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**NUCLEAR REACTOR TECHNOLOGY
AND SCIENTIFIC COMPUTATIONS**

WSRC-TR-93-682

KEYWORDS:
ONSET OF FLOW INSTABILITY
ONSET OF SIGNIFICANT VOID
DEMAND CURVES
LOSS OF COOLANT ACCIDENT
CU-HTRF-T4

RETENTION:
PERMANENT

**COLUMBIA UNIVERSITY FLOW INSTABILITY
EXPERIMENTAL PROGRAM, VOLUME 1**

**SINGLE TUBE UNIFORMLY HEATED TESTS
PART I, TECHNICAL DISCUSSION (U)**

by

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January, 1990

Authorized Derivative Classifier/
Reviewing Official

SRTC

**SAVANNAH RIVER TECHNOLOGY CENTER, AIKEN, SC 29808
Westinghouse Savannah River Corporation
Prepared for the U.S. Department of Energy under
Contract DE-AC09-89SR18035**

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EXPERIMENTAL PROGRAM

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The coolant in the Savannah River Site (SRS) production nuclear reactor assemblies is circulated as a subcooled liquid under normal operating conditions. This coolant is evenly distributed throughout multiple annular flow channels with a uniform pressure profile across each coolant flow channel. During the postulated Loss of Coolant Accident (LOCA), which is initiated by a hypothetical guillotine pipe break, the coolant flow through the reactor assemblies is significantly reduced. The flow reduction and accompanying power reduction (after shutdown is initiated) occur in the first 1 to 2 seconds of the LOCA. This portion of the LOCA is referred to as the Flow Instability (FI) phase [1].

The reactor assemblies are subject to a type of FI known as a Ledinegg flow excursion. This type of instability is common in low pressure subcooled flow channels that exhibit a demand curve with a negative sloped region and a relative maximum and minimum as shown in Figure 1. The relative minimum is the result of the flow acceleration created by the change in fluid density, and an increase in the frictional pressure loss created by vapor nucleating on the heater surface and effectively increasing the flow channel roughness. The postulated LOCA can initiate such a flow excursion.

Assembly power limits are calculated for LOCA conditions using the FLOWTRAN-FI code. The code calculates a dimensionless ratio known as the Stanton number at each axial position in the channel through the course of the transient. This Stanton number was introduced by Saha and Zuber [2] to describe the Onset of Significant Void (OSV) in channels where subcooled nucleate boiling is present.

$$(1) \quad St = \frac{\phi}{Gc_p(T_{sat} - T_b)}$$

where:

ϕ = local heat flux
 G = mass velocity
 c_p = liquid specific heat
 T_{sat} = saturation temperature
 T_b = bulk liquid temperature

The Stanton number will vary both with time and position in the assembly. The reactor operating power is limited to preclude Stanton numbers in excess of 0.00455 during the LOCA. This value is 70 percent of the 0.065 value proposed by Saha and Zuber (2). This difference is a safety margin that accounts for data and calculation uncertainties.

Equation 1 was developed with data where the Peclet number did not exceed 400,000. The Peclet numbers in the SRS reactors can be an order of magnitude higher than this. To evaluate the suitability of the above described criteria additional test data at high Peclet numbers was required. Columbia University was tasked (AX-1811457) with obtaining this data. In addition Columbia University obtained data to evaluate the effect of spacer ribs in a concentric annulus.

This is one of a series of reports that documents the testing effort by Columbia University. Table 1 provides of the WSRC technical report volumes. The volumes which contain a hard copy version of the data files are also listed. The electronic media that contain the data have been stored as part of the Thermal-Fluids Laboratory (TFL), Building 786-A electronic records.

References

1. *Action Plan to Upgrade Thermal-Hydraulic Limits for Savannah River Site Production Reactors (U)*. 30 June 1989. WSRC-RP-89-373.
2. Saha, P., and N. Zuber, 1974, Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling. In *Proceedings of the 5th International Heat Transfer Conference, Tokyo, Japan, September 3-7, 1974*, 175-79.

Figure 1. Demand curves for subcooled isothermal and diabatic systems

Table 1.--Columbia University Onset of Flow Instability Experimental Program Technical Reports

Volume	WSRC document number	Authors	Sub-Title	Columbia University document number	Date prepared
1	WSRC-TR-93-682	Dougherty, et al.	Single Tube Uniformly Heated Tests, Part I, Technical Discussion	CU-HTRF-T4	January 1990
2	WSRC-TR-93-683	Dougherty, et al.	Single Tube Uniformly Heated Tests, Part II, Uncertainty Analysis and Data	CU-HTRF-T4	May 1990
3	WSRC-TR-93-684	Dougherty, et al.	Single Tube, Parallel Flow Tests	CU-HTRF-T6	June 1990
4	WSRC-TR-93-685	Dougherty, et al.	Single Tube, Non-Uniformly Heated Tube Tests	CU-HTRF-T5	October 1990
5	WSRC-TR-93-686	Carrano, et al.	Single Annulus Tests, Steady State Test Program	CU-HTRF-T3A	July 1991
6	WSRC-TR-93-687	Carrano, et al.	Single Annulus Tests, Transient Test Program	CU-HTRF-T3B	September 1992
7	WSRC-TR-93-688	Carrano, et al.	Single Tube Tests, Critical Heat Flux Test Program	CU-HTRF-T8	September 1992
8	WSRC-TR-93-659	Yang	Single Annulus Tests, Final Report	CU-HTRF-05-92	December 1992
9	WSRC-TR-93-690	Coutts	Single Tube Test Program Demand Curve Data Tables	...	September 1993
10	WSRC-TR-93-691	Coutts	Critical Heat Flux Test Program Data Tables	...	September 1993
11	WSRC-TR-93-692	Coutts	Single Annulus Steady State Test Program Data Tables	...	September 1993
12	WSRC-TR-93-693	Coutts	Single Annulus Transient Test Program Data Tables, Part I	...	September 1993
13	WSRC-TR-93-694	Coutts	Single Annulus Transient Test Program Data Tables, Part II	...	September 1993
14	WSRC-TR-93-695	Coutts	Single Annulus Transient Test Program Data Tables, Part III	...	September 1993

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**WESTINGHOUSE SAVANNAH RIVER COMPANY
FLOW EXCURSION EXPERIMENTAL PROGRAM
SINGLE TUBE UNIFORMLY HEATED TESTS**

PART I - Technical Discussion

January 1990

Heat Transfer Research Facility

Columbia University

New York City, NY

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Many individuals and organizations have contributed to the overall effort of designing and constructing the flow loop and test section. Some of the individuals that were directly responsible for obtaining the flow instability data presented in this report are acknowledged below.

We would like to express our appreciation to our colleagues at the Heat Transfer Research Facility of Columbia University for their continued interest and support throughout this project, especially to Messrs V. Carrano and W. Hovemeyer for the design and maintenance of the electrical system and instrumentation; Messrs S. Kokolis, A. Kaam, Ms. A. Girshovich for the mechanical design of the test sections and flow loop. We would also like to acknowledge Mr. J. Dechert and the machine shop personnel. In addition, we appreciate the important contribution of Mr. J. Zimmerman and the electrical shop personnel.

We are grateful to our sponsor, in particular Dr. Zafar Qureshi for his technical advice and direction.

ABSTRACT

An experimental program has been conducted to investigate flow instability in circular tubes under vertical down-flow conditions. The test section L/D ratio range was 86 to 270. The maximum test section surface heat flux was one million Btu/hr-ft².

Over 1700 data points were obtained. The effect of flowrate, inlet temperature, exit pressure, and heat flux on the initiation of flow instability was determined. In addition, the data was used to evaluate various methods of predicting the onset of flow instability.

Using the measured wall temperatures, surface temperatures and heat transfer coefficients have been obtained. Correlations for the heat transfer coefficient along the tube under both single and two phase conditions were developed.

**FLOW EXCURSION EXPERIMENTAL PROGRAM
SINGLE TUBE UNIFORMLY HEATED TESTS**

SUBCONTRACT AX-721092

REPORT No. CU-HTRF-T4

JANUARY 1990

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1. INTRODUCTION

1.1 Background

In June 1988, Savannah River Laboratory requested that the Heat Transfer Research Facility modify the flow excursion program, which had been in progress since November 1987, to include testing of single tubes in vertical down-flow over a range of length to diameter (L/D) ratios of 100 to 500. The impetus for the request was the desire to obtain experimental data as quickly as possible for code development work. In July 1988, HTRF submitted a proposal to SRL indicating that by modifying a facility already under construction the data could be obtained within three to four months.

The facility in question was the bench test instrumentation evaluation facility. As part of the flow excursion program, HTRF was evaluating instrumentation for use in two-phase. These instruments included fast response thermocouples, fast response pressure transducers, and drag disks. Most of the flow loop equipment was already in place. The major changes included the installation of power for the test section (approximately 1.5 MW), preparation of test sections, development of instrumentation, and the construction of a control room. An overall height limitation in the facility of 12 feet and a maximum pump head capacity of 70 psi restricted the allowable L/D range to 90 to 270. SRL approved the proposal in July 1988 and the initial data were obtained in October 1988.

Since fall 1988, the limited objective of obtaining demand curve information has been expanded to include a larger L/D range, parallel mode operation, transient testing, non-uniformly heated tubes, and critical heat flux testing. The present report will be limited to the results covered by the initial proposal. Because of the addition of a high head pump to the test facility in August 1989, testing of smaller diameter tubes became possible and the overall L/D range was increased to 330 from 270. However, tests on this tube (0.29 inch diameter) have not been completed because of the addition of higher priority tasks to the overall program. When these tests are complete, they will be issued as an addendum to this report.

For the purposes of this program, the onset of flow instability (OFI) is defined as the occurrence of a minimum in the pressure drop versus flowrate curve. For a

fixed set of test conditions, the pressure drop across a test section will decrease with flowrate until vapor begins to form in the channel. Vapor appears in the form of bubbles at the heated surface. Initially, the effect of these bubbles is insignificant; however, as the bubble population increases, the resistance to flow increases. At this point, the pressure drop begins to increase even though the flowrate is decreasing (see figure 1.1). Since the bulk fluid temperature is below saturation, bubbles, which formed at the wall, collapse in the main channel flow. This process of formation and collapse causes the pressure reading to oscillate. Beyond the OFI point, the channel is unstable; however, because a positive flow supply is available no flow excursion occurs. If an alternate flow path were available, the possibility of rapid flow loss and burnout would exist.

1.2 Test Objective

The primary objective of the single tube program was to obtain as quickly as possible experimental data in the form of demand curves for use in the prediction of the onset of flow instability (OFI). Aside from the flow direction (vertically downward), there was no attempt to make conditions prototypic. To meet schedule requirements, commercial grade 300 series stainless steel tubing was selected for the test sections. Later, concern was expressed by SRL over possible non-uniform heating caused by temperature induced resistivity changes in stainless steel. HTRF was then able to purchase 600 series inconel to replace stainless steel as the test section material for tests later in the program.

Test section pressure drop was to be measured over the heated length. In addition, the primary test data included flowrate, test section inlet temperature, and exit pressure. The latter parameters established inlet subcooling and saturation temperature respectively.

The test section was designed to provide maximum flexibility and ease of test section replacement. Calming lengths were provided upstream and downstream of the heated length. These sections were also used to connect the test section to the power system.

Although test section wall temperature data was not initially needed with respect to the primary objective, instrumentation was required to provide safety

information to prevent excessive tube temperatures. A secondary objective was, therefore, defined to obtain wall temperature data so that heat transfer studies could be conducted. To this end, thermocouples were mounted on the exterior of each test section at various axial locations. By combining this measured data with test section geometry and heat flux, both inside surface temperatures and heat transfer coefficients could be calculated.

The test conditions for the experiment were selected to provide data in a range encompassing the anticipated reactor conditions. Limitations of the flow loop or available equipment imposed some restrictions on test conditions. For instance, initially, SRL requested operation at 5 psig and 50 psig test section exit pressure. The 5 psig condition could not be achieved without a major modification of the test loop and resulting delay in the program. It was finally agreed to test at 20 psig and 50 psig. The initial proposal contained no specific test tolerances; however, in November 1988, SRL imposed very strict test conditions at specific test levels. This required some changes to the flow loop, the control system, and the power system. They were achieved with minimum delay and have contributed to very good experimental results.

1.3 Report Format

This report presents data obtained during the uniform flux testing of six test sections covering an L/D range from 86 to 267. The present report consists of two parts. Part I contains the technical discussion of the test loop, procedures, and results. Part II contains a listing of all the experimental data.

To date, HTRF has obtained over 1700 test points in the single tube facility. Each test point yields approximately 80 pieces of data. The report contains analyses of all the data and presentation of the key experimental results. In addition, appendices containing the computer programs used to reduce the data are provided.

FIGURE 1.1 SCHEMATIC OF DEMAND CURVE

2. DESCRIPTION OF TEST FACILITY

2.1 Introduction

The single tube test program was developed in several phases which included controlled flow tests, parallel flow tests with large bypass flows, transient testing, non-uniform heating tests, and critical heat flux tests. The present report describes the controlled flow testing to obtain demand curves for six tubes of different size inside diameter.

2.2 Test Facility Physical Description

2.2.1 Single Tube Test Loop for Controlled Flow Test Mode

For these tests, the controlled flow mode of operation was used. In this mode, the flowrate to the test is varied to provide the range of experimental information desired. After steady state conditions of inlet temperature, exit pressure, and surface heat flux have been established, the flowrate is reduced until the minimum in the test section pressure drop occurs. To insure that flow instability has been achieved, several test points beyond the minimum are also recorded.

The test apparatus consists of the test loop which supplies cooling water at the required conditions, and the test section which consists of the heater tube. Figure 2.1 presents a schematic of the complete single tube test apparatus. The flow loop is capable of supplying 260 gpm to the test section at a pump head of 75 psi. The test loop can be pressurized for a range of operating pressures. Heat input to the test section is supplied by a generator which can deliver approximately 1.5 MW of DC power. This energy source is capable of generating a 1 million Btu/hr-ft² surface heat flux to the various diameter test sections selected for this program. All components in the flow loop are stainless steel or nickel plated. The water in the loop is maintained at a pH of slightly less than 7.

As shown in figure 2.1, a 100 gallon accumulator supplies deionized water to the pump inlet. System pressure is maintained by adjusting the liquid

level and by changing the helium blanket pressure in the accumulator. The test section inlet temperature is controlled by adjusting the loop external heat rejection rate.

The pump used for the first portion of this test program was a centrifugal pump capable of providing a maximum flowrate of 250 gpm. Figure 2.2 presents the pump performance curve for this unit. The flow to the test section is controlled by an air operated valve which is located upstream of the test section (see figure 2.1). Since the pump flow output exceeds the test section requirements (for test section diameters of 0.60 inches and greater), most of the flow is by-pass directly to the heat exchangers shown on the loop schematic. Since most of the pressure drop occurs across the air operated valve, no flow excursion occurs when flow instability is experienced. The flow loop has also been operated with the by-pass closed. No effect on the experimental results was observed. However, loop control was more difficult and, therefore, this mode was not used in the program. When testing the 0.36 inch diameter test section, the test section pressure drop was a significant fraction of the pump head. In one case this pressure drop was large enough to cause test section failure probably due to flow diversion. For this reason, a second pump with a high head was added to the loop (see section 2.2.2)

The test assembly is 126 inches in length. It is composed of a 96 inch heated test section and upstream and downstream 15 inch calming lengths which also serve as a connection to the power system. The calming lengths have an outside diameter of 1.5 inches and a variable inside diameter to accommodate the different size heater tubes. Six different size heater tubes and two different tube materials were used. The tubes were uniform wall thickness 300 series stainless steel and 600 series inconel. Table 2.1 presents the specifications of the test sections used in the program. During the program, three test sections were burned out. Using replacement test sections, the test matrix was completed for all units. Test section ST-7 was used to show the comparison between an inconel and stainless steel. In all cases the test sections were constructed from commercial grade tubing. This means that the nominal uniform tube wall thickness can vary by as much as 10%. In table 2.1, the column marked measured ID is used in the data analysis and to identify the tube. As noted in table 2.1, three different methods were

used to measure the tube inside diameter. Where gages were not available, the inside diameter was calculated from outside diameter and wall thickness measurements. In later sections of this report, the measured ID rounded to two decimals is used to identify the tube.

The test section construction was essentially the same for all units. The heated portion of the test section was brazed to nickel plated copper end pieces which provided flow calming length and also a connection to the power system. The inside diameter of the end pieces were gunned bored to match the inside diameter of the inconel or stainless steel piece. To eliminate any non-uniformities in the heated section, there were no penetrations made in the tube walls. Pressure measurement taps were located in the copper end pieces. These taps, which were 2.25 inches from the end of the units, were used for absolute and differential pressure measurements. Voltage taps were brazed at either end of the test sections. In addition some test sections had a third voltage tap brazed approximately 12 inches from the test section exit. This tap was used for power trip in the event of a large change in tube resistivity.

Downstream of the test section is the heat rejection system which includes a plate type heat exchanger and shell and tube heat exchangers. These units remove energy from the water before it is returned to the accumulator.

Two types of loop instrumentation are used. The primary instrumentation, which is used for data analysis, includes flow, temperature, absolute pressure and differential pressure transducers, are sampled by the Data Acquisition System (DAS). These instruments have been calibrated against standards traceable to the National Institute of Standards and Technology (NIST). They are routinely checked at the beginning of each day's operation and are constantly monitored during testing. Secondary loop instrumentation is used to help the loop operator in controlling loop functions and also as back-up to the primary instrumentation. These instruments have also been calibrated but this calibration may not be traceable to NIST standards.

Test section instrumentation includes thermocouples for wall temperature measurement, taps and transducers for pressure drop measurement, and voltage tap leads and shunts for power measurements. These instruments are also calibrated and traceable to NIST standards.

Power to the test section is provided by a single motor generator set capable of supplying 6,000 Amperes at 230 Volts DC. The voltage can be varied continuously from zero to full power. The voltage control is operated from the test area.

Power to the test section is determined by multiplying the measured voltage across the test section by the current which is measured by two calibrated shunts located in the positive and negative polarities. Test section resistance is measured by a calibrated Kelvin bridge during test section assembly, and is constantly monitored during operation. All instruments used for power measurements are calibrated and traceable to NIST standards.

2.2.2 Single Tube Test Loop with High Head Pump

For test sections with large L/D ratios, the pressure fluctuations following OFI can be very large. For instance when testing the 0.36 inch diameter test section, the pressure drop just prior to OFI was of the order of 20 psi. The pressure drop fluctuations following OFI were estimated to range from 60 to 100 psi. These fluctuations can result in flow loss and burnout which did occur on this test section. To overcome this effect, the centrifugal pump has been replaced by a high head screw type pump. The output from this pump is controlled by varying the speed of the motor. Figure 2.3 presents a schematic of the loop with this pump. The maximum flowrate from this pump is approximately 25 gpm; however, this is sufficient to obtain OFI data for tubes with L/D ratios exceeding 250. Figure 2.4 presents the pump performance curve for this pump. A screw type is not a positive displacement pump; however, it does have a very steep head curve. This means that, for a fixed pump speed, the flowrate from the pump is independent of pressure drop.

2.3 Test Matrix

The single tube uniformly heated tests have been performed in accordance with the following test conditions:

1. Test Section: Stainless Steel, 0.745"ID
Test Mode: Controlled Flow
Heat Flux: 0;400,000;600,000;800,000
1,000,000 Btu/hr-ft²
Inlet Temperature: 77 °F, 121 °F
Exit pressure: 20, 50 psig

2. Test Section: Stainless Steel, 0.995"ID
Test Mode: Controlled Flow
Heat Flux: 0;400,000;600,000;800,000
1,000,000 Btu/hr-ft²
Inlet Temperature: 77 °F, 121 °F
Exit pressure: 20, 50 psig

3. Test Section: Inconel, 0.612"ID
Test Mode: Controlled Flow
Heat Flux: 0;400,000;600,000;800,000
1,000,000 Btu/hr-ft²
Inlet Temperature: 77 °F, 121 °F
Exit pressure: 20, 50 psig

4. Test Section: Inconel, 1.12"ID
Test Mode: Controlled Flow
Heat Flux: 0;400,000;600,000;800,000
1,000,000 Btu/hr-ft²
Inlet Temperature: 77 °F, 121 °F
Exit pressure: 20, 50 psig

5. Test Section: Stainless Steel, 0.6"ID
Test Mode: Controlled Flow
Heat Flux: 0;400,000;800,000 Btu/hr-ft²
Inlet Temperature: 77 °F, 121 °F
Exit Pressure: 50 psig

6. Test Section: Inconel, 0.360"ID
Test Mode: Controlled Flow
Heat Flux: 0;400,000;600,000;800,000
1,000,000 Btu/hr-ft²
Inlet Temperature: 77 °F, 122 °F
Exit pressure: 20, 50 psig

2.4 Test Loop Operation

The operation of the loop is the responsibility of the test engineer. Prior to conducting a test, the loop is filled and leak checked. Loop instrumentation will be checked to insure proper operation. The test start-up procedure is as follows:

- 1) at the highest point in the system, a vacuum pump is connected and system pressure is reduced to approximately 22" Hg vacuum.
- 2) at the lowest point deionized water is added to system until water reaches vacuum pump.
- 3) system bleed valves are opened selectively to remove any remaining air.
- 4) system is pressurized to 100 psia and leak check performed.
- 5) pumps are energized and nominal flowrate established to check for any remaining leaks.

6) loop operating pressures and temperatures will be established and maintained for 10 minutes to insure satisfactory operation of loop controls.

In addition to the above procedures, a set of formal instructions for test loop operation was prepared. These are presented in appendix A.

For controlled flow testing, the flowrate to the test section is established at a high enough level to insure single phase conditions. The test parameters are then set as required by the test matrix. The following criteria have been used to establish a valid test condition:

- 1) Exit Pressure ± 1 psig
- 2) Inlet Temperature $\pm 1^{\circ}$ F
- 3) Heat Flux $\pm 1\%$

When the test conditions satisfy the above criteria, the data is recorded and assigned a run number. The flowrate is then reduced and the loop parameters adjusted to maintain the required conditions. After steady state is achieved, the run is recorded. The process is repeated until OFI has been established. The criteria for OFI is a minimum in the demand curve. Generally, a few points are obtained beyond the minimum to insure that OFI has been established. As the test conditions approach OFI, the pressure readings begin to fluctuate; however, the flowrate, power, and inlet temperature remain constant. These fluctuations mean that the pressure drop reading at OFI and beyond represent an average value. For tests 7 through 9, the standard deviations in the primary measurements were calculated and recorded.

TABLE 2-1							
SRL							
UNIFORMLY HEATED SINGLE TUBE TEST							
	TEST SECTION SPECIFICATIONS						
TEST #	TUBE#	MATERIAL	ID (NOMINAL)	ID (measured)	OD (measured)	RUN#	RUN#
(IN)			(INCH)	(INCH)	(INCH)	FROM	TO
ST-1	4.995-001S	SS	0.995	1.002*	1.1262	1	112
ST-2	4.745-001S	SS	0.745	0.751*	0.8777	113	301
ST-3	4.995-002S	SS	0.995	1.002*	1.1260	302	597
ST-2.1	4.745-002S	SS	0.745	0.752*	0.8757	598	820
ST4	4.620-001I	INCONEL	0.620	0.612**	0.7485	821	1100
ST-5	4.370-001I	INCONEL	0.370	0.360*	0.4979	1101	1154
ST-6	4.1120-004I	INCONEL	1.120	1.120***	1.2510	1155	1453
ST-7	4.620-001S	SS	0.620	0.603*	0.7485	1490	1590
ST-9	4.370-003I	INCONEL	0.370	0.359***	0.4970	1663	1852
*Calculated ID by measuring OD and wall thickness at the tube ends							
**Measured ID by using gages GO-NO GO							
***Measured ID and OD with vernier at the tube ends							
Note: Runs 1 through 112 are shake down data

Figure 2.1- Schematic of the single Tube Test Loop

Figure 2.2 Pump head vs. flowrate for centrifugal pump

Figure 2.3 - Schematic of the Single Tube Test Loop with High Head Pump

Figure 2.4 Pump head vs. flowrate for high head screw pump

3. INSTRUMENTATION AND DATA ACQUISITION

3.1 Instrumentation

3.1.1 Instrumentation Philosophy

Loop instrumentation consists of ten pressure transducers, two differential pressure transducers, six turbine flowmeters, one orifice flowmeter, and two thermocouples. The loop instrumentation was primarily used to operate the loop and establish the steady state test condition. A list of general instruments used is presented in the Table 3.1. All the flowmeters were located so that they can be checked against two or more flowmeters.

The test section instrumentation was designed to provide the required test data which includes test section pressure drop, heater wall temperature, test section resistance, test section voltage, inlet and exit fluid temperature, inlet and exit pressure, as well as test section flow rate. All primary measurements were accomplished through two or more redundant instruments.

The test section volumetric flow rate was measured by the turbine flowmeters (FTI1 and FTI2) provided by Hoffer Flow Controls Inc.. The flowmeter located at the inlet to the test section, which was checked regularly with loop flowmeter FLI1 (turbine flowmeter) and DLI1 (orifice flowmeter), as well as heat exchanger flowmeter FXI1 or FXI2 (turbine flowmeters). Since deionized water was used, a hard carbon composite sleeve bearing was selected for the flowmeter. The rotation of the turbine is sensed by an externally mounted electronic pick-off coil. The signals in electrical pulses were transmitted to an Anadex PI-68 frequency to DC voltage converter where they were converted to analog signals.

Test section pressure was monitored by two Sensotec strain gage pressure transducers model TJE at both inlet and exit locations. Transducers were mounted on the copper end pieces 2.25" away from the top and bottom of the heater. The transducers feature fast response (microsecond rise time), high accuracy (0.1%), shock resistance and long term stability. In addition, two calibrated Heise gages were mounted in parallel with the test section outlet pressure transducers and another

pressure gage in parallel with inlet pressure transducer to check the transducer measurement during the tests.

The pressure drop across the test section was measured using strain gage diaphragm, differential pressure transducers provided by Sensotec and T-HYDRONICS. These two transducers both feature high accuracy and good stability. Prior to every test operation, the readings from these two differential pressure transducers were checked against the difference between the readings of the inlet and exit absolute pressure transducers with hydrostatic head correction. In addition, the reading was also confirmed with the manometer measurement during the operation.

Power to the test section was calculated from the measured current and voltage applied to the test section. The current was measured by a calibrated shunt and the test section voltage was measured through the data acquisition system using a calibrated voltage divider setup. The diameter and wall thickness were measured by a calibrated gage. After the assembly of the test section, the overall test section resistance was also measured using a calibrated bridge.

The fluid temperature was monitored by two types of thermal sensors namely type J (iron-constantan) thermocouples and resistance temperature detectors (RTD). The inlet and exit fluid temperatures of the test section were measured by four platinum RTD provided by Weed Instrument Company. The primary inlet and outlet fluid temperature were measured using two high precision and fast response (0.5 seconds at 20 ft/sec water flow rate) resistance temperature detectors, model A9507. In addition, two high accuracy RTDs model 101 (accuracy 0.1% of span) were used to check the temperature measurement of the primary RTDs at steady state condition.

The basic instrumentation philosophy was to make all of measurements by non-intrusive devices to avoid any flow disturbance. Based on this approach, thermocouples were attached to the exterior of the heater to obtain steady state thermal data. For a uniformly heated tube, the hottest region will be near the exit of the test section. Therefore, thermocouples were heavily distributed near the exit of test section.

Type E (chromel-constantan) 40 mil ungrounded thermocouples were cemented to the heater by an alumina oxide type of high thermal conductive cement for an accurate temperature measurement. In addition, type K (chromel-alumel) exposed thermocouples were brazed directly to the heater wall for a fast response detection on the temperature change. Considering the possible effect of the residual brazed material on the local temperature, the brazed thermocouples were recommended only for burn-out trip detection.

3.1.2 Instrumentation Layout

A total of 18 ungrounded thermocouples were used in each test section to monitor the heater wall temperature. As shown in the Figure 3-1 through Figure 3-3 two thermocouples were mounted every foot along the heated length of the test section for the first three tests (ST-1, ST-2, ST-3). The two thermocouples at the same elevation were located 180 degrees apart and each set was rotated with respect to the preceding set by 90 degrees. The thermocouples were connected to a reference box where the reference temperature was constantly monitored. As shown in the Figure 3-4 to Figure 3-10, the thermocouple locations were modified so that more thermocouples were installed near the exit of the heater. For the first 83 inches portion of the heater, two thermocouples were located every two feet along the test section. In the exit region of the test section, two thermocouples were mounted approximately every 3 inches in the last 13 inches of the heater.

3.2 Data Acquisition System

3.2.1 Description of Data Acquisition System

The data during flow instability tests were collected, processed, reduced to engineering units, and stored on a magnetic tape unit using a high speed data acquisition system. The computer controlled data acquisition system (CCDAS) is comprised of the following components:

- HP 1000 computer system operated under RTE-IV system.
- 15 MB disc system and a 9 track magnetic tape unit for data storage.
- graphic CRT's for system displays.
- line and character printers.
- 2313B data acquisition system.

The Hewlett Packard 2313B Analog-Digital interface subsystem is a highly flexible unit which satisfies the input and output requirements of a computer-based data acquisition and control system. The component parts of the HP-2313B subsystem include the following:

- a sample and hold amplifier,
- a 12 bit 45 KHz analog-to-digital converter (up to +10.24 volts full scale),
- a subsystem control card,
- a main frame assembly with slots for inner multiplexer or analog output cards,
- a computer interface card and cable,
- a Dual 12-bit digital-to-analog converter,
- a programmable pacer,
- twelve sets of 16 channel differential input high level (+10.24 V fs) multiplexer boards.

Figure 3.11 shows the CCDAS schematically. Specifications of this subsystem are given in Table 3.2.

3.2.2 Description of Data Acquisition Procedure

The software consists of a main program which controls a number of subroutines for data acquisition and reduction to engineering units. The main program is an on-line contact with the operator at the loop control area through one of its terminals. Depending on the option selected, the computer initiates a scanning procedure and performs on line data reduction to engineering units. During the data reduction sequence, the program reduces the data to engineering units, and performs various checks on loop parameters.

At the inception of testing, each day, all absolute pressure transducers and differential pressure transducers are set to zero position and all channels are scanned using the computer program to determine zero shifts of the transducers. These values are used by the program to offset the readings of the transducers until new zero shifts are calculated. With the instruments in zero position, all channels are scanned and reduced to engineering units and printed on the Diablo printer to check that the transducers read zero values with the zero shift corrections. Then the loop is pressurized to 50 psig, and all instruments are scanned and reduced to engineering units to check the consistency of the data. The procedure is repeated with the loop pressurized to 20 psig.

During a typical steady state run, the program is in a continuous scanning mode. In this mode all the data channels are sequentially scanned forty (40) times and the average of the 40 scans is calculated. The data matrix of the previous 30 averaged readings is updated, the latest reading is reduced to engineering units, and the important parameters of the test section such as, exit pressure, pressure drop, inlet and outlet temperatures of the coolant, the heat flux, and wall temperatures are displayed on the CRT monitor. The program checks for the operator interruption and goes back to sequential scanning if no interruption is detected.

When steady state conditions are achieved, the sequential scanning is manually interrupted using a scan default option. Then the latest 40 sequential scans are stored on a magnetic tape. The operator enters the run number, gauge exit pressure, and the manometer reading (for overall pressure drop of the test section) through an interactive terminal. The latest averaged reading of the 40 sequential scans is reduced to engineering units, stored on the magnetic tape, and printed on the printer. The following parameters are printed for each run:

1. Loop pressures
2. Test section inlet and exit pressures
3. Test section pressure drops
4. Test section inlet and exit temperatures
5. Flow rates
6. Standard deviations for the values of primary instruments based on 40 sequential scans
7. Outside wall temperatures of the test section
8. Heat flux, power, voltage, quality, and heat ratio.

Table 3-1

SRL - UNIFORMLY HEATED SINGLE TUBE TEST INSTRUMENTATION LIST

Page 1

INSTRUMENT (symbol)	TYPE OF SENSOR	MANUFACTURER	LOCATION
Volt BB	Voltage		Bus to bus voltage
Volt TS*	Voltage		Test section voltage
Curr TS*	Current (shunt)		Test section current
Curr TS2	Current (shunt)		Test section current
PT11*	Absolute pressure transducer	SENSOTEC	Inlet of test section
PT12	Absolute pressure transducer	CEC	Inlet of test section (after split)
PTO1*	Absolute pressure transducer	SENSOTEC	Outlet of test section
PTO3	Absolute pressure transducer	CEC	Outlet of test section
	Absolute pressure transducer	SENSOTEC	Parallel line inlet
PBO1	Absolute pressure transducer	SENSOTEC	Parallel line outlet
PL1	Absolute pressure transducer	SENSOTEC	Loop pressure
PL2	Absolute pressure transducer	SENSOTEC	Loop pressure (exit of parallel)
PD1	Absolute pressure transducer	SENSOTEC	Short to tank (bypass H.E.)
PX11	Absolute pressure transducer	SENSOTEC	Heat exchanger inlet
PXO1	Absolute pressure transducer	SENSOTEC	Heat exchanger outlet
PPI1	Absolute pressure transducer	SENSOTEC	Pump inlet
PPO1	Absolute pressure transducer	SENSOTEC	Pump outlet
PA1	Absolute pressure transducer	SENSOTEC	Tank pressure
DT1*	Differential pressure transducer	T-HYDRONICS	Pressure drop of test section
DT2	Differential pressure transducer	SENSOTEC	Pressure drop of test section
DP1	Differential pressure transducer	BLH	Diff. pressure across pump
DLV1	Differential pressure transducer	SENSOTEC	Control valve pressure drop
OLV1	Differential pressure transducer	SENSOTEC	Orifice pressure drop
FLI1	Turbine flowmeter	HOFFER	Loop flowrate
FT11 (FT12)**	Turbine flowmeter	HOFFER	Test section flowrate
FBI1	Turbine flowmeter	HOFFER	Parallel line flowrate
FXI1	Turbine flowmeter	HOFFER	Heat exchanger flowrate
FXI2	Turbine flowmeter	HOFFER	Heat exchanger flowrate
FS1	Turbine flowmeter	HOFFER	Bypass to tank (pump exit)

SRL - UNIFORMLY HEATED SINGLE TUBE TEST INSTRUMENTATION LIST

Page 2

INSTRUMENT (symbol)	TYPE OF SENSOR	MANUFACTURER	LOCATION
RTI1*	Resistance temperature detector	WEED	Inlet of test section
RTI2	Resistance temperature detector	WEED	Inlet of test section
RTO1*	Resistance temperature detector	WEED	Exit of test section
RTO2	Resistance temperature detector	WEED	Exit of test section
JXI1	Ungrounded type J thermocouple	CGS	Inlet to heat exchanger
JXO1	Ungrounded type J thermocouple	CGS	Exit of heat exchanger
EW1 (95W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW2 (95E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW3 (72N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW4 (72S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW5 (48W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW6 (48E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW7 (24N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW8 (24S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW9 (13W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW10 (13E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW11 (10N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW12 (10S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW13 (7W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW14 (7E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW15 (4N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW16 (4S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW17 (1W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW18 (1E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
TCB1 (7W)	Grounded type K thermocouple	CGS	Test section wall temp.
TCB2 (4E)	Grounded type K thermocouple	CGS	Test section wall temp.
TCB2 (1S)	Grounded type K thermocouple	CGS	Test section wall temp.

*:Primary instrument

**:FTI2 is primary instrument for ST1, ST2, ST3, ST2.1, ST4, ST5 and ST6

**:FTI1 is primary measurement for ST7,ST8, and ST9

Table 3.2 Data Acquisition System Specification

Number of Inputs	144 (Nine 16-channel differential inputs, high level multiplexer cards)
Input Circuit	Floated and guarded signal pairs for each channel.
Noise Rejection	80 db up to 1 Kohm source unbalanced, 105 db at all frequencies.
Common Mode Voltage	15 V line to chassis.
Accuracy for Voltage Measurement	+ 0.09% of full scale + 1/2 Least Significant Bit
Resolution for Voltage Measurement	12 bit including sign, LSB = 5 mV, 100 nV at 1000 V range
Analog-to-Digital Conversion Rate Rejection	45 KHz minimum with direct Memory Access

3.2.3 Description of Data Files

Appendix B presents the format of the data files. Part II of this report presents a listing of these files. HTRF has also sent these data to SRL on floppy diskette.

The file format in Appendix B is organized in eight tests (i.e., tests 2 through 9). Test 1 is considered to be part of the loop shakedown period and is, therefore, not part of the official data set. The format for each test number is constant. The format did change as data requirements were modified. Between test 6 and 7, the number of words per run (data) was increased from 64 to 100. Table 3.3 presents a summary of the information contained in appendix B.

Table 3.3 File Arrangement

Test Number	Run Number	Test Section Number	ID
2	113-301	ST-2	0.75
3	302-597	ST-3	1.00
2.1	598-820	ST-2.1	0.75
4	821-1100	ST-4	0.61
5	1101-1154	ST-5	0.36
6	1155-1453	ST-6	1.12
7	1454-1609	ST-7	0.60
8	1610-1662	ST-8	0.61
9	1663-1797	ST-9	0.36

Test section numbers ST-2.1 and ST-9 represent replacements for burned out test sections.

TEST NO.: ST-1
MATERIAL: SS304

TUBE NO.: 4.995-001S
ID: 1.00"

○ : Cemented thermocouple

Figure 3.1 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-2
MATERIAL : SS304

TUBE NO.: 4.745-001S
ID: 0.75"

○ : Cemented thermocouple

Figure 3.2 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-3
MATERIAL : SS304

TUBE NO.: 4.995-002S
ID: 1.00"

Figure 3.3 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

Figure 3.4 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-4

TUBE NO.: 4.620-001I

MATERIAL: Inconel 600

ID: 0.61"

Figure 3.5 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-5 TUBE NO.: 4.370-0011
 MATERIAL : Inconel 600 ID: 0.36"

Figure 3.6 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-6

TUBE NO.: 4.1120-004I

MATERIAL: Inconel 600

ID: 1.12"

Figure 3.7 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-7
 MATERIAL : SS 304

TUBE NO.: 4.620-001S
 ID: 0.60"

Figure 3.8 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-8

TUBE NO.: 4.620-003I

MATERIAL : Inconel 600

ID: 0.61"

Figure 3.9 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

TEST NO.: ST-9

TUBE NO.: 4.370-003I

MATERIAL : Inconel 600

ID: 0.36"

Figure 3.10 UNIFORMLY HEATED TEST SECTION INSTRUMENT ARRANGEMENT

FIGURE 3.11 High Speed Computer Controlled Data Acquisition System

4. ERROR AND UNCERTAINTY ANALYSIS

4.1 Instrumentation Accuracy

The errors attributed to the measurement can be categorized into three main sources; namely, the errors due to installation procedures, the instrument errors, and the errors derived from the measurement data acquisition system. Since most of the installation errors in these tests existed systematically as a fixed deviation, this type of error should be corrected prior to the determination of the measurement uncertainties.

4.1.1 Installation Errors

In order to eliminate any possible power and flow disturbance, the pressure transducers were installed on the copper end pieces 2.25" away from the top and bottom of the heater. This causes a 2.25" (or 0.092psi) hydrostatic head correction for the absolute pressure transducers. To account for this additional tube length (100.5 inches instead of 96 inches), the pressure drop measurements at steady state require a correction of approximately 4%.

The installation errors for the fluid temperature measurement have not been considered in detail. The errors are expected to be negligible. The thermocouples for wall temperature measurement were installed in a way to minimize the installation errors. The thermocouples were installed on the exterior of the heater to eliminate any flow disturbance. A high thermal conductive cement was used to eliminate any possible effects of any foreign substance (such as residual brazed materials) on the local current and heat distribution. Small diameter thermocouples (0.040") were used and the thermocouple sheath was covered by a heavy layer of fiberglass insulation material to minimize any stem conduction effects. The overall installation error for the primary wall temperature thermocouples should be negligible.

4.1.2 Measurement Uncertainties

The residual errors associated with the measurement after proposed correction include the instrument errors and the data acquisition errors.

4.1.2.1 Instrument Errors

Each instrument used in the tests has been calibrated prior to installation. In addition, all instruments used to provide data necessary for test data analysis have been calibrated and certified to an NIST standard. Instruments which were used as backup to check the functioning of a primary instrument have been calibrated and are traceable to a NIST standard but may not have traceability certification.

The uncertainties of the instruments include instrument calibration, effects of repeatability, hysteresis, linearity, zero shift, and temperature sensitivity of the instruments themselves as well as the excitation uncertainty for the absolute and differential pressure transducers, the uncertainty of the Anadex frequency to DC voltage convertor, and the uncertainty of the Rosemont bridge for the RTDs.

The turbine flowmeters were calibrated by Hoffer Flow Controls, Inc. and certified to 0.5% accuracy with 0.05% repeatability in the 10:1 turn down ratio range. The Anadex frequency to DC converters were also calibrated and an in position check was performed daily. The combined uncertainty is approximate 0.51% of full scale reading.

The Weed resistance temperature detectors along with the CU 414L Rosemont bridge were calibrated by Weed Instruments, Inc. The combined repeatability, hysteresis and linearity in the temperature range 60 to 360 °F yields an accuracy of 0.06% of the scale.

All thermocouples used in these tests have been calibrated and certified to meet the special accuracy limits of error as recommended by ANSI MC96.1-1982. For the type E thermocouple, the special limits of error as 1°C or 0.4% (whichever is greater) were certified and traceable to NIST standards.

4.1.2.2 Temperature Sensitivity and Zero Shift

For the absolute and differential pressure transducers, since the manufacturer quoted temperature effect shift only 0.0025% F.S./°F and the transducers were located at least 1 foot away from the test section, the temperature effect on the accuracy is negligible. The errors due to day to day zero shift were also monitored by a daily checkout procedure.

The zero of absolute and differential pressure transducers were checked before each test run. The absolute pressure transducers were calibrated in position at various set points (0, 25, 50 psi) with a 0 to 150 psig Heise gage. The gage was calibrated by PTC Electronic Co. using a dead weight tester and has a visual reading uncertainty of one division (0.1 psi).

Prior to each test, the transducer lines were bled to eliminate any possible air entrapment. At high temperature operating conditions, the error due to the density difference between two transducer connecting legs has maximum uncertainty of approximately 4%. At two-phase condition, the hydrostatic correction between two transducer connecting legs also depends on the void fraction in the test section. In these tests, the void fraction in the test section has not been measured. However, at low void fraction, subcooled condition, the error is expected to be small.

4.1.2.3 Data Acquisition Errors

The measuring system errors include errors from various sources such as ripple in the power supplies of the data acquisition system, errors in gain of various amplifiers, drift due to temperature effects, and digital run-off errors. Detailed descriptions of such errors are discussed in the section of data acquisition system. The errors introduced by the data acquisition system was estimated by an end-to-end calibration. A known and constant input was provided to each channel of the data acquisition system and the channel's output was recorded to estimate the fixed (offset from input) and variable uncertainties.

4.2. Overall System Accuracy

The flow instability (pressure drop) data are subject to uncertainties due to any inaccuracies of the instruments and of the techniques for obtaining and processing the data. This section presents the uncertainties that have been estimated on the basis of instrument specifications, calibration data, electronics of the data acquisition systems, testing procedures and variations in test section dimensions from specifications.

The analysis is in five parts to corresponding to five types of measurements for primary instruments. The errors included are in:

1. Absolute pressure measurement using pressure transducer.
2. Differential pressure measurement using pressure transducer.
3. Temperature measurement using RTD.
4. Flow rate using turbine flow meter.
5. Power measurement.

In combining errors, the basic approach recommended by Kline and McClintock (1953) will be used. The uncertainty interval δR of a dependent variable is given by:

$$\delta R = \sqrt{\sum (\delta r / \delta v_i)^2 \delta v_i^2}$$

Where $v_1, v_2, \dots, v_n$ are independent variables.

The magnitude of the estimated errors presented here are assumed to be a reasonable approximation of the largest errors possible. More precisely, these errors are assumed to equal to double the standard deviation of that would be computed from a reasonable large sample of data - it should be recalled that 95% of a body of data will fall within two standard deviations of a mean.

4.2.1 Uncertainty in Absolute Pressure Measurement

Total error in pressure measured by absolute pressure transducer consists of:

- a) Accuracy of the instrument and excitation voltage

stated by the manufacturer as 0.112% of full scale (200 psi).

b) Error in the line from the source to the multiplexer digitizer. This was measured to be 0.304% of the reading.

c) Error in the multiplexer digitizer (0.005 V)

The following table presents the uncertainty in absolute pressure measurement:

Abs. Pres. Psi	Signal Voltage volt	Instrument Error psi	Line Error psi	Digitizer Error psi	Total Error psi
20	0.5	0.224	0.061	0.200	0.31
50	1.25	0.224	0.152	0.200	0.34

4.2.2 Uncertainty in Differential Pressure Measurement

Total error in pressure measured by differential pressure transducer consists of:

a) Accuracy of the instrument and excitation voltage stated by the manufacturer as 0.112% of full scale.

b) Error in the line from the source to the multiplexer digitizer measured to be 0.304% of the signal.

c) Error in the multiplexer digitizer (0.005 V)

The following table presents the uncertainty in the differential pressure measurement:

Press. Drop Psi	Signal Voltage Volt	Instrument Error Psi	Line Error Psi	Digitizing Error Psi	Total Error Psi
20	5.00	0.022	0.061	0.020	0.07
10	2.50	0.022	0.030	0.020	0.04
5	1.25	0.022	0.015	0.020	0.03
2	0.50	0.022	0.006	0.020	0.03

4.2.3 Uncertainty in Temperature Measurement

Total error in temperature measured by RTD consists of:

a) Accuracy of the instrument and Rosemont bridge stated by the manufacturer as 0.25 Deg. F.

b) Error in the line from the Rosemont bridge to the multiplexer digitizer measured to be 0.005% of the reading.

c) Error in the multiplexer digitizer (0.005 V)

The following table presents the uncertainty in temperature measurement:

Temp °F	signal Voltage Volts	Instrument Error °F	Line Error °F	Digitizing Error °F	Total Error °F
70	0.70	0.250	0.004	0.500	0.56
120	1.20	0.250	0.006	0.500	0.56
200	2.00	0.250	0.010	0.500	0.56
300	3.00	0.250	0.015	0.500	0.56

4.2.4 Uncertainty in Flowrate Using Flow Meter

Total error in flow rate measured by turbine flow meter consists of:

a) Accuracy of the instrument and Anadex frequency converter stated by the manufacturer as 0.5106% of full scale (60 GPM).

b) Error in the line from the Anadex output to the multiplexer digitizer measured to be 0.200% of the reading.

c) Error in the mutiplexer digitizer (0.005 V)

Flow Rate GPM	Signal Voltage Volts	Instrument Error GPM	Line Error GPM	Digitizing Error GPM	Total Error GPM
36	3.00	0.306	0.072	0.060	0.32
20	1.67	0.306	0.040	0.060	0.31
10	0.83	0.306	0.020	0.060	0.31
5	0.42	0.306	0.010	0.060	0.31

4.2.5 Uncertainty in Test Section Voltage Measurement

Total error in test section voltage measurement consists of:

a) Accuracy of the voltage divider stated by the manufacturer as 0.050% of the reading.

b) Error in the line from the source to the multiplexer digitizer measured to be 0.304% of the reading.

c) Error in the mutiplexer digitizer (0.005 V)

The following table presents the uncertainty in voltage measurement:

T.S. voltage Volts	Signal Voltage Volts	Instrument Error Volts	Line Error Volts	Digitizing Error Volts	Total Error Volts
160	4.00	0.080	0.486	0.200	0.53
80	2.00	0.040	0.243	0.200	0.32
40	1.00	0.020	0.122	0.200	0.23

4.2.6 Uncertainty in Test Section Current Measurement

Total error in test section current measurement consists of:

- a) Accuracy of the shunt stated by the manufacturer as 0.100% of the reading.
- b) Error in the line from the source to the multiplexer digitizer measured to be 0.304% of the reading.
- c) Error in the mutiplexer digitizer (0.005 V)

The following table presents the uncertainty in the current measurement:

T.S. Current Amps	Signal Voltage Volts	Instrument Error Amps	Line Error Amps	Digitizing Error Amps	Total Error Amps
10000	5.0	10	30	10	34
5000	2.50	5	15	10	19
2000	1.0	2	6	10	12

4.2.7 Uncertainty in Test Section Dimensional Measurement

The total error in measurement of the test section dimension depends upon the measurement technique used. For the error represents the resolution of the measurement instrument. For several test sections, the test section inside diameter was measured using a go no-go gages. In these cases, the error is one half of the difference between the go gage and the no-go gage. The following presents the uncertainty in the dimensional measurements.

Test Section	ID (inch)	Heated length (inch)	Pressure Tap Separation (inch)
ST-1	0.005	0.038	0.058
ST-2	0.005	0.038	0.058
ST-3	0.005	0.038	0.058
ST-2.1	0.005	0.038	0.058
ST-4	0.005	0.038	0.058
ST-5	0.0015	0.038	0.058
ST-6	0.0045	0.038	0.058
ST-7	0.005	0.038	0.058
ST-9	0.0015	0.038	0.058

5. RESULTS

5.1 Introduction

The primary objective of this phase of the flow excursion experimental program was to obtain demand curves for a single tube in vertical down-flow over an L/D range of 100 to 300. In addition, the test sections were instrumented to provide wall temperature information at various axial locations along the heated tube.

As noted earlier in this report, a considerable amount of data on the test section and flow loop were recorded. Part II of this report presents all the data obtained for the test program. This data has also been transmitted in electronic form to SRL.

This section will present demand curve data and temperatures for each test section. As part of the data reduction process, the inside surface temperature and local heat transfer coefficient for each test section have been calculated. Because of the volume of this thermal data only representative samples will be presented. However, the computer programs used to produce these results are included in Appendix C.

5.2 Test Section Pressure Drop

The demand curve is defined as the test section pressure drop versus test section flowrate. In general, as the test section flowrate decreases, the pressure drop decreases; however, as bubbles are formed at the heated surface, the resistance to flow increases, and the pressure drop will experience a minimum point. This minimum point is defined as the OFI point. As the OFI point is reached, the pressure drop will oscillate rapidly as bubbles form and collapse. If the test section is connected to a parallel flow path, the potential for flow diversion exists. The flow loop used in these tests was operated in a controlled flow mode so that the flowrate to the test section is maintained. In the controlled flow mode, the flowrate to the test section can be reduced if the pressure oscillations exceed the pump capacity. This occurred on the 0.36 inch test section and resulted in burnout of the test section.

This condition was remedied by installing a high head pump in the loop for the testing of small diameter test sections. With this pump, the test matrix for the 0.36 inch diameter tube was completed without difficulty.

As discussed in the data acquisition section, the data presented in this report is based upon 40 scan averages, which represent approximately a five second time period. Prior to the OFI point, all readings were steady. As the minimum in the demand curve was approached, the manual pressure gauges in the loop showed that oscillations were present. For the 0.36 inch tube, the mean and standard deviations were also calculated. These results showed that the flowrate and fluid temperatures remained fairly constant through the complete flow regime. The pressure transducer deviations were negligible before reaching OFI. Following OFI, the standard deviation in the pressure reading exceeded 100%. Therefore, the pressure drop measurement following OFI is only a qualitative indication of the trend. The data presented in the following sections represent five second time averages.

The OFI point is a function of the test section flowrate, test section inside diameter, inlet temperature, exit pressure, and surface heat flux. Figures 5.1 through 5.12 present the demand curves for each test section. Each figure presents the demand curve for a given inlet temperature.

Figure 5.1 presents the test section pressure drop versus flowrate for the 0.36 inch tube with an inlet temperature of 77 °F. Demand curves are presented for both 20 and 50 psig test section exit pressures and a range of surface heat fluxes from 0 to 1,000,000 Btu/hr-ft². Figure 5.2 presents a similar set of data for a test section inlet temperature of 122 °F. For each figure, the minimum point in the curve is well defined. The flowrate at which the minimum occurs increases with surface heat flux and decreases with exit pressure. Increasing the inlet temperature also increases the flowrate at which OFI occurs.

The results for the inconel and stainless steel test sections show little if any effect of test section material. Figures 5.3 and 5.4 present results for the 0.60 inch diameter stainless steel test section, and figures 5.5 and 5.6 present results for the 0.61 inch diameter inconel tube. For the same operating conditions, the OFI flowrate is essentially the same. There is a slight difference between the demand curves at high flowrate due to the difference in test section inside diameter.

These size tubes were used for this comparison because of availability and cost. It appears that OFI results from an integrated heating effect and that any variation of OFI due to the large resistivity change present in stainless steel as compared to inconel is negligible.

As the test section diameter increases, the point of minimum pressure in the demand curve shifts to higher flowrates. However, the pressure drops for the larger test sections are relatively small. For instance in figure 5.12, it can be seen that at maximum flux the pressure at OFI is less than 3 psi. There appears to be more scatter in the data for the larger test sections; however, these pressure variations are only fractions of a psi. Because the loop peak flowrate was approximately 50 gpm, it was not possible to operate the 1.12 inch test section at $1,000,000 \text{ Btu/hr-ft}^2$ because the OFI flowrate exceeded 50 gpm.

5.3 Test Section Temperature Data

The primary test section temperature measurements were provided by 18 thermocouples mounted on the exterior of the test section. The location of these thermocouples varied somewhat between test sections; however, two thirds of the instruments were located in the lower 25% of the test section and one third were distributed over the upper part of the test section. The exact location of the instrumentation has been presented in the instrumentation section of this report. At each axial location, there are two thermocouples located 180 degrees apart. The circumferential position of these thermocouples is rotated 90 degrees at each axial position. Theoretically, the measurements at each axial position should be equal since the flow is axisymmetric. However, examination of the data indicates that the measured temperatures can differ by up to 20°F . This difference has been attributed to the variation in wall thickness in commercial tubing of this type. For data analysis purposes, the outside wall temperature presented in this report represents an average of a pair of axial measurements.

The amount of temperature data developed during this task is quite large (over 33,000 temperature measurements). Part II of this report contains all this data. The present section will present only a small fraction of this data. Results will be presented for an inlet temperature of 77°F and an exit pressure of 50 psig. For each of these test conditions, figures 5.13 through 5.22 show the measured outside wall

temperature as a function of the test section flowrate and position for each size test section. For each diameter, results are given for surface heat fluxes of 600,000 Btu/hr-ft² and 1,000,000 Btu/hr-ft². In these figures, the test section exit is located at $x/L = 0.0$. The wall temperature increases with test section diameter for the same flowrate because of the greater total energy input for a given flux. As the flowrate is decreased, the wall temperature increases until two phase conditions are established on the inner surface. When this occurs, the temperature is independent of flowrate (e.g., see figure 5.16).

Since the tube is uniformly heated along its length, the wall temperature under single phase conditions should increase monotonically from entrance to exit. Several factors can alter this pattern. The tube wall thickness can vary by as much as 10% for commercial grade tubing. In addition, the end of the test section is brazed into a thick walled copper cylinder which can act as a heat sink.

Several brazed thermocouples were added in the lower section of the tube. These units created local hot spots because current is diverted through the brazed material. This diversion results in lower temperature reading on the sensors in the vicinity of these brazed units. Finally, an additional voltage tap was located approximately 12 inches from the exit plane. This tap was part of the burnout detector system; unfortunately, it acted as a fin and depressed local temperatures. Although the general trend is correct, there are some deviations which are attributed to the preceding factors. In figure 5.15, the outside wall temperature at $x/L = 0.105$ is very low than expected. Examination of the raw data for this location showed that one of the two thermocouples was almost 100 °F below the other. If this reading were dropped and only one unit at this elevation were used, the results would agree with the expected trend. In figure 5.16 for the same tube at 1,000,000 Btu/hr-ft², these two thermocouples agree very well.

When nucleate boiling occur, the local temperature can be suppressed by the increased surface heat transfer coefficients. This result can be seen in figures 5.16 and 5.22.

The inside surface temperature of the tube is not measured directly; however, it can be calculated, given the test section geometry, material, and power dissipation. Figures 5.23 through 5.32 present the calculated inside wall temperature for the same

conditions as given in figures 5.13 through 5.22. The tubes under discussion have the same wall thickness and approximately the same thermal conductivity. This means that the temperature difference between inside and outside is only a linear function of the surface heat flux. The effect of nucleate boiling is very apparent in these figures because the peak surface temperature is independent of flowrate. For the data presented in this section, the saturation temperature is 298 °F. For a fixed surface heat flux, the initiation of sub-cooled boiling occurs at a higher flowrate as test section diameter increases. This is caused by the combined effects of test section size on the total energy disposition and heat transfer coefficient. In figure 5.32, it appears that the test section is in sub-cooled boiling for the entire flowrate range.

At ONB, there is a drop in surface temperature; several figures (i.e., figures 5.23, 5.26, and 5.32) show this effect. It appears that the wall superheat under nucleate boiling conditions decreases with increasing test section diameter. Since the nucleate boiling conditions occurred in the unstable region, the temperatures presented represent an average condition over a five second time period. These results, therefore, are not a steady state condition but rather a dynamic steady state.

5.4 Heat Transfer Data

Using the results from section 5.3, the local heat transfer coefficient can be calculated. This has been done for three test section sizes. The heat transfer is based upon the calculated surface temperature and the local fluid temperature. The latter quantity is based upon the inlet and exit RTD readings and the assumption of a linear fluid temperature distribution. The heat transfer data will be presented as a function of local quality (equivalent to local fluid temperature) and flowrate. The local quality is also related to axial location along the test section.

For the same test conditions as section 5.3, figures 5.33 through 5.38 present the heat transfer coefficient for the 0.36 inch, the 0.61 inch, and the 1.00 inch test sections. The heat transfer coefficient increases with local quality and flowrate. However, in the two-phase region, the increase with quality is very dramatic and the effect of flowrate disappears. Figure 5.35 contains several points outside of the general trend. It is felt that these points are the result of bad thermocouple readings. The region of rapid increase in heat transfer coefficient occurring between -10% and

-5% quality depending on test section size is associated with the transition to nucleate boiling. This condition is observed before flow instability occurs.

Figure 5.1
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.36 inches
 Test Section Inlet Temperature = 77 °F

Figure 5.2
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.36 inches
 Test Section Inlet Temperature = 122 °F

Figure 5.3
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.60 inches
 Test Section Inlet Temperature = 77 °F

Figure 5.4
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.60 inches
 Test Section Inlet Temperature = 122 °F

Figure 5.5
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.61 inches
 Test Section Inlet Temperature = 77 °F

Figure 5.6
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.61 inches
 Test Section Inlet Temperature = 121 °F

Figure 5.7

Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.75 inches
 Test Section Inlet Temperature = 77 °F

Figure 5.8
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 0.75 inches
 Test Section Inlet Temperature = 121 °F

Figure 5.9
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 1.00 inches
 Test Section Inlet Temperature = 77 °F

Figure 5.10
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 1.00 inches
 Test Section Inlet Temperature = 121 °F

Figure 5.11
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 1.12 inches
 Test Section Inlet Temperature = 77 °F

Figure 5.12
 Pressure Drop vs. Test Section Flowrate
 Test Section Inside Diameter = 1.12 inches
 Test Section Inlet Temperature = 121 °F

Figure 5.13
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 0.36 inches

Figure 5.14

Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 0.36 inches

Figure 5.15
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{inlet} = 77^\circ\text{F}$, $P_{exit} = 50$ psig
 Inside Test Section Diameter = 0.61 inches

Figure 5.16

Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 0.61 inches

Figure 5.17
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{inlet} = 77$ °F, $P_{exit} = 50$ psig
 Inside Test Section Diameter = 0.75 inches

Figure 5.18
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 0.75 inches

Figure 5.19
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{inlet} = 77$ °F, $P_{exit} = 50$ psig
 Inside Test Section Diameter = 1.00 inches

Figure 5.20
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 1.00 inches

Figure 5.21
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 T_{Inlet} = 77 °F, P_{exll} = 50 psig
 Inside Test Section Diameter = 1.12 inches

Figure 5.22
 Outside Wall Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{exit} = 50$ psig
 Inside Test Section Diameter = 1.12 inches

Figure 5.23

Inside Surface Temperature vs. Flowrate₂
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 0.36 inches

Figure 5.24

Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{tot} = 50$ psig
 Inside Test Section Diameter = 0.36 inches

Figure 5.25

Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{tot} = 50$ psig
 Inside Test Section Diameter = 0.61 inches

Figure 5.26
 Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{\text{Inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 0.61 inches

Figure 5.27

Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{exit} = 50$ psig
 Inside Test Section Diameter = 0.75 inches

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Centimeter

Inches

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2 of 2

Figure 5.28
 Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 0.75 inches

Figure 5.29

Inside Surface Temperature vs. Flowrate₂
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{\text{Inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 1.00 inches

Figure 5.30
 Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{exit} = 50$ psig
 Inside Test Section Diameter = 1.00 inches

Figure 5.31

Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 600,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50$ psig
 Inside Test Section Diameter = 1.12 inches

Figure 5.32

Inside Surface Temperature vs. Flowrate
 Surface Heat Flux = 1,000,000 Btu/hr-ft²
 T_{inlet} = 77 °F, P_{exit} = 50 psig
 Inside Test Section Diameter = 1.12 inches

Figure 5.33

Heat Transfer Coefficient vs. Local Quality
 Test Section Inside Diameter = 0.36 inches
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50$ psig
 Surface Heat Flux = 600,000 Btu/hr-ft²

Figure 5.34

Heat Transfer Coefficient vs. Local Quality
 Test Section Inside Diameter = 0.36 inches
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50$ psig
 Surface Heat Flux = 1,000,000 Btu/hr-ft²

Figure 5.35
Heat Transfer Coefficient vs. Local Quality
Test Section Inside Diameter = 0.61 inches
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
Surface Heat Flux = $600,000 \text{ Btu/hr-ft}^2$

Figure 5.36
Heat Transfer Coefficient vs. Local Quality
Test Section Inside Diameter = 0.61 inches
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50$ psig
Surface Heat Flux = 1,000,000 Btu/hr-ft^2

Figure 5.37
 Heat Transfer Coefficient vs. Local Quality
 Test Section Inside Diameter = 1.00 inches
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50$ psig
 Surface Heat Flux = 600,000 Btu/hr-ft^2

Figure 5.38
Heat Transfer Coefficient vs. Local Quality
Test Section Inside Diameter = 1.00 inches
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{out}} = 50$ psig
Surface Heat Flux = 1,000,000 Btu/hr-ft^2

6. DISCUSSION OF RESULTS

6.1 Introduction

Section 5 of this report presented the basic pressure drop and temperature that was obtained during this phase of the flow excursion experimental program. This section will be devoted to the presentation of various correlations methods which can be used to describe the data. Most of the correlation techniques are already available in the open literature. The coefficients used, however, have been developed from the current data set.

6.2 Test Section Pressure Drop Analysis

The objective of this section is to present methods for predicting the OFI point based upon test conditions. There are two potential methods. Saha and Zuber (1974) developed a technique for predicting the point of net vapor generation OSV. Using experimental data, they determined that OSV was a function of Stanton Number and Peclet Number. These quantities are defined as follows:

$$\text{Stanton Number} = q'' / (G c_{pf} (T_{\text{sat}} - T_{\lambda}))$$

$$\text{Peclet Number} = (G c_{pf} D) / k_f$$

T_{λ} represents the temperature of the bulk fluid at the point of net vapor generation. The point of net vapor generation occurs when there is a significant increase in the local void fraction. In this program, void fraction measurements were not made; however, for a uniformly heated tube, net vapor generation will initiate at the channel exit as flowrate is decreased. Further reduction in flowrate will cause the OSV point to propagate into the channel. As the OSV point moves up the channel, the bubble formation increases to a sufficient extent to cause OFI. It has been postulated that a conservative prediction of OFI can be based upon a criterion using the Stanton Number defined by the channel exit temperature. Since the Peclet Number exceeds 100,000 for the present program, the Saha-Zuber criteria is that OSV will occur at a Stanton Number equal to 0.0065. The Saha-Zuber (1974) criteria is stated with an accuracy of +/- 25%. During the experimental program it is very difficult to obtain the OFI point exactly. From the experimental data given in section 5 of this report, the demand curves have been measured accurately and the general

shape well established. Manual selection of the OFI point or data point just before OFI tends to spread the data. For this reason, a different method of presenting OFI has been developed.

Dormer and Bergles (1964) developed a method for correlating flow instability data based two parameters:

- 1) the ratio of pressure drop to the pressure drop at zero flux
- 2) the ratio of the flux to the flux required to attain saturation conditions at the channel exit. This ratio is given by equation 6.1.

$$Q_{ratio} = q'' / (m c_{pf} (T_{sat} - T_{inlet}) / \pi DL) \quad (6.1)$$

Using these parameters, Dormer and Bergles (1964) showed that the only geometry remained as an independent parameter. Figures 6.1 through 6.6 show that these parameters also correlate the data for the current program. In figures 6.5 and 6.6, there is some scatter in the results, but this is due to the small magnitude of the overall pressure drop. The Q_{ratio} parameter contains all the important test information. The demand curves have been re-plotted using the Q_{ratio} as the independent variable rather than the flowrate. Figures 6.7 through 6.17 present these results. These figures show that the minimum in the pressure drop curve occurs at the same value of the Q_{ratio} for a given tube diameter. This is in agreement with the work of Whittle and Forgan (1967). These researchers showed that the OFI point was a function of the L/D ratio for the test section. Dormer and Bergles (1964) established the same result; however, they indicated that there was also a secondary diameter effect. Since the current test program was based upon the same test section length, this latter point can not be evaluated.

For each test section, the Q_{ratio} for the minimum pressure drop given in figures 6.7 through 6.17 has been determined and defined as the OFI point. Figure 6.18 presents the variation of the Q_{ratio} at OFI as a function of test section length to diameter ratio. As the L/D ratio increases (i.e., diameter decreases), the Q_{ratio} also increases. Increasing Q_{ratio} for fixed test conditions corresponds to lowering test section flowrate. At an L/D ratio of 267, the average Q_{ratio} at OFI is $0.912 \pm 5\%$. For the larger diameter tubes, the experimental scatter is greater. For instance, the average value of Q_{ratio} at OFI for the 1.12 inch tube ($L/D = 86$) is 0.681 with a variation of approximately $\pm 8\%$. In comparing the 0.61 inconel tube and the 0.60 inch stainless steel tube, there appears to be a slight inconsistency with the overall trend. In figure 6.18, the average value of the Q_{ratio} at OFI for the 0.60 inch tube is slightly lower than 0.61 inch tube. The variation is less than 1% for an L/D difference of 2%. The data set for the 0.60 inch tube is only 4 points compared to 16 for the 0.61 inch tube. This difference is well within the experimental accuracy. The solid line in figure 6.18 represents a curve of the data. The correlation is given by the equation 6.2.

$$Q_{ratio} = 0.210492 * \ln (L/D) - 0.258275 \quad (6.2)$$

Figures 6.19 through 6.24 present the variation of the exit Stanton Number (i.e., based upon exit temperature) with the ratio of flux to flux to saturation (Q_{ratio}). Data is plotted for all test conditions. Each figure contains approximately 150 to 200 test points. The correlation with Q_{ratio} is excellent. On each figure, the average Q_{ratio} at OFI is also shown. The correlation of Stanton Number and Q_{ratio} is not surprising because both parameters contain similar variables. Equation 6.3 shows this relationship.

$$Q_{ratio} = \frac{4L/D}{(4L/D + St^{-1})} \quad (6.3)$$

The above equation shows that the Q_{ratio} is fairly insensitive to Stanton Number at larger L/D ratios. The Saha-Zuber criteria at OSV is 0.0065. For the largest L/D ratio, this factor represents only 15% of the denominator. Using the $\pm 25\%$ error band on the criteria, the predicted variation of Q_{ratio} is only 5%. An

interesting comparison can be made between the Q_{ratio} from the minimum in the pressure drop curve and the Q_{ratio} based upon the Stanton Number of 0.0065 in figures 6.19 through 6.24. Figure 6.25 presents this comparison. The Stanton Number criterion over-predicts the flux / flux to saturation ratio (predicts lower OFI flowrates than actual) at the small L/D range. At the large L/D ratios (corresponding to reactor geometries), the Stanton Number criteria provides a conservative estimate of the OFI flowrate.

6.3 Heat Transfer Analysis

The heat transfer coefficients presented in section 5.4 cover both the single and two-phase flow regimes. Under single phase conditions, the heat transfer coefficient decreases with flowrate until boiling. At this point, the heat increases very sharply with local quality.

Figure 6.26 presents a plot of the ratio of local heat transfer coefficient to the heat transfer coefficient at the channel inlet versus local quality for the 0.36 inch tube at a surface heat flux of 600,000 Btu/hr-ft². For most of the test domain, single phase conditions exist at the inlet; therefore, figure 6.26 shows the effect of the presence of two-phase flow. Using these parameters, the test results for ten different flowrates correlate very well. Figure 6.27 through 6.31 present similar results for different tubes sizes and fluxes. We have not attempted to develop the geometry or flux correlation. However, it appears that the effect of flux is small.

Figure 6.32 shows that the inlet Nusselt Number can be correlated using a modified form of the Sieder-Tate equation. The latter equation is used in turbulent single phase flow when the temperature difference between the wall and fluid is large. Figure 6.32 includes all fluxes and all but one tube (0.60 inch). The solid line in this figure is given by equation 6.4.

$$\frac{Nu}{Pr^{0.33} (\mu_f/\mu_w)^{0.14}} = 0.165928 Re^{0.659724} \quad (6.4)$$

Equation 6.4 has been designated the HTRF-1 correlation. The dashed lines show the +/- 25% bands. Figures 6.33 through 6.37 are similar to figure 6.32 but show the effect of tube size. The usual Sieder-Tate correlation is also shown in these

figures. There appears to be geometry effect because the small diameter tube is at the low end of the 25% band and the largest tube falls at the high end. This may be associated with an entrance effect.

Using the results presented in this section the heat transfer coefficient can be reasonably predicted over the entire flow regime.

Figure 6.1
 $\Delta P / \Delta P_{zero}$ vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.36 inches

Figure 6.2
 $\Delta P / \Delta P_{zero}$ vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.60 inches

Figure 6.3
 $\Delta P / \Delta P_{zero}$ vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.61 inches

Figure 6.4
 $\Delta P / \Delta P_{zero}$ vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.75 inches

Figure 6.5
 $\Delta P / \Delta P_{zero}$ vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 1.00 inches

Figure 6.6
 $\Delta P / \Delta P_{zero}$ vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 1.12 inches

Figure 6.7
 Pressure Drop vs. Flux/Flux to Saturation
 Test Section Inside Diameter = 0.36 inches
 Test Section Inlet Temperature = 77 °F

Figure 6.8
 Pressure Drop vs. Flux/Flux to Saturation
 Test Section Inside Diameter = 0.36 inches
 Test Section Inlet Temperature = 122 °F

Figure 6.9
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.60 inches
 Test Section Exit Pressure = 50 psig

Figure 6.10
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.61 inches
 Test Section Inlet Temperature = 77 °F

Figure 6.11
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.61 inches
 Test Section Inlet Temperature = 121 °F

Figure 6.12
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.75 inches
 Test Section Inlet Temperature = 77 °F

Figure 6.13

Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.75 inches
 Test Section Inlet Temperature = 121 °F

Figure 6.14
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 1.00 inches
 Test Section Inlet Temperature = 77 °F

Figure 6.15
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 1.00 inches
 Test Section Inlet Temperature = 121 °F

Figure 6.16
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 1.12 inches
 Test Section Inlet Temperature = 77 °F

Figure 6.17
 Pressure Drop vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 1.12 inches
 Test Section Inlet Temperature = 121 °F

Figure 6.18
Flux / Flux to Saturation vs. L/D

Figure 6.19
 Stanton Number vs Flux/Flux to Saturation
 Test Section Inside Diameter = 0.36 inches

Figure 6.20
 Stanton Number vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.60 inches

Figure 6.21
 Stanton Number vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.61 inches
 All Fluxes

Figure 6.22
 Stanton Number vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 0.75 inches

Figure 6.23
Stanton Number vs. Flux / Flux to Saturation
Test Section Inside Diameter = 1.00 inches

Figure 6.24
 Stanton Number vs. Flux / Flux to Saturation
 Test Section Inside Diameter = 1.12 inches

Figure 6.25
Flux / Flux to Saturation vs. L/D

Figure 6.26
 HTC/HTC_{inlet} vs. Local Quality
 Test Section Inside Diameter = 0.36 inches
 Test Section Inlet Temperature = 77 °F
 Surface Heat Flux = 600,000 Btu/hr-ft²

Figure 6.27
 HTC / HTC_{inlet} vs. Local Quality
 Test Section Inside Diameter = 0.36 inches
 $T_{inlet} = 77^{\circ}F$, $P_{exit} = 50$ psig
 Surface Heat Flux = 1,000,000 Btu/hr-ft²

Figure 6.28
 HTC / HTC_{inlet} vs. Local Quality
 Test Section Inside Diameter = 0.61 inches
 $T_{inlet} = 77^{\circ}F$, $P_{exit} = 50$ psig
 Surface Heat Flux = 600,000 Btu/hr-ft²

Figure 6.29
 HTC / HTC_{inlet} vs. Local Quality
 Test Section Inside Diameter = 0.61 inches
 $T_{inlet} = 77^{\circ}F$, $P_{exit} = 50$ psig
 Surface Heat Flux = 1,000,000 Btu/hr-ft²

Figure 6.30
 HTC / HTC_{inlet} vs. Local Quality
 Test Section Inside Diameter = 1.00 inches
 $T_{inlet} = 77^{\circ}F$, $P_{exit} = 50$ psig
 Surface Heat Flux = 600,000 Btu/hr-ft²

Figure 6.31
 HTC / HTC_{inlet} vs. Local Quality
 Test Section Inside Diameter = 1.00 inches
 $T_{inlet} = 77^{\circ}F$, $P_{exit} = 50$ psig
 Surface Heat Flux = 1,000,000 Btu/hr-ft²

Figure 6.32
 Inlet Nusselt Number $/ ((Pr)^{0.33} (\mu_t/\mu_w)^{0.14})$
 vs.
 Reynolds Number
 for all experimental data

Figure 6.33
 Inlet Nusselt Number / $((Pr)^{0.33} (\mu_f/\mu_w)^{0.14})$
 vs.

Reynolds Number
 for 0.360 inch diameter tube

Figure 6.34
 Inlet Nusselt Number $/((Pr)^{0.33}(\mu_f/\mu_w)^{0.14})$
 vs.
 Reynolds Number
 for 0.61 inch diameter tube

Figure 6.35
 Inlet Nusselt Number $/((Pr)^{0.33}(\mu_f/\mu_w)^{0.14})$
 vs.
 Reynolds Number
 for 0.75 inch diameter tube

Figure 6.36
Inlet Nusselt Number $/ ((Pr)^{0.33} (\mu_f/\mu_w)^{0.14})$
vs.

Reynolds Number
for 1.00 inch diameter tube

Figure 6.37
 $Nusselt\ Number / ((Pr)^{0.33} (\mu_t/\mu_w)^{0.14})$
 vs.
 Reynolds Number
 for 1.12 inch diameter tube

7. CONCLUSIONS

The program to investigate flow instability in a vertical single tube has yielded considerable data on the onset of flow instability (OFI), the onset of nucleate boiling, and heat transfer coefficients under two-phase conditions. Demand curves have been obtained for six different diameter tube under uniform heating conditions.

The demand curves show that the pressure drop in the channel will experience a minimum which depends upon the surface heat flux, test section inlet temperature, test section exit pressure, and the test section L/D ratio. Some investigators have indicated that there may also be a slight diameter effect; however, since the tests were conducted for a fixed length (i.e., 96 inches) test section, the effect of diameter alone could not be inferred.

The Saha-Zuber (1974) criterion for the onset of significant voiding (OSV) provides a reasonable method for predicting the OFI. Comparison of this criteria with the experimental data shows that for large L/D ratios the Saha-Zuber relationship provides a conservative estimate of the OFI flowrate. It should be noted that for large L/D ratios the prediction of OFI using the Saha-Zuber criterion (i.e., Stanton Number = 0.0065) is fairly insensitive to value of Stanton Number used.

Using correlation parameters available in the open literature, it has been shown that the Q_{ratio} (flux / flux to saturation) at OFI is the same for a particular L/D ratio tube independent of flux, inlet temperature, and exit pressure. It has also been shown that the ratio of pressure drop to the pressure drop at zero flux can be correlated using the Q_{ratio} . The variation in predicted OFI using the Q_{ratio} method is less than +/- 10%. The overall accuracy of predicting OFI using either the Saha-Zuber or Q_{ratio} method are within reasonable.

Wall temperature data has been obtained which shows that nucleate boiling conditions exist in the channel prior to the OFI point. These data indicate that nucleate boiling conditions are present in the last 10%-15% of the channel length. For the larger diameter tubes, the OFI flowrates were near the maximum test section allowable flowrates. This meant that the surface temperature of these tubes exceeded saturation for almost their entire length. For the smaller tubes, the OFI

flowrate was only 10%-20% of the system maximum, and, therefore, it was possible to obtain data in both the single and two-phase regions.

Heat transfer coefficients have been calculated for selected portions of the data. These results indicate that the local heat coefficient can be correlated using the inlet coefficient which represents single phase conditions. Any general statement regarding this correlation will require data analysis of the complete data set. A correlation of the inlet heat transfer coefficient based upon approximately 1800 data points has been developed and compares favorably with the Seider-Tate correlation.

8. REFERENCES

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Kline, S.J. and McClintock, F.A., 1953, "Describing Uncertainties in Single Sample Experiments," Mechanical Engineering, Jan. 1953.

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Maulbetsch, J.S. and Griffith, P., 1966, "System Induced Instabilities in Forced-Convective Flows with Sub-cooled Boiling", Proc. of the Third Int. Heat Transfer Conf., pp. 247-257.

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APPENDIX A
Test Loop Operating Instructions

Columbia University ENGINEERING RESEARCH LABORATORIES HEAT TRANSFER RESEARCH FACILITY	PROJECT PROCEDURE		No. <u>HTRF-014</u> Revision <u>1</u> Page <u>1</u> of <u>1</u>
Subject OPERATING THE FLOW TEST LOOP FOR THE SINGLE TUBE TEST	Effective Date 8/25/89	Initiated By Project Coordinator	
	Supersedes Rev. 0 12/28/88	Approved By Project Director	

This procedure formalizes a series of instructional documents to be used when placing the flow test loop in operation. Nothing in this procedure is intended to prevent the test engineer or other test personnel from taking action to prevent, or minimize the impact of, conditions which could result in personnel injury or equipment damage.

Responsibility

Action

Test Engineer

1. Directs test personnel conducting evolution indicated in the attached project instructions.

Project Coordinator

2. Establishes the Test Matrix for the Single Tube Test.
3. Determines the criteria for the validation of the test condition.

PROJECT INSTRUCTIONS

TL-01	Assembly and preoperational test of the test section
TL-02	Installation and Testing of Thermocouples.
TL-03	Flow Loop Operation
TL-04	Pressure Transducer Operation
TL-05	Test Matrix for Single Tube Test
TL-06	Test Conditions for the Single Tube Experiments - Parallel Flow

NOTE

No modification to the test loop or instrumentation shall be made without the approval of the Test Engineer. The modification will be recorded on the test log book.

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HEAT TRANSFER RESEARCH FACILITY

PROJECT INSTRUCTION

No. TL-01
Revision 0
Page 1 of 1

SUBJECT

**ASSEMBLY AND PREOPERATIONAL
TEST OF THE TEST SECTION**

Effective Date

12/28/88

Initiated By

Test Engineer

Supersedes

Approved By

Project Director

1. Install pressure taps.
2. Assemble the test section (TS) and copper end pieces. Use Project Instruction HTRF-005.1 "High Temperature Brazing."
3. Install voltage taps.
4. Flush with hot water for 5 minutes.
5. Pressure test (100 lbs water pressure) the TS.
6. Install thermocouples (TC). Use Project Instruction TL-02 "Installation and Testing of Thermocouples."
7. Install test section into the loop.
8. Plug in the thermocouples into the reference box.
9. Check the "ground" of the TS (approximate 2000 Ohms with water).

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PROJECT INSTRUCTION

No. TL-02
Revision 0
Page 1 of 1

Subject

**INSTALLATION AND TESTING
OF THERMOCOUPLES**

Effective Date

12/28/88

Supersedes

Initiated By

Test Engineer

Approved By

Project Director

1. Wrap the TS with ceramic paper as the base layer of insulation.
2. Measure and mark the thermocouple (TC) locations according to the appropriate drawing. Make an approximately 1/2" x 1/2" square hole for each TC in the ceramic paper thru to the TS.
3. Put the first cement layer on every TC spot on the TS.
4. Air dry the first cement layer for a minimum of 2 hours.
5. Lay each TC on the top of the first layer of cement and cover the TC with a second layer of cement.
6. Air dry the second cement layer for a minimum of 2 hours.
7. Label all the TCs.
8. Check all TCs with a calibrated meter (eg. Dynisco) for the following:
 - a. Resistance & continuity between TC wires (should be between 7 to 20 Ohms at room temp.)
 - b. Resistance between TC & TS should be greater than 10 Mega-ohms.
9. Measure the test section resistance. Record the measured value of the TS resistance in the Laboratory Notebook.

Columbia University ENGINEERING RESEARCH LABORATORIES HEAT TRANSFER RESEARCH FACILITY	PROJECT INSTRUCTION		No <u>TL-03</u> Revision <u>0</u> Page <u>1</u> of <u>2</u>
SUBJECT FLOW LOOP OPERATION	Effective Date 12/28/88	Initiated By <i>Thomas Dougherty</i> Test Engineer	
	Supersedes	Approved By <i>[Signature]</i> Project Director	
<ol style="list-style-type: none"> 1. Flush and clean the loop with hot water after the test section (TS) is installed. 2. Open all valves in loop (except vent and drain valves). Place instrument valves in closed position. 3. Power on the reference box and excitation for flowmeters and transducers. Load the computer program. 4. Vacuum the loop to 20" Hg. 5. Fill the loop with distilled deionized water. Pressurize with helium and adjust the gas volume until no water escapes to the helium discharge. 6. Check the "ground" of the TS (approximate 2000 Ohms with water) 7. Bleed all the pressure lines through vents and drains. 8. Set all the valves to the initial test positions (all valves are closed except the bypass valve V12 at discharge of the circulation pump). 9. Check zero of all the pressure transducers (including the differential pressure transducers - see operation procedure for pressure transducer). 10. Open all instrument valves and the valves in flow lines. Bypass valves on DP cells remain open. 11. Check pressure transducers at 0, 20, 35 and 50 psig. 12. Close all valves in the flow lines except bypass to CHROMALOX (heater). 13. Close valves to pressure transducer and manometer. Place all DP cells in zero position. 14. Start the circulation and cooling water pumps. 15. Put all instruments in line in read position. 16. Check all instruments with cold flow (TCs, RTDs, Flowmeters, and Pressure Transducers). 17. Check ice bath thermocouples. Check TC reference junctions. 			

18. Reduce control to minimum and close the breaker.
19. Run loop at standard operating condition, then start the test. Use Project Instruction TL-05 "Test Matrix for Single Tube Test".
20. Reduce power to zero. Trip breaker.
21. Reduce flow to TS. Stop circulation pump.
22. Open all loop valves. Set all pressure transducers to zero positions.

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HEAT TRANSFER RESEARCH FACILITY

PROJECT INSTRUCTION

TL-04
Revision 0
Page 1 of 1

Subject

**PRESSURE TRANSDUCER
OPERATION**

Effective Date

12/28/88

Initiated By

Test Engineer

Supervises

Approved By

Project Director

All pressure transducers should be isolated from the loop by valves after the operation. The pressure transducers should be operated by engineer or authorized technician and the following should be observed.

1. Take zero reading while the zero balancing valves are open and the valves to the loop (including the valves on both high and low sides of the differential pressure transducers) are closed.
2. Open the valves to the loop after the loop has been filled with water and a vacuum of 20" Hg drawn. Bleed all pressure lines (including DP cells, absolute pressure transducers and manometer).

NOTE

NEVER CLOSE THE ZERO BALANCING VALVE WHILE THE LOOP IS PRESSURIZED AND ONLY ONE END OF THE DIFFERENTIAL PRESSURE TRANSDUCER IS OPEN.

3. Close the zero balancing valves, start the test with standard condition.
4. After the run, open the zero balancing valves.
5. Close all the valves to the loop.

APPENDIX B
Data File Format

SRL FLOW INSTABILITY TESTS
TEST#2 RUN NUMBERS 113-301
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
1	1	1	Run#	Run Number	
1	2	2	Test#	Test Number	
1	3	3	PTI1	Pressure - Heater Inlet	Psia
1	4	4	PTI2	Pressure - T.S. Inlet	Psia
1	5	5	PTO1	Pressure - Heater Outlet	Psia
1	6	6	PTO2	Pressure - Heater Outlet (Gauge)	Psia
1	7	7	PTO3	Pressure - T.S. Outlet	Psia
1	8	8	DPT1	Pressure Drop - Across Heater	Psi
2	1	9	DPT2	Pressure Drop - Across Heater	Psi
2	2	10	DPT3	Pressure Drop - Across Heater (Manometer)	Psi
2	3	11	FTI1	Flow - T.S. Inlet (Turbine meter) (2")	GPM
2	4	12	FTI2	Flow - T.S. Inlet (Turbine meter) (1")	GPM
2	5	13	FXO1	Flow - HX Outlet (Turbine meter) (2")	GPM
2	6	14	FXO2	Flow - HX Outlet (Turbine meter) (3/4")	GPM
2	7	15	FMO1	Flow - Mixer Outlet (Turbine meter) (2")	GPM
2	8	16	FMO2	Flow - Mixer Outlet (Turbine meter) (1")	GPM
3	1	17	OTI1	Flow - T.S. Inlet (Orifice Meter)	GPM
3	2	18	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	3	19	TRTO1	Temperature (RTD) - T.S. Outlet	Degrees F.
3	4	20	TJT11	Temperature (T/C) - T.S. Inlet	Degrees F.
3	5	21	TJXO1	Temperature (T/C) - HX Outlet	Degrees F.
3	6	22	TJTO1	Temperature (T/C) - T.S. Outlet	Degrees F.
3	7	23	BLANK	0.0	
3	8	24	BLANK	0.0	
4	1	25	TEW1	Wall Temperature - Position 1	Degrees F.
4	2	26	TEW2	Wall Temperature - Position 2	Degrees F.
4	3	27	TEW3	Wall Temperature - Position 3	Degrees F.
4	4	28	TEW4	Wall Temperature - Position 4	Degrees F.
4	5	29	TEW5	Wall Temperature - Position 5	Degrees F.
4	6	30	TEW6	Wall Temperature - Position 6	Degrees F.
4	7	31	TEW7	Wall Temperature - Position 7	Degrees F.
4	8	32	TEW8	Wall Temperature - Position 8	Degrees F.

SRL FLOW INSTABILITY TESTS
TEST#2 RUN NUMBERS 113-301
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
5	1	33	TEW9	Wall Temperature - Position 9	Degrees F.
5	2	34	TEW10	Wall Temperature - Position 10	Degrees F.
5	3	35	TEW11	Wall Temperature - Position 11	Degrees F.
5	4	36	TEW12	Wall Temperature - Position 12	Degrees F.
5	5	37	TEW13	Wall Temperature - Position 13	Degrees F.
5	6	38	TEW14	Wall Temperature - Position 14	Degrees F.
5	7	39	TEW15	Wall Temperature - Position 15	Degrees F.
5	8	40	TEW16	Wall Temperature - Position 16	Degrees F.
6	1	41	TEW17	Wall Temperature - Position 17	Degrees F.
6	2	42	TEW18	Wall Temperature - Position 18	Degrees F.
6	3	43	PWRKW	Power - Heater	KW
6	4	44	HFLX	Heat Flux - Heater	M.Btu/Hr/Sqft
6	5	45	VOLTB	Voltage - Bus to Bus	Volts
6	6	46	VOLTT	Voltage - Heater	Volts
6	7	47	CURRT	Current - Heater	Amps
6	8	48	QUALITY	Quality - Heater Outlet	(%)
7	1	49	HRATIO	Heat Output / Heat Input Ratio	
7	2	50	BLANK	0.0	
7	3	51	BLANK	0.0	
7	4	52	BLANK	0.0	
7	5	53	BLANK	0.0	
7	6	54	BLANK	0.0	
7	7	55	BLANK	0.0	
7	8	56	ID	Diameter (ID) - Heater	Inches
8	1	57	HL	Heated Length - Heater	Inches
8	2	58	DPL	Distance Between Pressure Taps	Inches
8	3	59	YEAR	Year - Test Date	
8	4	60	MONTH	Month - Test Date	
8	5	61	DAY	Day - Test Date	
8	6	62	HOURS	Hour - Test Date	
8	7	63	MIN	Minute - Test Date	
8	8	64	RUN#	Run Number	

SRL FLOW INSTABILITY TESTS
TEST#2.1 RUN NUMBERS 598-820
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89
10:06 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
1	1	1	Run#	Run Number	
1	2	2	Test#	Test Number	
1	3	3	PTI1	Pressure - Heater Inlet	Psia
1	4	4	PTI2	Pressure - T.S. Inlet	Psia
1	5	5	PTO1	Pressure - Heater Outlet	Psia
1	6	6	PTO2	Pressure - Heater Outlet (Gauge)	Psia
1	7	7	PTO3	Pressure - T.S. Outlet	Psia
1	8	8	DPT1	Pressure Drop - Across Heater	Psi
2	1	9	DPT2	Pressure Drop - Across Heater	Psi
2	2	10	DPT3	Pressure Drop - Across Heater (Manometer)	Psi
2	3	11	FTI1	Flow - T.S. Inlet (Turbine meter) (2")	GPM
2	4	12	FTI2	Flow - T.S. Inlet (Turbine meter) (1")	GPM
2	5	13	FBI1	Flow - Bypass Line (Turbine meter) (2")	GPM
2	6	14	FXO2	Flow - HX Outlet (Turbine meter) (3/4")	GPM
2	7	15	FMO1	Flow - Mixer Outlet (Turbine meter) (2")	GPM
2	8	16	FMO2	Flow - Mixer Outlet (Turbine meter) (1")	GPM
3	1	17	OTI1	Flow - T.S. Inlet (Orifice Meter)	GPM
3	2	18	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	3	19	TRTO1	Temperature (RTD) - T.S. Outlet	Degrees F.
3	4	20	TJT11	Temperature (T/C) - T.S. Inlet	Degrees F.
3	5	21	TJT12	Temperature (T/C) - T.S. Inlet	Degrees F.
3	6	22	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	7	23	PPO1	Pressure - Pump Discharge	Psia
3	8	24	PPI1	Pressure - Pump Inlet	Psia
4	1	25	TEW1	Wall Temperature - Position 1	Degrees F.
4	2	26	TEW2	Wall Temperature - Position 2	Degrees F.
4	3	27	TEW3	Wall Temperature - Position 3	Degrees F.
4	4	28	TEW4	Wall Temperature - Position 4	Degrees F.
4	5	29	TEW5	Wall Temperature - Position 5	Degrees F.
4	6	30	TEW6	Wall Temperature - Position 6	Degrees F.
4	7	31	TEW7	Wall Temperature - Position 7	Degrees F.
4	8	32	TEW8	Wall Temperature - Position 8	Degrees F.

SRL FLOW INSTABILITY TESTS
TEST#2.1 RUN NUMBERS 598-820
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89
10:06 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
5	1	33	TEW9	Wall Temperature - Position 9	Degrees F.
5	2	34	TEW10	Wall Temperature - Position 10	Degrees F.
5	3	35	TEW11	Wall Temperature - Position 11	Degrees F.
5	4	36	TEW12	Wall Temperature - Position 12	Degrees F.
5	5	37	TEW13	Wall Temperature - Position 13	Degrees F.
5	6	38	TEW14	Wall Temperature - Position 14	Degrees F.
5	7	39	TEW15	Wall Temperature - Position 15	Degrees F.
5	8	40	TEW16	Wall Temperature - Position 16	Degrees F.
6	1	41	TEW17	Wall Temperature - Position 17	Degrees F.
6	2	42	TEW18	Wall Temperature - Position 18	Degrees F.
6	3	43	PWRKW	Power - Heater	KW
6	4	44	HFLX	Heat Flux - Heater	M.Btu/Hr/Sqft
6	5	45	VOLTB	Voltage - Bus to Bus	Volts
6	6	46	VOLTT	Voltage - Heater	Volts
6	7	47	CURRT	Current - Heater	Amps
6	8	48	QUALITY	Quality - Heater Outlet	(%)
7	1	49	HRATIO	Heat Output / Heat Input Ratio	
7	2	50	DPP1	Pressure Difference - Across Pump	Psi
7	3	51	TKW14	Wall Temperature - Position 14	Degrees F.
7	4	52	TKW17	Wall Temperature - Position 17	Degrees F.
7	5	53	BLANK	0.0	
7	6	54	BLANK	0.0	
7	7	55	VL	Distance Between Voltage Taps	Inches
7	8	56	ID	Diameter (ID) - Heater	Inches
8	1	57	HL	Heated Length - Heater	Inches
8	2	58	DPL	Distance Between Pressure Taps	Inches
8	3	59	YEAR	Year - Test Date	
8	4	60	MONTH	Month - Test Date	
8	5	61	DAY	Day - Test Date	
8	6	62	HOURS	Hour - Test Date	
8	7	63	MIN	Minute - Test Date	
8	8	64	RUN#	Run Number	

SRL FLOW INSTABILITY TESTS
TEST#3 RUN NUMBERS 302-597
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89
10:20 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
1	1	1	Run#	Run Number	
1	2	2	Test#	Test Number	
1	3	3	PTI1	Pressure - Heater Inlet	Psia
1	4	4	PTI2	Pressure - T.S. Inlet	Psia
1	5	5	PTO1	Pressure - Heater Outlet	Psia
1	6	6	PTO2	Pressure - Heater Outlet (Gauge)	Psia
1	7	7	PTO3	Pressure - T.S. Outlet	Psia
1	8	8	DPT1	Pressure Drop - Across Heater	Psi
2	1	9	DPT2	Pressure Drop - Across Heater	Psi
2	2	10	DPT3	Pressure Drop - Across Heater (Manometer)	Psi
2	3	11	FTI1	Flow - T.S. Inlet (Turbine meter) (2")	GPM
2	4	12	FTI2	Flow - T.S. Inlet (Turbine meter) (1")	GPM
2	5	13	FBI1	Flow - Bypass Line (Turbine meter) (2")	GPM
2	6	14	FXO2	Flow - HX Outlet (Turbine meter) (3/4")	GPM
2	7	15	FMO1	Flow - Mixer Outlet (Turbine meter) (2")	GPM
2	8	16	FMO2	Flow - Mixer Outlet (Turbine meter) (1")	GPM
3	1	17	OTI1	Flow - T.S. Inlet (Orifice Meter)	GPM
3	2	18	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	3	19	TRTO1	Temperature (RTD) - T.S. Outlet	Degrees F.
3	4	20	TJT11	Temperature (T/C) - T.S. Inlet	Degrees F.
3	5	21	TJT12	Temperature (T/C) - T.S. Inlet	Degrees F.
3	6	22	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	7	23	PPO1	Pressure - Pump Discharge	Psia
3	8	24	PPI1	Pressure - Pump Inlet	Psia
4	1	25	TEW1	Wall Temperature - Position 1	Degrees F.
4	2	26	TEW2	Wall Temperature - Position 2	Degrees F.
4	3	27	TEW3	Wall Temperature - Position 3	Degrees F.
4	4	28	TEW4	Wall Temperature - Position 4	Degrees F.
4	5	29	TEW5	Wall Temperature - Position 5	Degrees F.
4	6	30	TEW6	Wall Temperature - Position 6	Degrees F.
4	7	31	TEW7	Wall Temperature - Position 7	Degrees F.
4	8	32	TEW8	Wall Temperature - Position 8	Degrees F.

SRL FLOW INSTABILITY TESTS
TEST#3 RUN NUMBERS 302-597
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89
10:20 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
5	1	33	TEW9	Wall Temperature - Position 9	Degrees F.
5	2	34	TEW10	Wall Temperature - Position 10	Degrees F.
5	3	35	TEW11	Wall Temperature - Position 11	Degrees F.
5	4	36	TEW12	Wall Temperature - Position 12	Degrees F.
5	5	37	TEW13	Wall Temperature - Position 13	Degrees F.
5	6	38	TEW14	Wall Temperature - Position 14	Degrees F.
5	7	39	TEW15	Wall Temperature - Position 15	Degrees F.
5	8	40	TEW16	Wall Temperature - Position 16	Degrees F.
6	1	41	TEW17	Wall Temperature - Position 17	Degrees F.
6	2	42	TEW18	Wall Temperature - Position 18	Degrees F.
6	3	43	PWRKW	Power - Heater	KW
6	4	44	HFLX	Heat Flux - Heater	M.Btu/Hr/Sqft
6	5	45	VOLTB	Voltage - Bus to Bus	Volts
6	6	46	VOLTT	Voltage - Heater	Volts
6	7	47	CURRT	Current - Heater	Amps
6	8	48	QUALITY	Quality - Heater Outlet	(%)
7	1	49	HRATIO	Heat Output / Heat Input Ratio	
7	2	50	DPP1	Pressure Difference - Across Pump	Psi
7	3	51	TKW15	Wall Temperature - Position 15	Degrees F.
7	4	52	TKW16	Wall Temperature - Position 16	Degrees F.
7	5	53	TKW17	Wall Temperature - Position 17	Degrees F.
7	6	54	TKW18	Wall Temperature - Position 18	Degrees F.
7	7	55	VL	Distance Between Voltage Taps	Inches
7	8	56	ID	Diameter (ID) - Heater	Inches
8	1	57	HL	Heated Length - Heater	Inches
8	2	58	DPL	Distance Between Pressure Taps	Inches
8	3	59	YEAR	Year - Test Date	
8	4	60	MONTH	Month - Test Date	
8	5	61	DAY	Day - Test Date	
8	6	62	HOURS	Hour - Test Date	
8	7	63	MIN	Minute - Test Date	
8	8	64	RUN#	Run Number	

SRL FLOW INSTABILITY TESTS
TEST#4.0 RUN NUMBERS 821-1100
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

18-Apr-89
11:11 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
1	1	1	Run#	Run Number	
1	2	2	Test#	Test Number	
1	3	3	PTI1	Pressure - Heater Inlet	Psia
1	4	4	PTI2	Pressure - T.S. Inlet	Psia
1	5	5	PTO1	Pressure - Heater Outlet	Psia
1	6	6	PTO2	Pressure - Heater Outlet (Gauge)	Psia
1	7	7	PTO3	Pressure - T.S. Outlet	Psia
1	8	8	DPT1	Pressure Drop - Across Heater	Psi
2	1	9	DPT2	Pressure Drop - Across Heater	Psi
2	2	10	DPT3	Pressure Drop - Across Heater (Manometer)	Psi
2	3	11	FTI1	Flow - T.S. Inlet (Turbine meter) (2")	GPM
2	4	12	FTI2	Flow - T.S. Inlet (Turbine meter) (1")	GPM
2	5	13	FBI1	Flow - Bypass Line (Turbine meter) (2")	GPM
2	6	14	FXO2	Flow - HX Outlet (Turbine meter) (3/4")	GPM
2	7	15	FMO1	Flow - Mixer Outlet (Turbine meter) (2")	GPM
2	8	16	FMO2	Flow - Mixer Outlet (Turbine meter) (1")	GPM
3	1	17	OTI1	Flow - T.S. Inlet (Orifice Meter)	GPM
3	2	18	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	3	19	TRTO1	Temperature (RTD) - T.S. Outlet	Degrees F.
3	4	20	TJT11	Temperature (T/C) - T.S. Inlet	Degrees F.
3	5	21	TJT12	Temperature (T/C) - T.S. Inlet	Degrees F.
3	6	22	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	7	23	PPO1	Pressure - Pump Discharge	Psia
3	8	24	PPI1	Pressure - Pump Inlet	Psia
4	1	25	TEW1	Wall Temperature - Position 1	Degrees F.
4	2	26	TEW2	Wall Temperature - Position 2	Degrees F.
4	3	27	TEW3	Wall Temperature - Position 3	Degrees F.
4	4	28	TEW4	Wall Temperature - Position 4	Degrees F.
4	5	29	TEW5	Wall Temperature - Position 5	Degrees F.
4	6	30	TEW6	Wall Temperature - Position 6	Degrees F.
4	7	31	TEW7	Wall Temperature - Position 7	Degrees F.
4	8	32	TEW8	Wall Temperature - Position 8	Degrees F.

SRL FLOW INSTABILITY TESTS
TEST#4.0 RUN NUMBERS 821-1100
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

18-Apr-89
11:11 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
5	1	33	TEW9	Wall Temperature - Position 9	Degrees F.
5	2	34	TEW10	Wall Temperature - Position 10	Degrees F.
5	3	35	TEW11	Wall Temperature - Position 11	Degrees F.
5	4	36	TEW12	Wall Temperature - Position 12	Degrees F.
5	5	37	TEW13	Wall Temperature - Position 13	Degrees F.
5	6	38	TEW14	Wall Temperature - Position 14	Degrees F.
5	7	39	TEW15	Wall Temperature - Position 15	Degrees F.
5	8	40	TEW16	Wall Temperature - Position 16	Degrees F.
6	1	41	TEW17	Wall Temperature - Position 17	Degrees F.
6	2	42	TEW18	Wall Temperature - Position 18	Degrees F.
6	3	43	PWRKW	Power - Heater	KW
6	4	44	HFLX	Heat Flux - Heater	M.Btu/Hr/Sqft
6	5	45	VOLTB	Voltage - Bus to Bus	Volts
6	6	46	VOLTT	Voltage - Heater	Volts
6	7	47	CURRT	Current - Heater	Amps
6	8	48	QUALITY	Quality - Heater Outlet	(%)
7	1	49	HRATIO	Heat Output / Heat Input Ratio	
7	2	50	DPP1	Pressure Difference - Across Pump	Psi
7	3	51	TKW14	Wall Temperature - Position 14	Degrees F.
7	4	52	TKW17	Wall Temperature - Position 17	Degrees F.
7	5	53	BLANK	0.0	
7	6	54	BLANK	0.0	
7	7	55	VL	Distance Between Voltage Taps	Inches
7	8	56	ID	Diameter (ID) - Heater	Inches
8	1	57	HL	Heated Length - Heater	Inches
8	2	58	DPL	Distance Between Pressure Taps	Inches
8	3	59	YEAR	Year - Test Date	
8	4	60	MONTH	Month - Test Date	
8	5	61	DAY	Day - Test Date	
8	6	62	HOURS	Hour - Test Date	
8	7	63	MIN	Minute - Test Date	
8	8	64	RUN#	Run Number	

SRL FLOW INSTABILITY TESTS
TESTS 5 and 6; RUN NUMBERS 1101-1453
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89
11:33 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
1	1	1	Run#	Run Number	
1	2	2	Test#	Test Number	
1	3	3	PTI1	Pressure - Heater Inlet	Psia
1	4	4	PTI2	Pressure - T.S. Inlet	Psia
1	5	5	PTO1	Pressure - Heater Outlet	Psia
1	6	6	PTO2	Pressure - Heater Outlet (Gauge)	Psia
1	7	7	PTO3	Pressure - T.S. Outlet	Psia
1	8	8	DPT1	Pressure Drop - Across Heater	Psi
2	1	9	DPT2	Pressure Drop - Across Heater	Psi
2	2	10	DPT3	Pressure Drop - Across Heater (Manometer)	Psi
2	3	11	FTI1	Flow - T.S. Inlet (Turbine meter) (2")	GPM
2	4	12	FTI2	Flow - T.S. Inlet (Turbine meter) (1")	GPM
2	5	13	FBI1	Flow - Bypass Line (Turbine meter) (2")	GPM
2	6	14	FXO2	Flow - HX Outlet (Turbine meter) (3/4")	GPM
2	7	15	FMO1	Flow - Mixer Outlet (Turbine meter) (2")	GPM
2	8	16	FMO2	Flow - Mixer Outlet (Turbine meter) (1")	GPM
3	1	17	OTI1	Flow - T.S. Inlet (Orifice Meter)	GPM
3	2	18	TRTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
3	3	19	TRTO1	Temperature (RTD) - T.S. Outlet	Degrees F.
3	4	20	TJT11	Temperature (T/C) - T.S. Inlet	Degrees F.
3	5	21	TRTI2	Temperature (T/C) - T.S. Inlet	Degrees F.
3	6	22	TRTO2	Temperature (RTD) - T.S. Inlet	Degrees F.
3	7	23	PPO1	Pressure - Pump Discharge	Psia
3	8	24	PPI1	Pressure - Pump Inlet	Psia
4	1	25	TEW95W	Wall Temperature - Position 1	Degrees F.
4	2	26	TEW95E	Wall Temperature - Position 2	Degrees F.
4	3	27	TEW72N	Wall Temperature - Position 3	Degrees F.
4	4	28	TEW72S	Wall Temperature - Position 4	Degrees F.
4	5	29	TEW48W	Wall Temperature - Position 5	Degrees F.
4	6	30	TEW48E	Wall Temperature - Position 6	Degrees F.
4	7	31	TEW24N	Wall Temperature - Position 7	Degrees F.
4	8	32	TEW24S	Wall Temperature - Position 8	Degrees F.

SRL FLOW INSTABILITY TESTS
TESTS 5 and 6; RUN NUMBERS 1101-1453
EACH RUN HAS 64 WORDS IN 8 RECORDS
CARD IMAGE FORMAT (8F10.4)

6-Oct-89
11:33 AM

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
5	1	33	TEW13W	Wall Temperature - Position 9	Degrees F.
5	2	34	TEW13E	Wall Temperature - Position 10	Degrees F.
5	3	35	TEW10N	Wall Temperature - Position 11	Degrees F.
5	4	36	TEW10S	Wall Temperature - Position 12	Degrees F.
5	5	37	TEW07W	Wall Temperature - Position 13	Degrees F.
5	6	38	TEW07E	Wall Temperature - Position 14	Degrees F.
5	7	39	TEW04N	Wall Temperature - Position 15	Degrees F.
5	8	40	TEW04S	Wall Temperature - Position 16	Degrees F.
6	1	41	TEW01W	Wall Temperature - Position 17	Degrees F.
6	2	42	TEW01E	Wall Temperature - Position 18	Degrees F.
6	3	43	PWRKW	Power - Heater	KW
6	4	44	HFLX	Heat Flux - Heater	M.Btu/Hr/Sqft
6	5	45	VOLTB	Voltage - Bus to Bus	Volts
6	6	46	VOLTT	Voltage - Heater	Volts
6	7	47	CURRT	Current - Heater	Amps
6	8	48	QUALITY	Quality - Heater Outlet	(%)
7	1	49	HRATIO	Heat Output / Heat Input Ratio	
7	2	50	DPP1	Pressure Difference - Across Pump	Psi
7	3	51	DPSTD1	Standard Deviation of DPT1	(%)
7	4	52	TKW07S	Wall Temperature - Position 19	Degrees F.
7	5	53	TKW01N	Wall Temperature - Position 20	Degrees F.
7	6	54	DPSTD3	Standard Deviation of DPT3	(%)
7	7	55	VL	Distance Between Voltage Taps	Inches
7	8	56	ID	Diameter (ID) - Heater	Inches
8	1	57	HL	Heated Length - Heater	Inches
8	2	58	DPL	Distance Between Pressure Taps	Inches
8	3	59	YEAR	Year - Test Date	
8	4	60	MONTH	Month - Test Date	
8	5	61	DAY	Day - Test Date	
8	6	62	HOURS	Hour - Test Date	
8	7	63	MIN	Minute - Test Date	
8	8	64	RUN#	Run Number	

SRL FLOW INSTABILITY TESTS

TESTS 7; RUN NUMBERS 1454-1609

EACH RUN HAS 100 WORDS IN 10 RECORDS

CARD IMAGE FORMAT (10F8.3)

9/6/89 10:19

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
1	1	1	PWR1	Power - Heater	KW
1	2	2	HFLX	Heat Flux - Heater	M.Btu/Hr/Sqft
1	3	3	VOLTB	Voltage - Bus to Bus	Volts
1	4	4	VOLTT	Voltage - Heater	Volts
1	5	5	CURRT1	Current - Heater	Amps
1	6	6	CURRT2	Current - Heater Backup	Amps
1	7	7	PTI1	Pressure - T.S. Inlet	Psig
1	8	8	PTI2	Pressure - T.S. Inlet	Psig
1	9	9	PTO1	Pressure - Heater Outlet	Psig
1	10	10	PTO3	Pressure - Heater Outlet	Psig
2	1	11	PBI1	Pressure - By Pass Inlet	Psig
2	2	12	PBO1	Pressure - By Pass Outlet	Psig
2	3	13	PL1	Pressure - Loop 1	Psig
2	4	14	PL2	Pressure - Loop 2	Psig
2	5	15	PD1	Pressure - Heat Exchanger Divert	Psig
2	6	16	PXI1	Pressure - Heat Exchanger Inlet	Psig
2	7	17	PXO1	Pressure - Heat Exchanger Outlet	Psig
2	8	18	PPI1	Pressure - Pump Inlet	Psig
2	9	19	PPO1	Pressure - Pump Discharge	Psig
2	10	20	PA1	Pressure - Tank	Psig
3	1	21	DT1	Pressure Drop - Test Section DP1	Psi
3	2	22	DT2	Pressure Drop - Test Section DP2	Psi
3	3	23	DP1	Pressure Drop - Pump	Psi
3	4	24	DLV1	Pressure Drop - Valve	Psi
3	5	25	OLI1	Flow - Loop Inlet (Orifice Meter 2")	GPM
3	6	26	FLI1	Flow - Loop Inlet (Turbine meter) (2")	GPM
3	7	27	FTI1	Flow - T.S. Inlet (Turbine meter) (1")	GPM
3	8	28	FBI1	Flow - Bypass Line (Turbine meter) (2")	GPM
3	9	29	FXI1	Flow - HX Inlet (Turbine meter) (2")	GPM
3	10	30	FXI2	Flow - HX Inlet (Turbine meter) (1")	GPM

SRL FLOW INSTABILITY TESTS

TESTS 7; RUN NUMBERS 1454-1609

EACH RUN HAS 100 WORDS IN 10 RECORDS

CARD IMAGE FORMAT (10F8.3)

9/6/89 10:19

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
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4	1	31	FS1	Flow - Bypass to Tank (Turbine meter) (2")	GPM
4	2	32	TRT11	Temperature (RTD) - T.S. Inlet	Degrees F.
4	3	33	TRT12	Temperature (RTD) - T.S. Inlet	Degrees F.
4	4	34	TRTO1	Temperature (RTD) - T.S. Outlet	Degrees F.
4	5	35	TRTO2	Temperature (RTD or T/C) - T.S. Outlet	Degrees F.
4	6	36	JX11	Temperature (RTD) - T.S. Inlet	Degrees F.
4	7	37	JXO1	Temperature (RTD) - T.S. Outlet	Degrees F.
4	8	38	PTO2	Pressure - Heater Outlet (Gauge)	Psig
4	9	39	DT3	Pressure Drop - Test Section DP3 (Manometer)	Psi
4	10	40	TEW95W	Wall Temperature - Position 1	Degrees F.

5	1	41	TEW95E	Wall Temperature - Position 2	Degrees F.
5	2	42	TEW72N	Wall Temperature - Position 3	Degrees F.
5	3	43	TEW72S	Wall Temperature - Position 4	Degrees F.
5	4	44	TEW48W	Wall Temperature - Position 5	Degrees F.
5	5	45	TEW48E	Wall Temperature - Position 6	Degrees F.
5	6	46	TEW24N	Wall Temperature - Position 7	Degrees F.
5	7	47	TEW24S	Wall Temperature - Position 8	Degrees F.
5	8	48	TEW13W	Wall Temperature - Position 9	Degrees F.
5	9	49	TEW13E	Wall Temperature - Position 10	Degrees F.
5	10	50	TEW10N	Wall Temperature - Position 11	Degrees F.

6	1	51	TEW10S	Wall Temperature - Position 12	Degrees F.
6	2	52	TEW07W	Wall Temperature - Position 13	Degrees F.
6	3	53	TEW07E	Wall Temperature - Position 14	Degrees F.
6	4	54	TEW04N	Wall Temperature - Position 15	Degrees F.
6	5	55	TEW04S	Wall Temperature - Position 16	Degrees F.
6	6	56	TEW01W	Wall Temperature - Position 17	Degrees F.
6	7	57	TEW01E	Wall Temperature - Position 18	Degrees F.
6	8	58		BLANK	
6	9	59	TKW07W	Wall Temperature - Position 19	Degrees F.
6	10	60	TKW04E	Wall Temperature - Position 20	Degrees F.

SRL FLOW INSTABILITY TESTS

TESTS 7; RUN NUMBERS 1454-1609

EACH RUN HAS 100 WORDS IN 10 RECORDS

CARD IMAGE FORMAT (10F8.3)

9/6/89 10:19

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
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7	1	61	TKW01S	Wall Temperature - Position 21	Degrees F.
7	2	62		BLANK	
7	3	63	TEREF	E Reference Junction Temperature	Degrees F.
7	4	64	TJREF	J Reference Junction Temperature	Degrees F.
7	5	65		BLANK	
7	6	66		BLANK	
7	7	67		BLANK	
7	8	68		BLANK	
7	9	69	PWR2	Power - Heater (Backup)	KW
7	10	70	RTS	Test Section Resistance	Ohms

8	1	71	QUALITY	Quality - Heater Outlet	(%)
8	2	72	HRATIO	Heat Output / Heat Input Ratio	
8	3	73	HLOSS	Heat Losses	(%)
8	4	74	SVOLT	Standard Deviation of TS Voltage	(%)
8	5	75	SCURR	Standard Deviation of TS Current	(%)
8	6	76	SPT01	Standard Deviation of TS Exit Pressure	(%)
8	7	77	SDPT1	Standard Deviation of TS Pressure Drop DT1	(%)
8	8	78	SDPT2	Standard Deviation of TS Pressure Drop DT2	(%)
8	9	79	SFT11	Standard Deviation of TS Flow Rate	(%)
8	10	80	SRT11	Standard Deviation of TS Inlet Temperature	(%)

9	1	81		BLANK	
9	2	82		BLANK	
9	3	83		BLANK	
9	4	84	DPL	Distance Between Pressure Taps	Inches
9	5	85	VTL	Distance Between Voltage Taps	Inches
9	6	86	HL	Heated Length - Heater	Inches
9	7	87	ID	Diameter (ID) - Heater	Inches
9	8	88	DATE	Test Date	YYMM.DD
9	9	89	TIME	Test Time	HHMM.SS
9	10	90	TEST#	Test Number	

SRL FLOW INSTABILITY TESTS

TESTS 7; RUN NUMBERS 1454-1609

EACH RUN HAS 100 WORDS IN 10 RECORDS

CARD IMAGE FORMAT (10F8.3)

9/6/89 10:19

RECORD	WORD	SERIA	INSTRU-		
NO.	NO.	NO.	MENT	PARAMETER	UNITS

10	1	91	RUN#	Run Number	
10	2	92	PTO2	Pressure - Heater Outlet (Gauge)	Psig
10	3	93	DT3	Pressure Drop - Test Section DP3 (Manometer)	IN HG
10	4	94		BLANK	
10	5	95		BLANK	
10	6	96		BLANK	
10	7	97		BLANK	
10	8	98		BLANK	
10	9	99		BLANK	
10	10	100		BLANK	

SRL FLOW INSTABILITY TESTS

TESTS 9; RUN NUMBERS 1663-1797

EACH RUN HAS 100 WORDS IN 10 RECORDS

CARD IMAGE FORMAT (10F8.3)

10/30/89

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
1	1	1	PWR1	Power - Heater	KW
1	2	2	HFLX	Heat Flux - Heater	M.Btu/Hr/Sqft
1	3	3	VOLT B	Voltage - Bus to Bus	Volts
1	4	4	VOLT T	Voltage - Heater	Volts
1	5	5	CURRT1	Current - Heater	Amps
1	6	6	CURRT2	Current - Heater Backup	Amps
1	7	7	PTI1	Pressure - T.S. Inlet	Psig
1	8	8	PTI2	Pressure - T.S. Inlet	Psig
1	9	9	PTO1	Pressure - Heater Outlet	Psig
1	10	10	PTO3	Pressure - Heater Outlet	Psig
2	1	11	PBI1	Pressure - By Pass Inlet	Psig
2	2	12	PBO1	Pressure - By Pass Outlet	Psig
2	3	13	PL1	Pressure - Loop 1	Psig
2	4	14	PL2	Pressure - Loop 2	Psig
2	5	15	PD1	Pressure - Heat Exchanger Divert	Psig
2	6	16	PXI1	Pressure - Heat Exchanger Inlet	Psig
2	7	17	PXO1	Pressure - Heat Exchanger Outlet	Psig
2	8	18	PPI1	Pressure - Pump Inlet	Psig
2	9	19	PPO1	Pressure - Pump Discharge	Psig
2	10	20	PA1	Pressure - Tank	Psig
3	1	21	DT1	Pressure Drop - Test Section DP1	Psi
3	2	22	DT2	Pressure Drop - Test Section DP2	Psi
3	3	23	DP1	Pressure Drop - Pump	Psi
3	4	24	DLV1	Pressure Drop - Valve	Psi
3	5	25	OLI1	Flow - Loop Inlet (Orifice Meter 2")	GPM
3	6	26	FLI1	Flow - Loop Inlet (Turbine meter) (2")	GPM
3	7	27	FTI1	Flow - T.S. Inlet (Turbine meter) (1")	GPM
3	8	28	FBI1	Flow - Bypass Line (Turbine meter) (2")	GPM
3	9	29	FXI1	Flow - HX Inlet (Turbine meter) (2")	GPM
3	10	30	FXI2	Flow - HX Inlet (Turbine meter) (1")	GPM

SRL FLOW INSTABILITY TESTS

TESTS 9; RUN NUMBERS 1883-1907

EACH RUN HAS 100 WORDS IN 10 RECORDS

CARD IMAGE FORMAT (10F8.3)

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
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4	1	31	FS1	Flow - Bypass to Tank (Turbine meter) (2")	GPM
4	2	32	TRT11	Temperature (RTD) - T.S. Inlet	Degrees F.
4	3	33	TRT12	Temperature (RTD) - T.S. Inlet	Degrees F.
4	4	34	TRTO1	Temperature (RTD) - T.S. Outlet	Degrees F.
4	5	35	TRTO2	Temperature (RTD or T/C) - T.S. Outlet	Degrees F.
4	6	36	JX11	Temperature (T/C) - T.S. Inlet	Degrees F.
4	7	37	JXO1	Temperature (T/C) - T.S. Outlet	Degrees F.
4	8	38	PTO2	Pressure - Heater Outlet (Gauge)	Psig
4	9	39	DT3	Pressure Drop - Test Section DP3 (Manometer)	Psi
4	10	40	TEW95W	Wall Temperature - Position 1	Degrees F.

5	1	41	TEW95E	Wall Temperature - Position 2	Degrees F.
5	2	42	TEW72N	Wall Temperature - Position 3	Degrees F.
5	3	43	TEW72S	Wall Temperature - Position 4	Degrees F.
5	4	44	TEW48W	Wall Temperature - Position 5	Degrees F.
5	5	45	TEW48E	Wall Temperature - Position 6	Degrees F.
5	6	46	TEW24N	Wall Temperature - Position 7	Degrees F.
5	7	47	TEW24S	Wall Temperature - Position 8	Degrees F.
5	8	48	TEW14W	Wall Temperature - Position 9	Degrees F.
5	9	49	TEW14E	Wall Temperature - Position 10	Degrees F.
5	10	50	TEW10N	Wall Temperature - Position 11	Degrees F.

6	1	51	TEW10S	Wall Temperature - Position 12	Degrees F.
6	2	52	TEW07W	Wall Temperature - Position 13	Degrees F.
6	3	53	TEW07E	Wall Temperature - Position 14	Degrees F.
6	4	54	TEW04N	Wall Temperature - Position 15	Degrees F.
6	5	55	TEW04S	Wall Temperature - Position 16	Degrees F.
6	6	56	TEW01W	Wall Temperature - Position 17	Degrees F.
6	7	57	TEW01E	Wall Temperature - Position 18	Degrees F.
6	8	58		BLANK	
6	9	59	TKW11N	Wall Temperature - Position 19	Degrees F.
6	10	60	TKW05E	Wall Temperature - Position 20	Degrees F.

SRL FLOW INSTABILITY TESTS

TESTS 9; RUN NUMBERS 1663-1797

EACH RUN HAS 100 WORDS IN 10 RECORDS

CARD IMAGE FORMAT (10F8.3)

10/30/89

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
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7	1	61	TKW01S	Wall Temperature - Position 21	Degrees F.
7	2	62		BLANK	
7	3	63	TEREF	E Reference Junction Temperature	Degrees F.
7	4	64	TJREF	J Reference Junction Temperature	Degrees F.
7	5	65		BLANK	
7	6	66		BLANK	
7	7	67		BLANK	
7	8	68		BLANK	
7	9	69	PWR2	Power - Heater (Backup)	KW
7	10	70	RTS	Test Section Resistance	Ohms

8	1	71	QUALITY	Quality - Heater Outlet	(%)
8	2	72	HRATIO	Heat Output / Heat Input Ratio	
8	3	73	HLOSS	Heat Losses	(%)
8	4	74	SVOLT	Standard Deviation of TS Voltage	(%)
8	5	75	SCURR	Standard Deviation of TS Current	(%)
8	6	76	SPTO1	Standard Deviation of TS Exit Pressure	(%)
8	7	77	SDPT1	Standard Deviation of TS Pressure Drop DT1	(%)
8	8	78	SDPT2	Standard Deviation of TS Pressure Drop DT2	(%)
8	9	79	SFTI1	Standard Deviation of TS Flow Rate	(%)
8	10	80	SRTI1	Standard Deviation of TS Inlet Temperature	(%)

9	1	81		BLANK	
9	2	82		BLANK	
9	3	83		BLANK	
9	4	84	DPL	Distance Between Pressure Taps	Inches
9	5	85	VTL	Distance Between Voltage Taps	Inches
9	6	86	HL	Heated Length - Heater	Inches
9	7	87	ID	Inside Diameter (ID) - Heater	Inches
9	8	88	DATE	Test Date	YYMM.DD
9	9	89	TIME	Test Time	HHMM.SS
9	10	90	TEST#	Test Number	

SRL FLOW INSTABILITY TESTS
TESTS 9; RUN NUMBERS 1663-1797
EACH RUN HAS 100 WORDS IN 10 RECORDS
CARD IMAGE FORMAT (10F8.3)

10/30/89

RECORD NO.	WORD NO.	SERIAL NO.	INSTRUMENT	PARAMETER	UNITS
---------------	-------------	---------------	------------	-----------	-------

10	1	91	RUN#	Run Number	
10	2	92	PTO2	Pressure - Heater Outlet (Gauge)	Psig
10	3	93	DT3	Pressure Drop - Test Section DP3 (Manometer)	IN HG
10	4	94		BLANK	
10	5	95		BLANK	
10	6	96		BLANK	
10	7	97		BLANK	
10	8	98		BLANK	
10	9	99		BLANK	
10	10	100		BLANK	

APPENDIX C

Program Listing for Data Reduction and Analysis

Program	Purpose
RDSRL.FOR	Program to reduce data based upon format used in tests 1454 through 1797. Program generates pressure drop information and temperature data for the last axial station.
RDSRL1.FOR	Program to reduce data based upon format used in tests 113 through 1453. Program generates pressure drop information and temperature data for the last axial station.
RDSRL2.FOR	Program to reduce data based upon format used in tests 1454 through 1797. Program generates heat transfer data along the test section for various flow conditions.
RDSRL4.FOR	Program to reduce data based upon format used in tests 113 through 1453. Program generates heat transfer data along the test section for various flow conditions.

C PROGRAM TO REDUCE SRL DATA

C ***** RDSRL.FOR *****

C

```

    DIMENSION RUN(300),PTI1(300),PTI2(300),PTO1(300),
    1PTO3(300),DT1(300),DT2(300),FTI1(300),FLI1(300),
    2TRTI1(300),FBI1(300),
    3TRTI2(300),TRTO1(300),TRTO2(300),XL(18),
    4TEW(21,300),PWRKW(300),HFLX(300),DIA(300),SDVT(7,300)
    REAL MDOT,KF,KW
    DATA XL/.996,.996,.755,.755,.503,.503,.252,.252,.136,.136,
    1.105,.105,.073,.073,.042,.042,.010,.010/
    PIE = 3.14159
    CP = 1.0
    KF = .363
    KW = 132.
    THICK = 0.065

```

C

```

    OPEN(UNIT=3,FILE='INPUT')

```

C

```

    I=1
    9 FORMAT(10F8.3)
    10 READ(3,9,END=30)PWRKW(I),HFLX(I),X1,X2,X3,X4,
    1PTI1(I),PTI2(I),PTO1(I),PTO3(I)
    READ(3,9,END=30)PBI1,PBO1,PL1,PL2,X1,X2,
    1X3,PPI1,PPO1,PA1
    READ(3,9,END=30)DT1(I),DT2(I),DP1,DLV1,OLI1,
    1FLI1(I),FTI1(I),FBI1(I),FXI1,FXI2
    READ(3,9,END=30)FS1,TRTI1(I),TRTI2(I),TRTO1(I),TRTO2(I),
    1XI1,XO1,PTO2,DT3,TEW(1,I)
    READ(3,9,END=30)TEW(2,I),TEW(3,I),TEW(4,I),TEW(5,I),
    1TEW(6,I),TEW(7,I),TEW(8,I),TEW(9,I),TEW(10,I),TEW(11,I)
    READ(3,9,END=30)TEW(12,I),TEW(13,I),TEW(14,I),TEW(15,I),TEW(16,I),
    1TEW(17,I),TEW(18,I),X1,TEW(19,I),TEW(20,I)
    READ(3,9,END=30)TEW(21,I),X2,X3,X4,X5,X6,X7,X8,X9,X10
    READ(3,9,END=30)QUAL,X1,X2,SDVT(1,I),SDVT(2,I),SDVT(3,I),
    1SDVT(4,I),SDVT(5,I),SDVT(6,I),SDVT(7,I)
    READ(3,9,END=30)X1,X2,X3,X4,X5,HL,DIA(I),DATE,X6,TEST
    READ(3,9,END=30)RUN(I),X1,X2,X3,X4,X5,X6,X7,X8,X9
    IF(DT1(I).LT.0.25)DT1(I)=DT2(I)
    I=I+1
    IPOINT =I-1
    GO TO 10
    30 WRITE(*,1000)
    1000 FORMAT(1X,'INPUT DONE',//,1X,'INPUT DPZERO COEFFICIENTS',/,
    1'DPZERO = A0 + A1*X + A2*X*X')
    35 READ(*,*)A0,A1,A2
    WRITE(*,1002)A0,A1,A2
    1002 FORMAT(1X,'A0=',F10.4,/,1X,'A1=',F10.4,/,1X,'A2=',F10.4,
    1//1X,'READ IN RUN NUMBERS')
    900 FORMAT(8F10.4)
    36 READ(*,*)LSRUN,LERUN
    IF(LSRUN.LT.0.0) STOP
    WRITE(*,1001)LSRUN,LERUN
    1001 FORMAT(1X,'START RUN',I5,5X,'STOP RUN',I5)
    OPEN(UNIT=4,FILE='OUTPUT',STATUS='UNKNOWN')
    DO 50 I=1,IPOINT
        J=17
        IF(RUN(I).LT.LSRUN.OR.RUN(I).GT.LERUN) GO TO 50
        IF(PTO1(I).GT. 18.AND.PTO1(I).LT.28) TSAT= 259.29
        IF(PTO1(I).GT. 18.AND.PTO1(I).LT.28) HFG= 939.2
    
```

```

IF(PTO1(I).GT. 32.AND.PTO1(I).LT.58) TSAT= 297.98
IF(PTO1(I).GT. 32.AND.PTO1(I).LT.58) HFG = 911.6
TWAV = (TEW(J,I)+TEW(J+1,I))/2
TSURF = TWAV- THICK*1E06*HFLX(I)/2/KW
TFLUID= TRTI1(I) + (TRTO1(I)-TRTI1(I))*(0.996-XL(J))/0.996
HTCOEF = (HFLX(I)*1E06)/(TSURF-TFLUID)
DTSAT = (TSURF-TSAT)
QUAL = (TFLUID- TSAT)/HFG
X = FTI1(I)
MDOT= X*62.4*60/7.48
AF = PIE*DIA(I)*DIA(I)/4/144
AH = PIE*DIA(I)*HL/144
DPZERO = A0 +A1*X + A2*X*X
QSAT = MDOT*CP*(TSAT-TRTI1(I))/AH/1.0E06
DPRATIO = DT1(I)/DPZERO
QRATIO = HFLX(I)/QSAT
STANTON = HFLX(I)*1.0E06/(MDOT/AF)/CP/(TSAT-TRTO1(I))
PECLET = (MDOT/AF)*DIA(I)*CP/KF/12
C   WRITE(4,1200)RUN(I),DIA(I)
C   WRITE(4,1210)PTI1(I),PTO1(I),DT1(I),FTI1(I),
C   1TRTI1(I),TRTO1(I),PWRKW(I),QUAL(I)
C   DO 50 J=1,17,2
C   WRITE(4,1220)J,TEW(J,I),TEW(J+1,I)
WRITE(4,1230)RUN(I),DT1(I),FTI1(I),FBI1(I),DIA(I),PTO1(I),
1TRTI1(I),HFLX(I),DPRATIO,QRATIO,STANTON,PECLET,TSURF,TFLUID,
2HTCOEF,DTSAT,QUAL,XL(J)
49 CONTINUE
50 CONTINUE
60 CONTINUE
1000 FORMAT(1X,25X,'RUN =',F10.4,/25X,'DIAMETER=',F10.4)
1210 FORMAT(5X,'INLET PRESSURE =',F10.4,'PSIA',5X,
1'EXIT PRESSURE=',F10.4,'PSIA',/5X,'PRESSURE DROP=',
2F10.4,'PSI',5X,'INLET FLOWRATE=',F10.4,'GPM',/
35X,'INLET TEMPERATURE=',F10.4,'DEGF',5X,'OUTLET TEMPERATURE=',
4F10.4,'DEGF',/5X,'POWER=',F10.4,'KW',5X,'QUALITY=',F10.4,/
45X,'***** WALL TEMPERATURE *****')
1220 FORMAT(1X,I3,2F10.4)
1230 FORMAT(10F10.4,2E10.4,2F10.4,E10.4,3F10.4)
WRITE(*,1003)
1003 FORMAT(1X,'READ NEXT SET OF CASES')
GO TO 36
END

```

C PROGRAM TO REDUCE SRL DATA

***** RDSRL1.FOR *****

* PROGRAM TO REDUCE DATA FOR EARLY FORMAT DATA OUTPUT ****

```

    DIMENSION RUN(500),PTI1(500),PTI2(500),PTO1(500),PTO2(500),
    1PTO3(500),DPT1(500),DPT2(500),DPT3(500),FTI1(500),FTI2(500),
    2FXO1(500),FXO2(500),FMO1(500),FMO2(500),OTI1(500),TRTI1(500),
    3TRTO1(500),TJTI1(500),TJXO1(500),TJTO1(500),TEW(18,500),
    4PWRKW(500),HFLX(500),DIA(500),HL(500),XL(18)
    REAL MDOT,KF,KW
    DATA XL/0.996,0.996,0.755,0.755,0.503,0.503,0.252,0.252,0.136,
    10.136,0.105,0.105,0.073,0.073,0.042,0.042,0.010,0.010/
    PIE = 3.14159
    CP = 1.0
    KF = .363
    KW = 132.
    THICK = 0.065
    FBI1 =0.0

    OPEN(UNIT=3,FILE='INPUT')

    I=1
10  READ(3,*,END=30)RUN(I),X1,PTI1(I),PTI2(I),PTO1(I),PTO2(I),
    1PTO3(I),DPT1(I)
    READ(3,*,END=30)DPT2(I),DPT3(I),FTI1(I),FTI2(I),FXO1(I),FXO2(I),
    2FMO1(I),FMO2(I)
    READ(3,*,END=30)OTI1(I),TRTI1(I),TRTO1(I),TJTI1(I),TJXO1(I),
    3TJTO1(I),X2,X3
    READ(3,*,END=30)TEW(1,I),TEW(2,I),TEW(3,I),TEW(4,I),TEW(5,I),
    4TEW(6,I),TEW(7,I),TEW(8,I)
    READ(3,*,END=30)TEW(9,I),TEW(10,I),TEW(11,I),
    5TEW(12,I),TEW(13,I),TEW(14,I),TEW(15,I),TEW(16,I)
    READ(3,*,END=30)TEW(17,I),TEW(18,I),PWRKW(I),HFLX(I),X4,
    6X5,X6,QUAL
    READ(3,*,END=30)X1,X2,X3,X4,X5,X6,X7,DIA(I)
    READ(3,*,END=30)HL(I),X12,X13,X14,X15,X16,X17,X18
    I=I+1
    IPOINT =I-1
    GO TO 10
30  WRITE(*,1000)
1000 FORMAT(1X,'INPUT DONE',//,1X,'INPUT DPZERO COEFFICIENTS',/,
    1'DPZERO = A0 + A1*X + A2*X*X')
35  READ(*,*)A0,A1,A2
    WRITE(*,1002)A0,A1,A2
1002 FORMAT(1X,'A0=',F10.4,/,1X,'A1=',F10.4,/,1X,'A2=',F10.4,
    1//1X,'READ IN RUN NUMBERS')
900  FORMAT(8F10.4)
36  READ (*,*)LSRUN,LERUN
    IF(LSRUN.LT.0.0) STOP
    WRITE(*,1001)LSRUN,LERUN
1001 FORMAT(1X,'START RUN',I5,5X,'STOP RUN',I5)
    OPEN(UNIT=4,FILE='OUTPUT',STATUS='UNKNOWN')
    J = 17
    DO 50 I=1,IPOINT
    IF(RUN(I).LT.LSRUN.OR.RUN(I).GT.LERUN) GO TO 50
    IF(PTO1(I).GT. 32.AND.PTO1(I).LT.38) TSAT= 259.29
    IF(PTO1(I).GT. 32.AND.PTO1(I).LT.38) HFG = 939.2
    IF(PTO1(I).GT. 62.AND.PTO1(I).LT.68) TSAT= 297.98
    IF(PTO1(I).GT. 62.AND.PTO1(I).LT.68) HFG = 911.6
    TWAV = (TEW(J,I) +TEW(J+1,I))/2

```

```

TSURF = TWAV - THICK*1.0E06*HFLX(I)/2/KW
TFLUID = TRTI1(I) + (TRTO1(I)-TRTI1(I))*(0.996-XL(J))/0.996
HTCOEF = (HFLX(I)*1.0E06)/(TSURF-TFLUID)
DTSAT = TSURF-TSAT
QUAL = DTSAT*CP/HFG
X = FTI2(I)
MDOT= X*62.4*60/7.48
AF = PIE*DIA(I)*DIA(I)/4/144
AH = PIE*DIA(I)*HL(I)/144
DPZERO = A0 +A1*X + A2*X*X
QSAT = MDOT*CP*(TSAT-TRTI1(I))/AH/1.0E06
DPRATIO = DPT1(I)/DPZERO
QRATIO = HFLX(I)/QSAT
STANTON = (HFLX(I)*1.0E06)/(MDOT/AF)/CP/(TSAT-TRTO1(I))
PECLET = (MDOT/AF)*DIA(I)*CP/KF/12
WRITE(4,1230)RUN(I),DPT1(I),FTI2(I),FBI1,DIA(I),PTO1(I),
1TRTI1(I),HFLX(I),DPRATIO,QRATIO,STANTON,PECLET,TSURF,TFLUID,
2HTCOEF,DTSAT,QUAL,XL(J)
50 CONTINUE
1200 FORMAT(1X,25X,'RUN =',F10.4,/25X,'DIAMETER=',F10.4)
1210 FORMAT(5X,'INLET PRESSURE =',F10.4,'PSIA',5X,
1'EXIT PRESSURE=',F10.4,'PSIA',/5X,'PRESSURE DROP=',
2F10.4,'PSI',5X,'INLET FLOWRATE=',F10.4,'GPM',/
35X,'INLET TEMPERATURE=',F10.4,'DEGF',5X,'OUTLET TEMPERATURE=',
4F10.4,'DEGF',/5X,'POWER=',F10.4,'KW',5X,'QUALITY=',F10.4,/
45X,'***** WALL TEMPERATURE *****')
1220 FORMAT(1X,I3,2F10.4)
1230 FORMAT(10F10.4,2E10.4,2F10.4,E10.4,3F10.4)
WRITE(*,1003)
103 FORMAT(1X,'READ NEXT SET OF CASES')
GO TO 36
END

```

C PROGRAM TO REDUCE SRL DATA

C ***** RDSRL2.FOR

C ***** HEAT TRANSFER ANALYSIS PROGRAM

```

    DIMENSION RUN(300),PTI1(300),PTI2(300),PTO1(300),
    1PTO3(300),DT1(300),DT2(300),FTI1(300),FLI1(300),
    2TRTI1(300),
    3TRTI2(300),TRTO1(300),TRTO2(300),XL(18),
    4TEW(21,300),PWRKW(300),HFLX(300),DIA(300),SDVT(7,300)
    REAL MDOT,KF,KW,MUF,MUS,NU,NUSED
    DATA XL/.996,.996,.755,.755,.503,.503,.252,.252,.136,.136,
    1.105,.105,.073,.073,.042,.042,.010,.010/
    PIE = 3.14159
    CP = 1.0
    KF = .363
    KW = 132.
    THICK = 0.065

```

C OPEN(UNIT=3,FILE='INPUT')

```

C
    I=1
    9 FORMAT(10F8.3)
    10 READ(3,9,END=30)PWRKW(I),HFLX(I),X1,X2,X3,X4,
    1PTI1(I),PTI2(I),PTO1(I),PTO3(I)
    READ(3,9,END=30)PBI1,PBO1,PL1,PL2,X1,X2,
    1X3,PPI1,PPO1,PA1
    READ(3,9,END=30)DT1(I),DT2(I),DP1,DLV1,OLI1,
    1FLI1(I),FTI1(I),FBI1,FXI1,FXI2
    READ(3,9,END=30)FS1,TRTI1(I),TRTI2(I),TRTO1(I),TRTO2(I),
    1XI1,XO1,PTO2,DT3,TEW(1,I)
    READ(3,9,END=30)TEW(2,I),TEW(3,I),TEW(4,I),TEW(5,I),
    1TEW(6,I),TEW(7,I),TEW(8,I),TEW(9,I),TEW(10,I),TEW(11,I)
    READ(3,9,END=30)TEW(12,I),TEW(13,I),TEW(14,I),TEW(15,I),TEW(16,I),
    1TEW(17,I),TEW(18,I),X1,TEW(19,I),TEW(20,I)
    READ(3,9,END=30)TEW(21,I),X2,X3,X4,X5,X6,X7,X8,X9,X10
    READ(3,9,END=30)QUAL,X1,X2,SDVT(1,I),SDVT(2,I),SDVT(3,I),
    1SDVT(4,I),SDVT(5,I),SDVT(6,I),SDVT(7,I)
    READ(3,9,END=30)X1,X2,X3,X4,X5,HL,DIA(I),DATE,X6,TEST
    READ(3,9,END=30)RUN(I),X1,X2,X3,X4,X5,X6,X7,X8,X9
    IF(DT1(I).LT.0.1)DT1(I)=DT2(I)
    I=I+1
    IPOINT =I-1
    GO TO 10
    30 WRITE(*,1000)
    1000 FORMAT(1X,'INPUT DONE',//,1X,'INPUT DPZERO COEFFICIENTS',/,
    1'DPZERO = A0 + A1*X + A2*X*X')
    35 READ(*,*)A0,A1,A2
    WRITE(*,1002)A0,A1,A2
    1002 FORMAT(1X,'A0=',F10.4,/1X,'A1=',F10.4,/1X,'A2=',F10.4,
    1//1X,'READ IN RUN NUMBERS')
    900 FORMAT(8F10.4)
    36 READ(*,*)LSRUN,LERUN
    IF(LSRUN.LT.0.0) STOP
    WRITE(*,1001)LSRUN,LERUN
    101 FORMAT(1X,'START RUN',I5,5X,'STOP RUN',I5)
    OPEN(UNIT=4,FILE='OUTPUT',STATUS='UNKNOWN')
    DO 60 J=1,17,2
    DO 50 I=1,IPOINT
        J=1

```

```

IF(RUN(I).LT.LSRUN.OR.RUN(I).GT.LERUN) GO TO 50
IF(PTO1(I).GT. 18.AND.PTO1(I).LT.28) TSAT= 259.29
IF(PTO1(I).GT. 18.AND.PTO1(I).LT.28) HFG= 939.2
IF(PTO1(I).GT. 32.AND.PTO1(I).LT.58) TSAT= 297.98
IF(PTO1(I).GT. 32.AND.PTO1(I).LT.58) HFG = 911.6
TWAV = (TEW(J,I)+TEW(J+1,I))/2
TSURF = TWAV- THICK*1E06*HFLX(I)/2/KW
TFLUID= TRTI1(I) + (TRTO1(I)-TRTI1(I))*(0.996-XL(J))/0.996
HTCOEF = (HFLX(I)*1E06)/(TSURF-TFLUID)
  IF(J.EQ.1)HT1 = HTCOEF
DTSAT = (TSURF-TSAT)
QUAL = (TFLUID- TSAT)/HFG
X = FTI1(I)
MDOT= X*62.4*60/7.48
AF = PIE*DIA(I)*DIA(I)/4/144
AH = PIE*DIA(I)*HL/144
C ***** SINGLE PHASE HEAT TRANSFER CALCULATION
  TAV= (TFLUID)
  KF = .305744 + .6944E-03*TAV -1.318E-06*TAV*TAV
  PR = 1/(-0.008255 + 0.002217*TFLUID +2.5384E-06*TFLUID*TFLUID)
  MUF = 0.00166546 -2.28734E-05*TAV + 1.49972E-07*TAV*TAV
1-5.06055E-10*TAV*TAV*TAV + 8.39295E-13*TAV*TAV*TAV*TAV
2-5.39307E-16*TAV*TAV*TAV*TAV*TAV
  TAV = TSURF
  MUS = 0.00166546 -2.28734E-05*TAV + 1.49972E-07*TAV*TAV
1-5.06055E-10*TAV*TAV*TAV + 8.39295E-13*TAV*TAV*TAV*TAV
2-5.39307E-16*TAV*TAV*TAV*TAV*TAV
  RE = 4*MDOT/3600/MUF/PIE/(DIA(I)/12)
  NU = HTCOEF*DIA(I)/KF/12
  NUSED = NU/((MUF/MUS)**0.14)/((PR)**0.33)
  QSAT = MDOT*CP*(TSAT-TRTI1(I))/AH/1.0E06
C  DPRATIO = DT1(I)/DPZERO
  QRATIO = HFLX(I)/QSAT
  HRATIO = HTCOEF/HT1
C  STANTON = HFLX(I)*1.0E06/(MDOT/AF)/CP/(TSAT-TRTO1(I))
C  PECLET = (MDOT/AF)*DIA(I)*CP/KF/12
C  WRITE(4,1200)RUN(I),DIA(I)
C  WRITE(4,1210)PTI1(I),PTO1(I),DT1(I),FTI1(I),
C  1TRTI1(I),TRTO1(I),PWRKW(I),QUAL(I)
C  DO 50 J=1,17,2
C  WRITE(4,1220)J,TEW(J,I),TEW(J+1,I)
  WRITE(4,1230)RUN(I),DT1(I),FTI1(I),DIA(I),PTO1(I),
1TRTI1(I),HFLX(I),QRATIO,TSURF,TFLUID,TWAV,
2HTCOEF,HRATIO,DTSAT,QUAL,XL(J),RE,NU,NUSED
49 CONTINUE
50 CONTINUE
60 CONTINUE
1200 FORMAT(1X,25X,'RUN =',F10.4,/25X,'DIAMETER=',F10.4)
1210 FORMAT(5X,'INLET PRESSURE =',F10.4,'PSIA',5X,
1'EXIT PRESSURE=',F10.4,'PSIA',/5X,'PRESSURE DROP=',
2F10.4,'PSI',5X,'INLET FLOWRATE=',F10.4,'GPM',/
35X,'INLET TEMPERATURE=',F10.4,'DEGF',5X,'OUTLET TEMPERATURE=',
4F10.4,'DEGF',/5X,'POWER=',F10.4,'KW',5X,'QUALITY=',F10.4,/
45X,'***** WALL TEMPERATURE *****')
1220 FORMAT(1X,I3,2F10.4)
.30 FORMAT(11F10.4,1E10.4,4F10.4,3E10.4)
  WRITE(*,1003)
1003 FORMAT(1X,'READ NEXT SET OF CASES')
  GO TO 36
END

```


C PROGRAM TO REDUCE SRL DATA

C ***** RDSRL4.FOR *****

C * PROGRAM TO REDUCE DATA FOR EARLY FORMAT DATA OUTPUT ****

C * Program is used to generate heat transfer data

C*

```

    DIMENSION RUN(500),PTI1(500),PTI2(500),PTO1(500),PTO2(500),
    1PTO3(500),DPT1(500),DPT2(500),DPT3(500),FTI1(500),FTI2(500),
    2FXO1(500),FXO2(500),FMO1(500),FMO2(500),OTI1(500),TRTI1(500),
    3TRTO1(500),TJTI1(500),TJXO1(500),TJTO1(500),TEW(18,500),
    4PWRKW(500),HFLX(500),DIA(500),HL(500),XL(18)
    REAL MDOT,KF,KW,NU,MUF,MUS,NUSED
    DATA XL/0.996,0.996,0.755,0.755,0.503,0.503,0.252,0.252,0.136,
    10.136,0.105,0.105,0.073,0.073,0.042,0.042,0.010,0.010/
    PIE = 3.14159
    CP = 1.0
    KF = .363
    KW = 132.
    THICK = 0.065
    FBI1 =0.0

```

C

C

```

    OPEN(UNIT=3,FILE='INPUT')

```

```

    I=1

```

```

10 READ(3,*,END=30)RUN(I),X1,PTI1(I),PTI2(I),PTO1(I),PTO2(I),
    1PTO3(I),DPT1(I)
    READ(3,*,END=30)DPT2(I),DPT3(I),FTI1(I),FTI2(I),FXO1(I),FXO2(I),
    2FMO1(I),FMO2(I)
    READ(3,*,END=30)OTI1(I),TRTI1(I),TRTO1(I),TJTI1(I),TJXO1(I),
    3TJTO1(I),X2,X3
    READ(3,*,END=30)TEW(1,I),TEW(2,I),TEW(3,I),TEW(4,I),TEW(5,I),
    4TEW(6,I),TEW(7,I),TEW(8,I)
    READ(3,*,END=30)TEW(9,I),TEW(10,I),TEW(11,I),
    5TEW(12,I),TEW(13,I),TEW(14,I),TEW(15,I),TEW(16,I)
    READ(3,*,END=30)TEW(17,I),TEW(18,I),PWRKW(I),HFLX(I),X4,
    6X5,X6,QUAL
    READ(3,*,END=30)X1,X2,X3,X4,X5,X6,X7,DIA(I)
    READ(3,*,END=30)HL(I),X12,X13,X14,X15,X16,X17,X18
    I=I+1
    IPOINT =I-1
    GO TO 10
30 WRITE(*,1000)
1000 FORMAT(1X,'INPUT DONE',//,1X,'INPUT DPZERO COEFFICIENTS',/,
    1'DPZERO = A0 + A1*X + A2*X*X')
35 READ(*,*)A0,A1,A2
    WRITE(*,1002)A0,A1,A2
1002 FORMAT(1X,'A0=',F10.4,/,1X,'A1=',F10.4,/,1X,'A2=',F10.4,
    1//1X,'READ IN RUN NUMBERS')
900 FORMAT(8F10.4)
36 READ(*,*)LSRUN,LERUN
    IF(LSRUN.LT.0.0) STOP
    WRITE(*,1001)LSRUN,LERUN
1001 FORMAT(1X,'START RUN',I5,5X,'STOP RUN',I5)
    OPEN(UNIT=4,FILE='OUTPUT',STATUS='UNKNOWN')
    DO 60 J=1,17,2
    DO 50 I=1,IPOINT
        DO 49 J=1,17,2
            IF(RUN(I).LT.LSRUN.OR.RUN(I).GT.LERUN) GO TO 50
            IF(PTO1(I).GT. 32.AND.PTO1(I).LT.38) TSAT= 259.29
            IF(PTO1(I).GT. 32.AND.PTO1(I).LT.38) HFG = 939.2

```

```

IF(PTO1(I).GT. 62.AND.PTO1(I).LT.68) TSAT= 297.98
IF(PTO1(I).GT. 62.AND.PTO1(I).LT.68) HFG = 911.6
TWAV = (TEW(J,I) +TEW(J+1,I))/2
TSURF = TWAV - THICK*1.0E06*HFLX(I)/2/KW
TFLUID = TRTI1(I) + (TRTO1(I)-TRTI1(I))*(0.996-XL(J))/0.996
HTCOEF = (HFLX(I)*1.0E06)/(TSURF-TFLUID)
  IF(J.EQ.1)HT1=HTCOEF
DTSAT = TSURF-TSAT
QUAL = (TFLUID-TSAT)*CP/HFG
X = FTI2(I)
MDOT= X*62.4*60/7.48
AF = PIE*DIA(I)*DIA(I)/4/144
AH = PIE*DIA(I)*HL(I)/144
C ***** HEAT TRANSFER CALCULATIONS
TAV = TFLUID
KF = 0.305744+0.6944E-03*TAV-1.318E-06*TAV*TAV
PR = 1/(-0.008255+0.002217*TAV+2.5384E-06*TAV*TAV)
MUF = 0.00166546 -2.28734E-05*TAV +1.49972E-07*TAV*TAV
1 -5.06055E-10*TAV*TAV*TAV +8.39295E-13*TAV*TAV*TAV*TAV
2 -5.39307E-16*TAV*TAV*TAV*TAV*TAV
TAV = TSURF
MUS = 0.00166546 -2.28734E-05*TAV +1.49972E-07*TAV*TAV
1 -5.06055E-10*TAV*TAV*TAV +8.39295E-13*TAV*TAV*TAV*TAV
2 -5.39307E-16*TAV*TAV*TAV*TAV*TAV
RE = 4*MDOT/3600/MUF/PIE/(DIA(I)/12)
NU = HTCOEF*DIA(I)/KF/12
  NUSED = NU/((MUF/MUS)**0.14)/((PR)**0.333)
HRATIO = HTCOEF/HT1
C DPZERO = A0 +A1*X + A2*X*X
QSAT = MDOT*CP*(TSAT-TRTI1(I))/AH/1.0E06
C DPRATIO = DPT1(I)/DPZERO
QRATIO = HFLX(I)/QSAT
C STANTON = (HFLX(I)*1.0E06)/(MDOT/AF)/CP/(TSAT-TRTO1(I))
C PECLET = (MDOT/AF)*DIA(I)*CP/KF/12
WRITE(4,1230)RUN(I),DPT1(I),FTI2(I),DIA(I),PTO1(I),
1TRTI1(I),HFLX(I),QRATIO,TSURF,TFLUID,TWAV,
2HTCOEF,HRATIO,DTSAT,QUAL,XL(J),RE,NU,NUSED
49 CONTINUE
50 CONTINUE
60 CONTINUE
1200 FORMAT(1X,25X,'RUN =',F10.4,/25X,'DIAMETER=',F10.4)
1210 FORMAT(5X,'INLET PRESSURE =',F10.4,'PSIA',5X,
1'EXIT PRESSURE=',F10.4,'PSIA',/5X,'PRESSURE DROP=',
2F10.4,'PSI',5X,'INLET FLOWRATE=',F10.4,'GPM',/
35X,'INLET TEMPERATURE=',F10.4,'DEGF',5X,'OUTLET TEMPERATURE=',
4F10.4,'DEGF',/5X,'POWER=',F10.4,'KW',5X,'QUALITY=',F10.4,/
45X,'***** WALL TEMPERATURE *****')
1220 FORMAT(1X,I3,2F10.4)
1230 FORMAT(11F10.4,1E10.4,4F10.4,3E10.4)
WRITE(*,1003)
1003 FORMAT(1X,'READ NEXT SET OF CASES')
GO TO 36
END

```

DATE

FILMED

10/7/94

END