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COLUMBIA UNIVERSITY FLOW INSTABILITY
EXPERIMENTAL PROGRAM, VOLUME 6

SINGLE ANNULUS TESTS, TRANSIENT TEST PROGRAM (U)

by
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SRTC

SAVANNAH RIVER TECHNOLOGY CENTER, AIKEN, SC 29808
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The coolant in the Savannah River Site (SRS) production nuclear reactor assemblies is circulated as a subcooled liquid under normal operating conditions. This coolant is evenly distributed throughout multiple annular flow channels with a uniform pressure profile across each coolant flow channel. During the postulated Loss of Coolant Accident (LOCA), which is initiated by a hypothetical guillotine pipe break, the coolant flow through the reactor assemblies is significantly reduced. The flow reduction and accompanying power reduction (after shutdown is initiated) occur in the first 1 to 2 seconds of the LOCA. This portion of the LOCA is referred to as the Flow Instability (FI) phase [1].

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

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

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

where:

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

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

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

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

References

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

Figure 1. Demand curves for subcooled isothermal and diabatic systems

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

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

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

**SINGLE ANNULUS TESTS
TRANSIENT TEST PROGRAM**

REPORT No. CU-HTRF-T3B

September, 1992

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

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

SINGLE ANNULUS TESTS

Transient Test Program

SUBCONTRACT AX-721092

REPORT No. CU-HTRF-T3B

Part I Technical Discussion

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ABSTRACT

This report presents the experimental results for the transient portion of the single annulus test program. The test program was designed 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 ribless heater and a ribbed heater under steady state as well as transient conditions. The ribbed heater testing is currently underway and will be reported separately. The steady state portion of this test program with ribless heater was completed and reported in report no. CU-HTRF-T3A.

The present report presents transient test results obtained from a ribless, uniform annulus test section. A total of thirty five transients were conducted with six cases in which flow excursion occurred. No unstable conditions resulted for tests in which the steady state Q_{ratio} OFI limit was not exceeded.

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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. The test program was divided into two geometries, finless and finned, and two operating modes, steady state and transient. The results from the finless steady state tests have already been reported in CU-HTRF-T3A-91-04.

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.

The test section for the single annulus test consisted of two Inconel 625 heater tubes. Down flow cooling water circulated in the annulus between the tubes. The exterior of the heater 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 were 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 transient results for the finless heater tests. 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 geometry for the finless heater transient tests is the same as the steady state test revision IV. A complete description of the flow loop and test section is given in CU-HTRF-T3A. The present report will not duplicate this document but will present the unique features related to the transient test.

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.

2.2 Test Loop Facility Physical Description

2.2.1 Flow Loop Description

The loop configuration was the same as that used for the steady state tests.

2.2.2 Test Section

The test section was the same as that used for the steady state test program. Since the transient tests were conducted after the steady state program, the last revision of the test section (IV) was used.

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 2.3). 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 tubing. From the tubing a connection is made to the heater clamps 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 portion of the program required more extensive circuit design and construction than the steady state program in order to meet the specified power profile.

The profile dictated that the power decay be accomplished in three distinct stages. The first and last stages were relatively mild decays, while the middle stage was a steep, fast decay where the power drops some 70%.

A sequential circuit was constructed which accomplished the desired profile, as well as initiating the flow transient at a prescribed length of time before the onset of the power decay.

When the operator starts the tranient, the flow decay begins and after a specified time, the first part of the power decay begins. This initial mild decay is accomplished by changing the gating angle of the SCR field excitation. After approximately one second, the second stage is begun by a separate circuit which is switched into the generator fields through DC contactors, and by the removal of the SCR's. This circuit changes the inherent generator time constant and allows a steep decay in approximately one second. Finally, the SCR circuit is switched back into the system, at a different gating angle, and the final mild transient is accomplished.

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:

Parameter	Inner Tube	Outer Tube
Resistance	0.01685 ohms	0.01306 ohms
Current	11,355 amps	14,000 amps
Voltage	191 volts	183 volts

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 objective of the test matrix was to simulate transient conditions which are predicted to occur in the reactor. The power decay profile is based upon a reactor shutdown profile. The present flow loop can not simulate both a flow and pressure transient profile. The test transient is therefore based upon a flow decline that is accomplished by bypassing coolant from the inlet plenum to a bypass line. The magnitude of the flow decay is approximately 40%; however, the actual settings were adjusted to provide by stable and unstable transients. Table 2.1 presents the test matrix accomplished during this transient program. The exit pressures shown represent conditions before the initiation of the transient.

Table 2.1 Single Annulus Transient Test Matrix

#	Test	QO	QI	P _{ex}	T _{in}	Description
1	SAT0609A	.4	.4	50	77	power decay at steady flow
2	SAT0609B	0	0	50	77	flow reduction at zero power
3	SAT0609C	.4	.4	50	77	power decay at steady flow
4	SAT0609D	0	0	50	77	no instability
5	SAT0609E	0	0	50	77	no instability
6	SAT0609F	.4	.4	50	77	power decay at steady flow
7	SAT0609G	.4	.4	50	77	power decay at steady flow
8	SAT0609H	.15	.15	50	77	no instability
9	SAT0609I	.4	.4	50	77	no instability
10	SAT0609J	.4	.4	50	77	no instability
11	SAT0609K	.4	.4	50	77	power decay at steady flow
12	SAT0609L	.4	.4	50	77	no instability
13	SAT0609M	.4	.4	50	77	no instability
14	SAT0609N	.4	.4	50	77	no instability
15	SAT0612A	0	0	50	77	no instability
16	SAT0612B	.4	.4	50	77	no instability
17	SAT0612C	.4	.4	50	77	no instability

18	SAT0612D	.4	.4	50	77	no instability
19	SAT0612E	.4	.4	50	122	no instability
20	SAT0612F	.4	.4	50	122	instability
21	SAT0612G	.4	.4	50	122	no instability
22	SAT0612H	.4	.4	50	122	no instability
23	SAT0612I	.6	.6	50	77	power decay at steady flow
24	SAT0612J	.4	.4	50	77	no instability
25	SAT0612K	.6	.6	50	77	no instability
26	SAT0612L	.6	.6	50	77	no instability
27	SAT0612M	.6	.6	40	77	no instability
28	SAT0612N	.6	.6	34	77	instability
29	SAT0612O	.6	.6	38	77	instability
30	SA0914A	.6	.6	59	77	no instability
31	SA0914B	.6	.6	59	77	no instability
32	SA0914C	.6	.6	59	77	instability
33	SA0914D	.6	.6	62	77	instability
34	SA0914F	.6	.6	60	77	instability
35	SA0914G	.6	.6	60	77	no instability

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.
- 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.

The transient test procedure consisted of the following steps.

- 1) The flow-rate was set at specified level. The exit pressure, inlet temperature, and surface heat flux was established at levels given in the test matrix.
- 2) Using the quick acting valve located on the bypass line, a specified amount of flow was diverted from the test section. The magnitude of flow diversion was set

at approximately 40% of the initial flow-rate; however, this number was adjusted to provide results just above or below the stability limit. The steady state OFI controlled flow data was estimate to determine the stability point.

3) Following the flow diversion, the power decay was initiated approximately 10 seconds later.

The tests were terminated either by completion of the power decay or by a power trip. The power trips were caused by low flow to the test section. Thermocouple trips were also included but the flow trips occurred before temperature excursions.

Figure 2.1

Figure 2.2

Figure 2.3

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 end piece (34 inches downstream of the end of the heated length) to measure the exit temperature during transient operation. Figure 3.1 shows the exact location of the fluid temperature measurements at exit of the test section.

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 3.1). 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 3.2, 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 3.1 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 3.3 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.

3.2.3 Description of Data Files

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

Table 3-1 Instrumentation List

<u>INSTRUMENT</u> (symbol)	<u>TYPE OF</u> <u>SENSOR</u>	<u>MANUFACTURER</u>	<u>LOCATION</u>
Volt BB	Voltage		Bus to bus voltage
Volt TS*	Voltage		Test section voltage
Curr TS*	Current (shunt)		Test section current
Curr TS2	Current (shunt)		Test section current
PT11*	Absolute pressure transducer	SENSOTEC	Inlet of test section
PT12	Absolute pressure transducer	CEC	Inlet of test section (after split)
PTO1*	Absolute pressure transducer	SENSOTEC	Outlet of test section
PTO3	Absolute pressure transducer	CEC	Outlet of test section
	Absolute pressure transducer	SENSOTEC	Parallel line inlet
PBO1	Absolute pressure transducer	SENSOTEC	Parallel line outlet
PL1	Absolute pressure transducer	SENSOTEC	Loop pressure
PL2	Absolute pressure transducer	SENSOTEC	Loop pressure (exit of parallel)
PD1	Absolute pressure transducer	SENSOTEC	Short to tank (bypass H.E.)
PX11	Absolute pressure transducer	SENSOTEC	Heat exchanger inlet
PXO1	Absolute pressure transducer	SENSOTEC	Heat exchanger outlet
PPI1	Absolute pressure transducer	SENSOTEC	Pump inlet
PPO1	Absolute pressure transducer	SENSOTEC	Pump outlet
PA1	Absolute pressure transducer	SENSOTEC	Tank pressure
DT1*	Differential pressure transducer	T-HYDRONICS	Pressure drop of test section
DT2	Differential pressure transducer	SENSOTEC	Pressure drop of test section
DP1	Differential pressure transducer	BLH	Diff. pressure across pump
DLV1	Differential pressure transducer	SENSOTEC	Control valve pressure drop
OLI1	Differential pressure transducer	SENSOTEC	Orifice pressure drop
FLI1	Turbine flowmeter	HOFFER	Loop flowrate
FTI1 (FTI2)**	Turbine flowmeter	HOFFER	Test section flowrate
FBI1	Turbine flowmeter	HOFFER	Parallel line flowrate
FXI1	Turbine flowmeter	HOFFER	Heat exchanger flowrate
FXI2	Turbine flowmeter	HOFFER	Heat exchanger flowrate

Table 3.1 Cont'd

<u>INSTRUMENT</u> <u>(symbol)</u>	<u>TYPE OF</u> <u>SENSOR</u>	<u>MANUFACTURER</u>	<u>LOCATION</u>
FS1	Turbine flowmeter	HOFFER	Bypass to tank (pump exit)
RTI1*	Resistance temperature detector	WEED	Inlet of test section
RTI2	Resistance temperature detector	WEED	Inlet of test section
RTO1*	Resistance temperature detector	WEED	Exit of test section
RTO2	Resistance temperature detector	WEED	Exit of test section
JXI1	Ungrounded type J thermocouple	CGS	Inlet to heat exchanger
JXO1	Ungrounded type J thermocouple	CGS	Exit of heat exchanger
EW1 (95W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW2 (95E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW3 (72N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW4 (72S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW5 (48W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW6 (48E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW7 (24N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW8 (24S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW9 (13W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW10 (13E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW11 (10N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW12 (10S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW13 (7W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW14 (7E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW15 (4N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW16 (4S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW17 (1W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW18 (1E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
TCB1 (7W)	Grounded type K thermocouple	CGS	Test section wall temp.
TCB2 (4E)	Grounded type K thermocouple	CGS	Test section wall temp.
TCB2 (1S)	Grounded type K thermocouple	CGS	Test section wall temp.

*:Primary instrument

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.

SRL SINGLE ANNULUS TEST SECTION INSTRUMENT ARRANGEMENT

TUBE No.: 3.010-001

INNER HEATER ID: 2.217" OD: 2.347"
OUTER HEATER ID: 2.899 OD: 3.028

Figure 3.2

FIGURE 3.3 High Speed Computer Controlled Data Acquisition System

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./°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 dR of a dependent variable is given by:

$$dR = \sqrt{S \sum (dr/dv_i)^2 dv_i^2}$$

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:

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

- a) Accuracy of the instrument stated by the manufacturer as 1.8 °F or 0.4% of reading.
- b) 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.
- c) Uncertainty in the reference box (1.0 °F).
- d) 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:

- Accuracy of the voltage divider stated by the manufacturer as 0.050% 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 (0.005V).

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

During the transient single annulus test program, a total of 35 transient cases were conducted. The tests were relatively short; however, even for a thirty second run, a large amount of data is accumulated with a 16 millisecond scan rate. The following section presents the results for all the transients. To facilitate data presentation, the test results will be presented using a series of four curves which are identified in table 5.1.

Table 5.1 Curve Format

Curve Number	Curve Characteristic	Information
1	Event	inner heater flux bypass flowrate test section pressure drop
2	Flows	plenum inlet flow bypass flowrate heat exchanger exit flowrate test section flowrate
3	Pressures	test section inlet pressure test section exit pressure test section pressure drop bypass pressure drop
4	Temperatures	test section inlet temperature saturation temperature wall temperatures 2 and 3 inches from exit

5.2 Results

As indicated in table 2.1, there were a number of different types of transients run. Figure type 1 shows the type of transient event for a particular test. For instance Figure 5.1.1 shows that test SAT0609A was a power decay test with steady flow through the test section and bypass lines. Figure 5.2.1 presents test SAT0609B which involved a flow diversion through the bypass line, but without power applied to the test section. Test SAT0612F, see Figure 5.20.1, involved a test section flow reduction from 128 gpm to approximately 72 at a surface heat flux of 400,000 Btu/hr-ft². This test resulted in a flow instability with the test section flowrate continuing to drop after the initial diversion. The test section power was tripped approximately 3 seconds after the initial bypass opening. It is interesting to note that for this test there was no temperature excursion.

Test SAT 0914 C, SAT0914D, and SAT0914F were operated at exit pressures of 60 psig and flux of 600,000 Btu/hr-ft². The flow reduction to the test section due to flow diversion through the bypass line was approximately 60%. For each of these tests, the test section became unstable and was tripped by the test section low flow trip. The trips occurred approximately 3 seconds after the initial bypass opening. It is interesting to observe that test SAT0914B did not experience flow excursion. In this case, the bypass flow diversion was set a few gpm lower than the unstable tests. Test SAT0609K was conducted as a calibration run.

Two types of safety protections were used in these tests to protect the heaters from physical burn-out. Flow trip was installed to trip the power in case of flow excursion and thermocouple trips were used to trip the power in case of temperature excursion. None of the power trips were caused by temperature excursions during all the transient tests. Examination of these Figures does not reveal any significant temperature increased other than an increase associated with decreased flow. It is felt that the temperature measurements are not fast enough to respond the rapid wall temperature changes in the inner heater. This is mainly due to that the inner heater has a fairly long time constant because of the ceramic inserts. The overall wall operating temperature is quite high exceeding 700 °F in many cases. Throughout all the tests, the flow trip was set at 10 to 20 % safety margin (10 to 20 % below the expected onset of flow instability flowrate) calculated from steady state test results or previous transient results. A low flow trip only indicated that the flow was reduced to a level below that

particular set point. This does not necessary represent an irreversible flow drift or an irreversible thermal-hydraulic limit.

Figure 5.1.1 Single annulus transient test SAT0609A, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.1.2 Single annulus transient test SAT0609A, flux = 400,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.1.3 Single annulus transient
 test SAT0609A, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.1.4 Single annulus transient
 test SAT0609A, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.2.1 Single annulus transient
 test SAT0609B, flux = 0.0 Btu/hr-ft^2
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.2.2 Single annulus transient
 test SAT0609B, flux = 0.0 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.2.3 Single annulus transient
 test SAT0609B, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.2.4 Single annulus transient
 test SAT0609B, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.3.1 Single annulus transient
 test SAT0609C, flux = $400,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.3.2 Single annulus transient
 test SAT0609C, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○○○ Test section inlet pressure - psig/10
 ■■■■■■ Test section exit pressure - psig/10
 ▲▲▲▲▲ Test section pressure drop - psi
 ◆◆◆◆◆ Bypass pressure drop - psi

Figure 5.3.3 Single annulus transient
 test SAT0609C, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.3.4 Single annulus transient
 test SAT0609C, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.4.1 Single annulus transient
 test SAT0609D, flux = 0.0 Btu/hr-ft^2
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.4.2 Single annulus transient
 test SAT0609D, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.4.3 Single annulus transient
 test SAT0609D, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet temperature
 □□□□ Saturation Temperature
 ●●●● Wall temperature, TWI142NW
 ■■■■ Wall temperature, TW0143SE
 ▲▲▲▲ Wall temperature, TW0142SW

Figure 5.4.4 Single annulus transient
 test SAT0609D, flux = 0.0 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.5.1 Single annulus transient
 test SAT0609E, flux = 0.0 Btu/hr-ft^2
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.5.2 Single annulus transient test SAT0609E, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.5.3 Single annulus transient
 test SAT0609E, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.5.4 Single annulus transient
 test SAT0609E, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.6.1 Single annulus transient
 test SAT0609F, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.6.2 Single annulus transient
test SAT0609F, flux = 400,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.6.3 Single annulus transient
 test SAT0609F, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.6.4 Single annulus transient
 test SAT0609F, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.7.1 Single annulus transient
 test SAT0609G, flux = $400,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.7.2 Single annulus transient
test SAT0609G, flux = 400,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.7.3 Single annulus transient
test SAT0609G, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.7.4 Single annulus transient
 test SAT0609G, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.8.1 Single annulus transient
 test SAT0609H, flux = $150,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.8.2 Single annulus transient
 test SAT0609H, flux = 150,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.8.3 Single annulus transient
 test SAT0609H, flux = 150,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.8.4 Single annulus transient
 test SAT0609H, flux = 150,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.9.1 Single annulus transient test SAT0609I, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.9.2 Single annulus transient
 test SAT0609I, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.9.3 Single annulus transient
 test SAT0609I, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.9.4 Single annulus transient
 test SAT0609I, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.10.1 Single annulus transient
 test SAT0609J, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.10.2 Single annulus transient test SAT0609J, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.10.3 Single annulus transient
 test SAT0609J, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.10.4 Single annulus transient
 test SAT0609J, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.11.1 Single annulus transient test SAT0609K, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.11.2 Single annulus transient
test SAT0609K, flux = 400,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.11.3 Single annulus transient
 test SAT0609K, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.11.4 Single annulus transient
 test SAT0609K, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.12.1 Single annulus transient
 test SAT0609L, flux = $400,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.12.2 Single annulus transient
 test SAT0609L, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

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Figure 5.12.3 Single annulus transient
 test SAT0609L, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.12.4 Single annulus transient
 test SAT0609L, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.13.1 Single annulus transient
 test SAT0609M, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.13.2 Single annulus transient
 test SAT0609M, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.13.3 Single annulus transient
 test SAT0609M, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.13.4 Single annulus transient
 test SAT0609M, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

▲▲▲▲ Inner heater flux - 10^5 Btu/hr-ft^2
 □□□□ Bypass flow-rate - gpm/10
 ○○○○ Test section pressure drop - psi

Figure 5.14.1 Single annulus transient
 test SAT0609N, flux = $400,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.14.2 Single annulus transient
 test SAT0609N, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77^\circ\text{F}$

Figure 5.14.3 Single annulus transient
 test SAT0609N, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.14.4 Single annulus transient
 test SAT0609N, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.15.1 Single annulus transient test SAT0612A, flux = 0.0 Btu/hr-ft^2
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.15.2 Single annulus transient
 test SAT0612A, flux = 0.0 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.15.3 Single annulus transient
 test SAT0612A, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet temperature
 □□□□ Duration Temperature
 ●●●● Wall temperature, TWI142NW
 ■■■■ Wall temperature, TW0143SE
 ▲▲▲▲ Wall temperature, TW0142SW

Figure 5.15.4 Single annulus transient
 test SAT0612A, flux = 0.0 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.16.1 Single annulus transient
 test SAT0612B, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.16.2 Single annulus transient
 test SAT0612B, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.16.3 Single annulus transient
 test SAT0612B, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.16.4 Single annulus transient
 test SAT0612B, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.17.1 Single annulus transient
 test SAT0612C, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.17.2 Single annulus transient
 test SAT0612C, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.17.3 Single annulus transient
 test SAT0612C, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.17.4 Single annulus transient
 test SAT0612C, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.18.1 Single annulus transient
 test SAT0612D, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.18.2 Single annulus transient
 test SAT0612D, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.18.3 Single annulus transient
 test SAT0612D, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.18.4 Single annulus transient
 test SAT0612D, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.19.1 Single annulus transient
 test SAT0612E, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 122 \text{ }^\circ\text{F}$

Figure 5.19.2 Single annulus transient
 test SAT0612E, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◆◆◆◆ Bypass pressure drop - psi

Figure 5.19.3 Single annulus transient
 test SAT0612E, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122^\circ\text{F}$

Figure 5.19.4 Single annulus transient
 test SAT0612E, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

Figure 5.20.1 Single annulus transient
 test SAT0612F, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 122 \text{ } ^\circ\text{F}$

Figure 5.20.2 Single annulus transient
 test SAT0612F, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.20.3 Single annulus transient
 test SAT0612F, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 122 °F

Figure 5.20.4 Single annulus transient
 test SAT0612F, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

Figure 5.21.1 Single annulus transient
 test SAT0612G, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 122 \text{ }^\circ\text{F}$

Figure 5.21.2 Single annulus transient
 test SAT0612G, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.21.3 Single annulus transient
 test SAT0612G, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 122 °F

Figure 5.21.4 Single annulus transient
 test SAT0612G, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

Figure 5.22.1 Single annulus transient
 test SAT0612H, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 122 °F

Figure 5.22.2 Single annulus transient
 test SAT0612H, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◆◆◆◆ Bypass pressure drop - psi

Figure 5.22.3 Single annulus transient
 test SAT0612H, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 122 °F

Figure 5.22.4 Single annulus transient
 test SAT0612H, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

Figure 5.23.1 Single annulus transient
 test SAT0612I, flux = $600,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.23.2 Single annulus transient
 test SAT0612I, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.23.3 Single annulus transient
 test SAT0612I, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.23.4 Single annulus transient
 test SAT0612I, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.24.1 Single annulus transient
 test SAT0612J, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.24.2 Single annulus transient
 test SAT0612J, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.24.3 Single annulus transient
 test SAT0612J, flux = 400,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.24.4 Single annulus transient
 test SAT0612J, flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.25.1 Single annulus transient
 test SAT0612K, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.25.2 Single annulus transient
 test SAT0612K, flux = 600,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

○○○○ Test section inlet pressure - psig/10
 ■■■■ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◆◆◆◆ Bypass pressure drop - psi

Figure 5.25.3 Single annulus transient
 test SAT0612K, flux = 600,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 5.25.4 Single annulus transient
 test SAT0612K, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.26.1 Single annulus transient
 test SAT0612L, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.26.2 Single annulus transient
 test SAT0612L, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.26.3 Single annulus transient
 test SAT0612L, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.26.4 Single annulus transient
 test SAT0612L, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.27.1 Single annulus transient
 test SAT0612M, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 40 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.27.2 Single annulus transient
 test SAT0612M, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 40$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.27.3 Single annulus transient
 test SAT0612M, flux = 600,000 Btu/hr-ft²
 P_{exit} = 40 psig, T_{inlet} = 77 °F

Figure 5.27.4 Single annulus transient
 test SAT0612M, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 40$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.28.1 Single annulus transient
 test SAT0612N, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 34 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

o-o-o-o-o Plenum inlet flow-rate
 s-s-s-s-s Bypass flow-rate
 ^-^-^-^-^ Heat exchanger exit flow-rate
 <-<-<-<-< Test section flow-rate

Figure 5.28.2 Single annulus transient
 test SAT0612N, flux = 600,000 Btu/hr-ft²
 P_{exit} = 34 psig, T_{inlet} = 77 °F

○○○○○○ Test section inlet pressure - psig/10
 ■■■■■■ Test section exit pressure - psig/10
 ▲▲▲▲▲ Test section pressure drop - psi
 ◆◆◆◆◆ Bypass pressure drop - psi

Figure 5.28.3 Single annulus transient
 test SAT0612N, flux = 600,000 Btu/hr-ft²
 P_{exit} = 34 psig, T_{inlet} = 77 °F

Figure 5.28.4 Single annulus transient
 test SAT0612N, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 34$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.29.1 Single annulus transient
 test SAT06120, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 38 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.29.2 Single annulus transient
 test SAT06120, flux = 600,000 Btu/hr-ft²
 P_{exit} = 38 psig, T_{inlet} = 77 °F

Figure 5.29.3 Single annulus transient
 test SAT06120, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 38$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.29.4 Single annulus transient
 test SAT06120, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 38$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.30.1 Single annulus transient
 test SA0914A, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.30.2 Single annulus transient
 test SA0914A, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.30.3 Single annulus transient
 test SA0914A, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.30.4 Single annulus transient
 test SA0914A, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.31.1 Single annulus transient
 test SA0914B, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.31.2 Single annulus transient
 test SA0914B, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.31.3 Single annulus transient
test SA0914B, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.31.4 Single annulus transient
 test SA0914B, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.32.1 Single annulus transient
 test SA0914C, flux = $600,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 59 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.32.2 Single annulus transient
 test SA0914C, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

○○○○ Test section inlet pressure - psig/10
 ■■■■ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.32.3 Single annulus transient
 test SA0914C, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.32.4 Single annulus transient
 test SA0914C, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 59$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.33.1 Single annulus transient
 test SA0914D, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 62 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.33.2 Single annulus transient
 test SA0914D, flux = 600,000 Btu/hr-ft²
 P_{exit} = 62 psig, T_{inlet} = 77 °F

○○○○ Test section inlet pressure - psig/10
 □□□□ Test section exit pressure - psig/10
 ▲▲▲▲ Test section pressure drop - psi
 ◇◇◇◇ Bypass pressure drop - psi

Figure 5.33.3 Single annulus transient
 test SA0914D, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 62$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.33.4 Single annulus transient
 test SA0914D, flux = 600,000 Btu/hr-ft²
 P_{exit} = 62 psig, T_{inlet} = 77 °F

Figure 5.34.1 Single annulus transient
test SA0914F, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 60 \text{ psig}$, $T_{\text{inlet}} = 77 \text{ }^\circ\text{F}$

Figure 5.34.2 Single annulus transient
 test SA0914F, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 63$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.34.3 Single annulus transient
 test SA0914F, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 60$ psig, $T_{\text{inlet}} = 77$ °F

Figure 5.34.4 Single annulus transient
 test SA0914F, flux = 600,000 Btu/hr-ft²
 P_{exit} = 60 psig, T_{inlet} = 77 °F

Figure 5.35.1 Single annulus transient
 test SA0914G, flux = $600,000 \text{ Btu/hr-ft}^2$
 $P_{\text{exit}} = 60 \text{ psig}$, $T_{\text{inlet}} = 77^\circ \text{F}$

Figure 5.35.2 Single annulus transient
 test SA0914G, flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 60$ psig, $T_{\text{inlet}} = 77$ °F

○-○-○-○ Test section inlet pressure - psig/10
□-□-□-□ Test section exit pressure - psig/10
△-△-△-△ Test section pressure drop - psi
◇-◇-◇-◇ Bypass pressure drop - psi

Figure 5.35.3 Single annulus transient
test SA0914G, flux = 600,000 Btu/hr-ft²
P_{exit} = 60 psig, T_{inlet} = 77 °F

Figure 5.35.4 Single annulus transient
 test SA0914G, flux = 600,000 Btu/hr-ft²
 P_{exit} = 60 psig, T_{inlet} = 77 °F

6. Discussion of Results

6.1 Introduction

The previous section of this report presents the data obtained during the transient portion of the single annulus test program. This section will review these results and discuss criteria for flow instability.

6.2 Results

For the thirty five transient cases, there were six tests in which flow instability occurred. Since these transients were initiated by opening a bypass line, flow diversion was possible. For each unstable case, the test was terminated by a power trip caused by the test section low flow condition. Since the flow trip was set at 10 to 20 % below the expected onset of flow instability flowrate, a low flow trip only indicated that the flow was reduced to a level below that particular set point. This does not necessarily represent an irreversible flow drift or an irreversible thermal-hydraulic limit.

Figure 6.1.1 presents the test section flow-rate for three tests. Test SAT0612F experienced a flow excursion. Tests SAT0612G and SAT0612H were classified as stable, but, as can be seen in the Figure, there is very little difference between these tests and test F. The test section pressure drops for all three tests (see Figure 6.1.2) are also similar although test SAT0612F had slightly higher pressure drop oscillations. The reason for the occurrence of flow instability can be seen in Figure 6.1.3 which presents the variation of Q_{ratio} with time. Figure 6.1.3 also presents the steady state OFI Q_{ratio} limit. The parameter Q_{ratio} as defined by equation (1) was used to correlated the flow instability data obtained by the HTRF using both vertical tube^{1, 2} and annulus³ test sections. A very good correlation was established using data obtained from test sections with various L/D ratio. The Q_{ratio} can be used to predicted the flow instability limit for steady state operation conditions.

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$$Q_{ratio} = \frac{Q}{\dot{m}C_p(T_{sat}-T_{inlet})} \quad (1)$$

Q : total heat input (btu/hr)

$\dot{m}$: mass flowrate (lb/hr)

C_p : specific heat (btu/lb/F)

T_{sat} : saturation temperature (F)

T_{inlet} : inlet temperature (F)

For test SAT0612F, the instantaneous Q_{ratio} exceeds the steady state by a greater amount than the other two tests. Figures 6.2.1 through 6.2.3 present similar results for tests SAT0612L through SAT0612O. Tests N and O were unstable. Both these tests show similar Q_{ratio} responses. In these tests, the flow instable was caused by lowering the test section exit pressure for the same magnitude flow diversion.

For the tests conducted in 1991, the procedure was modified and the magnitude of flow diversion was adjusted to cause flow excursion while holding the exit pressure constant. Figure 6.3.1 presents results for four tests of which two were classified unstable. For tests SAT0914A and SAT0914B, the test section flow-rate after the bypass opened was set at 95 gpm. For tests SAT0914C and SAT0914D, the level was 88 gpm. Loop controls were not sufficient to reduce this flow-rate range between stable and unstable conditions. Figure 6.3.3 shows that the unstable tests exceeded the steady state OFI criteria. Figures 6.4.1 through 6.4.3 presents similar results for another series of tests.

1. Dougherty, T., Fighetti, McAssey, E., C., Reddy, G., Yang, B., Chen, K., Qureshi, Z., "Flow Instability in Vertical Down-Flow at High Fluxes", Heat Transfer in High Energy/High Flux Applications, HTD-Vol. 199, ASME Winter Annual Meeting, San Francisco, CA, pp 17-23 (1989).
2. Dougherty, T., Fighetti, Reddy, G., Yang, B., Jafri, T., McAssey, E., Qureshi, Z., "Flow Boiling in Vertical Down-Flow", Proceedings of the Ninth International Heat Transfer Conference, Jerusalem, Israel, Vol. II (1990).

3. Carrano, V., Kokolis, S., Maciucă, C., McAssey, E., Reddy, D., Yang, B.,
"Flow Excursion Experimental Program Single Annulus Steady State Tests ", Report
CU-HTRF-T3A, Columbia University Heat Transfer Research Facility, Part I, July 1991.

Figure 6.1.1 Single annulus transient,
flux = 400,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 122$ °F

Figure 6.1.3 Single annulus transient,
 flux = 400,000 Btu/hr-ft²
 $P_{exit} = 50$ psig, $T_{inlet} = 122$ °F

Figure 6.2.1 Single annulus transient,
 flux = 600,000 Btu/hr-ft²
 $P_{\text{exit}} = 50$ psig, $T_{\text{inlet}} = 77$ °F

Figure 6.2.2 (a) Test SATQ612L
flux = 600,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77°F

Figure 6.2.2 (b) Test SATQ612M
flux = 600,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77°F

Figure 6.2.2 (c) Test SATQ612N
flux = 600,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77°F

Figure 6.2.2 (d) Test SATQ612O
flux = 600,000 Btu/hr-ft²
P_{exit} = 50 psig, T_{inlet} = 77°F

Figure 6.2.3 Single annulus transient,
 flux = 600,000 Btu/hr-ft²
 P_{exit} = 50 psig, T_{inlet} = 77 °F

Figure 6.3.1 Single annulus transient,
 flux = 600,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77$ °F

Figure 6.3.2 (a) Test SATQ914A
flux = 600,000 Btu/hr-ft²
P_{exit} = 59 psig, T_{inlet} = 77°F

Figure 6.3.2 (b) Test SATQ914B
flux = 600,000 Btu/hr-ft²
P_{exit} = 59 psig, T_{inlet} = 77°F

Figure 6.3.2 (c) Test SATQ914C
flux = 600,000 Btu/hr-ft²
P_{exit} = 59 psig, T_{inlet} = 77°F

Figure 6.3.2 (d) Test SATQ914D
flux = 600,000 Btu/hr-ft²
P_{exit} = 62 psig, T_{inlet} = 77°F

○○○○ Test SAT0914A, $P_{exit} = 59$ psig
 □□□□ Test SAT0914B, $P_{exit} = 59$ psig
 ▲▲▲▲ Test SAT0914C, $P_{exit} = 59$ psig
 ◇◇◇◇ Test SAT0914D, $P_{exit} = 62$ psig
 ——— Steady state OFI Q_{ratio}

Figure 6.3.3 Single annulus transient,
 flux = 600,000 Btu/hr-ft²
 $T_{inlet} = 77$ °F

Figure 6.4.1 Single annulus transient,
 flux = 600,000 Btu/hr-ft²
 $T_{\text{inlet}} = 77$ °F

Figure 6.4.2 (b) Test SATQ914B
flux = 600,000 Btu/hr-ft²
 $P_{sat} = 59$ psig, $T_{wall} = 77^\circ\text{F}$

Figure 6.4.2 (d) Test SATQ914G
flux = 600,000 Btu/hr-ft²
 $P_{sat} = 60$ psig, $T_{wall} = 77^\circ\text{F}$

Figure 6.4.2 (a) Test SATQ914A
flux = 600,000 Btu/hr-ft²
 $P_{sat} = 59$ psig, $T_{wall} = 77^\circ\text{F}$

Figure 6.4.2 (c) Test SATQ914F
flux = 600,000 Btu/hr-ft²
 $P_{sat} = 60$ psig, $T_{wall} = 77^\circ\text{F}$

Figure 6.4.3 Single annulus transient,
 flux = 600,000 Btu/hr-ft²
 $T_{inlet} = 77$ °F

7. CONCLUSIONS

The transient test phase of the single annulus finless heater test program has been completed. A total of thirty five transients were conducted with six cases in which flow excursion occurred.

The steady stability limit can be used to determine a conservative transient limit. No unstable conditions resulted for tests in which the steady state Q_{ratio} OFI limit was not exceeded.

APPENDIX A
DATA FILE FORMAT

SRL Single Annulus Transient Tests
Flow and Power Transients (6/9/90)
EACH SCAN HAS 21 WORDS IN ONE RECORD
FORMAT(I5,F6.2,2F6.3,8F6.1,5F5.0,4F5.1)

20-Jun-90
2:37 PM

WORD NO.	FORMAT	INSTRUMENT	PARAMETER	UNITS
1	I5	Scan#	Scan Number	
2	F6.2	Time	Relative Time	Seconds
3	F6.3	QI	Heat Flux - Inner Heater	M.Btu/Hr/Sqft
4	F6.3	QO	Heat Flux - Outer Heater	M.Btu/Hr/Sqft
5	F8.1	VTI	Voltage - Inner Heater	Volts
6	F8.1	VTO	Voltage - Outer Heater	Volts
7	F8.1	FP1	Flow - Pump Exit (Turbine meter)	GPM
8	F8.1	FI1	Flow - T.S. Inlet (Turbine meter)	GPM
9	F8.1	FB3	Flow - By Pass (Turbine meter)	GPM
10	F8.1	FXO1	Flow - Heat Exchanger Exit (Turbine meter)	GPM
11	F8.1	PTI1	Pressure - Heater Inlet	Psia
12	F8.1	PTO1	Pressure - Heater Outlet	Psia
13	F5.0	RTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
14	F5.0	TWI1	Wall Temperature - 2" from EOHL	Degrees F.
15	F5.0	TWO1	Wall Temperature - 1" from EOHL	Degrees F.
16	F5.0	TWO2	Wall Temperature - 2" from EOHL	Degrees F.
17	F5.0	TWO3	Wall Temperature - 4" from EOHL	Degrees F.
18	F4.1	V21P	Valve Position	Volts
19	F4.1	V21S	Valve Switch	Volts
20	F4.1	DT1	Pressure Drop - Across Heater	Psi
21	F4.1	DB3	Pressure Drop - Across By Pass Line	Psi

SRL SINGLE ANNULUS TRANSIENT TESTS

9/14/91

EACH RUN HAS 26 WORDS IN ONE RECORD

FORMAT (I4,I5,2F5.0,2F5.1,F6.1,9F5.0,F6.1,F5.1,8F5.0)

SA0914A.DAT, SA0914B.DAT SA0914C.DAT

SA0914D.DAT, SA0914F.DAT SA0914G.DAT

WORD NO.	FORMAT	INSTRUMENT	PARAMETER	UNITS
1	I4	SCAN	Scan Number	Number
2	I5	TIME	Elapsed Test Time in Seconds	SS.MS
3	F5.0	VTI	Voltage - Test Section Inner Heater	Volts
4	F5.0	VTO	Voltage - Test Section Outer Heater	Volts
5	F5.1	PTO1	Pressure - Test Section Exit	Psig
6	F5.1	DT1	Pressure Drop - Test Section	Psi
7	F6.1	FTS	Test section flow (FI1-FB4)	GPM
8	F5.0	FXO1	Flow - Heat Exchanger Exit	GPM
9	F5.0	RTI1	Temperature (RTD) - T.S. Inlet	Degrees F.
10	F5.0	ETO1	Temperature (T/C) - T.S. Exit	Degrees F.
11	F5.0	IEW142NW	Inner Heater Wall Temperature	Degrees F.
12	F5.0	OEW143NE	Outer Heater Wall Temperature	Degrees F.
13	F5.0	OEW142SW	Outer Heater Wall Temperature	Degrees F.
14	F5.0	VP	Valve Position	Volts*10.
15	F5.0	QI	Heat Flux - T.S. Inner Heater	K.Btu/hr/sqft
16	F5.0	QO	Heat Flux - T.S. Outer Heater	K.Btu/hr/sqft
17	F6.1	PTI1	Pressure - Test Section Inlet	Psig
18	F5.1	DT2	Pressure Drop - Test Section	Psi
19	F5.0	FP1	Flow - Pump Outlet	GPM
20	F5.0	FI1	Flow - T.S. Inlet	GPM
21	F5.0	FB4	Flow - T.S. Bypass 4	GPM
22	F5.0	RTO2	Temperature (RTD) - T.S. Outlet	Degrees F.
23	F5.0	ETO2	Temperature (T/C) - T.S. Outlet	Degrees F.
24	F5.0	IEW138SE	Inner Heater Wall Temperature	Degrees F.
25	F5.0	FB3	Flow - T.S. Bypass 3	GPM
26	F5.0	DB3	Pressure Drop - Bypass 3	Psi

APPENDIX B
DATA REDUCTION PROGRAM

```

C
C ***** PROGRAM TO REDUCE SRL SINGLE ANNULUS DATA *****
C ***** FOR TRANSIENT TESTS *****
C
    DIMENSION X(60)
    SCAN = 0.0556
    ALAMBDA = 1.96E+06
    C = 4200
    AREA = 1.95E-04
    ISCAN = 55

C
    OPEN(UNIT=3,FILE='INPUT')
    JCOUNT = 0
  9  FORMAT(11F7.2)
 10  JCOUNT = JCOUNT + 1
    TEST = (-1)**JCOUNT
    READ(3,9,END=30) (X(I),I=1,ISCAN)
    IF(TEST.GE.0.0) GO TO 10
    NSCAN = INT(X(1))
    TIME = SCAN*(NSCAN-1)
    RTIME = X(2)
    QI = X(3)
    QO = X(4)
    VTI = X(5)
    VTO = X(6)
    FP1 = X(7)
    FI1 = X(8)
    FB3 = X(9)
    FXO1 = X(10)
    PTI1 = X(11)
    PTO1 = X(12)
    RTI1 = X(13)
    TWI1 = X(14)
    TWO1 = X(15)
    TWO2 = X(16)
    TWO3 = X(17)
    V21P = X(18)
    V21S = X(19)
    DT1 = X(20)
    DB3 = X(21)
C
    TSAT = 108.282 +0.0998052*XX -3.31756E-05*XX*XX
    1+ 4.64923E-09*XX*XX*XX
    VL = 0.00105449+ 7.9586E-08*XX -8.7506E-12*XX*XX
C
    RHOL = 1/VL
    VG = 1.20413-0.00278796*XX +3.04853E-06*XX*XX
    1-1.68337E-09*(XX**3)+4.53509E-13*(XX**4)
C
    2-4.73143E-17*(XX**5)
C
    RHOG = 1/VG
 30  WRITE(*,1000)NSCAN
1000  FORMAT(1X,'SCAN =',I5)
    OPEN(UNIT=4,FILE='NPROUT',STATUS='UNKNOWN')
    WRITE(4,1200)NSCAN,TIME,RTIME,QI,QO,PTO1,RTI1,
    1FP1,FI1,FB3,DT1,DB3
1200  FORMAT(1X,I5,11F7.3)
    GO TO 10
    END

```


***** PROGRAM TO REDUCE SRL SINGLE ANNULUS DATA *****
 C ***** FOR TRANSIENT TESTS *****

```

    DIMENSION X(60)

    OPEN(UNIT=3,FILE='INPUT')
    ISCAN = 26
    SCAN= 0.016
    JCOUNT = 0
  9  FORMAT(I4,I5,2F5.0,2F5.1,F6.1,9F5.0,F6.1,F5.1,8F5.0)
 10  JCOUNT = JCOUNT + 1
    TEST = (-1)**JCOUNT
    READ(3,9,END=30)IX1,IX2,(X(I),I=3,ISCAN)
    IF(TEST.GE.0.0) GO TO 10
    NSCAN =IX1
    TIME = SCAN*(NSCAN-1)
    NRTIME = IX2
    VTI = X(3)
    VTO = X(4)
    PTO1 = X(5)
    DT1 = X(6)
    FTS = X(7)
    FXO1 = X(8)
    RTI1 = X(9)
    ETO1 = X(10)
    TI1 = X(11)
    TO1 = X(12)
    TO2 = X(13)
    VP = X(14)
    QI = X(15)
    QO = X(16)
    PTI1 = X(17)
    DT2 = X(18)
    FP1 = X(19)
    FI1 = X(20)
    FB4 = X(21)
    RTO2= X(22)
    ETO2 = X(23)
    TI2 = X(24)
    FB3 = X(25)
    DB3 = X(26)
    TSAT = 250.34 + (312.04-250.34)/50*(PTO1-15)
    MDOT = FTS*62.4*60/7.481
    QRATIO = (QO*2.899+QI*2.347)*3.14159*1000/MDOT/(TSAT-RTI1)
    QI = QI/100
    QO = QO/100
    FP1 = FP1/10
    FB4 = FB4/10
    FI1 = FI1/10
    FTS = FTS/10
    FXO1 = FXO1/10
    PTO1 = PTO1/10
    PTI1 = PTI1/10
 30  WRITE(*,1000)NSCAN
1000  FORMAT(1X, SCAN =',I5)
    OPEN(UNIT=4,FILE='SAOUT',STATUS='UNKNOWN')
    WRITE(4,1200)NSCAN,TIME,QI,QO,PTI1,PTO1,RTI1,
    1FP1,FI1,FB4,FXO1,FTS,DT1,DB3,TSAT,TI1,TO1,TI2,TO2,ETO1,
    2RTO1,VTI,VTO,QRATIO
  
```

1200 FORMAT(1X,I10,E10.4,22F10.3)
GO TO 10
END

DATE

FILMED

8/24/94

END