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**NUCLEAR REACTOR TECHNOLOGY
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CU-HTRF-T3A

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**COLUMBIA UNIVERSITY FLOW INSTABILITY
EXPERIMENTAL PROGRAM, VOLUME 5**

**SINGLE ANNULUS TESTS, STEADY-STATE TEST
PROGRAM (U)**

by
T. DOUGHERTY, C. MACIUCA, E. V. MCASSEY, JR.,
D. G. REDDY, AND B. W. YANG

JULY, 1991

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Reviewing Official

SRTC

SAVANNAH RIVER TECHNOLOGY CENTER, AIKEN, SC 29808
Westinghouse Savannah River Corporation
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EXPERIMENTAL PROGRAM

Approvals

4/12/94

D. R. Muhlbaier, Responsible Manager Date:

4/6/94

A. J. Garrett, Level 3 Manager Date:

SRTC Perspective

D. A. Coutts

Senior Engineer

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

Columbia University in the City of New York | New York, N.Y. 10027-2399

ENGINEERING RESEARCH LABORATORIES
HEAT TRANSFER RESEARCH FACILITY

632 West 125th Street
212-280-4163
FAX: 212-678-5279

August 5, 1991

Ms. P.L. Walker
Westinghouse Savannah River Company
Building 773-55A
Aiken, SC 29808

Ref: Contract AX-721092, Report No. CU-HTRF-T3A.

Dear Ms. Walker,

Enclosed please find five copies of the Report No. CU-HTRF-T3A,
Part I - Technical Discussion and Part II - Data.

Sincerely,

Constantin Maciucă
HTRF - Senior Project Engineer

cc James Laurent - Pls advise WSRC evaluation.
John Thomas
Garrett
Dave Muhlbauer } FYI

DJK 8/7

**WESTINGHOUSE SAVANNAH RIVER COMPANY
FLOW EXCURSION EXPERIMENTAL PROGRAM**

**SINGLE ANNULUS TESTS
STEADY STATE TEST PROGRAM**

REPORT No. CU-HTRF-T3A

JULY 1991

PART I - Technical Discussion

PART II -DATA

**Heat Transfer Reseach Facility
Columbia University
New York City, NY**

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**WESTINGHOUSE SAVANNAH RIVER COMPANY
FLOW EXCURSION EXPERIMENTAL PROGRAM**

SINGLE ANNULUS TESTS

Steady State Test Program

SUBCONTRACT AX-721092

REPORT No. CU-HTRF-T3A

Part I Technical Discussion

**COLUMBIA UNIVERSITY
Heat Transfer Research Facility
Department of Chemical Engineering
New York, NY 10027**

Principal Investigators

**H. Y. Cheh
C. F. Fighetti**

Prepared by

**V. Carrano
S. Kokolis
C. Maciucă
E. V. McAssey Jr.
D. G. Reddy
B. W. Yang**

Prepared for

**Westinghouse Savannah River Company
Project Manager
Z. Qureshi**

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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 Mr. W. Hovemeyer for the design and maintenance of the electrical system and instrumentation; Mr. A. Kaam, and 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

This report presents results for the steady state portion of the finless single annulus test program. The objective of the experimental study was to investigate the onset of flow instability in an annular geometry similar to the MARK 22 reactor. The test program involved testing of both a finless or ribless heater and a ribbed heater. The latter program is currently underway and will be reported separately. For finless heater, testing was conducted in both a steady state and transient mode. The transient tests have been completed and will be reported in report no. CU-HTRF-T3B.

The present report presents steady state results for a series of experiments with uniform and asymmetric heating. The demand curves obtained under uniform heating yielded OFI flow-rates which were slightly below those obtained for a circular tube geometry with the same L/D ratio; however, the single annulus had a hydraulic diameter which was approximately fifty percent larger than the circular tube. The asymmetric heating cases were selected to provide the same average power input as the uniform cases. The results for these tests indicated that the flow-rate at OFI increased with the degree of asymmetry.

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1. BACKGROUND AND TEST OBJECTIVE

The single annulus test program was designed to provide data on flow excursions in a channel simulating coolant channel number 3 of the SRP Mark 22 assembly. This test was intended to study thermal and hydraulic response of a single annular channel under flow excursions in a test section comprised of a heated annulus and an exit restriction.

For the steady state phase of this program, the study encompassed the determination of the test section demand curves (pressure drop versus flow rate curves) for both controlled flow and parallel flow (controlled pressure drop) conditions. In controlled flow, the flow-rate to the test section was controlled directly. In parallel operation, the test section flow was adjusted by varying the total flow before the split between bypass and test section lines. In the latter mode of operation, flow diversion during flow instability can occur.

For the transient phase of the program, the loop was operated in a parallel mode with pressure and flow excursions as well as power ramp transients simulating reactor accidents imposed on the test section. For this test program, the objective was to determine the history of the channel pressure drop, the thermal response of the heater, and the flow-rate variation during the transient. This report will not present the transient results which will be presented in a separate report.

The test section for the single annulus test consisted of two Inconel 625 heater tubes. Downflow cooling water circulated in the annulus between the tubes. The exterior of the outer tube was insulated to minimize heat loss. Two heater designs, finless and finned, were developed. The initial finless test section used short insulated posts mounted on the inner heater surface to locate the heater. These posts maintained the test section geometry and provided electrical isolation between two heaters with minimum circumferential resistance. A second test section design used four axial ribs. These ribs are mounted on the outside of the inner heater. The ribs position the tubes and provide four longitudinal channels similar to those existing in the MARK 22 reactor. The rib material is electrically nonconducting and provides isolation between the heaters. The present report will be limited to the steady state finless heater results. A separate report will be issued at the completion of the ribbed

heater tests.

In both finless and finned designs, the heaters were heated electrically and were capable of producing a surface heat flux of 1×10^6 Btu/hr/ft². The inner and outer heaters were powered by two separated sets of generators operating in parallel. Each heater was controlled independently so that symmetric as well as asymmetric heating were feasible.

The heated length of both inner and outer heaters was 144 inches. All tests carried out in this portion of test program had a circular annulus with fixed length-to-diameter (L/D) ratio of 261. Upstream of the heated section was a 36-inch calming length. This length was a combination of copper and nickel to minimize the heat dissipation. Downstream of the heated section was a 33-inch length of nickel and copper followed by an exit restriction tube.

The single annulus test program involved testing at steady state and transient conditions. This report describes in detailed the test facility and instrumentation which are common to all phases of these tests, as well as presenting the steady state test results.

The special requirements of the transient test phase and the results from that phase will be reported separately.

2. DESCRIPTION OF TEST FACILITY

2.1 Introduction

The objective of this test program was to investigate the thermal and hydraulic response under flow excursion conditions in a single annular channel. This experimental program consisted of several phases of study which included controlled flow and parallel flow tests as well as transient testing in both finless (pinned) and finned single annulus heaters. The present report describes the controlled flow, and parallel flow in a finless heater.

2.2 Test Loop Facility Physical Description

2.2.1 Flow Loop Description

The HTRF's medium pressure loop was modified to provide the required flow-rates and pressure conditions. Figure 2.1 and 2.2 present a schematic of the flow loop. Two centrifugal pumps capable of producing approximately 800 gpm total were operated in parallel to provide the flow required under various operating conditions.

The test section is located between the inlet and exit plenums. The inlet plenum has two inlet ports and two or four exit ports. There are two inlet plenum designs. The first plenum is used for steady state testing which has two exit ports and one non-prototypical inlet port. One exit port connects directly to the test section. The other port connects to a bypass line. The bypass line is connected to the exit plenum and to the mixing tank. The direct bypass from the inlet plenum to the mixing tank is necessary because the heat exchanger located downstream of the exit plenum can not handle the maximum bypass flow.

Figure 2.1 shows a 3" bypass line located near the inlet to the upper plenum which exhausts directly into the mixing tank. This parallel line can be used as the second bypass line for bypass tests. This line not only enhances the mixing effect for a better temperature control but also provides a better pressure stabilizing flow near the inlet plenum during transient testing. As shown in the Figure 2.1, a 2" spray line between the inlet stream to the upper plenum and the lower plenum can be used as the third bypass flow line. With the valve in the spray bypass line fully open, it can

provide a two to one bypass ratio for an alternative parallel operation. The exit plenum is connected to a 100 gal surge tank through a 4" stand pipe. The surge tank services as a pressure buffer for exit pressure regulation.

The main flow stream leaving the exit plenum is directed to a plate type heat exchanger which has a heat transfer rating of 23.5 MBtu/hr. This was used as the primary device for removing energy from the system. Four additional shell and tube type heat exchangers were also used for auxiliary heat rejection. A 4" heat exchanger bypass line was installed to divert part of the exit plenum flow directly to the mixing tank.

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. Deionized and deaerated water was used. During the test the water quality was constantly monitored by routine sample testing on conductivity and dissolved oxygen levels.

Depending upon the mode of operation, the flow control was accomplished either by a motorized valve located upstream of the test section or by valves located in the bypass lines. The latter valves include one air-operated butterfly valve for gradual adjustment and one electrically operated quick acting valve for rapid transient flow control. When the second or third bypass line was used for parallel operation, there was one air-operated butterfly valve on each bypass line for gradual adjustment for desired bypass ratio condition. The test section inlet temperature was controlled by adjusting the loop external heat rejection rate. The air operated valve on the secondary side (cooling water line) of the plate heat exchanger was used as the primary temperature control unit. A Bristol microprocessor-based expert controller was used to regulate the control valve for temperature control. An air operated valve was also used in the heat exchanger bypass line as an auxiliary temperature control unit.

The system pressure is maintained by adjusting the liquid level and by varying the helium blanket pressure in the surge tank as well as in the mixing tank. During steady state operation, the exit plenum pressure was controlled by regulating the water inventory through the 10 HP water make-up pump as well as the water and air bleed valves which consist series of 1/4" and 1/2" bleed valves on the bottom and top of the mixing tank.

2.2.2 Test Section Description

The annular test section is composed of two inconel 625 tubes. The total heated length of each tube is 144 inches. The outside diameter of the inner tube is 2.347 inches and the inside diameter of the outer tube is 2.899 inches. The wall thickness of both tubes is 0.065 inches. Each tube is capable of producing a thermal flux of 10^6 Btu/hr-ft² independently.

Two types of annular test sections were investigated. The first test section is a simple annulus with the inner and outer tubes separated by insulated pins. The size and number of pins have been selected to minimize the disturbance to the flow. At the initial stage of this test program, in order to minimize the thermal and hydraulic effects, there were no pins in the last third of the heated test section. Five sets of pins (total 20 pins) at four axial locations on the inner heater was initially used to maintain the annulus geometry. Due to the vigorous vibration during testing, additional pins were added to the inner heater, and then to the outer heater to overcome the difficulty of maintaining the test section geometry. The pins and the insulation caps were fixed and modified four times during the test operation (see Figure 2.3). Although the total pressure drop increased slightly due to the additional pins, there was no effect observed on the minimum points of the pressure drop demand curves. The second annulus is divided into four quadrants by axial fins mounted on the inner tube. These fins also provide electrical isolation between the inner and outer heater tubes.

Upstream and downstream of the heated section are 36 and 33 inch calming lengths respectively. On the outer heater tube, these calming length sections are composed of copper and nickel. The copper sections are used to connect the heater tubes to the electrical power system. Nickel is used to provide a connection to the inconel test section. The exterior of the outer heater was instrumented with thermocouples for temperature measurement and then insulated to minimize the heat loss. On the inner heater tube, the nickel section is continued for the entire distance of the calming length. This was necessary to provide a mounting surface for the fins. At the end of these two nickel sections, the inner tube is continued by two sections of copper pieces with lengths of 50 and 51 inches connected to the upstream

and downstream of these two calming length nickel pieces. The copper sections extended through the inlet and exit plenums and were used for electrical system connection.

2.2.3 Test Section Power Supply

The HTRF electrical system has been modified to meet the power load and time dependent histories required for this single annulus test program (see Figure 2.4). Power for the inner and outer heaters were provided by four General Electric DC generators which can each provide 6000 amp and 240 volts continuously. These generators are part of motor-generator sets. The motors of which are directly fed by 13,000 volt feeders. In order to achieve the heat flux required, the inner and outer tubes conduct different currents and have separately applied voltages. This requires splitting of the four DC generators into two independent groups of two generators. Each heater was powered by a set of two generators operating in parallel.

The generator fields are excited by a pair of custom designed SCR power supplies which were fed from a less than 0.5% voltage regulator. The SCR power supplies are phase angle controlled with a potentiometer used to vary the output voltage from zero to maximum. These power supplies in turn provide the field currents for the generators, and thus the terminal voltages. Power is delivered from the generator terminal to the heaters via water-cooled copper piping. From the piping, a connection is made to the heaters with flexible copper braid.

For steady state operation, the operator closes the DC breakers and adjusts the potentiometers on the generator console until the desired heat flux is obtained.

The transient part of the program required a special control system for the generators. An alteration of the generator field excitation circuits was necessary to obtain the power decay profile. A timing circuit was built which initiated the flow transient upon activation by the operator, and activates the changes in excitation to produce the three stages of the power decay. The first and last stages, which involved a relatively mild decay, were realized by a change in the phase angle control of the SCR circuits. The middle stage, which involved a steep decay, required altering the generators' inherent time constants, enabling the terminal

voltages to drop quickly. Care was taken to protect the generator during this phase of operation as very high induced voltages occur.

The DC breaker interlock system trips all the DC breakers if a trouble signal occurs, such as from the under-flow or thermocouple triggers. There is also an AC interlock system and a network of warning lights, all of which insure the maximum possible protection of equipment and personnel.

The electrical characteristics of the heater tubes are:

	<u>Inner Tube</u>	<u>Outer Tube</u>
Resistance	0.01685 ohms	0.01306 ohms
Current	11,335 amps	14,000 amps
Voltage	191 volts	183 volts

The control system has been designed to accommodate separate control circuits which can supply two different excitations to the generator fields. The inputs were programmed independently to accommodate the separation of the generators. The resulting characteristics are controlled during transients by variations designed into the function generators.

Instrumentation was provided to monitor the performance of the flow loop, the electrical system, and the test section. Loop instrumentation was used primarily to operate the loop and establish the test section conditions. The test section instrumentation provided the required test data, namely: pressure drop; test section inlet and outlet temperature; test flow-rate; and tube wall temperature. Prior to installation in the test section each instrument was calibrated. In addition, those instruments which provide data necessary for test data analysis have also been calibrated to an NIST standard. Instruments which were used as backup to check functioning of a primary instrument or which were required for loop operation were calibrated but might not be traceable to an NIST standard.

The instrument response time was one of the most important criteria used to select the instrumentation for the transient portion of the test program. The complete transient lasts 15 seconds for both flow and power transients. However, most of the significant events occurring within the duration between the beginning

of flow transient and the beginning of the power transient which is about 10 seconds. The loop instrumentation and test section instrumentation have been selected to provide time constants on the order of 0.1 seconds.

2.3. Test Matrix

The test matrix (Table 2.1) provides two types of test conditions:

- a) steady state operation with controlled flow to the test section.
- b) steady state operation with a bypass flow in parallel to test section. This is referred to as the constant pressure condition.

Case (a) provides the demand curve data through the flow instability point. Case (b) provides data related to parallel flow instability study which has conditions more closely simulating actual reactor operation. Case (b) is a potentially more dangerous experiment because the possibility of loss of coolant to the test section exists. For both cases (a) and (b), two inlet pressure conditions were investigated. The pressures correspond to conditions before and after the pressure transient.

2.4. Test Loop Operating Procedure

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

- 1) open all loop internal valves and close all external valves.
- 2) at the highest point in the system, a vacuum pump is connected and system pressure is reduced to approximately 22" Hg vacuum.
- 3) at the lowest point, the mixing tank, deionized water is added to system until water reaches the vacuum pump.

Table 2.1 Test Conditions for the Single Annulus Experiments

A. STEADY STATE OPERATION WITH CONTROLLED FLOW

A1. Symmetric heat flux

Test No	Flux Inner heater BTU/hr-ft ²	Flux Outer heater BTU/hr-ft ²	Temp. inlet °C	Pressure exit pig
1	0.0	0.0	25	50
2	0.0	0.0	50	50
3	0.0	0.0	80	50
4	200,000	200,000	25	50
5	400,000	400,000	25	50
6	400,000	400,000	50	50
7	400,000	400,000	25	20
8	400,000	400,000	50	20
9	200,000	200,000		25.3
10	600,000	600,000	25	50
11	800,000	800,000	50	50

A2. Asymmetric heat flux

12	446,400	0.0	25	50
13	892,800	0.0	25	50
14	0.0	362,300	25	50
15	0.0	724,600	25	50
16	276,000	138,000	25	50
17	552,000	276,000	25	50

B. STEADY STATE OPERATION WITH PARALLEL FLOW

Spray line bypass ratio 3:2

18	0.0	0.0	25	50
19	200,000	200,000	25	50
20	400,000	400,000	50	50

- 4) system bleed valves are opened selectively to remove any remaining air.
- 5) system is pressurized to 100 psia and a leak check is performed.
- 6) pumps are energized and the flow-rate is established to check for flow switch operation.
- 7) loop operating pressures and temperatures will be established and maintained for 10 minutes to insure satisfactory operation of loop controls.

At the satisfactory conclusion of the above procedure the loop was certified for operation.

During a test, loop parameters were recorded in a test log as well as by the data acquisition system.

For both controlled flow and parallel flow testings, the flow-rate to the test section was established at a high enough level to insure single phase conditions. The test parameters were then set as required by the test matrix.

When the test conditions satisfied the above criteria, the data were recorded and assigned a run number. The flow-rate was then reduced and the loop parameters were adjusted to maintain the required conditions. After steady state was achieved the run was recorded. The process was repeated until OFI was established. The criterion for OFI for both controlled flow and parallel operations was defined as the minimum point in the pressure drop demand curve.

For the controlled flow test, a few points were obtained beyond the minimum to insure that OFI had been established. For the parallel flow test, it is more difficult to establish the OFI point. During parallel flow testing, the flow-rate is reduced to a value as close as possible to the OFI flow-rate determined under controlled flow conditions. This value is then defined as the parallel flow OFI flow-rate.

Figure 2.1

Figure 2.2

LEGEND:

- GEN** - DC GENERATOR, GENERAL ELECTRIC 6,000 A, 240V, SEPARATELY EXCITED.
- V** - VOLTMETER, DIGITAL, 0-300 V.
- A** - AMMETER, SIMPSON, 0-50 MILLIVOLTS. 0-100/10,000/15,000 AMP.
- SHUNT** - SHUNT, 0-50 MV, 0-10,000/15,000 AMP.
- FIELD SHUNT** - FIELD SHUNT, 0-50 MV, 0-100 AMP.
- SCR EXC** - SCR EXCITER.

NOTES:

ITEMS IN PARENTHESES DENOTE LOCATION:

(III) - TASK III TEST AREA.

(MG) - MOTOR GENERATOR ROOM.

(CRP) - SHOP CONTROL ROOM PANEL.

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CHEMICAL ENGINEERING RESEARCH LAB			
PROJECT NO.	DUPONT-TASK III	DATE	N.T.S.
SCALE	0.005	PROJECTED	1/64
TASK III			
OVERALL ELECTRICAL SCHEMATIC			
DATE	02-01-63	CP2-T3-TN-3	

Figure 2.4

3. INSTRUMENTATION AND DATA ACQUISITION

3.1 Instrumentation

3.1.1 Instrumentation Philosophy

Loop instrumentation consists of nine pressure transducers, six differential pressure transducers, five turbine flowmeters, one orifice flowmeter, and three 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 on-site mass balance cross checking can be conducted among 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. In the case of parallel tests and transient operations, the bypass line pressure drop and flow-rate were also monitored. All primary measurements were accomplished through two or more redundant instruments.

The test section volumetric flow-rate was measured by the turbine flowmeter (FI1) provided by Hoffer Flow Controls Inc. 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-up 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. The flowmeter located at the inlet to the inlet plenum was checked regularly with loop flowmeter FP1 (Flow Technology turbine flowmeter) and the heat exchanger flowmeter FXO1 (Hoffer turbine flowmeter). As shown in Figure 2.1, during the parallel operation, the test section flow rate was also cross checked with the bypass line flowmeters FB1, FB2, or FB3 (Hoffer turbine flowmeters) and DO1 (orifice flowmeter). When the two inch spray line was used as the bypass line for parallel flow tests, the test section flow rate was measured using the test section flowmeter FI1. This reading was cross checked by the difference between the heat exchanger flowmeter FXO1 and the bypass flowmeter FB1 or by the difference between the loop overall flowmeter FP1 and the

bypass line flowmeter FB1. When the mixing bypass line (3 inches) was used for bypass flow in the parallel operation, the test section flowrate was measured by FI1, and it was cross checked by the heat exchanger flowmeter FXO1 as well as the difference between the overall loop flowmeter FP1 and the bypass flowmeter FB2. However, in cases of parallel flow testing using the plenum bypass line (4 inches) for bypass flow, the test section flowrate measurement was accomplished either by calculating the difference between the overall flow measurement (FI1 or FP1) and the bypass flowmeter FB3 or by the heat exchanger flowmeter FXO1 while the exit plenum bypass valve V20 was closed.

Test section pressure was monitored by two Sensotec strain gage pressure transducers, model TJE, at both inlet (PTI1) and exit (PTO1) locations. Transducers were mounted on the outer heater copper end pieces 1.75 inches away from the top and bottom of the outer heater. The transducers feature fast response (microsecond rise time), high accuracy (0.1%), shock resistance and long term stability. In addition, one calibrated Heise gage (PTO2) was mounted on the outer heater 180 degrees opposite the outlet pressure transducer (PTO1). This pressure gage as well as another Sensotec pressure transducer (PTO3) mounted on the top of the bottom plenum were used to cross check the exit pressure measurement. In parallel with the inlet pressure transducer (PTI1), there was also a calibrated Heise gage (PTI2) mounted on the top of the inlet plenum to check the inlet pressure measured by the inlet pressure transducer PTI1.

The pressure drop across the test section was measured using two strain gage diaphragm differential pressure transducers provided by Sensotec and T-HYDRONICS. Both of these two transducers 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 a hydrostatic head correction. In addition, the reading was also confirmed with the manometer measurement obtained from the same pressure lines.

Power to the test section was calculated from the measured current and voltage applied to the inner and the outer heaters. The current to the inner and outer heater was measured separately by two calibrated shunts. The current measurement was consistently checked by the total generators' current measured

through four separated shunts for the four generators. The test section voltage was measured through the data acquisition system using a calibrated voltage divider setup. Both the inner and outer heater voltage measurements were performed between the two ends of the heater as well as between the buses. 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 J calibration (iron-constantan) thermocouples and resistance temperature detectors (RTD). The inlet and exit fluid temperatures of the test section were measured by four platinum RTD's provided by Weed Instrument Company and Conax Company. The primary inlet and outlet fluid temperatures were measured using two high precision and fast response (0.5 seconds at 20 ft/sec water flow rate) Weed RTDs model 4001DT. In addition, two high accuracy RTDs (Weed RTD for inlet and Conax RTD for exit) were used as backup instrument to check the temperature measured by the primary RTDs at steady state conditions. While both inlet and outlet RTDs were located in the inlet and outlet plenums, two additional fast response exposed-type thermocouples were installed on the outer heater bottom orifice tee (see figure 3.1) to measure the exit temperature during transient operation. Assembly drawing number SR-2-T3-600-1 shows the exact location of the fluid temperature measurements.

3.1.2 Test Section Instrumentation Layout

The basic instrumentation philosophy for the test section was to make all measurements by non-intrusive devices to avoid any flow disturbance. Based on this approach, all test section measurements (such as wall temperature, test section voltage and current) were performed only through the sensors attached to the exterior of the outer heater and the inside wall of the inner heater.

A total of eight fast response 40 mil type E thermocouples were brazed directly to the bottom section of the outer and inner heaters. These thermocouples were used as burn-out protection devices. Considering the possible local hot spot caused by the residual braze material around the thermocouples, the data obtained by these brazed thermocouples should not be used for thermal analysis.

For more accurate data reduction, heater wall temperature measurement were obtained by the thermocouples directly cemented to the heater wall. The cold junctions for these thermocouples were connected to a reference box where the reference temperature was constantly monitored. For the finless heaters, total 31 thermocouples were applied to the exterior of the outer heater and 29 thermocouples were used in the inside of the inner heater to measure the heater walls temperature (see Figure 3.2). On the outer heater, thermocouples were cemented directly to the outside heater wall by an alumina oxide type of high thermal conductive cement, which not only provided good temperature response but also prevented any possible local hot spot due to any residual electrically conductive material. On the inner heater, thermocouples were spring-loaded against the inside of the heater wall and were mounted onto a ceramic thermocouple holder. As shown on the Figure 3.3, this ceramic holder was supported and located inside a ceramic block.

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 for both inner and outer heaters. About 60 percent of thermocouples were installed in the bottom 30 percent of the heater length. All heater wall thermocouples were grouped into 15 pairs and installed at 12 elevations on the inside of the inner heater as well as on the exterior of the outer heater. Figure 3.2 shows the detailed thermocouple locations. For each thermocouple on the inner heater, there was a corresponding thermocouple located at the similar location on the outer heater. At the first 72 inches portion of the heaters, two thermocouples were located every two feet along the test section. In the exit region of the test section, the density of thermocouples was increased.

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 3.4 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. Accounting for the scanning and the calculations, these readings represent approximately a five second average. 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. Inner wall temperatures of the test section
8. Outside wall temperatures of the test section
9. Heat flux, power, voltage, quality, and heat ratio.

3.2.3 Description of Data Files

Appendix A presents the format of the data files for steady state controlled flow as well as parallel tests.

REV	DATE	BY	APP
1	10-12-39	DP-2-T3-100-15	
2	10-12-39	DP-2-T3-100-15	
3	10-12-39	DP-2-T3-100-15	
4	10-12-39	DP-2-T3-100-15	
5	10-12-39	DP-2-T3-100-15	
6	10-12-39	DP-2-T3-100-15	
7	10-12-39	DP-2-T3-100-15	
8	10-12-39	DP-2-T3-100-15	
9	10-12-39	DP-2-T3-100-15	
10	10-12-39	DP-2-T3-100-15

Figure 3.1

COLUMBIA UNIVERSITY CHEMICAL ENGINEERING RESEARCH			
ORIGINAL	DUPONT-38	SCALE	GRADE BY A J
1 .005	TASK 3	1/1	APPROVED BY
FRACTIONAL	ORIFICE TEE		
1 1/10	DATE	DESIGN NUMBER	REV
1 0 3/4	10-12-39	DP-2-T3-100-15	2

Figure 3.2

SRL SINGLE ANNULUS TEST SECTION INSTRUMENT ARRANGEMENT
 TEST NO.: SA-1 TUBE NO.: 3010-001
 MATERIAL: Inconel 625

INNER HEATER ID: 2.217"

OD: 2.347"

OUTER HEATER ID: 2.899"

OD: 3.028"

Figure 3.3

FIGURE 3.4 High Speed Computer Controlled Data Acquisition System

Table 3.1

INSTRUMENTATION LIST - SINGLE ANNULUS STEADY STATE TESTS

INSTRUMENT (SYMBOL)	TYPE OF SENSOR	MANUFACTURER	LOCATION
Volt BB (VBI)	Voltage		bus to bus voltage (inner heater)
Volt TS (VTI)*	Voltage		test section voltage (inner heater)
Curr TS (ITI)*	Current (shunt)		inner heater
Volt BB (VBO)	Voltage		bus to bus voltage (outer heater)
Volt TS (VTO)*	Voltage		test section voltage (outer heater)
Curr TS (ITO)*	Current (shunt)		outer heater
Curr 1 (I1)	Current (shunt)		#1 generator
Curr 2 (I2)	Current (shunt)		#2 generator
Curr 3 (I3)	Current (shunt)		#3 generator
Curr 4 (I4)	Current (shunt)		#4 generator
PT11*	Absolute pressure transducer	SENSOTEC	Inlet of test section
PT12	Pressure gage	HEISE	top of inlet plenum
PTO1*	Absolute pressure transducer	SENSOTEC	outlet of test section
PTO2	Pressure gage	HEISE	outlet of test section
PTO3	Absolute pressure transducer	SENSOTEC	top of bottom plenum
PM1	Absolute pressure transducer	SENSOTEC	mixing tank
PXO1	Absolute pressure transducer	SENSOTEC	outlet of H.E.
PP11	Absolute pressure transducer	SENSOTEC	Inlet to pump
PPO1	Absolute pressure transducer	SENSOTEC	outlet of pump
PB1	Absolute pressure transducer	SENSOTEC	transient bypass line (4")
PS1	Absolute pressure transducer	SENSOTEC	stand pipe (4")
DT1*	Differential pressure transducer	T-HYDRONICS	test section pressure drop
DT2	Differential pressure transducer	T-HYDRONICS	test section pressure drop
DTO1	Differential pressure transducer	T-HYDRONICS	DP - bottom restriction
DO1	Differential pressure transducer	SENSOTEC	DP - transient bypass line orifice
DX1	Differential pressure transducer	SENSOTEC	DP-heat exchanger to mixing tank
DI1	Differential pressure transducer	SENSOTEC	DP- Inlet line to inlet plenum
DB1	Differential pressure transducer	SENSOTEC	2" bypass line (to bottom plenum)
DB2	Differential pressure transducer	T-HYDRONICS	3" bypass line (to mixing tank)
DB3	Differential pressure transducer	T-HYDRONICS	DP at transient bypass line
DP1	Differential pressure transducer	T-HYDRONICS	DP - Pump
DT3	Manometer	MERIAM	DP of test section
FP1	Turbine flowmeter	Flow Technology	pump outlet (3")
FI1*	Turbine flowmeter	Hoffer	Inlet to TS (3")
FB1	Turbine flowmeter	Hoffer	bypass to bottom plenum (2")
FB2	Turbine flowmeter	Hoffer	bypass to mixing tank (3")
FB3	Turbine flowmeter	Hoffer	transient bypass (3")
FXO1	Turbine flowmeter	Hoffer	H.E. outlet (3")

INSTRUMENTATION LIST

page 2

INSTRUMENT (SYMBOL)	TYPE OF SENSOR	MANUFACTURER	LOCATION
RTI1*	Resistance temperature detector	Weed	temp. at Inlet plenum
RTI2	Resistance temperature detector	Weed	temp. at Inlet plenum
RTO1*	Resistance temperature detector	Weed	temp. at bottom plenum
RTO2	Resistance temperature detector	CONAX	temp. at bottom plenum
ETO1	type E thermocouple	CONAX	temp. at exit of TS (subchannel)
ETO2	type E thermocouple	CONAX	temp. at exit of TS (subchannel)
EEO1	type E thermocouple	CONAX	exit of bottom plenum
EXO1	type E thermocouple	CONAX	exit of heat exchanger
EM1	type E thermocouple	CONAX	mixing tank
RR1	Resistance temperature detector	KAYE	Reference box #1
RR2	Resistance temperature detector	KAYE	Reference box #2
RR3	Resistance temperature detector	KAYE	Reference box #3
IEW141.5SW	grounded E thermocouple	CGS	Inner heater-141.5" from top (SW)
IEW141.5NW	**grounded E thermocouple	CGS	Inner heater-141.5" from top (NW)
IEW141.5N	grounded E thermocouple	CGS	Inner heater-141.5" from top (N)
IEW138SE	grounded E thermocouple	CGS	Inner heater- 138" from top (SE)
IEW132NW	grounded E thermocouple	CGS	Inner heater- 132" from top (NW)
IEW143NW	ungrounded E thermocouple	CGS	Inner heater- 143" from top (NW)
IEW143SE	ungrounded E thermocouple	CGS	Inner heater- 143" from top (SE)
IEW132SE	ungrounded E thermocouple	CGS	Inner heater- 132" from top (SE)
IEW120SW	ungrounded E thermocouple	CGS	Inner heater- 120" from top (SW)
IEW120NW	ungrounded E thermocouple	CGS	Inner heater- 120" from top (NW)
IEW120N	ungrounded E thermocouple	CGS	Inner heater- 120" from top (N)
IEW120SE	ungrounded E thermocouple	CGS	Inner heater- 120" from top (SE)
IEW108NW	ungrounded E thermocouple	CGS	Inner heater- 108" from top (NW)
IEW108SE	ungrounded E thermocouple	CGS	Inner heater- 108" from top (SE)
IEW096NW	ungrounded E thermocouple	CGS	Inner heater- 96" from top (NW)
IEW096SE	ungrounded E thermocouple	CGS	Inner heater- 96" from top (SE)
IEW084NW	ungrounded E thermocouple	CGS	Inner heater- 84" from top (NW)
IEW084SE	ungrounded E thermocouple	CGS	Inner heater- 84" from top (SE)
IEW072SW	ungrounded E thermocouple	CGS	Inner heater- 72" from top (SW)
IEW072NW	ungrounded E thermocouple	CGS	Inner heater- 72" from top (NW)
IEW072N	ungrounded E thermocouple	CGS	Inner heater- 72" from top (N)
IEW072NE	ungrounded E thermocouple	CGS	Inner heater- 72" from top (NE)
IEW072SE	ungrounded E thermocouple	CGS	Inner heater- 72" from top (SE)
IEW072S	ungrounded E thermocouple	CGS	Inner heater- 72" from top (S)
IEW048NW	ungrounded E thermocouple	CGS	Inner heater- 48" from top (NW)
IEW048SE	ungrounded E thermocouple	CGS	Inner heater- 48" from top (SE)
IEW024SW	ungrounded E thermocouple	CGS	Inner heater- 24" from top (SW)
IEW024NW	ungrounded E thermocouple	CGS	Inner heater- 24" from top (NW)
IEW024N	ungrounded E thermocouple	CGS	Inner heater- 24" from top (N)
IEW024SE	ungrounded E thermocouple	CGS	Inner heater- 24" from top (SE)

INSTRUMENTATION LIST

page 3

INSTRUMENT (SYMBOL)	TYPE OF SENSOR	MANUFACTURER	LOCATION
OEW143NE	**grounded E thermocouple	CGS	outer heater- 143" from top (NE)
OEW141.5SW	**grounded E thermocouple	CGS	outer heater- 141.5" from top (SW)
OEW140N	**grounded E thermocouple	CGS	outer heater- 140" from top (N)
OEW138NE	**grounded E thermocouple	CGS	outer heater- 138" from top (NE)
OEW132SW	**grounded E thermocouple	CGS	outer heater- 132" from top (SW)
OEW078NE	**grounded E thermocouple	CGS	outer heater- 78" from top (NE)
OEW006NE	**grounded E thermocouple	CGS	outer heater- 6" from top (NE)
OEW143NW	ungrounded E thermocouple	CGS	outer heater- 143" from top (NW)
OEW143SE	ungrounded E thermocouple	CGS	outer heater- 143" from top (SE)
OEW141.5NW	ungrounded E thermocouple	CGS	outer heater- 141.5" from top (NW)
OEW141.5SE	ungrounded E thermocouple	CGS	outer heater- 141.5" from top (SE)
OEW138NW	ungrounded E thermocouple	CGS	outer heater- 138" from top (NW)
OEW138SE	ungrounded E thermocouple	CGS	outer heater- 138" from top (SE)
OEW132NW	ungrounded E thermocouple	CGS	outer heater- 132" from top (NW)
OEW132SE	ungrounded E thermocouple	CGS	outer heater- 132" from top (SE)
OEW120SW	ungrounded E thermocouple	CGS	outer heater- 120" from top (SW)
OEW120NW	ungrounded E thermocouple	CGS	outer heater- 120" from top (NW)
OEW120N	ungrounded E thermocouple	CGS	outer heater- 120" from top (N)
OEW120SE	ungrounded E thermocouple	CGS	outer heater- 120" from top (SE)
OEW108NW	ungrounded E thermocouple	CGS	outer heater- 108" from top (NW)
OEW108SE	ungrounded E thermocouple	CGS	outer heater- 108" from top (SE)
OEW096NW	ungrounded E thermocouple	CGS	outer heater- 96" from top (NW)
OEW096SE	ungrounded E thermocouple	CGS	outer heater- 96" from top (SE)
OEW084NW	ungrounded E thermocouple	CGS	outer heater- 84" from top (NW)
OEW084SE	ungrounded E thermocouple	CGS	outer heater- 84" from top (SE)
OEW072SW	ungrounded E thermocouple	CGS	outer heater- 72" from top (SW)
OEW072NW	ungrounded E thermocouple	CGS	outer heater- 72" from top (NW)
OEW072N	ungrounded E thermocouple	CGS	outer heater- 72" from top (N)
OEW072SE	ungrounded E thermocouple	CGS	outer heater- 72" from top (SE)
OEW072S	ungrounded E thermocouple	CGS	outer heater- 72" from top (S)
OEW048NW	ungrounded E thermocouple	CGS	outer heater- 48" from top (NW)
OEWC48SE	ungrounded E thermocouple	CGS	outer heater- 48" from top (SE)
OEW024SW	ungrounded E thermocouple	CGS	outer heater- 24" from top (SW)
OEW024NW	ungrounded E thermocouple	CGS	outer heater- 24" from top (NW)
OEW024N	ungrounded E thermocouple	CGS	outer heater- 24" from top (N)
OEW024SE	ungrounded E thermocouple	CGS	outer heater- 24" from top (SE)
OEW001NW	ungrounded E thermocouple	CGS	outer heater- 1" from top (NW)
OEW001SE	ungrounded E thermocouple	CGS	outer heater- 1" from top (SE)

*Primary Instrument

**Brazed thermocouple

TABLE 3-2. DATA ACQUISITION SYSTEM SPECIFICATIONS

Number of Inputs	192 (twelve 16-channel differential input, high level multiplexercards
Input Circuit	Floated and guarded signal pair for each channel.
Noise Rejection	80db up to 1 KOhm source unbalanced, 105db 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(LSB) = 5mV.
Resolution for Voltage Measurement	12 bit including sign, 100nV at 1000V range.
Analog-to-Digital Conversion Rate Rejection	45Kz minimum with Direct Memory Access.

4. ERROR AND UNCERTAINTY ANALYSIS

4.1 Instrumentation Accuracy

The errors attributed to 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 1.75 inches away from the top and bottom of the heater. This causes a 1.75 inches (or 0.06 psi) hydrostatic head correction for the absolute pressure transducer on each end of heater. To account for this additional tube length (147.5 inches instead of 144 inches), the pressure drop measurements at steady state require a correction of approximately 2.2%.

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 outer heater and the inside of the inner heater to eliminate any flow disturbance. A high thermal conductivity 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 Uncertainties

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 an NIST standard but may not have traceability certification.

The uncertainties associated with the instruments have been summarized in the following sections. 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. These uncertainties stated by the manufacturer were based on percentage of reading. The Anadex frequency to DV converters were also calibrated and an in position check was performed daily. The average uncertainty of the Anadex frequency converters is about 0.03% of reading, which is negligible as compared to other uncertainties.

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 is only 0.0025% F.S./ $^{\circ}\text{F}$ 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 Uncertainties

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 eight parts to corresponding to eight types of measurements for primary instruments. The uncertainties included are in:

1. Absolute pressure measurement using pressure transducer.
2. Differential pressure measurement using pressure transducer.
3. Temperature measurement using RTD.
4. Temperature measurement using thermocouple.
5. Flow rate using turbine flow meter.
6. Voltage measurement.
7. Current measurement.
8. Test section dimension 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:

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

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 be 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 uncertainty in pressure measured by the 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) Uncertainty in the line from the source to the multiplexer digitizer. This was measured to be 0.304% of the reading.
- c) Uncertainty in the multiplexer digitizer (0.005 V).

The following table presents the uncertainty in absolute pressure measurement:

Abs. Pres. Psi	Signal Voltage volt	Instrument Uncertainty psi	Line Uncertainty psi	Digitizer Uncertainty psi	Total Uncertainty 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 uncertainty 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. The full scale of the differential pressure transducers was 60 psi for the tests with high flow rate and high pressure drop (over 20 psi). However, for the tests with low flow rate, low pressure drop (less than 20 psi), the transducers with full scale of 20 psi were used to obtain higher accuracy.
- b) Uncertainty in the line from the source to the multiplexer digitizer measured to be 0.304% of the signal.
- c) Uncertainty 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 Uncertainty Psi	Line Uncertainty Psi	Digitizing Uncertainty Psi	Total Uncertainty Psi
60	5.00	0.067	0.182	0.060	0.20

45	3.75	0.067	0.137	0.060	0.16
30	2.50	0.067	0.091	0.060	0.13
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 RTD Temperature Measurement

Total uncertainty in temperature measured by RTD consists of:

- Accuracy of the instrument and Rosemont bridge stated by the manufacturer as 0.25 °F.
- Uncertainty in the line from the Rosemont bridge to the multiplexer digitizer measured to be 0.005% of the reading.
- Uncertainty in the mutiplexer digitizer (0.005 V).

The following table presents the uncertainty in RTD temperature measurement:

Temp °F	Signal Voltage Volts	Instrument Uncertainty °F	Line Uncertainty °F	Digitizing Uncertainty °F	Total Uncertainty °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 Thermocouple Temperature Measurement

Total uncertainty in temperature measured by thermocouple consists of:

- Accuracy of the instrument stated by the manufacturer as 1.8 °F or 0.4% of reading.
- Uncertainty in the line from the thermocouple to the reference box and from the reference box to the multiplexer digitizer measured to be 0.01% of the reading.
- Uncertainty in the reference box (1.0 °F).
- Uncertainty in the mutiplexer digitizer (0.005 V).

The following table presents the uncertainty in thermocouple temperature measurement:

Temp °F	Instrument Uncertainty °F	Line Uncertainty °F	Reference box Uncertainty °F	Digitizing Uncertainty °F	Total Uncertainty °F
70	1.8	0.01	1.0	0.5	2.1
100	1.8	0.01	1.0	0.5	2.1
200	1.8	0.02	1.0	0.5	2.1
300	1.8	0.03	1.0	0.5	2.1
400	1.8	0.04	1.0	0.5	2.1
500	2.0	0.05	1.0	0.5	2.3
600	2.4	0.06	1.0	0.5	2.7
700	2.8	0.07	1.0	0.5	3.0

4.2.5 Uncertainty in Flowrate Using the Turbine Flow Meter

Total uncertainty in flow rate measured by the turbine flow meter consists of:

- a) Accuracy of the instrument stated by the manufacturer as 0.51% of reading.
- b) Accuracy of the Anadex frequency converter is 0.032% of reading.
- c) Uncertainty in the line from the Anadex output to the multiplexer digitizer measured to be 0.20% of the reading.
- d) Uncertainty in the mutiplexer digitizer (0.005 V).

The following table presents the uncertainty in flow rate measurement:

Flow Rate GPM	Signal Voltage Volts	Instrument Uncertainty GPM	Line Uncertainty GPM	Digitizing Uncertainty GPM	Total Uncertainty GPM
300	3.01	1.53	0.6	0.50	1.71
200	2.01	1.00	0.4	0.50	1.19
100	1.01	0.51	0.2	0.50	0.74
50	0.50	0.26	0.1	0.50	0.57
25	0.25	0.13	0.05	0.50	0.52

4.2.6 Uncertainty in Test Section Voltage Measurement

Total uncertainty in test section voltage measurement consists of:

- a) Accuracy of the voltage divider stated by the manufacturer as 0.050% of the reading.
- b) Uncertainty in the line from the source to the multiplexer digitizer measured to be 0.304% of the reading.
- c) Uncertainty in the mutiplexer digitizer (0.005V).

The following table presents the uncertainty in voltage measurement:

T.S. voltage Volts	Signal Voltage Volts	Instrument Uncertainty Volts	Line Uncertainty Volts	Digitizing Uncertainty Volts	Total Uncertainty 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

4.2.7 Uncertainty in Test Section Current Measurement

Total uncertainty in test section current measurement consists of:

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

The following table presents the uncertainty in the current measurement:

T.S. Current Amps	Signal Voltage Volts	Instrument Uncertainty Amps	Line Uncertainty Amps	Digitizing Uncertainty Amps	Total Uncertainty Amps
10000	2.50	10	30	20	38
5000	2.50	3	15	10	18
2000	1.25	1	6	8	10

4.2.8 Uncertainty in Test Section Dimensional Measurement

The total uncertainty in measuring the test section dimension depends upon the measurement technique used. Since the total heater length and the spacing between pressure taps were measured by a tape measure, the uncertainties of the above measurement represent the resolution of the measurement instrument. The inside diameter of the outer heater was measured using go and no-go gages. Therefore, the uncertainty of the outer heater inside diameter is one half of the difference between the diameters of the go and no-go gages. The outside diameter of the inner heater as well as the heater wall thickness were measured by calibrated micrometer.

The following is a summary of the uncertainty in dimensional measurements.

<u>Measurement</u>	<u>Uncertainty (inch)</u>
heater length inner & outer heaters	0.032
Pressure taps distance	0.054
outer heater inside diameter	0.005
inner heater outside diameter	0.001
wall thickness inner & outer heaters	0.001

5. Results

5.1 Introduction

This section describes the results obtained during the single annulus steady state test program. This program involved testing under controlled flow and controlled pressure drop conditions with symmetric heating, and controlled flow with non-symmetric heating. Section 2.3 of this report presented the test matrix accomplished.

The inlet temperature requirement of 77 °F could not be maintained for surface heat fluxes greater than 600,000 Btu/hr-ft². The system heat rejection heat exchanger had been sized based upon a 95 °F condition which was an earlier requirement. Additional plates can be added to the heat exchanger to increase its capacity; however, this was felt to be beyond the current program scope. The maximum test condition successfully achieved was 800,000 Btu/hr-ft² at an inlet temperature of 122 °F. A second test at this condition could not be completed because of generator overheating. The generators can provide a maximum flux of 1,000,000 Btu/hr-ft². The duration of operation at this condition represents a significant load on the generators. For the test which was terminated, the generator had been running at maximum for almost eight hours. The maximum conditions can be accomplished provided the test is run early in the daily operating cycle and the number of points is limited to reduce overheating.

The test results obtained during these single annulus tests clearly defined the OFI conditions and the parameters which affect OFI.

5.2 Test Section Pressure Drop

5.2.1 Controlled Flow

As noted earlier, the test section was modified several times to improve its structural integrity. These modifications tended to increase the test section pressure drop but as will be shown later did not significantly affect the OFI flow-rate. The decision to modify the test section was made based upon the repeatability of test points. In general, it was determined that the test

section geometry changed after OFI was achieved. It is felt that these changes were induced by the vibrations generated by bubbles during sub-cooled boiling. The final version of the test section, revision IV, exhibited excellent repeatability following OFI.

Figures 5.1 through 5.3 presents the demand curves for revisions I through III of the test section respectively. In figures 5.2 and 5.3, there are clear shifts in the demand curves at high flows. In both cases, these points were taken after OFI. The test procedure involved recording test points as the flow-rate was decreased toward and beyond OFI. The flow-rate was then increased and points were taken following OFI. The test section was dismantled after each of these tests and the physical condition examined. The visual observations indicated that movement had occurred between the inner and outer heater. Modifications were then made to prevent heater movement. In revision IV of the test sections. insulated positioning pins were mounted from the outer to the inner heater. Subsequent testing showed that these modifications provided the necessary structural rigidity.

Figures 5.4 and 5.5 present the demands curves at an inlet temperature of 77 °F and 122 °F respectively for revision IV of the test section. The minimum point in the pressure drop is well defined. Revision IV was the final form of the test section and was used for all subsequent tests. Analysis of the test results should be limited to revision IV of the test section because geometry of this section was maintained throughout the remainder of the program.

5.2.2 Controlled Pressure Drop

Several tests were conducted under controlled pressure drop conditions. In this configuration, the test section is connected in parallel with an unheated flow passage. As noted above these tests were conducted with revision IV of the test section. The ratio of test section flow-rate to bypass flow-rate was approximately 2 to 3. Two bypass configurations were used. In one case, the bypass was directed into the mixing tank directly (see figure 2.1), and in the second case the flow was bypassed to the exit plenum through the spray line. The latter arrangement limited the bypass flow-rate because of heat exchanger restrictions.

Figure 5.6 presents results for the case in which the bypass flow went directly into the mixing tank. In this case at 400,000 Btu/hr-ft² heat flux, conditions beyond OFI were achieved. It should be noted that a significant pressure drop existed between the test section and the mixing tank. Figure 5.7 presents results for the case in which the bypass was accomplished by the spray line. OFI was not achieved at the higher flux in this case because of the generator limitations discussed earlier. For both cases shown in this figure, the test section pressure drop is slightly higher than for the controlled flow case. The reason for this is not understood completely but it may be due to the fact that significant quenching occurred in the exit plenum. For both figures, the controlled flow results are also shown. These results indicate that the presence of a bypass does not increase the flow-rate at which OFI occurs.

5.2.3 Non-Symmetric Heating

The inner and outer heaters had the capability of independent operation. Several tests were conducted in which fluxes of different levels were applied to each heater. Figure 5.8 presents results for six different heating conditions. These tests were conducted under controlled flow conditions and at fluxes equivalent on an overall average basis to two symmetric heating cases (200,000 Btu/hr-ft² and 400,000 Btu/hr-ft²). For each average flux case, tests were conducted with all the power on either the inner or outer heaters. In additions, there were two cases in which the inner heater was operated at a flux of twice the outer heater. In general, OFI occurred at the same flow-rate as recorded during symmetric heating; however, there was some variation consistent with operating flux levels. For instance when all the power was applied to the inner heater, the OFI flow-rate increased by 10%. Conversely as the flux approached the average level, the OFI point moved toward the symmetric case.

5.3 Wall Temperature

In addition to the pressure drop data, there were approximately 67 wall temperature thermocouple measurements obtained. The amount of data obtained by these thermocouples is considerable. Figures 5.9 through 5.16 presents some of this data for various operating conditions and fluxes at various axial stations as a function of flow-rate. Station 143 is one inch from the test section exit, and station 24 is approximately 24 inches from the inlet. All the data in these figures is based upon

cemented thermocouple data. The general trends are as expected. It is interesting to note the relatively flat response at the highest flux (figures 5.15 and 5.16). From these results, it would appear that the entire channel is boiling. The inner heater tends to operate at a lower temperature than the outer heater. This will be discussed in the next chapter of this report.

Figure 5.1 Pressure drop versus flow-rate
 single annulus test section, rev. I
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.2 Pressure drop versus flow-rate
 single annulus test section, rev. II
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○○ flux = 400,000 Btu/hr-ft²
 □□□□□ flux = 600,000 Btu/hr-ft²
 - - - flux = 0

Figure 5.3 Pressure drop versus flow-rate
 single annulus test section, rev. III
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77^{\circ}\text{F}$

Figure 5.4 Pressure drop versus flow-rate
 single annulus test section, rev. IV
 $T_{\text{inlet}} = 77^{\circ}\text{F}$

Figure 5.5 Pressure drop versus flow-rate
single annulus test section, rev. IV
T_{inlet} = 121 °F

○○○○○○ $q = 200,000 \text{ Btu/hr-ft}^2$, (bypass)
 □□□□□ $q = 400,000 \text{ Btu/hr-ft}^2$, (bypass)
 ●●●●● $q = 200,000 \text{ Btu/hr-ft}^2$, (no-bypass)
 ■■■■■■ $q = 400,000 \text{ Btu/hr-ft}^2$, (no-bypass)

Figure 5.6 Pressure drop versus flow-rate
 single annulus test section, rev. IV
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ\text{F}$

oooo	q = 400,000	Btu/hr-ft ² ,	{bypass}
□□□□	q = 800,000	Btu/hr-ft ² ,	{bypass}
●●●●	q = 400,000	Btu/hr-ft ² ,	{no-bypass}
■ ■ ■ ■	q = 800,000	Btu/hr-ft ² ,	{no-bypass}

Figure 5.7 Pressure drop versus flow-rate
single annulus test section, rev. IV
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122^{\circ}\text{F}$

Figure 5.9 Measured wall temperature vs. flow-rate for inner heater, rev. IV

$T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 200,000 Btu/hr-ft²

Figure 5.10 Measured wall temperature vs. flow-rate for outer heater, rev. IV
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = $200,000 \text{ Btu/hr-ft}^2$

Figure 5.11 Measured wall temperature vs. flow-rate for inner heater, rev. IV
 $T_{\text{inlet}} = 77^\circ\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft²

○○○○ station 143
 □□□□ station 132
 △△△△ station 120
 ◇◇◇◇ station 108
 ●●●● station 96
 ■■■■ station 84
 ▲▲▲▲ station 72
 ◆◆◆◆ station 48
 ×××× station 24

Figure 5.12 Measured wall temperature vs.
 flow-rate for outer heater, rev. IV
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft

○○○○ station 143
 □□□□ station 132
 △△△△ station 120
 ◇◇◇◇ station 108
 ●●●● station 96
 ■■■■ station 84
 ▲▲▲▲ station 72
 ◆◆◆◆ station 48
 ×××× station 24

Figure 5.13 Measured wall temperature vs.
 flow-rate for inner heater, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft²

Figure 5.14 Measured wall temperature vs.
 flow-rate for outer heater, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft²

o o o o station 143
 □ □ □ □ station 132
 △ △ △ △ station 120
 ○ ○ ○ ○ station 108
 ● ● ● ● station 96
 ■ ■ ■ ■ station 84
 ▲ ▲ ▲ ▲ station 72
 ◆ ◆ ◆ ◆ station 48
 x x x x station 24

Figure 5.15. Measured wall temperature vs.
 flow-rate for inner heater, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 800,000 Btu/hr-ft²

Figure 5.16 Measured wall temperature vs. flow-rate for outer heater, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 800,000 Btu/hr-ft²

6. Discussion of Results

6.1 Introduction

The previous section of this report presents the data obtained during the steady state portion of the single annulus test program. This section will review these results and compare them to the appropriate single tube data.

6.2 Pressure Drop

During the single tube phase of the flow excursion test program, it was determined that the ratio of the flux to the flux required to raise the fluid temperature to saturation, Q_{ratio} , provided an excellent correlation of data over a wide range of conditions. The Q_{ratio} is given by equation (1).

$$Q_{ratio} = q / (m c_p (T_{sat} - T_{inlet})) \quad (1)$$

Figure 6.1 presents all the controlled flow without bypass data as a function of Q_{ratio} . In reference (1), it was shown that the Q_{ratio} at OFI could be correlated as a function of L/D . Figure 6.1 also includes the predicted Q_{ratio} at OFI for the single annulus L/D ratio. From this figure, it can be seen that OFI occurs at a slightly higher Q_{ratio} than predicted. Reference (2) indicated that the pressure drop under sub-cooled was primarily dependent upon the L/D ratio; however, it was also stated that there was a secondary dependence upon the channel diameter. The hydraulic diameter of the single annulus is approximately 50% bigger than the single tube with the same L/D . For the single annulus, the Q_{ratio} at OFI is 0.96 as compared to 0.90 for the single tube.

Figure 6.2 presents a comparison of the pressure drop data for the four versions of the test section. A flux of 400,000 Btu/hr-ft² was selected for this comparison because every revision of the test section was subjected to these conditions. From the figure, it can be seen that the pressure drop varies between various test sections but the minimum point is unchanged.

The effect of the bypass lines is shown in figure 6.3 as a function of Q_{ratio} . Although the pressure drop varied between bypass and no bypass cases, the OFI

point was not affected. The reason for the difference in pressure is not clear. The results for the 400,000 Btu/hr-ft² at an inlet temperature of 122 are significantly higher for the bypass case. The bypass line in this case is between the inlet line and the exit plenum. The bypass flow is approximately 50% larger than the test section flow. Based upon the temperature readings in the exit plenum, there considerable quenching in the plenum. However, it is not apparent why this downstream phenomena would effect the test section pressure drop which is measured across the test section.

Two different average flux cases were conducted as part of the non-symmetric heating phase. Figures 6.4 and 6.5 presents the results for the 200,000 Btu/hr-ft² and 400,000 Btu/hr-ft² cases respectively. For each case, there were the following three different operating modes:

- a) all power on the inner heater only.
- b) all power on the outer heater only.
- c) inner heater power twice the outer heater.

In each figure, it can be seen that the effect of higher local flux is to cause OFI to shift to a lower Q_{ratio} . This is equivalent to a higher OFI flow-rate. In figure 6.5, the change in Q_{ratio} between the symmetric case and the case in which all the power is on the inner heater is approximately 12%. This is probably due to the greater bubble production rate caused by the higher flux (889,000 Btu/hr-ft²).

A modified Saha-Zuber criterion can also be used to predict the onset of flow instability. The original Saha-Zuber criteria was proposed to predict the onset of significant voiding (OSV) based upon the Stanton Number at the point of net vapor generation (see reference 3). The point of net vapor generation enters the Stanton Number through the fluid temperature at that point (see equation 2).

$$\text{Stanton Number} = q / (G c_{pf} (T_{sat} - T_{\lambda})) \quad (2)$$

where:

G = mass velocity.

c_{pf} = specific heat of the fluid.

T_{sat} = saturation temperature.

T_{λ} = fluid temperature at the point of net vapor generation.

For a uniformly heated channel, the initial point of net vapor generation will occur at the channel exit; however, as the flow-rate is reduced, this point will move into the heated channel. The minimum point in the test section pressure drop (OFI) will occur when sufficient vapor has been generated to overcome the decreasing frictional pressure drop. During this test program, OFI is determined rather than OSV. Based upon exit conditions, OFI will occur at a lower flow-rate than OSV. In the modified Saha-Zuber criterion, the fluid temperature at the point of net vapor generation is replaced by the fluid temperature at the channel exit. It has been shown in reference (1) that the modified Saha-Zuber criterion yields a conservative prediction of OFI. Figure 6.6 presents the calculated Stanton number versus Peclet number at OFI. These results are in agreement with earlier data although the scatter is somewhat higher. In calculating the Stanton number in figure 6.6, the channel exit temperature measured by the RTD was used in all cases but the parallel flow with quenching (the 2" spray line emptied directly into exit plenum, run numbers 284-298 and 349-352). For the cases where the bypass flow went directly to the exit plenum, the RTD temperature was lowered by the quenching action of the bypass fluid. For this case, the fluid thermocouples mounted in the orifice tee were used. In general, the thermocouples read slightly below the RTD's for most of the tests. With the exception of the quenched test, it was felt that the RTD's were more accurate in reading the bulk fluid temperature at the channel exit.

6.3 Fluid Temperatures

A total of four instruments were used to measure the fluid exit temperature. There were two thermocouples mounted on the orifice tee downstream of the test section. These thermocouples were mounted by drilling through the outer heater and positioning the instruments in the flow stream. The RTD's were mounted in the exit plenum. The basis accuracy of the RTD's were higher than the thermocouples and therefore they were the primary instruments. The thermocouples were installed to provide fast response during the transient phase of the test program.

Figures 6.7 through 6.10 present the measured fluid temperatures as a function of test section flow-rate. The agreement between the various instruments is quite good. Figure 6.7 contains the largest variation between thermocouples and RTD's. This difference is due to the relatively high quality achieved in this test case. The last test point for this case was taken at a flow-rate of approximately 28 gpm which is considerably below the OFI flow-rate of 31 gpm. Figures 6.7 through 6.10 also contain a calculated exit temperature based upon adiabatic conditions. At high flow-rates, the calculated and measured results are in agreement. However, as the channel heats, the calculated exit temperature is always greater than the measured temperature. This is not unexpected since the channel is not truly adiabatic. In figure 6.7, the calculated temperature corresponding to the lowest flow-rate is greater than 298 °F which is the saturation temperature for a 50 psig exit pressure. The calculated temperature should be at the saturation temperature which would put the results very close to the thermocouple readings.

6.4 Wall Temperature

The wall temperature data obtained during this phase of the single annulus test program is considerable. Section 5.3 presented some of this data for revision IV of the test section as a function of flow-rate. Figures 6.11 and 6.12 presents measured wall temperature data for various axial stations as a function of Q_{ratio} . Comparing these figures, it can be seen that the inner and outer heaters responded very differently even though the heaters were operated symmetrically. Figure 6.12 appears to indicate that the entire outer heater is under boiling conditions. The average measured wall temperature given in figure 6.12 is 500 °F which at the given flux corresponds to a surface temperature of 330 °F. In figure 6.11, the level is considerably below this.

With symmetric heating, it is expected that both heater would operate at approximately the same temperature. Figures 6.13 through 6.16 present a comparison of measured inner and outer heater temperatures as a function of station location. In each of these figures, the flow-rates given correspond to conditions near OFI. Both heater temperatures agree in the region between stations 80 to 100. In figures 6.13 and 6.14, the inner heater temperature is considerably lower than that of the outer heater. Initially, it was felt that this depression was due to axial conduction; however, even though the ceramic inserts are highly conductive,

the axial conduction is orders of magnitude less than the radial flux. It is now felt that subcooled nucleate boiling was initiated on the outer wall and the liquid was directed toward the inner heater. These effects are not seen in figures 6.15 and 6.16 probably because the test section flow-rate is considerably higher. It appears that the subcooled boiling conditions are limited to the last 20 inches of the heaters.

ooooo q	= 200,000	Btu/hr-ft ²	T _{inlet} =	77°F	P _{exit} =	50 psig
ooooo q	= 400,000	Btu/hr-ft ²	T _{inlet} =	77°F	P _{exit} =	50 psig
aaaaa q	= 400,000	Btu/hr-ft ²	T _{inlet} =	121°F	P _{exit} =	50psig
ooooo q	= 800,000	Btu/hr-ft ²	T _{inlet} =	121°F	P _{exit} =	50psig
ooooo q	= 400,000	Btu/hr-ft ²	T _{inlet} =	77°F	P _{exit} =	20 psig
ooooo q	= 400,000	Btu/hr-ft ²	T _{inlet} =	121°F	P _{exit} =	20psig

Figure 6.1 Pressure drop versus Q_{ratio} single annulus test section, rev. IV

○○○○ test section rev. 1
 □□□□ test section rev. 2
 △△△△ test section rev. 3
 ●●●● test section rev. 4

Figure 6.2 Pressure drop versus Q_{ratio}
 for single annulus test sections
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{exit} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft²

ooooo	q	=	200,000	Btu/hr-ft ² ,	{	bypass},	T _{inlet} = 77°F
ooooo	q	=	400,000	Btu/hr-ft ² ,	{	bypass},	T _{inlet} = 77°F
△△△△△	q	=	400,000	Btu/hr-ft ² ,	{	bypass},	T _{inlet} = 122°F
●●●●●	q	=	200,000	Btu/hr-ft ² ,	{	no-bypass},	T _{inlet} = 77°F
■●●●●	q	=	400,000	Btu/hr-ft ² ,	{	no-bypass},	T _{inlet} = 77°F
△△△△△	q	=	400,000	Btu/hr-ft ² ,	{	no-bypass},	T _{inlet} = 122°F

Figure 6.3 Pressure drop versus Q_{ratio}
single annulus test section, rev. IV
 $P_{exit} = 50$ psig

○○○○○ $q_{\text{inner}} = 446,000 \text{ Btu/hr-ft}^2$, $q_{\text{outer}} = 0$
 □□□□ $q_{\text{inner}} = 0$, $q_{\text{outer}} = 364,000 \text{ Btu/hr-ft}^2$
 △△△△ $q_{\text{inner}} = 277,000 \text{ Btu/hr-ft}^2$, $q_{\text{outer}} = 138,000 \text{ Btu/hr-ft}^2$
 ●●●● q_{inner} and $q_{\text{outer}} = 200,000 \text{ Btu/hr-ft}^2$, symmetric

Figure 6.4 Pressure drop versus Q_{ratio}
 for symmetric and non symmetric heating
 single annulus test section, rev. IV
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^{\circ}\text{F}$

○○○○○○ $q_{\text{inner}} = 889,000 \text{ Btu/hr-ft}^2$, $q_{\text{outer}} = 0$
 □□□□□ $q_{\text{inner}} = 0$, $q_{\text{outer}} = 729,000 \text{ Btu/hr-ft}^2$
 ▲▲▲▲▲ $q_{\text{inner}} = 552,000 \text{ Btu/hr-ft}^2$, $q_{\text{outer}} = 364,000 \text{ Btu/hr-ft}^2$
 ●●●●● q_{inner} and $q_{\text{outer}} = 400,000 \text{ Btu/hr-ft}^2$, symmetric

Figure 6.5 Pressure drop versus Q_{ratio}
 for symmetric and non symmetric heating
 single annulus test section, rev. IV
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 6.6 Stanton Number vs. Peclet Number
single annulus test sections
OFI conditions

Figure 6.7 Exit temperature vs. flow-rate
 for single annulus, rev. IV
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 $\text{flux} = 200,000 \text{ Btu/hr-ft}^2$

Figure 6.8 Exit temperature vs. flow-rate
for single annulus, rev. IV
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
flux = 400,000 Btu/hr-ft²

Figure 6.9 Exit temperature vs. flow-rate
 for single annulus, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft²

Figure 6.10 Exit temperature vs. flow-rate
 for single annulus, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = $800,000 \text{ Btu/hr-ft}^2$

Figure 6.11 Measured wall temperature
vs. Q_{ratio} for inner heater, rev. IV
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{exit} = 50 \text{ psig}$
flux = 400,000 Btu/hr-ft²

Figure 6.12 Measured wall temperature vs. Q_{ratio} for outer heater, rev. IV
 $T_{inlet} = 77^{\circ}\text{F}$, $P_{exit} = 50 \text{ psig}$
flux = 400,000 Btu/hr-ft

○○○○○ flow-rate = 48.28 gpm, inner heater
 □□□□□ flow-rate = 43.04 gpm, inner heater
 △△△△△ flow-rate = 36.90 gpm, inner heater
 ◇◇◇◇◇ flow-rate = 30.92 gpm, inner heater
 ◆◆◆◆◆ flow-rate = 27.31 gpm, inner heater
 ●●●●● flow-rate = 48.28 gpm, outer heater
 ■■■■■ flow-rate = 43.04 gpm, outer heater
 ▲▲▲▲▲ flow-rate = 36.90 gpm, outer heater
 * * * * * flow-rate = 30.92 gpm, outer heater
 ◆◆◆◆◆ flow-rate = 27.31 gpm, outer heater

Figure 6.13 Wall temperature vs. distance from channel exit for inner and outer heaters, rev. IV
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 $\text{flux} = 200,000 \text{ Btu/hr-ft}^2$

Figure 6.14 Wall temperature vs. distance from
 channel exit for inner and outer heaters, rev. IV
 $T_{\text{inlet}} = 77^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft²

○○○○○ flow-rate = 85.46 gpm, inner heater
 □□□□□ flow-rate = 82.02 gpm, inner heater
 △△△△△ flow-rate = 79.66 gpm, inner heater
 ◇◇◇◇◇ flow-rate = 76.96 gpm, inner heater
 ◆◆◆◆◆ flow-rate = 73.67 gpm, inner heater
 ●●●●● flow-rate = 85.46 gpm, outer heater
 ■■■■■ flow-rate = 82.02 gpm, outer heater
 ▲▲▲▲▲ flow-rate = 79.66 gpm, outer heater
 ***** flow-rate = 76.96 gpm, outer heater
 ♦♦♦♦♦ flow-rate = 73.67 gpm, outer heater

Figure 6.15 Wall temperature vs. distance from channel exit for inner and outer heaters, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 400,000 Btu/hr-ft²

○○○○○ flow-rate = 178.30 gpm, inner heater
 □□□□□ flow-rate = 167.98 gpm, inner heater
 △△△△△ flow-rate = 159.88 gpm, inner heater
 ◇◇◇◇◇ flow-rate = 152.52 gpm, inner heater
 ◆◆◆◆◆ flow-rate = 146.19 gpm, inner heater
 ●●●●● flow-rate = 178.30 gpm, outer heater
 ■■■■■ flow-rate = 167.98 gpm, outer heater
 ▲▲▲▲▲ flow-rate = 159.88 gpm, outer heater
 ***** flow-rate = 152.52 gpm, outer heater
 ◆◆◆◆◆ flow-rate = 146.19 gpm, outer heater

Figure 6.16 Wall temperature vs. distance from channel exit for inner and outer heaters, rev. IV
 $T_{\text{inlet}} = 122^{\circ}\text{F}$, $P_{\text{exit}} = 50 \text{ psig}$
 flux = 800,000 Btu/hr-ft²

7. CONCLUSIONS

Test results have been obtained which clearly established the relationship between the OFI flow-rate and the test parameters of inlet temperature, exit pressure, and surface heat flux for the single annulus geometry. A number interesting results have been obtained.

For the controlled flow cases, the minimum point in the demand curve is well defined. When comparing these results with those for the single tube with the same L/D ratio, it can be seen that OFI occurs at a slightly lower flow-rate. For the same set of test conditions, saturation temperature, average flux, and inlet subcooling, the rate of bubble generation and the size of bubbles should be the same for the same flow-rate. In a larger hydraulic diameter channel, it would take more or larger bubbles to effect the pressure drop. However, the primary parameter is still the L/D ratio so that the single tube results are applicable to the single annulus to within 10%. The Q_{ratio} defined during the single tube test program provides a good correlation parameter for this geometry.

The controlled pressure test results show that the presence of a bypass line does not change the OFI flow-rate when compared to the controlled flow results.

The non-symmetric heating cases showed that the OFI flow-rate increased over the value recorded during symmetric heating at the same overall average flux. It is assumed that this change is due to the greater bubble production rate associated with the higher local flux. It should be noted that even though the local surface heat surface was more than twice the average the OFI flow-rate was increased by only 12%.

It has also been shown that predicting the OFI point based upon a modified Saha-Zuber criterion yields reasonable results. Some of the non-symmetric heating cases had Stanton numbers outside the $\pm 25\%$ error band associated with the Saha-Zuber criterion. For the non-symmetry heating cases, the Stanton numbers were based upon the overall average surface heat flux.

The fluid temperatures results are in good agreement. The adiabatic calculated fluid temperatures are quite close to the measured values. The excellent agreement between calculations and measurements at high flow-rates shows the quality of the test results.

The wall temperature results are as expected. In some cases, it appears that flow maldistribution occurred so that boiling conditions existed on the outer heater even though the inner heater was below the saturation temperature.

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