool piece, positive flow is toward the blowdown orifice and away from the test section. Immediately at blowdown, mass flow dropped to $\sim 1560 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($320 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$) and then more slowly decelerated to a flow reversal at nearly 2 sec. Maximum flow back toward the test section was $-1470 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($-300 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$) at 3 sec after blowdown, and flow reversed at about 4 sec. From 5 to 20 sec after blowdown, mass flow decreased from a maximum of $\sim 1860 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($380 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$) to zero.

Figures 2.6 to 2.8 show mass flows during test 023 for the three other spool pieces. Flow through the horizontal inlet (Fig. 2.6) was always positive (toward the inlet break), increasing immediately at blowdown to $\sim 5380 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($1100 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$) and decreasing to $1470 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($300 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$) at 15 sec. Flow through the horizontal outlet spool piece (Fig. 2.7) was always negative (toward outlet break), reversing immediately at blowdown from $+3180 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($+650 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$) to $-6060 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($-1240 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$) at 15 sec. From 25 to 35 sec, the turbine velocity was quite high and off scale, but steam density was too low to result in appreciable mass flow.

Trends in the mass flow at the vertical inlet spool piece (Fig. 2.8) were similar to those at the vertical outlet. However, after 5 sec the two mass flow models showed poor agreement with the values given by the turbine and the densitometer (circles in Fig. 2.8) near zero. The turbine signal later in the blowdown was quite erratic, and the turbine readings after 5 sec may have been in error.

Graphical integration of the four curves (Figs. 2.5 to 2.8) gave a net flow toward the breaks of 348 kg (766 lb_m) of water compared to an initial loop capacity of 432 kg (950 lb_m). That is, approximately 81%

Fig. 2.6. Flow through horizontal inlet spool piece during isothermal blowdown 023 (positive flow has direction same as that prior to blowdown and toward inlet break; Dec. 5, 1975).

of the system fluid mass was discharged through the inlet and outlet breaks in the first 20 sec of isothermal test 023.

The good agreement between the two, one-velocity mass flow models in Figs. 2.5 to 2.8 is partially attributed to the use of flow dispersion

Fig. 2.7. Flow through horizontal outlet spool piece during isothermal test 023 [positive flow has direction same as that prior to blowdown; negative flow is toward exit break; total area - 12.54 cm^2 (0.0135 ft^2), 30% inlet, 70% exit; Dec. 5, 1975].

Fig. 2.8. Mass flow at vertical inlet spool piece during isothermal blowdown 023 [positive flow is in same direction as flow prior to blowdown; negative flow is toward inlet break; total break = 12.54 cm² (0.0135 ft²), 30% inlet, 70% exit; Dec. 5, 1975].

screens in the spool pieces for test 023. For comparison, mass flows through the vertical inlet and outlet spool pieces during test 021 are shown in Figs. 2.9 and 2.10 respectively. Initial conditions were essentially the same as for test 023; the 1.25×10^{-3} m² (0.0135-ft²) break

Fig. 2.9. Mass flow at vertical inlet spool piece during isothermal test 021 (50-50 break; negative flow is toward break).

Fig. 2.10. Mass flow at vertical outlet spool piece during isothermal test 021 (50-50 break; negative flow is toward break).

area was split evenly between inlet and outlet legs for test 021. Comparison of Figs. 2.5 and 2.9 for the vertical outlet spool piece, for example, shows agreement of the two mass flow models to be significantly better in test 023 than in test 021. For example, in test 021 at ~ 2.5 sec the mass flow determined using the turbine reading was $-2810 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($-575 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$), while the flow determined by the drag disk reading was about a factor of 2 greater, $-5570 \text{ kg sec}^{-1} \text{ m}^{-2}$ ($-1140 \text{ lb}_m \text{ sec}^{-1} \text{ ft}^{-2}$).

3. FORCED-CONVECTION TEST FACILITY (FCTF) OPERATION

J. D. White

3.1 Heater W150-90 Tests

A second heater (W150-90) from the production lot used to assemble THTF bundle 1 has been installed in the FCTF and has undergone two blowdowns from 122 kW. The pressurizer was valved off prior to each blowdown, thereby reducing effective loop volume from 45.3 dm³ (1.6 ft³) to 34 dm³ (1.2 ft³). Critical heat flux (CHF) conditions occurred during each blowdown, and heater temperatures in excess of 1090°K (~1500°F) were reached during the first blowdown. The heater is still in good operating condition after a total of 15.5 hr of operation. The heater was energized at full power for 8.8 hr. Table 3.1 is a summary of the operational history of all BDHT heaters tested in the FCTF.

Heater W150-90 is a type H heater with 10 sheath thermocouples and 5 interior thermocouples, 14 of which are in good condition. Thermocouple IV-JM5 was open before installation in the FCTF. The axial and azimuthal locations of the thermocouples are shown in Fig. 3.1.

The first test on heater W150-90 was a series of steady-state power levels at a loop temperature of 422°K (300°F) with a test section flow rate of 3.8 dm³/sec (60 gpm). The data obtained during this test will be used to characterize the behavior of the heater thermocouples. The heater was also maintained at a loop temperature of 122 kW and 561°K (550°F) for 4 hr during this run to determine if the heater performance changed with time at full power. No significant changes in thermocouple outputs were observed during the 4-hr period. The data taken during the first part of the test are undergoing analysis.

3.2 Blowdown Test Results

Some of the measured parameters in blowdown experiments are time to CHF, pressure vs time, flow rate vs time, heater temperatures vs time, and density vs time. The important parameters which may be calculated from the measured parameters are CHF, quality, heater skin temperature,

Table 3.1. Operational history of Watlow indirect heater assemblies

	Preprototype heater			Prototype heater		Production heater	Production heater
	150-1	150-3	150-2	150-5	150-1	150-74	150-90
Number of blowdowns							
Total power at blowdown, kW							
75	1		3	1			
100	2	1	4		1	1	
122-144	<u>5</u>	<u>2</u>	<u>4</u>	<u>9</u>	<u>3</u>	<u>19</u>	<u>2</u>
Total	8	3	11	10	4	20	2
Total hours with power on	44	35	31	43	42	99.3	15.5
Total hours at full power	6	1	0.5	8.5	10	35.1	8.8
On-off cycles	34	22	11	18	12	34	3
Fate	Fail ^a	Fail ^b	Retire	O-ring failure	O-ring failure	Diverted to bench tests	Operating

^aSplit in sheath, sheath damaged by centering screw.

^bSplit in sheath.

Fig. 3.1. Schematic of FCTF heater (Watlow W150-90) showing thermocouple locations and heat zone layouts. Dimensions are in meters (to convert to feet, multiply by 0.3048 ft/m).

and pre- and post-CHF heat transfer coefficients. A few of the important parameters measured during the blowdown testing of the BDHT heaters are presented in this report.

The FCTF is presently limited to an operating pressure of 10.34 MN/m² (1500 psi) with a temperature at the inlet to the test section of 561°K (550°F) and an outlet temperature of 584°K (592°F) when the rod power is 144 kW. The test section is a concentric annulus formed by a 3.8-cm-OD, 3.2-cm-ID (1 1/2-in.-OD, 1 1/4-in.-ID) core barrel inside a pressure housing fabricated from 5.1-cm (2-in.) sched-80 pipe (ID = 4.93 cm, 1.939 in.). A schematic view of the test section cross section is shown as Fig. 3.2, and the principal loop components are illustrated in

ORNL-DWG 74-10784R

Fig. 3.2. Cross-sectional view of FCTF test section.

Fig. 3.3. A canned rotor pump delivers $1.26 \text{ dm}^3/\text{sec}$ (20 gpm) of demineralized water to the test section, and external loop heaters maintain the test section inlet water temperature at 561°K (550°F). The water flows into the test section, down the outside of the core barrel, and then up the inside of the core barrel through the annular region surrounding the heater. The mass velocity of water flowing by the heater is about $1360 \text{ kg m}^{-2} \text{ sec}^{-1}$ ($10^6 \text{ lb}_m \text{ hr}^{-1} \text{ ft}^{-2}$). The water then flows from the test section through an instrument line containing pressure transducers, thermocouples, a drag disk, a densitometer, and a turbine meter. A pressurizer maintains the loop pressure at 10.34 MN/m^2 (1500 psi). In its present configuration, the FCTF has a volume/power ratio of $0.3 \text{ m}^3/\text{MW}$ and only single-ended cold-leg break tests are possible.

A blowdown is initiated by overpressurizing the rupture disk station. After both disks rupture, flow through the test section reverses and exits the loop through a "break area" orifice immediately upstream of the upstream rupture disk. The drag disk and turbine meter indications demonstrate that reversal is very rapid and that no rereversal of flow occurs. The fluid in the inlet (cold-leg) side of the loop can communicate with the break by flowing around the core barrel rather than flowing back through the heat exchanger, instrument line, and the test section. No flow instrumentation is in the cold-leg side at this time. Modifications to provide a "double-ended" cold-leg break and to allow an operating pressure of 15.5 MN/m^2 (2250 psi) are planned.

Heater power is maintained at the preblowdown level until a portion of the heater enters a CHF regime. At onset of CHF, the heater sheath thermocouple outputs increase at a rate of about $110^\circ\text{K}/\text{sec}$ ($200^\circ\text{F}/\text{sec}$) until they reach about 867°K (1100°F). At this time, overtemperature trip monitors turn off heater current. Thirty seconds after blowdown initiation, a fine mist of water flows from a ring at the top of the test section, entering at about 300°K (80°F) and $12.6 \text{ cm}^3/\text{sec}$ (0.2 gpm), and quenches the heater.

During the blowdown, approximately 60 instruments — pressure transducers, thermocouples, flow indicators, etc. — are monitored 10 times per second and the measurements are recorded on magnetic tape. These digitized data are then analyzed to produce engineering units, statistical analyses, and calculations of heat transfer parameters.

Fig. 3.3. Forced Convection Test Facility (FCTF).

Typical pressure and heater temperature traces are shown in Fig. 3.4. The pressure curves labeled "outlet" and "inlet" are the outputs of pressure transducers located at the test section outlet and inlet respectively. The sheath thermocouple traces indicate that CHF conditions began at the level of thermocouple A1 approximately 8 sec after blowdown. This thermocouple is the bottom-most thermocouple in the heater and is nearest the

Fig. 3.4. Depressurization curves and sheath thermocouple response during blowdown in FCTF [rod power = 144 kW, break area 4.74 cm^2 (0.0051 ft^2), system volume = 0.071 m^3 (2.5 ft^3)].

test section outlet during a blowdown. The A1 thermocouple trace also shows evidence of a rewet and subsequent CHF. As shown by the traces of thermocouples B1 and B2, the CHF area spreads over the heater with time.

This effect is shown more clearly in Fig. 3.5, where the direction of blowdown flow is from the top of the heater to the bottom or from right to left. The data for the five blowdowns shown include the range of observed behavior during most of the blowdown testing done in the FCTF.

Fig. 3.5. Propagation of CHF along heater rod during blowdowns in FCTF (solid points indicate thermocouple showing highest temperature); $P = 10.34 \text{ MN/m}^2$ (1500 psi), $t_{in} = 561^\circ\text{K}$ (550°F).

The earliest time to CHF observed was about 4 sec, as shown in the bottom trace. In this case, the break area was the area of the pipe [23.3 cm^2 (0.025 ft^2)] and the initial rate of depressurization was about $1.38 \text{ MN/m}^2 \text{ sec}$ (200 psi/sec). The bar graph at the top of the figure shows the stepped chopped cosine heat flux distribution of the heaters. A comparison between the upper and lower graphs will determine the location of CHF area with respect to a certain heat flux zone. Two conditions limit the use of these figures to determine the extent of CHF area with long times after the first incidence of CHF. The first is that power was tripped off whenever a sheath couple reached a preset temperature; the second is that the heaters with which these data were obtained had no thermocouples in heat flux zones I, I', II, and II'.

The effect of break area on test section pressure during blowdown is shown in Fig. 3.6. These curves show that the fastest blowdown yielded a time to CHF of about 4 sec, while the slowest blowdown yielded a time to CHF of only 5 sec. The CHF pressure, however, was $\sim 4.14 \text{ MN/m}^2$ (600 psi) for the fast blowdown and $\sim 8.27 \text{ MN/m}^2$ (1200 psi) for the slow blowdown. The relationship between break area and system volume on time to first CHF is shown in Fig. 3.7. At break areas greater than 1.9 cm^2 (0.002 ft^2), the time to CHF decreases with increasing break area. In this region, the time of CHF is always greater for larger loop volumes.

At smaller break areas, the time to CHF begins to decrease with decreasing break area. (This effect has been investigated for only one value of loop volume at this time.) Each data point shown on the figure is repeatable, with little variation in time to CHF or location of first CHF. In the small-break-area regime, CHF occurs at considerably higher pressures than in the large-break-area regime. For large-break areas, densitometer indications are that the CHF is a dryout phenomenon; in the small-break range, the CHF may be caused by a departure from nucleate boiling. Further data analysis and subsequent experimentation to determine the cause of the maximum in the curve are planned. This work will be a complement to the normal heater testing.

Measured parameters for 31 blowdowns are shown in Table 3.2. In the table, the first two digits represent the calendar year (73 = 1973); the second two digits represent the month (11 = November); and the last digit

Fig. 3.6. Time to CHF observed in single-rod facility with different blowdown conditions.

represents the number of blowdowns performed during that month. The power is total heater power — maintained constant during blowdown until after CHF. The $\dot{q}''_{CHF}$ is the value of heat flux at steady state in the region where CHF was first observed.

Table 3.2. FCTF blowdown test data

Run No.	Power (kW)	Break area		Time to first CHF (sec)	$\dot{q}''$ CHF		Loop volume ^a		First CHF thermocouple designation	Distance from lower end of heated zone		Pressure at test section outlet at time of CHF		Time at power after blowdown (sec)	
		cm ²	ft ²		Btu/hr ft ² × 10 ⁻⁶	MN/m ²	dm ³	ft ³		m	in.	MN/m ²	psia	BD power	Decay
73-11-6 ^b	150	4.74	0.0051	8.1	0.587	1.85	70.8	2.5	NA	1.51	59.6	4.04	586	8.6	0
73-11-8	98	4.74	0.0051	10.7	0.325	1.02	70.8	2.5	NA	1.35	53.1	2.69	390	11.9	0
73-12-1	149	4.74	0.0051	8.3	0.587	1.85	70.8	2.5	NA	1.90	74.7	4.25	617	10.65	0
73-12-2	102	4.74	0.0051	10.7	0.398	1.25	70.8	2.5	NA	1.90	74.7	2.86	415	12.9	0
74-1-1	74	4.74	0.0051	11.0	0.245	0.77	70.8	2.5	NA	1.35	53.1	2.52	365	14.1	5.8
74-1-2	150	4.74	0.0051	8.2	0.498	1.57	70.8	2.5	NA	1.35	53.1	4.72	685	10.8	8.5
74-6-1 ^c	139	4.74	0.0051	7.4	0.477	1.50	70.8	2.5	IV-F1	1.10	43.2	3.62	525	7.95	12.5
74-6-2	139	4.74	0.0051	7.6	0.477	1.50	70.8	2.5	IV-E1	1.10	43.2	3.38	490	9.15	11.25
74-7-1	136	4.74	0.0051	7.8	0.588	1.85	70.8	2.5	V-H3	2.26	89	3.28	475	10.3	9.2
74-7-2	136	4.74	0.0051	8.0	0.588	1.85	70.8	2.5	V-H3	2.26	89	3.31	480	10.5	9.0
74-9-3 ^d	100	7.92	0.00852	6.6	0.348	1.10	70.8	2.5	NA	1.22	48	3.31	480	8.55	10.75
74-9-4	139	7.92	0.00852	6.4	0.480	1.51	70.8	2.5	NA	1.22	48	3.65	530	9.0	11.0
74-9-5	138	2.39	0.00257	8.4	0.480	1.51	70.8	2.5	NA	1.22	48	4.72	685	10.1	10.0
74-10-6	137	19.05	0.02051	6.6	0.600	1.89	70.8	2.5	NA	2.06	81	3.41	495	9.4	10.3
74-11-2 ^e	100	19.05	0.02051	7.1	0.431	1.36	70.8	2.5	V-H3	2.26	89	3.21	465	12.10	10.15
74-12-1	144	19.05	0.02051	6.2	0.621	1.96	70.8	2.5	V-F2	1.40	55	3.59	520	9.15	10.25
74-12-3	144	19.05	0.02051	4.0	0.621	1.96	45.3	1.6	V-F4	1.40	55	4.62	670	6.9	10.3
75-1-2	144	4.74	0.00513	4.8	0.621	1.96	45.3	1.6	V-F2	1.40	55	4.14	600	7.1	10.35
75-2-1	144	2.39	0.00257	6.1	0.621	1.96	45.3	1.6	V-F2	1.40	55	4.90	710	8.65	10.25
75-2-2	144	0.59	0.00064	4.7	0.621	1.96	45.3	1.6	V-F2	1.40	55	8.41	1220	6.4	0
75-2-3	144	1.19	0.00128	7.9	0.621	1.96	45.3	1.6	V-F2	1.40	55	6.17	895	9.85	8.25
75-2-4	144	0.81	0.00087	5.9	0.621	1.96	45.3	1.6	V-F2	1.40	55	7.21	1045	7.85	8.35
75-3-1	144	0.81	0.00087	6.7	0.621	1.96	45.3	1.6	V-F2	1.40	55	7.21	1045	8.75	8.38
75-5-2	144	2.39	0.00257	6.1	0.621	1.96	45.3	1.6	V-F2	1.40	55	4.79	695	8.25	8.3
75-5-7	122	2.39	0.00257	6.2	0.526	1.66	45.3	1.6	V-F2	1.40	55	4.74	688	8.7	8.8
75-5-8	122	1.19	0.00128	9.2	0.526	1.66	45.3	1.6	V-F2	1.40	55	5.45	790	11.55	8.15
75-5-9	121	0.81	0.00087	8.9	0.526	1.66	45.3	1.6	V-F2	1.40	55	6.52	945	10.75	6.3
75-7-1	143	0.46	0.00049	5.0	0.621	1.96	45.3	1.6	V-F2	1.40	55	8.58	1245	6.3	0
75-7-2	122	0.46	0.00049	5.5	0.334	1.05	45.3	1.6	III-D1	0.94	36 7/8	8.31	1205	9.75	0
75-7-3	122	0.46	0.00049	6.7	0.334	1.05	45.3	1.6	III-D1	0.94	36 7/8	8.03	1165	17.85	6.35
75-8-1	122	0.46	0.00049	6.8	0.334	1.05	45.3	1.6	III-D1	0.94	36 7/8	8.07	1170	16.25	6.5

^aIncludes 14.2 dm³ (0.5 ft³) pressurizer volume.^bW150-2 preprototype heater.^cW150-5 prototype heater.^dW150-1 prototype heater.^eW150-74 production heater.

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Fig. 3.7. Effect of break area and system volume on time to CHF [$P = 10.34 \text{ MN/m}^2$ (1500 psi), $t_{in} = 561^\circ\text{K}$ (550°F)].

4. PROGRAM PLANNING AND ANALYSIS

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N. E. Clapp* L. J. Ott
K. G. Turnage M. D. White

4.1 Double-Ended Blowdown Tests

Two double-ended isothermal blowdown tests have been conducted in the Thermal-Hydraulic Test Facility (THTF), which is shown schematically with instrument locations in Fig. 4.1. Test 021 was conducted with the break area equally divided between the inlet and outlet of the test section; for test 023 the break was split 70% at the outlet and 30% at the inlet. Both tests were conducted from initial conditions of loop temperature [$\sim 559.3^\circ\text{K}$ (547°F)], test section outlet pressure $\sim 15.513 \text{ MN/m}^2$ (2250 psig), and test section flow rate $\sim 0.0265 \text{ m}^3/\text{sec}$ (420 gpm).

The signals from the turbine meter at the test section inlet and outlet are shown in Figs. 4.2 and 4.3 respectively. These responses, taken during test 023, demonstrate the potential of the THTF for separate-effects tests of the effect of flow reversal and rereversal on events occurring during a hypothetical LOCA.

4.2 RELAP4 Modeling

Preliminary data from the isothermal test series have been incorporated into the loop response model. Improvements have been made in pressurizer response, pump modeling, critical flow calculation, and model running time.

Dry Run Commitment No. 4 was fulfilled on schedule with the transmittal of a powered-rod, double-ended blowdown calculation. The calculated response of the spool pieces from this run supplied boundary conditions for the multichannel core model. This model was then used to calculate the local fluid conditions and electric pin response for the hypothetical transient.

Specified operational upsets were modeled using the five-node core-loop model. These runs provided information necessary for setting of the safety

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Fig. 4.1. Thermal-Hydraulic Test Facility, ORNL-PWR Blowdown Heat Transfer Separate Effects Program.

Fig. 4.2. Flow rate from turbine meter (spool piece 2, inlet side of test section); isothermal blowdown test 023 (Oct. 17, 1975).

Fig. 4.3. Flow rate from turbine meter (spool piece 1, outlet side of test section); isothermal blowdown test 023 (Oct. 17, 1975).

interlocks which protect the major loop components during powered-rod operation.

4.3 Inverse Code Development

The development of an inverse code remains on schedule. This code will calculate heat transfer coefficients from experimental data and boundary conditions from a RELAP4 calculation. This code, which is in the first programming and debugging phase, is the first of a four-part inverse code package development.

4.4 Data-Acquisition Codes

The FOCAL system has been modified to provide additional capabilities. The operator's log program for the heated rod blowdown tests is being modified to incorporate the changes in the FOCAL system, and several new FOCAL programs have been written to support initial checkout of the loop instrumentation.

4.5 Data-Processing Codes

Data-processing codes are being prepared to handle the data that will be generated by the heated-rod blowdown tests. The engineering units code is being modified to include the conversion of the additional instrumentation required in the heated-rod tests, and a computer code is being developed to obtain statistical analyses for the digitized FM tape data. A computer code has been written to provide the capability of detailed examination of selected portions of the data.

4.6 Data-Analysis Codes

The plotting code is being revised to handle the increased number of plots that will be required for the heated-rod blowdown tests. In addition, the code is being modified to label axes with both SI units and English units as a preliminary step toward total conversion to SI units.

5. THERMAL-HYDRAULIC TEST FACILITY (THTF) OPERATION

R. E. Helms R. E. Bohanan

5.1 Mechanical Operation

During this period, the THTF was operated successfully, completing the last two planned isothermal tests prior to installation of the bundle. These were tests 021 (Sept. 30, 1975) and 023 (Oct. 17, 1975). The operating crew was:

R. E. Bohanan	R. E. Helms
N. E. Clapp	A. F. Johnson
B. G. Eads	W. L. Ragan
C. A. Gifford	M. D. White
R. A. Hedrick	J. E. Wolfe

Both tests were double-ended breaks of 12.54 cm^2 (0.0135 ft^2) total area. This area was divided equally between the test section inlet and outlet in test 021 and was divided 70% (outlet) and 30% (inlet) in test 023. For both tests, the loop temperature was $\sim 559.3^\circ\text{K}$ (547°F), the test section outlet pressure was $\sim 15.513 \text{ MN/m}^2$ (2250 psig), and the flow rate was $\sim 0.0265 \text{ m}^3/\text{sec}$ (420 gpm). Both tests are summarized below.

Test 021

The THTF rupture disk initiation system produced ruptures in the two disk assemblies within 10 msec of each other. These assemblies are shown in Figs. 5.1 and 5.2.

The leakage through the Bingham pump seals (Durametalllic design outboard and modified Bingham design inboard) was less than 10 cc/min.

Flow instrumentation calibration data were taken at a pressure of 10.342 MN/m^2 (1500 psig); flow rates of 0, 0.0221, 0.0303, and $0.0379 \text{ m}^3/\text{sec}$ (0, 350, 480, and 600 gpm); and temperatures of 477.59°K (400°F) and 533.15°K (500°F). Additional data were taken at the same pressure but at a temperature of 559.3°K (547°F) and flow rates of 0, 0.0189, 0.0265, 0.0347, and $0.0379 \text{ m}^3/\text{sec}$ (0, 300, 420, 550, and 600 gpm).

Additional cooling water capacity was provided to all densitometers. The cooling water temperature during this test did not exceed 294.26°K (70°F), and the erratic signals previously observed did not appear.

Fig. 5.1. Double-ended blowdown test C21. Test section outlet rupture disk, view from inlet end.

Fig. 5.2. Double-ended blowdown test 021. Test section inlet rupture disk, view from inlet end.

After the initial drop to saturation pressure, the depressurization curve followed quite closely the predicted curves for a guillotine break in a large PWR.

The pressure-suppression system adequately contained the discharge from the THTF. Maximum water temperature was 344.26°K (160°F), and no steam escaped from the 15.24-cm (6-in.) vent line.

Test 023

Reproducibility was shown in the THTF rupture disk initiation system by rupture of the two disk assemblies within 10 msec of each other. The assemblies for this test are shown in Figs. 5.3 and 5.4.

Bingham pump seal leakage was again minimal.

Additional calibration data for the flow instrumentation were taken at a pressure of 10.342 MN/m² (1500 psig); temperatures of 366.48, 449.82, 505.37, and 559.3°K (200, 350, 450, and 547°F); and flow rates of 0, 0.0126, 0.0189, 0.0379 m³/sec (0, 200, 300, and 600 gpm).

Comparisons of the results of tests 021 and 023 will allow evaluation of the effect of unequal break areas.

5.2 THTF Modifications

Installed in the Bingham pump are seals of different designs. The inboard is equipped with Bingham's latest design consisting of carbide on CEP-72 graphite as the primary seal and a secondary seal of Teflon (square cross-section) impregnated with fiberglass. The outboard has a seal designed by the Durametallic Corp. which uses carbide on carbide as the primary seal and an O-ring guided by a Teflon square ring as the secondary. Both seals are similar in design except for the materials involved. The Durametallic seal required a modification so that cooling water could flow directly on the seal surfaces rather than the seal cavity.

Both seals have survived two blowdowns (021 and 023) and several cold operations of the loop. Total time is approximately 31 hr. External observations while running as well as static pressurization tests have revealed no change in serviceability.

Fig. 5.3. Double-ended blowdown test 023. Test section outlet rupture disk, view from inlet end.

Fig. 5.4. Double-ended blowdown test 023. Test section inlet rupture disk, view from inlet end.

In case of seal failure, one complete seal of the Durametallic design and two complete seals of the Borg-Warner design are on hand. The Borg-Warner seals are significantly different from the Durametallic and Bingham seals in that the axial tracking face is built into the stationary gland rather than the rotating face.

Rod seal coolant system

With the installation of the bundle, the system was completed and its operation verified. The system is composed of three separate systems: a forced-air system, a 6.89 MN/m^2 (1000 psi) cooling-water system, and an inlet from the primary loop. The latter system is attached to the lower section of the O-rings and is driven through a heat exchanger from the primary loop downstream of HCV-2, the first control valve at the Bingham pump outlet. The 6.89-MN/m^2 (1000-psi) system circulates water between the lower and the upper O-rings and serves to cool and reduce the pressure across the O-rings.

The inner heater rod seal coolant system has been modified significantly. A Sprague pump was installed as a makeup system, and a letdown cooler was added for inventory reduction during operation. Since the O-rings are critical to the bundle life and THTF operation, emergency power is planned to be provided for the circulating pump. As an alternate to emergency power, it is now planned to add to this loop a makeup system from the process water through a demineralizer. In a power failure, the primary loop would be blown down through the relief valve, the pressure in the system reduced to atmospheric, and the process water turned on. Flow would be controlled by the letdown cooler outlet valve.

Relief valve modification

During the last two blowdowns as well as other operations, problems occurred with the two relief valves located on the test section outlet and the pressurizer. Both valves leaked and one was damaged during test 023.

The problem with the pressurizer valve is in the high-temperature characteristics of the seat. A rupture disk is being placed between the pressurizer and the valve, and a thermocouple will be used to detect rupture disk leakage.

The test section outlet relief valve leaked due to a poorly adjusted air cylinder actuation system. This has been rectified. During test 023, the expanding steam from the blowdown line entered the exhaust leg of the valve and damaged a flexible coupling in the line and rotated the valve support member (Fig. 5.5). The damage was repaired. To prevent a recurrence, a check valve was installed in the valve's exhaust line. A shock arrester was installed on this line to absorb the force generated during valve operation, and a thermocouple was installed to detect leaks.

Letdown cooler

For inventory control during operation, the facility is equipped with two Sprague pumps for makeup and a cooler for letdown. The cooler is used to lower the temperature to 373.15°K (212°F) or less before draining the system. The original design proved inadequate because it could not accommodate normal inventory changes during heatup of the system.

A larger cooler was installed in the loop during this quarter. The cooler holds approximately 11,356 cc (3 gal) of water and should be adequate for all heatup operations as well as powered operations.

Test section flow control

Flow to the test section is controlled by one of the electropneumatic valves, FCV-18, which is remotely controlled and is capable of manual as well as automatic operation. Automatic control has not been practical due to the unreliability of the turbine meters used in the control circuit. Since automatic control is vital to successful powered operations, an orifice ΔP cell has been installed for the flow control circuit. Calibration of this circuit will take place during the cold and hot runs prior to powered operation.

Bundle installation

During the first week of this quarter, the test section was opened and the 47-rod bundle lowered into place. After the system was pressure tested to 15.513 MN/m² (2250 psig) to assure that the installation was acceptable, the process of dc power and thermocouple hookup started. The thermocouples were carefully placed on a plywood platform, separated, hooked up to their

Fig. 5.5. Test section outlet relief valve, exhaust leg, and flexible coupling. Damage sustained during test 023.

proper receptacles, and then verified. The dc cables were connected to the heater rods, and the cable-rod hookup was verified to the shunt rack. Figures 5.6 and 5.7 show the installation.

The resistance of each heater rod as well as the resistance back to the shunt rack have been checked and compared to the original rod resistance to assure no heater or cable damage. Table 5.1 shows this comparison.

THTF dc power supply

The installation of the dc power supply was completed, including the water-cooled cables, the dummy loads, the shunt racks, the knife switches to the heater rods, and the necessary control circuits. R. D. Stulting, designer, has verification under way.

A significant problem has been uncovered in the water-cooled cables supplying dc power from the generator to the facility. To date, 10 cables have failed; 6 have ruptured, and 4 have clogged and reduced the flow of cooling water to an unacceptable value. This problem results from age deterioration. The failed cables have been examined and the cord has been found to be deteriorating. By careful testing and selection of cables, the operation is continuing.

During a preoperational check of the dc power system Dec. 13, 1975, it was discovered that the resistances to ground of the four dc generator armatures were low. Visual inspection showed the insulation of all generators in bad need of repair. General Electric, Westinghouse, and National Coil representatives inspected the machines and advised against running them until they had been cleaned and the insulation repaired. Each company has been asked to submit a bid on this repair. Repair should begin the second week of January and be completed within one month.

Fig. 5.6. THTF thermocouple and dc power installation — side view.

Fig. 5.7. THTF thermocouple and dc power installation — top view.

Table 5.1. Original and installed resistance to ground of THTF heaters

Heater serial No.	Heater grid No.	Date of reading	Resistance to ground (Ω)	Date of reading	Resistance to ground (Ω)
79	1	9-23-74	0.3838	11-17-75	0.3910
42	2	6-14-74	0.3660 ^a	11-17-75	0.3867
32	3	6-18-74	0.3696 ^a	11-17-75	0.3883
70	4	8-18-74	0.3947	11-17-75	0.3901
48	5	6-13-74	0.3721 ^a	11-17-75	0.3910
40	6	6-13-74	0.3627 ^a	11-17-75	0.3829
39	7	6-18-74	0.3681	11-17-75	0.3890
47	8	6-18-74	0.3768 ^a	11-17-75	0.3963
80	9	9-23-74	0.3817	11-17-75	0.3918
52	10	7-11-74	0.3860 ^a	11-17-75	0.3839
26	11	6-11-74	0.3710 ^a	11-17-75	0.3837
55	12	7-10-74	0.3812 ^a	11-17-75	0.3921
62	13	7-8-74	0.3707 ^a	11-17-75	0.3886
15	14	6-26-74	0.3640 ^a	11-17-75	0.3792
28	15	6-14-74	0.3626 ^a	11-17-75	0.3778
41	16	6-13-74	0.3692 ^a	11-17-75	0.3878
59	17	7-11-74	0.3894 ^a	11-17-75	0.3963
73	18	9-23-74	0.3800	11-17-75	0.3811
61	19	7-17-74	0.3785 ^a	11-17-75	0.3911
53	20	7-10-74	0.3836 ^a	11-17-75	0.3918
33	21	6-14-74	0.3685 ^a	11-17-75	0.3846
68	22	9-23-74	0.3931	11-17-75	0.3972
63	23	7-11-74	0.3879 ^a	11-17-75	0.3915
57	24	7-11-74	0.3760 ^a	11-17-75	0.3918
77	25	9-23-74	0.3811	11-17-75	0.3802
86	26	12-2-74	0.3887	11-17-75	0.3780
14	27	6-18-74	0.3798 ^a	11-17-75	0.3933
38	28	6-13-74	0.3682 ^a	11-17-75	0.3857
25	29	6-12-74	0.3700 ^a	11-17-75	0.3878
56	30	7-11-74	0.3783 ^a	11-17-75	0.3877
75	31	9-17-74	0.3770	11-17-75	0.3810
58	32	7-11-74	0.3786 ^a	11-17-75	0.3765
67	33	7-17-74	0.3638 ^a	11-17-75	0.3775
54	34	7-10-74	0.3847 ^a	11-17-75	0.3963
21	35	6-11-74	0.3786	11-17-75	0.3963
50	36	7-2-74	0.3742 ^a	11-17-75	0.3884
24	37	6-12-74	0.3759 ^a	11-17-75	0.3928
82	38	11-25-74	0.4048	11-17-75	0.3995
83	39	12-2-74	0.3908	11-17-75	0.3825
13	40	6-18-74	0.3760 ^a	11-17-75	0.3908
65	41	7-9-74	0.3593 ^a	11-17-75	0.3768
11	42	5-31-74	0.3792 ^a	11-17-75	0.3990
36	43	6-13-74	0.3721 ^a	11-17-75	0.3882
20	44	9-23-74	0.3810	11-17-75	0.3878
34	45	6-18-74	0.3706 ^a	11-17-75	0.3875
29	46	6-14-74	0.3625 ^a	11-17-75	0.3815
23	47	6-12-74	0.3738 ^a	11-17-75	0.3935
18	48	6-18-74	0.3717 ^a	11-17-75	0.3894
81	49	12-2-74	0.3979	11-17-75	0.3901

^aAfter construction and assembly.

6. THERMAL-HYDRAULIC TEST FACILITY INSTRUMENTATION

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6.1 Documentation Preparation

Revision of the instrumentation sections of the THTF Preliminary Project Description (PPD) has been completed, and the revised manuscript has been submitted for inclusion in the revised PPD.

Work is continuing on revision of startup and operating check lists for the instrumentation systems at the THTF. Some revisions reflect changes recommended by the operating crew after use of check lists during several isothermal blowdowns; others result from the need to update as corresponding operating procedures are prepared.

Operating procedures for instrumentation systems at the THTF have been prepared in draft form and are in various stages of in-house review.

6.2 Measurement of Magnetic Field at THTF

Tests were conducted at the THTF to predict the magnitude of the magnetic field induced by the large dc current (27.7 kA) that is required for the heater rods. At 122 kW per heater and 0.38 Ω heater resistance, the current in each of the 49 rods is about 566 A.

The current loop can be approximated by a rectangle where the vertical sides are ~ 7 m and the horizontal sides ~ 3 m. Using the formula for the magnetic field intensity:

$$B = \frac{\mu_o}{4\pi} \int_{-L_1}^{L_2} \frac{1}{r^2} \sin \theta \, dl$$

$$= \frac{\mu_o}{4\pi} \frac{I}{a} (\cos \theta_1 - \cos \theta_2) \quad ,$$

^{*} Instrumentation and Controls Division.

where a is the distance from a point to the conductor of finite length, the theoretical magnetic field intensity at a given location within the loop can be calculated by summing the contributions of each side. For the two locations shown in Fig. 6.1,

$$\begin{aligned}
 B_a &= \left(\frac{10^{-7}}{\text{A} \cdot \text{m}} \right) (27.7 \text{ kA}) \left(\frac{0.97 + 0.99}{0.5 \text{ m}} + \frac{0.24 + 0.78}{2 \text{ m}} \right. \\
 &\quad \left. + \frac{0.62 + 0.89}{2.5 \text{ m}} + \frac{0.45 + 0.1}{5 \text{ m}} \right) \\
 &= 1.42 \times 10^{-2} \text{ W/m}^2 \\
 &= 142 \text{ G.}
 \end{aligned}$$

In like manner for location b , $B_b = 93.7 \text{ G.}$

Fig. 6.1. Current path approximated by rectangular loop.

These calculations do not take into account any effects of the steel grating and structure inside the current loop. To find out if the metal attenuated the magnetic field strength inside the loop, a cable was placed alongside the actual conductors on the exterior of the test section and a current of 400 A dc was applied using a dc welding power supply. Expected values of the test field at 0.5 m and 1.0 m were $[(400/27,700) \times B_a]$ and $[(400/27,700) \times B_b]$, respectively, or $B_a \text{ test} = 2.06 \text{ G}$ and $B_b \text{ test} = 1.35 \text{ G}$.

The earth's magnetic field has a horizontal component of $\sim 0.25 \text{ G}$ in this region, so expected test measurements would be four to nine times the earth's magnetic field. Figure 6.2 shows magnetic field strengths measured with no test current, and Fig. 6.3 shows field strengths in approximately the same locations with $I_{\text{test}} = 400 \text{ A}$. Figure 6.4 shows anticipated field strengths around each of the densitometers. There is no significant deviation between the measured and anticipated values of test field strength, indicating that the metal structure has a minimal effect, at least at low current levels.

Fig. 6.2. Existing magnetic field intensity (G) at the THTF above first floor grating.

Since the gamma densitometers are highly sensitive to magnetic fields, the data obtained in the above experiment have been used to select the required amount of magnetic shielding.

Also of importance to the instrumentation system are the transient common-mode voltage signals induced on thermocouples and other twisted pair wires that connect sensors to signal-conditioning equipment and data-acquisition systems in the control room. The induced voltage, $d\theta/dt$, depends on the location of the twisted pair and the time constant with which the magnetic field decays when the breakers to the heater rods are opened. Large common-mode signals could feasibly overload preamplifiers, thus causing long recovery times from saturation. Further tests and calculations are being made to study the common-mode problem.

6.3 Gamma Densitometers

The photomultiplier tubes which are used in the BDHT gamma densitometer are very sensitive to magnetic fields (Fig. 6.5); therefore some magnetic shielding was included in the original detector design. At that time, detector protection against both an unspecified magnetic field and

Fig. 6.5. Variation of output current of 6342 A photomultiplier with magnetic field strength. (Figure from RCA phototube manual.) The electron optics of the tube used in the densitometer is similar to those of the 6342 A.

the unspecified mechanical shock of blowdown was being considered. As a result, two 3.175-mm-thick (0.125-in.) layers of polyethylene foam and three 0.102-mm-thick (0.004-in.) layers of magnetic shielding were placed in the 6.35-mm (0.25-in.) annulus between the detector and the water-cooled light shield.

The effectiveness of the magnetic shielding was questioned recently with respect to the magnetic field generated by the 27.7-kA dc current circuit of the reactor fuel rod simulator. An estimate of the magnetic field strength at the detectors was not available at the time, so the magnetic sensitivity of the detector was checked using a horseshoe magnet and a gauss meter as shown in Fig. 6.6. This check indicated that a 16-G field produced a 20% decrease in detector output signal. From the results of this measurement and of the magnetic field measurements and calculations, a decision was made to increase the magnetic shielding as much as possible within the existing space. Additional compression of the polyethylene foam allows an increase of the detector magnetic shielding from 0.305 mm (0.012 in.) to 1.016 mm (0.040 in.). There is also a 1.59-mm-thick (0.0625-in.) stainless steel sleeve between the water-cooled light shield and the lead

Fig. 6.6. Test of effect of permanent magnet on densitometer detector.

liner of the gamma shield that is being replaced with 1.27 mm (0.050 in.) of magnetic shielding.

Calculations and measurements discussed in Fig. 6.2 indicate that the fields near the detectors range from about 70 to 120 G. The new magnetic shielding is expected to be good to at least 100 G. The magnetic shielding material was received on Dec. 4, 1975, and modifications to the detectors to incorporate the additional shielding are complete. Should it prove necessary for blowdown tests at high power levels, additional magnetic shielding can be added on the exterior of the detector gamma shield.

Two modifications have been made in the densitometer cooling-water system. One modification, which resulted in significant improvement, was a change of the direction of the detector cooling water. In addition, another cooling coil was added on the exterior of the detector gamma shield. In test 002R2, the temperature of the detector cooling water rose to over 311°K (100°F) when the loop temperature was at 559°K (547°F). With the above modifications, the temperature only rose to ~295°K (77°F) in tests 021 and 023 and the densitometer output was more stable as loop temperature changed.

6.4 Turbine Meters

Rulon journal bearings of the type which had reportedly been used successfully in similar service at another installation were installed in two of the THTF turbine flowmeters at the supplier's plant (Flow Technology, Inc., Phoenix, Ariz.).

The two meters with Rulon bearings were installed in the THTF along with two meters having the original (crown retainer) ball bearings with modified spacers. Both types of meters performed well during test 021 (Sept. 30). Although both types of bearing assemblies survived the blowdown and produced acceptable data, posttest examination revealed that the ball bearings were badly worn and that the Rulon bearings were severely distorted and the rotors were off center and out of balance (Fig. 6.7). As shown in Figs. 6.8 and 6.9, the hole in one rotor was 0.32 cm (1/8 in.) off center and the rotor blade tips had been damaged by contact with the housing. The other rotor was about 0.32 cm (1/16 in.) off center and the

PHOTO 4797-75

Fig. 6.7. Rotor misalignment and tip damage in THTF turbine meter (FE-18) assembly resulting from damage to Rulon bearing during test 021.

PHOTO 1800 7b

Fig. 6.8. Offset in hole in THTF turbine meter (FE-18) Rulon bearing resulting from heated operation during test 021.

Fig. 6.9. Rotor misalignment and tip damage in THTF turbine meter (FE-18) assembly resulting from damage to Rulon bearing during test 021.

rotor tips were not damaged. Subsequent studies indicated that this damage was probably due predominantly to the large difference of the coefficient of linear expansion of the Rulon sleeve and the stainless steel rotor [2.8×10^{-5} and 3.3×10^{-6} per $^{\circ}\text{K}$, respectively, at 533°K (500°F)]. This problem can be corrected by the use of split-sleeve-type bearings.

In response to our inquiries, information was received from Flow Technology that a 7.62-cm-diam (3-in.) meter that had survived a number

of blowdowns at another installation had minimal bearing wear and that the rotors in the meter were lighter by a factor of 2.33 than those supplied in the 8.9-cm (3.5-in.) THTF meters (39 g compared to 91 g). Light-weight rotors for the 8.9-cm (3.5-in.) meters were ordered, fabricated, and received within one week.

The bearings in all four turbine meters for test 023 (Oct. 17, 1975) were the same as the crown retainer type bearings (New Hampshire SR4WK25) originally supplied with the meters; however, the bearing spacer assembly was modified and the original rotors were replaced with the new lightweight rotors. The bearing assembly modification consisted of the addition of a spacer between the outer races of the bearings and modification of the spacer between the inner races to incorporate lips which keep the crown retainer in place during blowdown. The replacement rotors have essentially the same calibration factor as the originals and should have faster response characteristics as a result of the reduced mass. All bearings survived the blowdown and were still intact when removed. Wear on the races was significantly reduced from that observed in previous tests, and retainer wear on all but one of the bearing retainers was negligible. The worn retainer was in meter FE-34, which underwent a violent acceleration at blowdown initiation and high overspeed during the steam phase. It is possible that the reduction in bearing damage was at least partially attributable to improvement made in cleanup (filtering) of the water supplied from the Building 9201-3 demineralized cooling-water system and used to fill the THTF system.

During the startup and initial approach to blowdown on test 023, turbine meters FE-18 and FE-34 behaved erratically. Observation of the signal from the meter pickup showed that the 2000-Hz noise present on the signal was of sufficient amplitude to cause multiple counting and/or interference with the electronic phase detection circuits in the monitor. This noise was also present on meters FE-166 and FE-216; however, in these cases, the noise level was much lower and did not present a problem. This noise was initially thought to be spurious electromagnetic pickup from an external source; however, further checks showed that its amplitude was flow related and was not due to pickup in the cables. The effects of the noise were eliminated by temporary installation of 1000-Hz low-pass filters in the

signal leads to FE-18 and FE-34. The source of the noise has not been definitely established, but it was probably due to magnetization of the rotors resulting from work hardening during machining. This is supported by the fact that the noise amplitude decreased significantly during heated operations prior to blowdown and was not present on FE-166 and FE-216 and had very low amplitude (less than 2% of signal) on FE-18 and FE-34 when the meters were tested in the air-water loop subsequent to blowdown. Further checks showed a very slight amount of magnetization (less than 0.3 G) in the rotor blades. All rotors were degaussed prior to reinstallation in the THTF.

Further efforts will be made to improve the life of the turbine meter bearings. Other types of bearing materials and configurations will be investigated. As a first step in this program, one of the original (heavy) rotors has been modified to accept a larger (heavier duty) bearing and is being tested. Several alternative bearing types, which were ordered in August, have been received and will be evaluated.

6.5 Data-Acquisition System

Extensive evaluation and testing of the analog input system used by the computer-controlled data-acquisition system (CCDAS) uncovered several situations under which the system digitization error could exceed the nominal specification of 0.3% of full scale. The errors introduced are of four types: (1) error due to overload recovery time of amplifiers, (2) offset due to voltage offsets and leakage in the switching field-effect transistors (FETs), (3) offset due to channel-to-channel interaction, and (4) error due to reduced common-mode rejection ratio (CMRR). The error mechanisms were characterized by further experiments, and the observed errors correlated well with calculated predictions.

The overload recovery time of the programmable-gain amplifier subsystem from "hard" saturation to within specifications is on the order of 100 msec, thus affecting several readings (10,000 readings/sec). Since the recovery time is inherent in the design, the solution adopted is to ensure that the signal ranges (gains) specified for each channel in the scan table are sufficiently wide that the signal will not exceed the range and drive

the amplifier into saturation under any expected conditions. Also, during test startup, any failed instruments that could cause an open circuit ("soft" saturation) or overrange are jumpered out appropriately.

The offsets due to voltage drop across switching FETs or leaky switching FETs are peculiar to individual eight-channel multiplexer cards or single channels on a card. This effect could cause a worst-case error of $\sim 200 \mu\text{V}$ referred to input (RTI). A test box is used to check multiplexer cards off line for leakage and to adjust for voltage null across the FETs. This check is then followed by several on-line (in-circuit) checks. A procedure is being prepared specifying the checkout and adjustment operations. These are procedures to be done periodically, but not prior to each test run.

If a low-level signal is scanned immediately following a high-level signal on the same multiplexer chassis, an offset can be introduced in the reading of the low-level signal that could cause a worst-case error of $\sim 20 \mu\text{V}$ RTI. Both this channel-to-channel interaction and a reduction in the CMRR are a strong function of the channel sampling rate and are directly attributable to the single-pole RC filter at the input of each FET multiplexer channel. It was determined that both effects were insignificant at the normal THTF data channel sampling rate of 20 samples/sec (system sampling rate of 10,000 samples/sec). In programs that require a higher sampling rate (mainly instrumentation checkout programs), further care will be taken to minimize the effects, for example, by scanning a shorted (zero) channel between high-level and low-level signals. The CMRR adjustment on all amplifiers was also set to minimize the common-mode error.

Several additional features have been added to the FOCAL^{*} system software on the CCDAS, and several bugs have been found and corrected. The application software packages, operator's log, and instrument verification are in the final stages of debugging. Each required major modifications to meet the requirements for powered-rod operation. A short course is also being given to the operating personnel and other interested parties on the operation of the CCDAS and the basics of FOCAL programming. This will include the use of the application software packages being developed.

^{*}FOCAL is a registered trademark of Digital Equipment Corp.

Because of continued operational problems with the analog tape recorder/reproducer units during replay of data tapes, a factory field service call was requisitioned in the period between tests 021 and 023. The mechanical alignment of the units was found to be out of specification. This was corrected, and several minor electronic adjustments were made. Both units performed well during test 023 and the subsequent data replay.

6.6 Safety Circuit Modifications

The design, installation, and checkout were completed for the modifications to the electrical safety control circuits. These modifications include the protective features of items B1, B2, B3, C10, and portions of C2 of the ORNL Response to the March 1975 Review.

6.7 Bundle Thermocouple Hookup

Prior to connection of any heater bundle or test section thermocouples to the data-acquisition system, several steps were taken to assure the integrity of the thermocouples and the measurement channels.

1. A visual and continuity inspection was made of all cables and connections in the thermocouple extension wiring from the test section patch rack to the CCDAS and the Metrascope.
2. The heater rod center thermocouples were wrapped with fiberglass tape to prevent contact with the heater element and any current-carrying conductors. The sheaths of these thermocouples were then connected to ground for the test section at one common point.
3. The heater rod sheath, subchannel, and shroud thermocouples are in contact with ground in the test section. These thermocouples were wrapped to prevent contact with any other ground point to prevent circulating ground currents through thermocouple sheaths.
4. The loop resistance of each thermocouple was measured to assure that the junction was still intact.
5. The insulation resistance of each thermocouple was measured to detect moisture absorption and short circuits from thermocouple leads to the sheath.

6. Prior to attaching the thermocouple sheaths to ground, the insulation resistance between the center thermocouples and the heater elements was measured to detect moisture absorption.

7. The thermocouple extension wiring was verified from the test section patch rack through the reference box patch panels to the CCDAS using a millivolt signal source. The procedure employed was sufficient to detect all likely single or multiple wiring errors or faults in individual signal paths, as well as all likely single or multiple interpath wiring errors or faults. In order to guarantee that multiple wiring errors could be detected, checkout was done in two steps. First, the wiring was verified from the reference boxes to the CCDAS, and then the reference box patch panels and the wiring were verified from the test section patch rack through to the CCDAS. Since there are 560 test section patch points and only 384 CCDAS channels assigned for thermocouples, several patching steps were used to cover all patch points. A test box was built that generated eight distinct voltage levels from 15 to 50 mV, each brought out to an individual thermocouple plug. The test signals were plugged into a block of eight thermocouple signal paths, and the measured voltage was checked and logged by the CCDAS. Any significant deviation from the expected voltage was noted on the log. Wiring errors or faults were corrected when found, and another log was made after the correction.

6.8 Error Analysis of Critical Instrumentation in the THTF

Summary of the work to date and important conclusions

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.

Specific results and the information and assumptions on which they are based

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:

1. Pressure transducer

Source of error	Error
Combined nonlinearity and hysteresis	<0.5% of span
Imprecision	<0.1% of span
Zero shift with temperature ^{1,2}	<0.0056% of span/°C
Sensitivity shift with temperature ¹⁻³	<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 294 and 366°K (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.

2. 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.

3. Instrumentation amplifier

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

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.

4. CCDAS

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

5. Analog tape system

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

6. 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.

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

1. 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 all 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.

2. 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.

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.

1. 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.

2. Span and zero adjustment network

Errors were assumed to be negligible.

3. Instrumentation amplifier

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

4. Overall system

The uncertainties in measurement of mass flow (momentum flux in $\text{kg m}^{-1} \text{sec}^{-2}$) were less than $6794 \text{ kg m}^{-1} \text{sec}^{-2}$ ($4565 \text{ lb}_m \text{ft}^{-1} \text{sec}^{-2}$) on the CCDAS and less than $7661 \text{ kg m}^{-1} \text{sec}^{-2}$ ($5148 \text{ lb}_m \text{ft}^{-1} \text{sec}^{-2}$) on the analog tape system, with 99.17% confidence.

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.

1. Differential pressure transducer

Source of error	Error
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/ $^{\circ}\text{C}$
Sensitivity shift with temperature	0.028% of span/ $^{\circ}\text{C}$

Note: It was assumed that the temperature of the transducer would vary between 294 and 339 $^{\circ}\text{K}$ (69.5 and 150.5 $^{\circ}\text{F}$) under the influence of ambient air temperature.

2. Zero and span adjustment network

Errors assumed to be negligible.

3. Instrumentation amplifier

Same as on pressure and mass flow measurement.

4. Overall system

The uncertainty in pressure difference measurement is less than $73.8 \times 10^3 \text{ Pa}$ (10.7 psi) on the CCDAS and less than $98.6 \times 10^3 \text{ Pa}$ (14.3 psi) on the analog tape system, with spans of $6894.8 \times 10^3 \text{ Pa}$ (1000 psi). For the systems with spans of $1378.96 \times 10^3 \text{ Pa}$ (200 psi) and $344.74 \times 10^3 \text{ Pa}$ (50 psi), the uncertainties are approximately the same percent of span.

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.

1. Scintillator and photomultiplier

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

2. 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:

Source of error	Error
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.

3. 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. 6.10.

6.9 Bundle 2 Thermocouples

The manufacturer of thermocouples for bundle 2 has continued to experience problems in fabrication of the dual-diameter 0.102-cm-OD (0.040-in.) to 0.051-cm-OD (0.020-in.) thermocouple assemblies. To date, only 20 assemblies have been received. These were tested and found to be marginal in some respects, although probably usable. The manufacturer advised ORNL that he would not meet the promised delivery date of Nov. 17, 1975, for 300 assemblies and asked for a meeting with ORNL personnel to review the status of the order. As a result of that meeting, the manufacturer was asked to present a revised delivery schedule and proposals for easing thermocouple

Fig. 6.10. Error in density measurement vs density.

fabrication problems. The revised schedule and proposals were received on Dec. 9, 1975, and negotiations with the manufacturer are under way.

The manufacturer of thermocouples for bundle 3 (backup thermocouples for bundle 2) has promised delivery of ~250 assemblies by Dec. 16, 1975.

6.10 Bundle 1 Thermocouple Identification

A simplified numbering system has been adopted for bundle 1 heater rod thermocouples. Each thermocouple will bear a different, two-letter designation as follows.

The first letter defines the radial position, either an "M" for a heater rod center thermocouple or by the letters "A" through "F" for sheath thermocouples, with the different letters referring to different grooves.

The second letter defines the axial position along the heater rod. The letters "A" through "O" refer to the 15 different levels at which a thermocouple may be located in the heater level. For example, level "G"

refers to a location 195.6 cm (77 in.) from the lower end of the heated zone.

Table 6.1 summarizes the heater rod locations for all the heater rod types that will be used in bundles 1 and 2 as well as the locations of grid spacers and the different heater rod power zones.

Table 6.1. 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		Thermo- couple level	Heater rod type									
		kW/m	kW/ft		Type H		Type J		Type K		Type M		Type P	
					Center	Sheath	Center	Sheath	Center	Sheath	Center	Sheath	Center	Sheath
-3/4 to +3/4 1	X	↑	↑	A						AA				
11 1/2 to 12 5/8 13 1/8 18	X	14.12 ↓	4.30 ↓	B						AB				
19 23 to 24 1/2 31 1/2	X	19.95 ↓	6.08 ↓	C						BC				
34 7/8 to 36 3/8 36 7/8 42	X	35.56 ↓	10.84 ↓	D		AD		AD		BD		AD		
43 45 1/2 to 47 54	X	42.91 ↓	13.08 ↓	E	ME	AE	ME	AE	ME	CE		AE		
55 58 5/8 to 60 1/8 70 1/2 to 72	X	↑	↑	F	MF	BF	MF	BF	MF	CF		BF		
77 82 3/8 to 83 7/8 89	X	55.77 ↓	17.0 ↓	G	MG	BG	MG	BG	MG	DG	MG	BG		
90 93 93 1/2 to 95	X	↑	↑	H	MH	CH	MH	CH	MH	DH		CH		AH
101 102 105 5/8	X	42.91 ↓	13.08 ↓	I		CI		CI		EI		CI		AI
106 1/8 to 107 5/8 111 1/2 112 1/2	X	35.56 ↓	10.84 ↓	J	MJ	DJ	MJ	DJ	MJ	EJ	MJ	DJ	MJ	CJ
118 to 119 1/2 125 126	X	↑	↑	K		DK		DK		FK		DK		
129 7/8 to 131 3/8 141 1/4 141 3/4 to 143 1/4	X	35.56 ↓	10.84 ↓	L		EL		EL		FL		EL		CL
144 145 1/4	X	19.95 ↓	6.08 ↓	M				EM						
		↑	↑	N				FN						
		14.12 ↓	4.30 ↓											
		1.21	0.37	O		EO		FO				EO		

^aDistances are given in inches, 1 in. = 2.54 cm.

7. HEATER ROD PROCUREMENT AND DEVELOPMENT

W. E. Baucum R. W. McCulloch

7.1 Bundle 2 Procurement

A bid for bundle 2 heaters has been received from Watlow Electric Manufacturing Company; however, the purchase order has not been placed due to pending resolution of an invention and discovery clause in the contract. A second problem which might affect completion of the order for bundle 2 heater rods is that Karman Sciences has not been able to supply thermocouples as scheduled. Claude S. Gordon, who was scheduled to deliver 25% of the backup thermocouples by Dec. 2, 1975, has delayed delivery by two weeks. The 50 thermocouples for the two prototype heaters can be inspected, have end plugs welded, and be delivered to Watlow by Jan. 5, 1976, if Gordon meets the schedule. Therefore, it is anticipated that Watlow may begin manufacture of bundle 2 heaters the first part of January and finish production during the early part of April 1976.

7.2 Heater Development

Watlow is attempting to eliminate the sheath gap problem discovered in the prototype THTF heater and has built shorter mock-THTF heaters and tested them with temperature transients up to $\sim 922^{\circ}\text{K}$ (1200°F) in boiling water at atmospheric pressure. Watlow found no significant shifts in radial ΔT until heat fluxes of $\sim 75\%$ of our planned operating value were reached. After giving the heater a high-temperature stress-relief treatment, the thermocouple readings returned to original values but again shifted on high-temperature cycling.

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