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MARTIN MARIETTA

Advanced Neutron Source Reactor Thermal-Hydraulic Test Loop Facility Description

Advanced Neutron Source

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-12397

ADVANCED NEUTRON SOURCE REACTOR THERMAL-HYDRAULIC TEST LOOP FACILITY DESCRIPTION

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Date Published—February 1994

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U.S. Department of Energy
under contract No. DE-AC05-84OR21400

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LIST OF ACRONYMS

ANSR	Advanced Neutron Source Reactor
CHF	critical heat flux
DNB	departure from nucleate boiling
FE	flow excursion
IB	incipient boiling
LOCA	loss of coolant accident
NPDM	ethylene propylene diene monomer
OFI	onset of flow instability
ONVG	onset of net vapor generation
OSV	onset of significant void
PID	proportional-integral-derivative
PLC	programmable logic control
RTD	resistance temperature device
SCR	silicon-controlled rectifier
THTL	Thermal-Hydraulic Test Loop
TIG	tungsten-inert gas (welding)
TTL	transistor-transistor logic

ADVANCED NEUTRON SOURCE REACTOR THERMAL-HYDRAULIC TEST LOOP FACILITY DESCRIPTION

D. K. Felde et al.

1. INTRODUCTION

The Thermal-Hydraulic Test Loop (THTL) is a facility for experiments constructed to support the development of the Advanced Neutron Source Reactor (ANSR) at Oak Ridge National Laboratory. The ANSR is both cooled and moderated by heavy water and uses uranium silicide fuel. The core is composed of two coaxial fuel-element annuli, each of different diameter. There are 684 parallel aluminum-clad fuel plates (252 in the inner-lower core and 432 in the outer-upper core) arranged in an involute geometry that effectively creates an array of thin rectangular flow channels. Both the fuel plates and the coolant channels are 1.27 mm thick, with a span of 87 mm (lower core), 70 mm (upper core), and 507-mm heated length. The coolant flows vertically upwards at a mass flux of 27 Mg/m^2s (inlet velocity of 25 m/s) with an inlet temperature of 45°C and inlet pressure of 3.2 MPa. The average and peak heat fluxes are approximately 6 and 12 MW/m^2, respectively.

The availability of experimental data for both flow excursion (FE) and true critical heat flux (CHF) at the conditions applicable to the ANSR is very limited. The THTL was designed and built to simulate a full-length coolant subchannel of the core, allowing experimental determination of thermal limits under the expected ANSR thermal-hydraulic conditions.

For these experimental studies, the involute-shaped fuel plates of the ANSR core with the narrow 1.27-mm flow gap are represented by a narrow rectangular channel. Tests in the THTL will provide both single- and two-phase thermal-hydraulic information. The specific phenomena that are to be examined are (1) single-phase heat-transfer coefficients and friction factors, (2) the point of incipient boiling, (3) nucleate boiling heat-transfer coefficients, (4) two-phase pressure-drop characteristics in the nucleate boiling regime, (5) flow instability limits, and (6) CHF limits.

Although the facility's primary aim is to develop the thermal-hydraulic correlations at the ANSR nominal conditions for normal operation and safety margin analysis, tests will also be conducted that are representative of decay heat levels at both high pressure (e.g., loss of off-site power) and low pressure [e.g., a loss of coolant accident (LOCA)] as well as other quasi-equilibrium conditions encountered during transient scenarios. Additional series of tests will examine the effects of oxide on the thermal limits as well as substituting D_2O for H_2O as the coolant to confirm the thermal limit behavior with heavy water.

This report provides a description of the test facility, the test channel, and associated measurement systems. In addition, the experimental approach used for thermal limit testing is described.

2. FACILITY DESCRIPTION

An isometric view of the facility is shown in Fig. 2.1. The loop is composed of two primary subsystems: a high-pressure system, which includes the test section, and a low-pressure system, used for monitoring and controlling water chemistry. Wetted materials in both subsystems are 300 series stainless steel (304 and 316), with the exception of the pump stator, which is ethylene propylene diene monomer (EPDM), and the pump rotor, which is 17-4 stainless steel. The loop has a rated design pressure of 6.9 MPa. Operating pressure is effectively limited to 5.5 MPa by an internal bypass on the pressurizing pump that provides system makeup water. Nominal operation for ANS testing will be at 3.2-MPa test section inlet pressure.

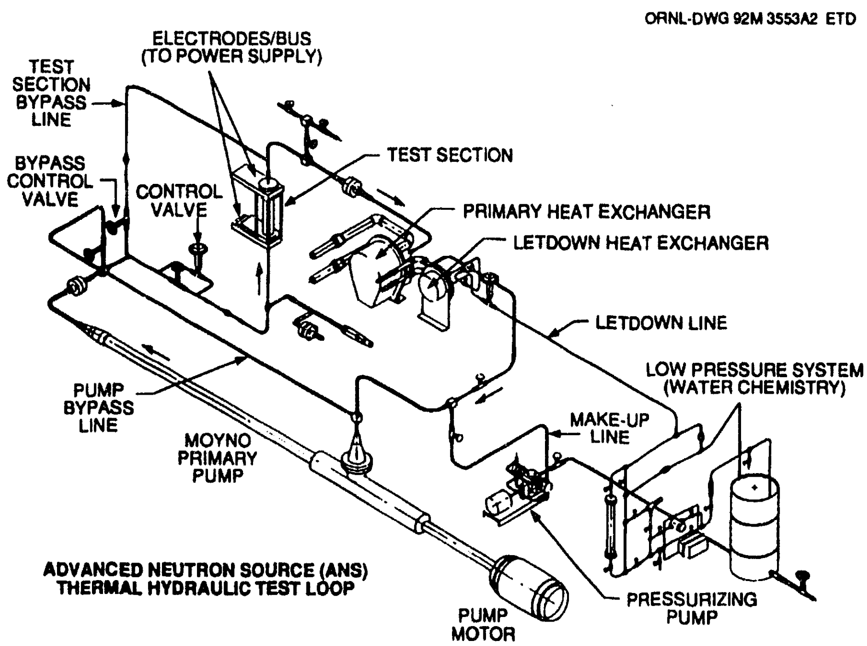

Fig. 2.1. Thermal-Hydraulic Test Loop, isometric view.

In the high-pressure system, water flows from the pump discharge through the primary line to the test section or through a bypass line around the test section. This flow split is controlled by a flow control valve on the test section line in conjunction with a manual valve on the test section bypass line. Flow in both lines is measured by turbine flowmeters. Pressure and temperature of the water are measured at the test section inlet and outlet as well as at the pump suction. An additional pressure measurement is made just upstream of the test section flow control valve to allow calculation of pressure drop in the test section flow leg. A heat exchanger downstream of the test section provides the heat sink for the system. The heat exchanger is designed to remove up to 410 kW. Inlet water temperature to the test section is controlled by varying the secondary flow to the heat exchanger. The primary flow leaving the main heat exchanger returns to the suction of the Moyno pump. A bypass line, downstream of the pump discharge but upstream of the test section/test section bypass flow split, is also available to direct flow back to the pump suction directly.

A pressure control valve on the letdown line downstream of the primary heat exchanger is used in conjunction with a pressurizing pump to control system pressure. The pressurizing pump provides makeup flow to the high-pressure system at a constant flow rate determined by its speed setting. Because the letdown pressure control valve automatically adjusts to maintain measured system pressure at the operator-selected set point, the speed setting on the pressurizing pump ultimately controls the letdown flow rate for the loop. A letdown heat exchanger is located upstream of the letdown pressure control valve to prevent flashing on the downstream side of the control valve. The letdown flow is routed to the low-pressure system, where water quality is monitored. Conductivity and pH are measured prior to sending the water through an ion-exchange column to remove impurities. The letdown flow is then discharged into the sump tank. The sump tank provides the suction source for the pressurizing pump, which discharges into the high-pressure system on the suction side of the Moyno pump. Control of water pH can also be maintained for the system by adding acid to the sump tank if desired.

Two dc power supplies provide direct electrical-resistance heating of the test section. These 12-V power supplies are rated at 16,000 A and 25,000 A and are bussed in parallel to provide a total rated power of 492 kVA. Actual power to the test channel will be limited by the voltage-current characteristics of the test channel itself.

A photograph of the facility is shown in Fig. 2.2. System-rated capacities are summarized in Table 2.1.

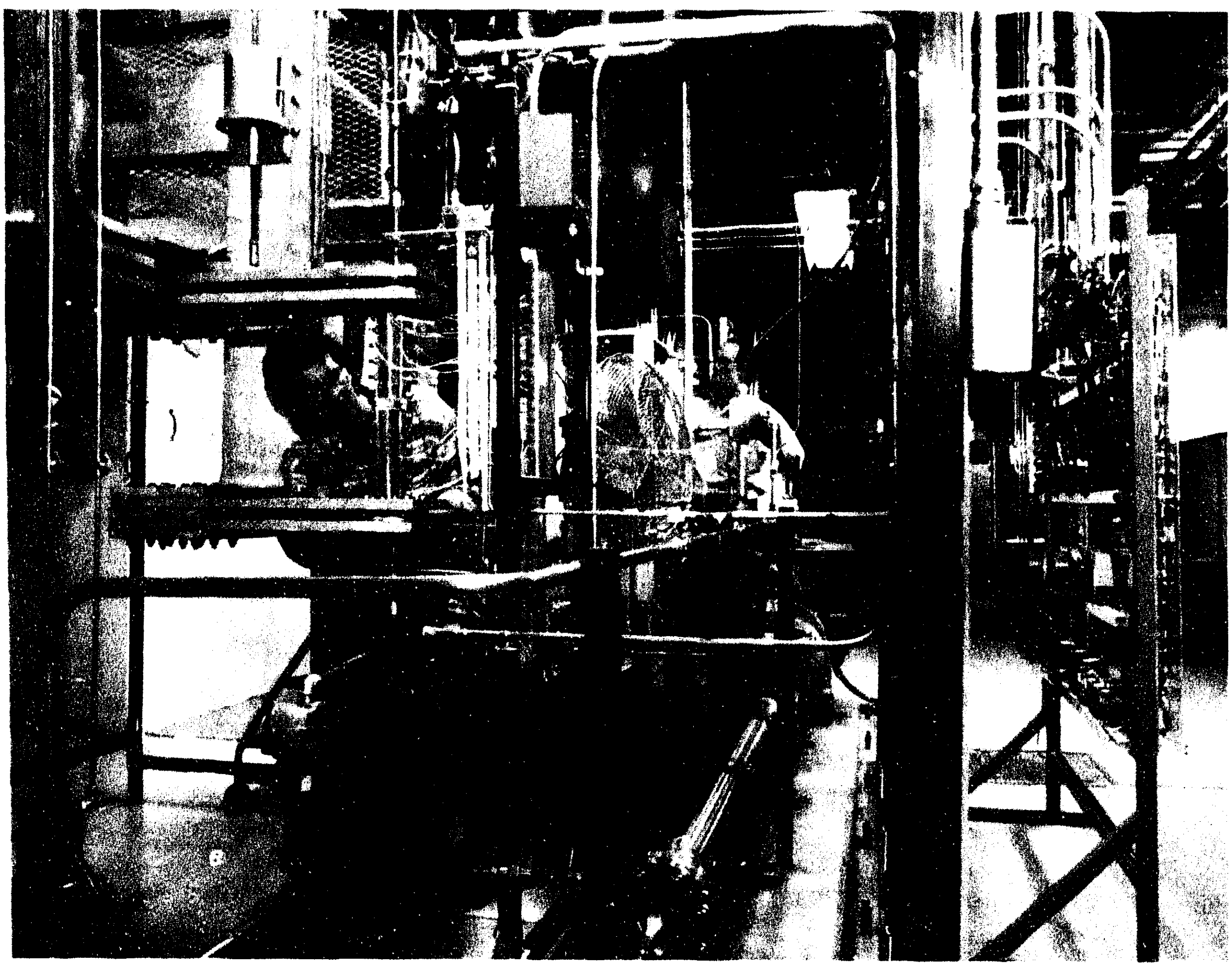

Fig. 2.2. Thermal-Hydraulic Test Loop.

Table 2.1. Thermal-Hydraulic Test Loop operating parameters

Component	Parameter	Range
Moyno pump	Volumetric flow	2.5 L/s
	Differential head	4.1 MPa
Power supplies[a]	PS-101A	12 V dc, 25,000 A, 300 kW
	PS-101B	12 V dc, 16,000 A, 192 kW
Heat exchanger	Heat removal capacity	410 kW
Pressure rating	Loop design pressure	6.9 MPa
	Operating pressure (max)	6.2 MPa
	Pump suction pressure[b]	5.5 MPa
	Nominal ANS inlet pressure	3.2 MPa
Loop bulk temperature	Nominal ANS inlet temperature	45°C
	Pump temperature limit	85°C

[a]Power supply systems are bussed in parallel.
[b]Pump suction pressure is limited by an internal by pass in the system pressurizing pump.

Instrumentation and control systems are designed to provide data for analysis of thermal-hydraulic conditions in the test channel as well as for system control input.

The test section and boundary conditions to the test section are of primary interest for thermal-hydraulic limit determination. Inlet and outlet water temperatures are measured by platinum resistance temperature devices (RTDs). Inlet pressure and differential pressure across the test section are measured by transmitters for process control and steady-state measurements. Redundant measurements are made using fast-response transducer-type instruments that input into a separate "fast" data-acquisition system. Test section volumetric flow and bypass volumetric flow are measured using turbine flowmeters. These instruments provide input into the standard data-acquisition system and into the fast data-acquisition system.

Measurements are also made on loop process parameters for control purposes. These measurements include pump suction pressure and temperature and electrical bus temperature at several locations. The low-pressure system is instrumented to measure water quality in the letdown flow. Temperature is measured downstream of the pressure control valve. Conductivity and pH of this letdown stream are measured before the water flows through the ion-exchange column. Sampling ports are available for off-line measurements.

A programmable logic control (PLC) system is used for system control and protection. The logic is designed to ensure correct operating sequences for system components and to provide operating limits for parameters such as pressure, flow, and test channel power. The system is designed to provide removal of power to the test section and subsequent shutdown of the loop upon detection of conditions that may affect loop integrity.

An integrated six-channel controller is used to maintain test section inlet temperature, test section velocity, test section power, and loop pressure. The six-channel controller has the capability for providing programmable set points for all six channels simultaneously.

The test section design, major facility components, and the instrumentation and controls system are described in more detail in the following sections.

2.1 TEST SECTION DESIGN

The cross section of the aluminum test channel design is shown in Fig. 2.3. The cross-sectional design is similar to that used by Gambill and Bundy.[1] The channel has the ANS prototypic 1.27 mm flow channel gap with a reduced channel width (12.7 mm vs the ANSR 87- and 70-mm fuel plate widths) in order to limit total power requirements to the test section. Channel wall thickness is determined by the necessity to match the voltage/current characteristics of the test channel to the power supplies. The reduced wall thickness at the radiused ends is designed to prevent heat flux peaking on the ends of the channel. The ratio of heat flux on the radiused ends to that on the flats for the design shown is 36%. The .est channel is enclosed inside a stainless steel pressure backing and is isolated thermally and electrically from this backing by Mycalex insulation. The cross section of the test section assembly is shown in Fig. 2.4. The test channel is welded into flanges on each end to provide electrical and loop water interfaces. The outer 25.4-mm periphery of the test section flanges are sandwiched between two 25.4-mm-thick aluminum electrical bus plates. The water connection to the test section is made concentrically inside this bus connection by a 50.8-mm flange and teflon gasket, which are fastened through the test section flange into the ends of the stainless steel backing. The teflon gasket and micarta bolt sleeves provide electrical isolation for the piping loop. The stainless steel backing, which is in direct contact with the test section flanges at both ends, is split in the center and isolated at that point by Mycalex insulation. A photograph of the installed test section assembly is shown in Fig. 2.5. This design effectively separates the electrical-contact requirements from the water-sealing requirements of the loop interface.

The test channel is fabricated from two halves, which are electron-beam welded along the axial length at the radiused edges. The test channel is then welded into aluminum flanges at each end by tungsten-inert gas (TIG) arc welding. The test channel extends through the flanges at each end. Following this welding procedure, the outside flange faces are machined flat and then provided with a 1.6-mm-deep recess to capture the teflon gasket (which provides the loop interface water seal). Measurements of critical dimensions are made throughout the fabrication process, including checks of wall thickness prior to channel fabrication.

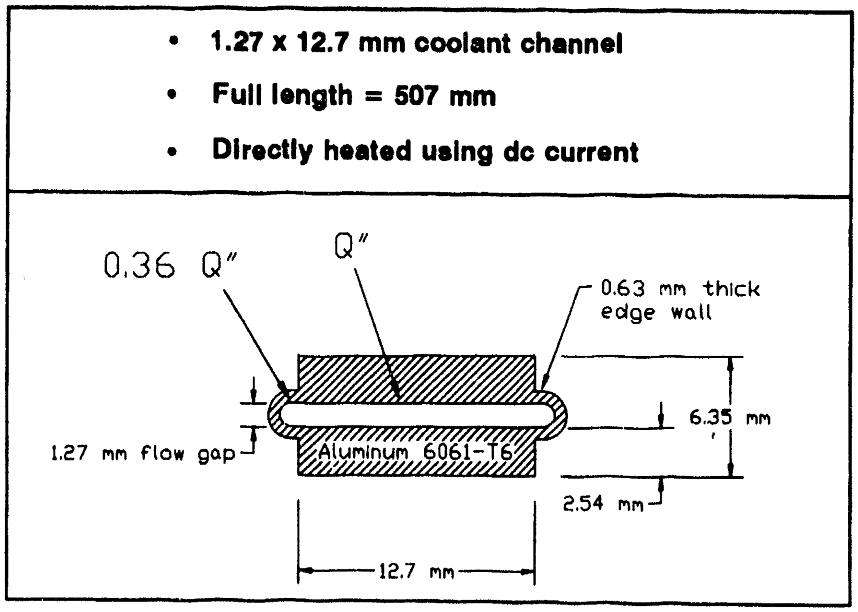

Fig. 2.3. Cross section of the test channel in the THTL.

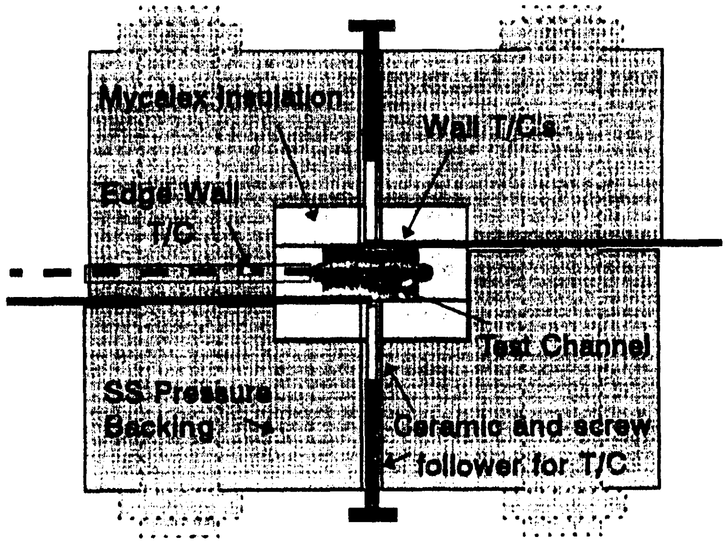

Fig. 2.4. Cross section of the THTL test section assembly.

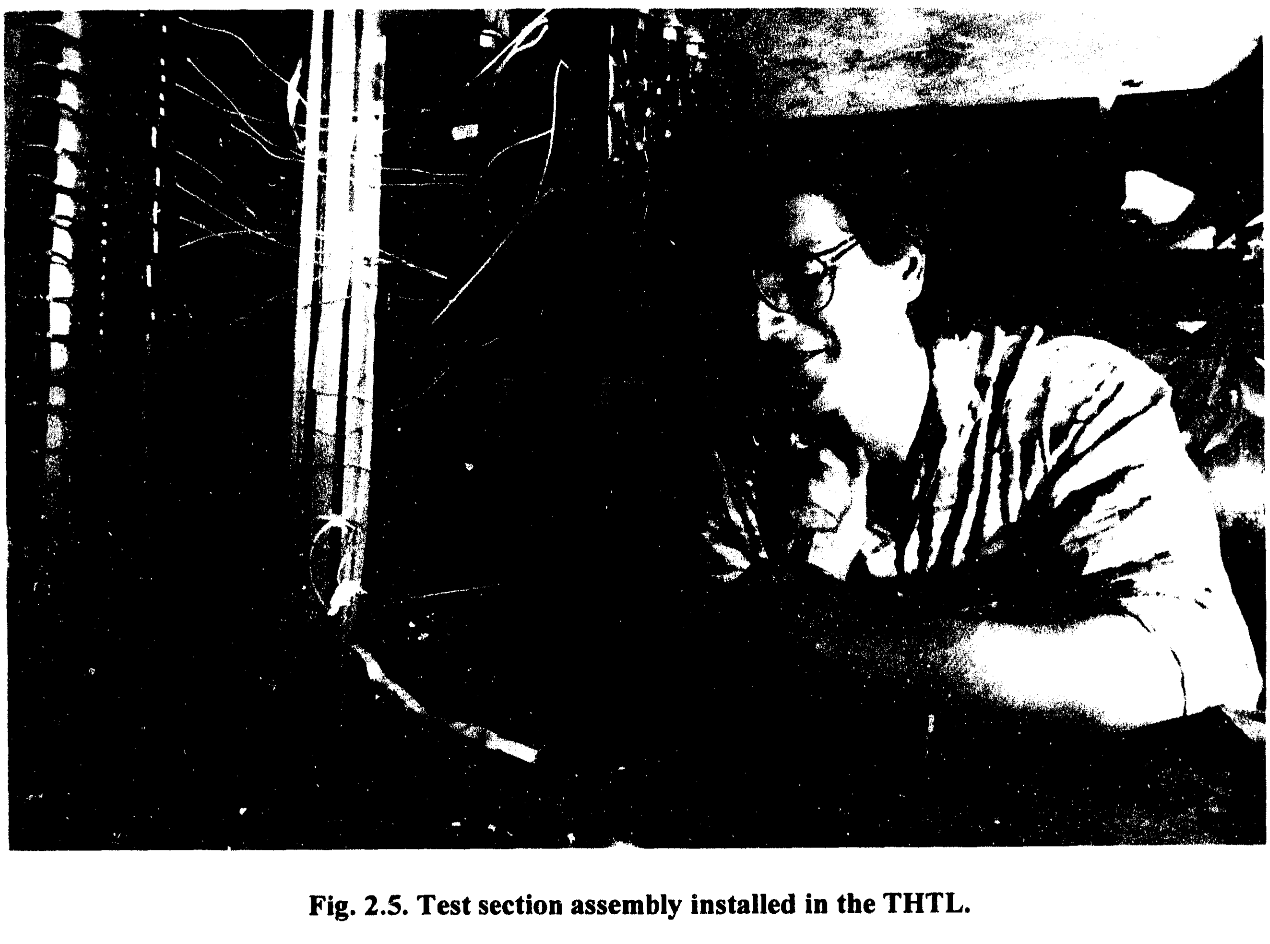

Fig. 2.5. Test section assembly installed in the THTL.

The test channel geometry is maintained through the 25.4-mm-thick end flanges. The interface flange to the loop piping has a machined transition from a rectangular flow channel to the loop tubing. Figure 2.6 shows the approximate dimensions of this transition.

2.2 PREINSTALLATION OF THE TEST SECTION

Prior to installation of the test channel assembly into the loop, the channel surface undergoes a surface treatment procedure similar to that used for fuel elements in the High Flux Isotope Reactor and expected to be used for the ANSR fuel elements. This procedure involves cleaning and degreasing followed by an acid treatment and hot water rinse. In addition, the as-fabricated flow channel gap is measured at locations along the axial length using a capacitance-type probe inserted into the channel. These data are used to provide improved conversion of volumetric flow measurements (made upstream of the test section) to local velocities in the channel.

2.3 MAJOR COMPONENTS

This section describes major system components in more detail. These include the primary pump, heat exchangers, and power supplies.

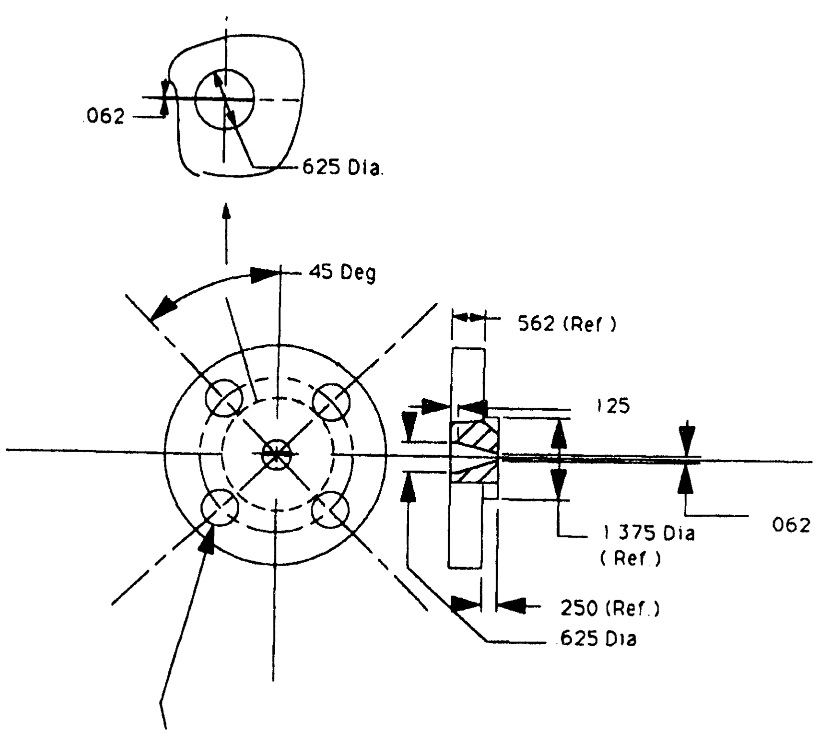

Fig. 2.6. Channel-to-loop piping transition.

2.3.1 Primary Pump

The primary recirculating pump is a Moyno pump driven by a variable-speed motor through a gear drive.[2] This pump-and-motor combination is capable of providing a wide range of flow and pressure conditions with near-positive displacement characteristics. The pump is a progressing cavity design. The rotor is a single external helix with a round cross section rotating in a double internal helix molded of an abrasion-resistant elastomer bonded within an alloy steel tube. As the rotor turns within the stator, cavities are formed that progress from the suction to the discharge end of the pump. The continuous seal between the rotor and the stator helices keeps the fluid moving steadily at a fixed flow rate proportional to the rotational speed of the pump. A representative set of pump performance curves is shown in Fig. 2.7. Using the variable-speed capability of the motor drive provides capability for operating over most of the flow-pressure diagram up to 2.5 L/s (40 gpm) flow and 4.1 MPa (600 psi) differential pressure developed across the pump. In combination with the test section bypass line, a very wide range of mass flow conditions (up to ~40 Mg/m^{2}s) at the test section are possible. These range from a "hard" system with a closed bypass line and near-constant mass flux through the test section to a "soft" system with a fully open bypass line and transient-affected mass flux through the test section.

2.3.2 Heat Exchangers

The primary heat exchanger is a Graham Heliflow size 15-20S. The heat exchanger is a compact shell-and-tube design comprising spiral coils held together between two flat surfaces (the base plate and the end of the casing). The plate and shell confine a closed, spiral-shaped fluid circuit outside the coil, running entirely counterflow to the companion circuit inside the coils (tubes). Design parameters for the primary heat exchanger are shown in Table 2.2.

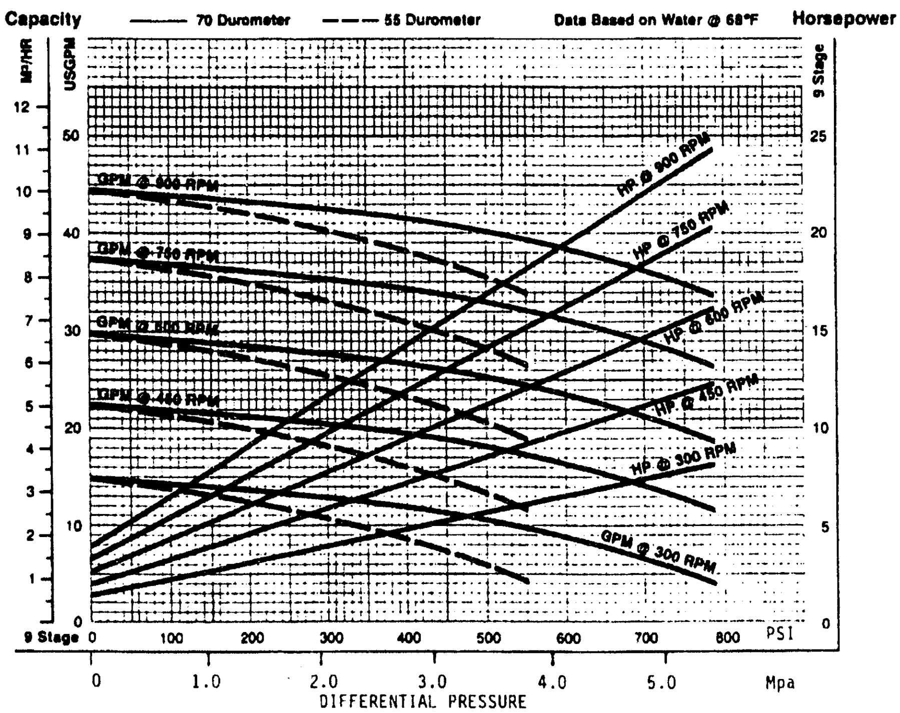

Fig. 2.7. Operating region for THTL primary pump (750 rpm maximum speed).

Table 2.2. THTL primary heat exchanger specifications

Type	Graham Heliflow
Size	15-20S
Surface area	3.0 m^2
Primary side	
Tube diameter	12.7 mm
Material	316 SS
Maximum working pressure	6.9 MPa
Design temperature	315°C
Shell side	
Material	Carbon steel
Maximum working pressure	1.0 MPa
Design temperature	175°C
Nominal capacity[a]	410 kW

[a]At nominal primary flow of 0.5 L/s and secondary flow of 3.1 L/s.

A smaller Graham Heliflow heat exchanger is used to cool the letdown flow upstream of the pressure control valve.

Plant process water provides the heat sink for the heat exchangers and cooling for the power supply. This system provides water at approximately 0.5 MPa and 20°C in a once-through process. The water is treated by activated-carbon filter tanks for chlorine removal prior to discharge to building storm sewer lines.

2.3.3 Power Supplies

The two power supplies convert 480-V,three-phase ac power to 12-v dc power at current ratings of 25,000 A and 16,000 A, respectively.

The primary ac line is connected to wye-delta power transformers by a main contactor. The wye-delta transformers provide power to two well-filtered six-phase rectifier sections (double wye with interphase circuits). These sections are combined by an interphase transformer to provide a twelve-phase system. Voltage and current control is provided by using 24 secondary silicon-controlled rectifiers (SCRs), which are gated in time proportional to the voltage or current required and are regulated by comparing the resulting output to operator-controlled reference signals. The power supplies are designed to be controlled either manually at the power supply control cabinet or externally (see Sect. 2.3.5.8). In the external mode of operation, the output voltage is regulated by a supplied reference signal. Two modes of regulation are available: a constant current-constant voltage with automatic crossover mode and a constant *dI/dt* mode.

The power supply is protected from all of the following conditions: ac under-voltage, ac phase rotation, ac phase loss, internal over-temperature, loss of water flow, open cabinet doors, ac overcurrent, and dc overcurrent. If any of these conditions exists, a power supply fault signal is generated that will drive the power supply into the invert mode of control, which will start to discharge the load and will open the external interlock circuit, which will disengage the main contactor.

The power supplies are of a direct water-cooled design. Most of the power load loss at full load will be removed by water. There are two 0.69-m^3/s blowers to remove the remaining heat. Protection against loss of cooling is provided by a water flow switch and air and water thermal switches.

Power is carried to the test section through a large aluminum plate bus system. The upper electrode interface to the test section includes a section of flexible copper and a spring-loaded support hanger, which allow expansion of the test section when heated. The section of the bus near the test section interface has fans installed for cooling. The remainder of the bus back to the power supplies is cooled only by ambient air.

Table 2.3 includes a summary of operational characteristics of the power supplies. Three additional 16,000-A power supplies of the same type are available in the facility area but are not currently tied to the THTL.

2.3.4 Low-Pressure System

The low-pressure system provides for measurement and control of the loop water chemistry. Letdown flow from the high-pressure system letdown control valve flows through a conductivity measurement cell, a pH measurement sensor and associated flowmeter, a low-pressure system flowmeter, a mixed-bed ion-exchange column, and then discharges into the sump tank. The sump tank serves as the suction source for the pressurizing pump, which supplies makeup water to the high-pressure system. This pressurizing pump is driven by a dc motor equipped with a variable-speed controller that ultimately controls the letdown flow

Table 2.3. Power supply specifications for THTL

Parameter	PS-101A	PS-101B
	Input	
Voltage	480 V ac, 3 phase	480 V ac, 3 phase
Current	570 A	340 A
	Output	
Voltage	12 V dc	12 V dc
Current	25,000 A	16,000 A
Power	300 kVA	192 kVA
	Cooling water	
Maximum pressure	0.69 MPa	0.69 MPa
Maximum inlet temperature	32°C	32°C
Minimum flow rate (14°C rise)	1.9 L/s	0.95 L/s

rate from the high-pressure system. The system also includes a rupture disc to protect the low-pressure components from high-pressure conditions in the event of failure of the high-pressure system pressure control valve. A schematic diagram of this system is shown in Fig. 2.8.

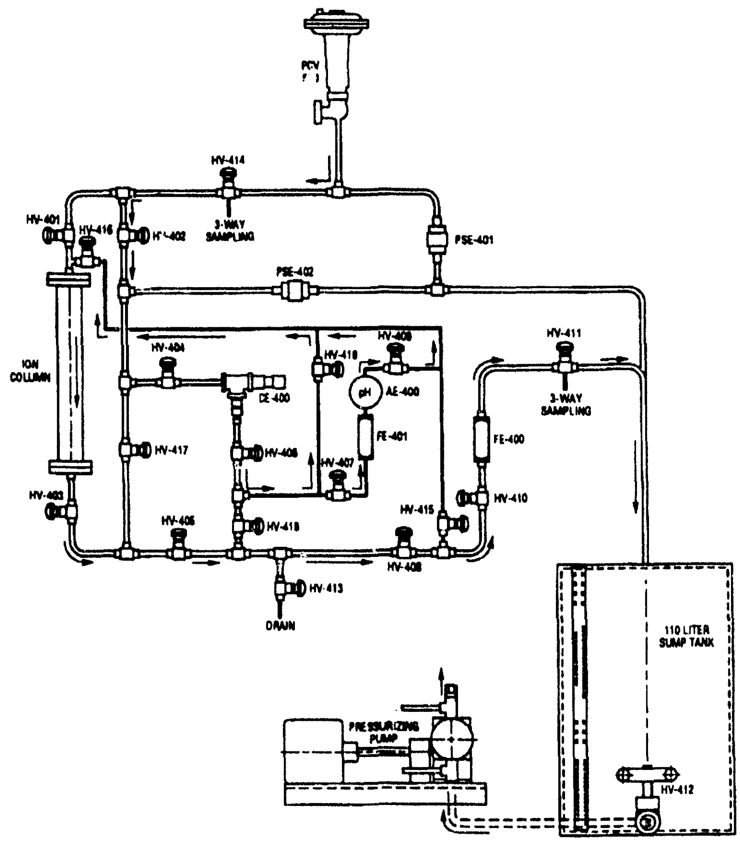

Fig. 2.8. Schematic diagram of the low-pressure (water chemistry) system.

2.3.5 Instrumentation and Controls

Instrumentation associated with the loop provides measurements of experimental variables of interest and input for control functions. A simplified schematic of the loop instrumentation is shown in Fig. 2.9. A more detailed view of test section instrumentation is shown in Fig. 2.10. A listing of instruments and measurement ranges is shown in Table 2.4. Primary instruments are described in more detail in the following section.

2.3.5.1 Temperature

Water coolant temperatures are measured at the inlet and outlet of the test section as well as at the pump suction and downstream of the letdown heat exchanger. Platinum RTDs are used for temperatures at the inlet and outlet of the test section, where greater accuracy is desired. In addition, redundant measurement locations are used at the inlet and outlet. The RTDs are stainless steel sheathed probes that are installed via compression-type tee fittings, with the sensor inserted into the center of the flow stream.

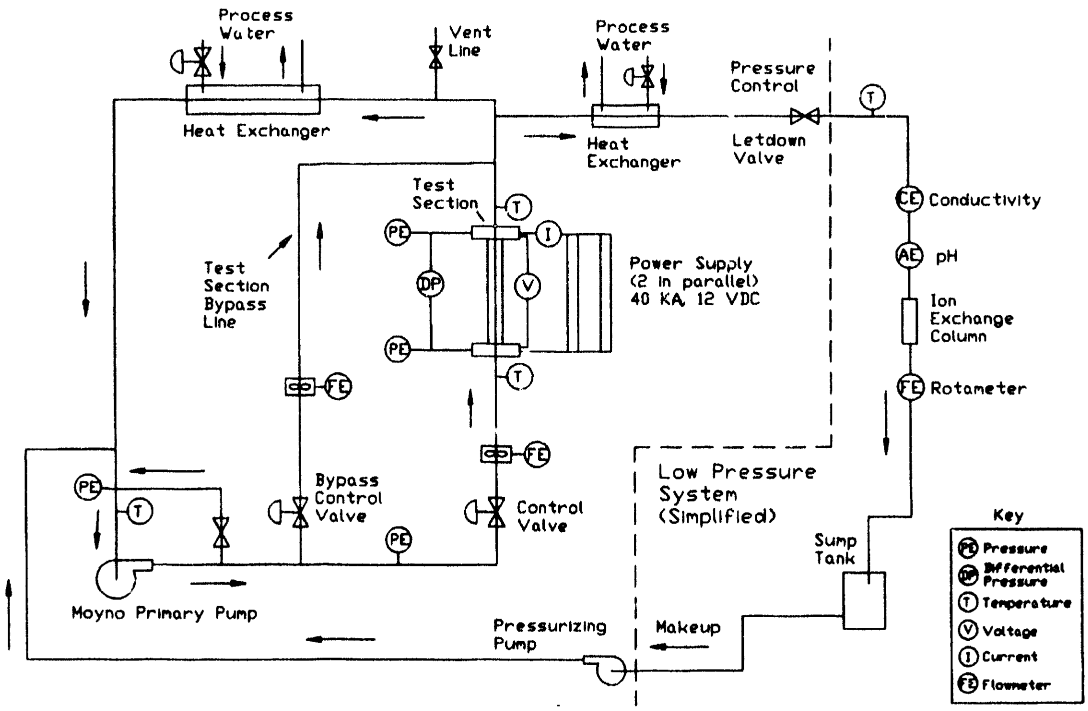

Fig. 2.9. Schematic diagram of the THTL.

These RTDs are located approximately 100 mm upstream and downstream of the inlet and outlet flanges, respectively (see Fig. 2.10).

Type K thermocouples are used at the pump suction and downstream of the letdown heat exchanger for bulk coolant measurements. Additional type K thermocouples are installed on the electrical bus at several locations for monitoring purposes.Two methods are used to measure the temperature of the back of the channel wall. Where access permits, a ribbon-type thermocouple manufactured by Nanmac Corporation is spring-loaded against the wall. Where access is not possible, 0.50-mm-diam thermocouples are inserted between the test channel wall and the ceramic insulator. The junction of the thermocouple is pressed against the wall by a ceramic rod inserted through the SS pressure backing and the ceramic backing. A threaded-screw follower applies pressure on the ceramic rod to force the thermocouple against the wall. Both methods use type N thermocouples. The locations of these thermocouples are shown in Fig. 2.4. The spacing is staggered as shown to provide improved definition in the region where burnout of the channel is expected. Measurements are made on both sides of the channel for the axial locations shown.

2.3.5.2 Flow

Volumetric flow measurements are made using Hoffer turbine flowmeters in the test section line and the test section bypass line. These instruments are capable of providing both a 4–20 mA output signal and a pulsed output for fast-response measurements (~5 ms).

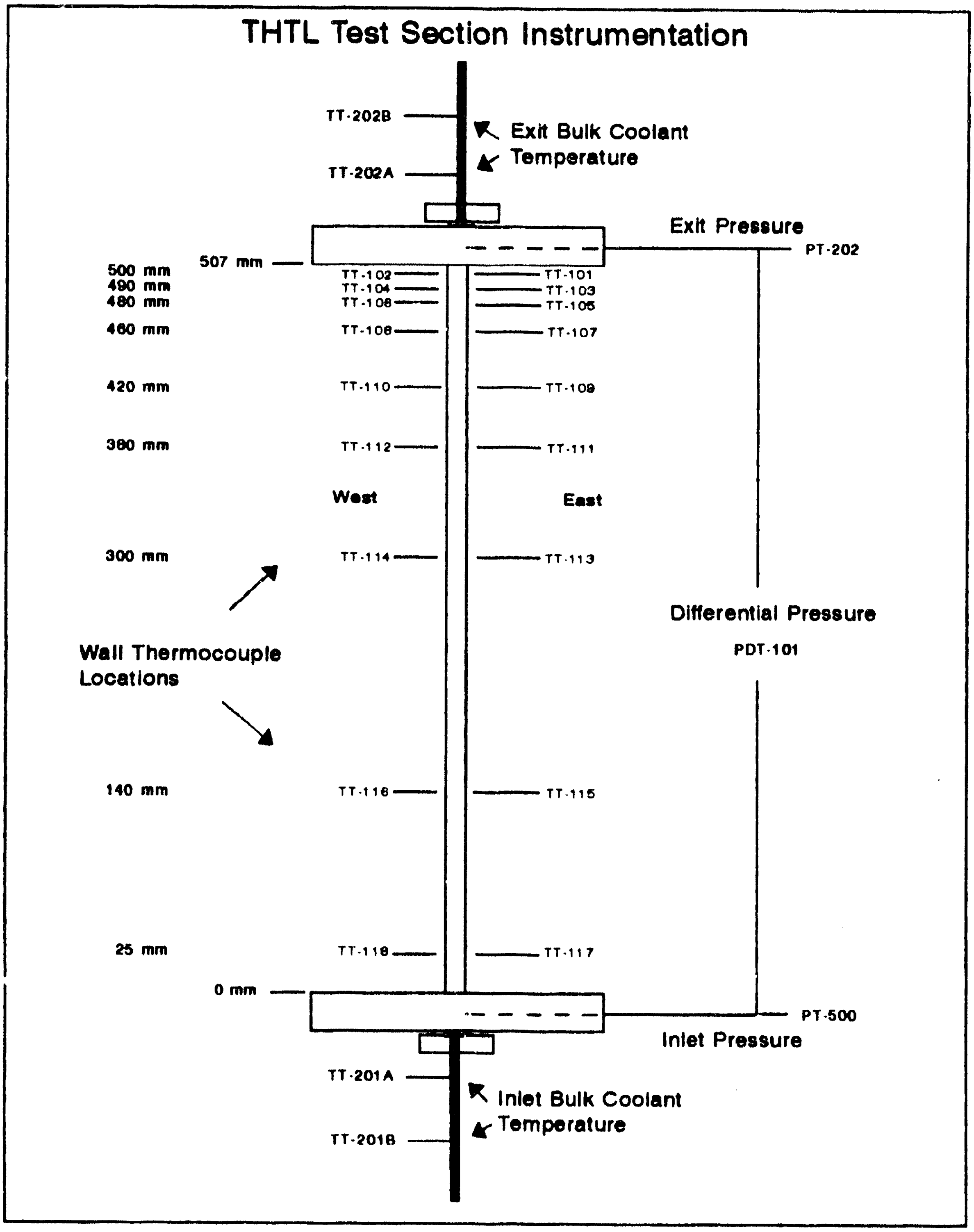

Fig. 2.10. Detail of THTL test section instrumentation.

Table 2.4. THTL Instrumentation

IAN	Type	Location	Range
TT-101 to TT-118	Temp (Type N T/C)	Test channel	0–700°C
TE-119	Temp (Type K T/C)	Aluminum bus	0–200°C
TE-120	Temp (Type K T/C)	Aluminum bus	0–200°C
TE-121	Temp (Type K T/C)	Aluminum bus	0–200°C
TE-202C	Temp (Type K T/C)	Pump suction	0–100°C
TE-500	Temp (Type K T/C)	Letdown line	0–100°C
TT-201A	RTD transmitter	Test section inlet	0–150°C
TT-202A	RTD transmitter	Test section exit	0–300°C
TE-201B	RTD	Test section inlet	0–150°C
TE-202B	RTD	Test section exit	0–300°C
PDT-101	Differential pressure	Test section differential	0–3.4 MPa
PT-200	Pressure	Pump suction	0–5.2 MPa
PT-202	Pressure	Test section exit	0–5.2 MPa
PT-203	Pressure	Upstream test section control valve	0–5.2 MPa
PT-500	Pressure	Test section inlet	0–5.2 MPa
FT-201	Volumetric flow	Test section line	0–75.7 L/s
FT-202	Volumetric flow	Test section bypass line	0–378.5 L/s
AT-400	pH	Low-pressure system	0–14
CT-400	Conductivity (water)	Low-pressure system	0–2,000 μS/m
JT-101A	Power (one supply)	PS-101A only	0–300 kW
IE-101A	Current	PS-101A	0–25,000 A
EE-101A	Voltage	PS-101A	0–12 V
IE-101B	Current	PS-101B	0–16,000 A
EE-101B	Voltage	PS-101B	0–12 V
EE-101	Voltage	Across test section	0–12 V
TT-130	Temp (Type N T/C)	Test section edge	0–700°C
TT-131	Temp (Type N T/C)	Test section edge	0–700°C

2.3.5.3 Pressure and Differential Pressure

Pressure is measured at several locations in the loop as shown in the loop instrument schematic (Fig. 2.9). The measurements are made using Rosemount pressure and differential pressure transmitters at all locations. Fast-response transducers, Sensotec model TJE, are used at two redundant locations, the test section inlet and for the test section differential pressure measurement. These have response times of ~1–5 ms.

The test section pressure taps are located in the end flanges. The nominal test channel dimensions extend through the flanges, so the tap is measuring pressure in the channel geometry prior to the transition to the loop tubing. These pressure taps are located (axially) approximately 12.7 mm from the end of the "heated" length. The locations of these pressure taps are shown in Fig. 2.10.

2.3.5.4 Power—Voltage and Current

Test section power is calculated from measured power supply current and the voltage drop across the test section. The current through the test section is measured via a shunt located in each of the two power supplies. The voltage drop across the test section is measured from taps located on the inlet and outlet flanges of the test section. The 0–12 V signal is reduced to a 0–8 V signal using a voltage divider and then input into a Promac Series XZ7 transmitter, which provides isolation and produces a 4–20 mA signal for transmission to the data-acquisition system.

2.3.5.5 Conductivity

A Rosemount model 1181C conductivity transmitter and associated in-line sensor provide a continuous measurement of conductivity (total dissolved solids) in the letdown flow stream. The transmitter provides an isolated 4–20 mA signal to the data-acquisition system. Reference solutions are used for calibration of the sensor and transmitter.

2.3.5.6 pH

A Rosemount model 320HP high-purity pH sensor is used in conjunction with a model 1181 pH two-wire transmitter for making in-line pH measurements of the system letdown flow. The sensor assembly consists of a stainless steel flow cell with a specially designed liquid junction, temperature compensator, and a weatherproof ABS junction box containing a preamplifier. A rotameter and needle valve are included on the inlet of the flow cell for monitoring and controlling sample flow. The reference electrode is a sealed, double junction type. The measuring electrode is high-impedance glass with a local preamplifier. The model 1181 transmitter provides circuitry for the measurement and transmission of an isolated 4–20 mA signal to the data-acquisition system. Reference buffer solutions are used for calibration of the complete measurement system.

2.3.5.7 Programmable Logic Control (PLC)

A programmable logic control (PLC) system is used to protect equipment and to ensure safe operation of the integrated loop systems. The system is a GE Fanuc Series One PLC, which is capable of handling both analog and digital inputs from process instruments and capable of providing logical control of outputs to system interfaces. The logic incorporated for the loop includes start-up sequences to ensure adequate conditions for component start-up as well as continuous monitoring of process limits within desired operating ranges. The logic provides automatic shutdown of the pumps and power supplies when process limits are exceeded.

Start-up Sequence

Start-up of the primary pump requires that the metering pump is on and that the loop is pressurized above a low-pressure limit set point. Application of power to the test section requires, in turn, that test section volumetric flow exceeds a low-flow-limit set point and that process water is available to the heat exchanger. The power supply controller also has internal flow limit switches that require minimum flow levels to allow closure of the main contactor.

Shutdown Interlocks

Once power has been applied, process measurements are monitored for operation within a selected range between high- and low-limit set points as appropriate. Limits that will result in system shutdown include low pump-suction pressure, low test-section inlet pressure, high loop pressure, low test-section flow, high outlet bulk-coolant temperature, high test-channel wall temperature, and high bulk-coolant inlet temperature. Actual limit settings are made on indicator switches located on the main control panel and are adjustable to match specific test conditions.

2.3.5.8 Process Controls

A CIMAC 2 controller provides proportional-integral-derivative (PID) automatic feedback control for up to six separate processes. The system currently uses automatic feedback control for system pressure, inlet coolant temperature, test section flow, pump speed, and test section power. In actual practice to date, the automatic control has been used primarily for pressure and inlet temperature control. The other parameters have been operated using the controller in the manual mode. One of the features of this multi-loop controller is the capability of providing synchronized programmable multi-loop control of the different processes. This feature provides the capability of introducing transient conditions during a test sequence that would be difficult to control manually, involving test section power, pressure, coolant temperature, and flow.

The controller receives 4–20 mA inputs from process measurement instruments and produces a 4–20 mA output, which is used to drive transducers or to control devices for process control. Each loop may be operated in manual or automatic mode, and the PID parameters are adjustable to match the specific control function. The following are specific functions of the six available control channels:

Channel 1. The test section flow measured by the turbine meter provides the input signal for the flow controller, which can be used to drive the flow control valve on the test section inlet line. For most modes of operation, this control channel is operated in the manual mode with the valve at a specified position.

Channel 2. Test section inlet bulk coolant temperature provides the signal input to the temperature controller. The output of the controller drives a flow control valve positioner on the secondary water flow line to the primary heat exchanger.

Channel 3. Test section exit pressure provides the input signal for pressure control. The output signal from the controller drives the letdown pressure control valve position, which controls letdown flow to the low-pressure system.

Channel 4. Measurement of the power produced by the 25,000-A power supply provides the input signal for the power control. The controller provides a demand signal back to the power supply.

Channel 5. Spare channel.

Channel 6. This channel is used in the manual mode to provide an external drive signal to the local pump speed controller. Pump speed is controlled by a high-performance pulse-width-modulated inverter that generates a sine-coded, adjustable voltage/frequency three-phase output to the 30-hp pump motor. The inverter can be controlled at its local panel or remotely from the CIMAC 2 controller (which is the normal operating mode).

2.3.5.9 Data Acquisition

A PC-based data-acquisition system is used for recording test data. The system was commercially procured from Dianachart, Inc., and is capable of measuring 48 inputs that are optically isolated and guarded. The system has 16-bit resolution over a range of 0.3-μV to 10-V input signals and has direct thermocouple and RTD input capability. The system includes menu-driven software and real-time graphing capability. Along with the 48 signal inputs, additional channels are available for generating calculated quantities based on measured channels for display and recording purposes. Some of the system specifications are shown in Table 2.5.

Table 2.5. Data-acquisition system specifications

Inputs	Voltage: 0.3 μV to 10 V Current: 4–20 mA, 0–50 mA Thermocouple types: JKEBRSTNW RTDs, strain gages with ranges −5 V to +10 V
Resolution	16 bits (1/65535), 0.3 μV minimum
Accuracy	±0.02%
Binary inputs	11 on/off, (expandable to 640), TTL or contact closure
Control outputs	10 TTL
Impedance	10,000 MΩ/0.1 μF
Linearity	±0.02%
Power	120 V, 50/60 Hz, 0.5 A

3. EXPERIMENTAL PROCEDURES

The cooling channels in the ANSR fuel assembly are all parallel and share common inlet and outlet plenums, effectively imposing a common pressure drop across all the channels. This core configuration is subject to FE and/or flow instability that may occur once boiling is initiated in any one of the channels.[3,4] The FE phenomenon constitutes a thermal limit different from a true CHF or a departure from nucleate boiling (DNB). In such a system, initiation of boiling in one of the channels (i.e., the hot channel) can result in flow redistribution to the other, cooler channels. This process can very rapidly lead to flow starvation, which in turn, leads to a DNB in the hot channel at flows lower than the nominal flow rate. The FE phenomenon is in contrast to a primary DNB that occurs at a nominally constant flow rate, referred to here as a "true CHF."

The more complete way to predict the occurrence of FE is to perform flow-vs-pressure-drop analysis of the parallel channels involved and to predict the subsequent flow redistribution under constant and common pressure-drop boundary conditions. Performing this prediction is quite complex because of the uncertainties involved in predicting void fractions and pressure drops in two-phase flow. In reality, after boiling starts, the flow resistance of the channel increases drastically, leading to flow reduction in the channel. The flow reduction promotes more boiling, which rapidly leads to FE. Therefore, it is normally accepted that FE [also referred to as the onset of flow instability (OFI)] will most likely occur near the point where sustained net vapor first appears. This point is called the onset of net vapor generation (ONVG) point[5] or the point of onset of significant void (OSV).

Maulbetsch and Griffith[6] and other investigators analytically and experimentally demonstrated the conditions under which excursive instability will occur. They have determined that such instability will occur "if the slope of the (demand) pressure-drop vs flow rate is more negative than that of the external supply system."[6] This statement is expressed mathematically as:

$$\frac{d(\Delta P_{ext})}{dV} > \frac{d(\Delta P_{ts})}{dV} \quad . \tag{1}$$

Figure 3.1 presents a typical plot of the pressure drop vs flow rate relationship under various boundary conditions. In the case of many parallel channels between large common headers, as is the case in the ANSR, the slope of the external supply system is practically zero and is represented in Fig. 3.1 by horizontal lines (A and B). Based on this observation, FE or OFI conditions were determined in most of the THTL FE experiments by detection of the test section pressure-drop minimum as the flow to the test section was reduced under a constant heat flux. This method allowed for repetition of many nondestructive FE tests without experiencing an actual FE, which normally causes test section failure. For confirmation and comparison, limited experiments were performed with an actual FE burnout, and some experimentswere run with true CHF burnout under constant flow. To accommodate these experiments, the design of the THTL system had to respond to three separate modes of operation as enumerated below.

1. A "soft" system was used to perform actual FE tests with burnout. In this mode, a large bypass around the test section was fully open so that the flow could split between the test section and the bypass to maintain an almost constant common pressure drop across both, thus closely simulating the ANSR configuration.

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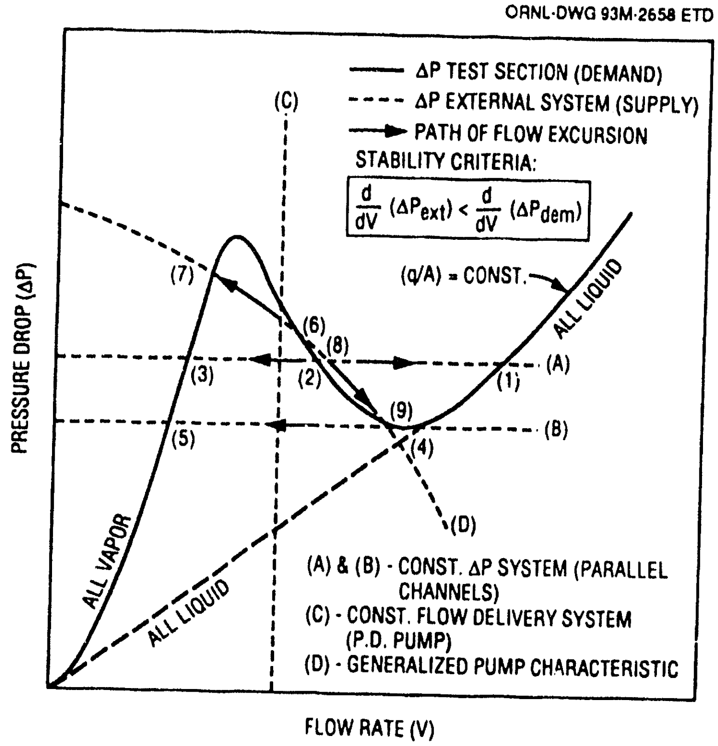

Fig. 3.1. Pressure drop vs flow rate relationship for various boundary conditions.

2. A "stiff" system was used to perform true CHF tests with actual burnout at constant and known flow rates. In this mode, the bypass around the test section was completely closed to maintain a constant flow through the test section. In addition, a near-positive-displacement pump that provides a nearly constant flow rate was used in the primary loop. This pump is insensitive to the system pressure-drop characteristics. Small-diameter piping (to reduce volume) and a throttling valve were also used upstream of the test section inlet to enhance flow stability.
3. A modified "stiff" system was used to perform simulated FE tests without experiencing actual FE. In this mode, a closed or minimal bypass configuration, along with a significant pressure drop across the flow control valve upstream of the test section, was used to prevent actual FE or other flow instability. In this case, the potential for FE was determined by detecting the minimum pressure drop in a plot of pressure drop vs flow rate (which coincides with the ONVG point) as demonstrated by Maulbetsch and Griffith,[6] Whittle and Forgan,[7] Costa,[5] Johnston,[8] Dougherty,[9] and others. Most of the FE tests were performed using this approach.

Because the ANSR has many channels in parallel, an ideal bypass simulation in the THTL would require a very large bypass flow ratio ("infinite bypass") and, therefore, an unrealistically large pump. In practice, however, a reasonable, but not ideal, flow ratio can provide a very close simulation with no significant error. The lowest bypass flow ratio necessary, which still provides sufficiently constant pressure-drop boundary conditions, was investigated in two independent studies—one transient and one steady state. Both studies are based on models simulating the THTL as a pressure-drop vs flow network to determine the sensitivity of the bypass pressure drop to changes in test section flow for a variety of bypass-to-test-section flow ratios. The first model showed that bypass ratios ≥ 4 begin to approach the response of an "infinite bypass," with absolute flow rates within 3% of the infinite bypass steady-state flow rates.[10] The second model showed in a preliminary way that the slope of the bypass pressure drop with the test section flow rate (supply side $d(\Delta P_{ext})/dV$ in Eq. 1) exceeds the slope of the test section pressure drop vs flow rate curve (demand side $d(\Delta P_{ts})/dV$ in Eq. 1) for a bypass ratio of ≥ 3, satisfying the condition for instability (Eq. 1). This supply-side slope becomes extremely small (practically horizontal) for bypass ratios above ~6, closely simulating the ANSR parallel channel configuration. (See Fig. 3.1 for the supply and demand pressure-drop relationships.)

3.1 TEST OPERATION

3.1.1 Flow Excursion Tests Without Burnout

These tests are conducted with additional pressure drops imposed on the test channel flow leg to prevent actual FE leading to channel failure. A closed or minimal bypass flow configuration, along with a significant pressure drop imposed by the position of the test section line flow control valve, is used to prevent actual excursion. The test is initiated by setting test section flow to a level where no boiling will exist at the target heat flux level. The applied power to the test section is then raised to produce the target heat flux level. Exit pressure is automatically controlled via the system letdown valve and high-pressure makeup pump at the desired setting (nominally 1.7 MPa for normal ANS conditions). Process water flow to the secondary side of the heat exchanger is also automatically controlled to maintain the inlet bulk coolant temperature at the desired set point (nominally 45 °C for normal ANS conditions). Data are recorded continuously during these processes by the PC-based data-acquisition system. Once the system is stabilized and data are obtained under steady-state conditions, the velocity is reduced to a lower level while the measured differential pressure across the test channel is monitored. This reduction is made through either pump speed reduction, flow control valve positioning, bypass flow adjustment, or some combination of these, depending on the proximity of the conditions to the expected minimum. As the minimum is approached, the loop configuration is adjusted to minimize the amount of bypass flow and to maximize the pressure drop across the control valve in order to prevent an actual excursion-to-channel failure. The system is allowed to stabilize at each of the velocity settings selected. Power supply adjustments are made concurrent with velocity changes to maintain the average heat flux constant (because the temperature coefficient of resistivity of the aluminum affects the current-voltage characteristics of the test channel as velocity is reduced and as test-channel wall temperatures increase). Once the minimum in pressure drop has been determined (by observation of increasing pressure drop as velocity is further decreased), the velocity is increased once again, and data are taken at some of the velocity points obtained during the earlier sequence for comparison.

3.1.2 Flow Excursion Tests With Burnout

These tests are conducted to simulate the bypass that exists because of the large number of channels in the reactor. The loop is configured with the test section control valve and the bypass line directly around this valve in the full open position. The tests are then run in the same manner as described above by setting heat flux, inlet coolant temperature, and exit pressure at the desired values, and reducing test section velocity in steps until failure of the test channel occurs. The test section velocity is controlled by adjusting the test section bypass line manual control valve and pump speed (Fig. 2.1). Ultimate bypass ratios available are limited by the pump capacity. The effect of limited bypass ratio on tests measuring the point-of-flow excursion to actual channel failure is currently being examined both experimentally and analytically. In general, channel failures have occurred at lower velocities than the actual minimum in pressure drop vs velocity (where the minimum is the expected point of failure for the "infinite" bypass case).

3.1.3 Critical Heat Flux (CHF) Tests

These tests are conducted under nominally constant mass flux conditions in order to measure a true CHF or DNB. The loop is configured with the test section bypass line manual control valve closed so that all of the mass flux delivered by the pump must flow through the test channel. The tests are operated in a manner similar to that described above, with velocity being reduced while holding constant the channel average heat flux, inlet bulk coolant temperature, and exit pressure.

4. SUMMARY

The THTL was constructed to provide experimental measurements of thermal limits and other thermal-hydraulic parameters required to support the design and licensing of the ANSR. In the design process, special consideration was given to include the proper pump, test section bypass configuration, and system valving and piping to allow measurement of both CHF and FE thermal limits.

The initial focus of the THTL experimentation for the ANSR is the determination of thermal limits under ANS nominal conditions using water as coolant. Plans include additional experiments to be performed with the existing facility and the basic test section design to capture the onset of incipient boiling, single-phase heat transfer coefficients and friction factors, and two-phase heat-transfer and pressure-drop characteristics.

Also included are plans for non-nominal conditions, including low-flow tests simulating shutdown and refueling conditions, low-pressure conditions simulating LOCA and other selective quasi-equilibrium conditions encountered during transient scenarios, the effects of oxide buildup (typical for aluminum), the effects of material and its surface roughness, and the effects of heavy water on the thermal limits (CHF, FE, and incipient boiling).

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