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COLUMBIA UNIVERSITY FLOW INSTABILITY
EXPERIMENTAL PROGRAM, VOLUME 7

SINGLE TUBE TESTS, CRITICAL HEAT FLUX
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 TUBE TESTS
CRITICAL HEAT FLUX TEST PROGRAM**

REPORT No. CU-HTRF-T8

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 TUBE TESTS

Critical Heat Flux Test Program

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ABSTRACT

The experimental portion of this report deals with critical heat flux (CHF) measurements in vertical down flow of water at low pressures in a round inconel tube, 96 inches long and 0.62 inch inside diameter. A total of 28 CHF points were obtained. These data were found to correlate linearly with the single variable q''_{sat} , defined as the heat flux required to raise the enthalpy from the inlet value to the saturation value.

These results were compared to the published results of Swedish investigators for vertical upflow of water at low pressures in round tubes of similar diameters and various lengths. These two sets of data do not overlap appreciably, but rather they complement each other. The Swedish data lie principally at lower values of q''_{sat} .

The parameter q''_{sat} depends on the inlet enthalpy and is, consequently, a nonlocal variable, thus this correlation is nonlocal unless the coefficients depend upon tube length in a particular prescribed manner. For the low pressure Swedish data, the coefficients are practically independent of length and hence the correlation is nonlocal. In the present investigation only one length was employed, so it is not possible to determine whether the correlation for these data is local or nonlocal, although there is reason to believe that it is local.

The same correlation was applied to a large data base (thousands of CHF points) compiled from the published data of a number of groups and found to apply, with reasonable accuracy over a wide range of conditions, yielding sometimes local and sometimes nonlocal correlations.

A linear equation in q''_{sat} can be transformed, by heat balance, into one linear in the product GX_e , where G represents the mass flux and X_e the equilibrium exit quality. This suggests that the product GX_t , where X_t represents the true mass fraction of vapor, is the significant variable. The parameter X_t can be (and, initially, was) estimated from a relation proposed by Kroger and Zuber which utilizes the correlation developed by Saha

and Zuber to estimate the quality at which significant voiding occurs (OSV); i.e.; the point of net steam generation. This approach suffers from certain deficiencies but, inspired by the efforts of these authors, a simple kinetic model was developed to attempt to relate X_t to the experimentally controlled parameters. The resulting correlation, a universal (in general, nonlinear) function of GX_t for a given pressure and diameter, was found to correlate reasonably well (considering the small number of adjustable parameters) with much of the data at medium (500 - 1500 psia) pressures, in the local regime. In this region length, of course is not a parameter.

For sufficiently small values of GX_t this function is linear in the variable $(GX_t)^{1/2}$ which in turn is linearly related to GX_e , thus reducing to a linear correlation in GX_e or, equivalently, q''_{sat} . Thus all previous observations regarding correlations linear in q''_{sat} can be considered as a limiting case of this more general relationship. Attempts to apply this approach to high pressure (>1500 psia) data encounter a difficulty associated with the estimation of the value of the quality at the point of net steam generation (OSV). At these pressures, the Saha-Zuber correlation sometimes predicts values which are greater than the reported exit qualities. Whether this represents a failure of the Saha-Zuber correlation (which has not been tested at these high pressures), inaccuracies in the data, or a general failure of this entire approach at these pressures is not known at this time.

The basic philosophy of data analysis adopted here was not to generate a single correlation which would reproduce all data with high accuracy, but to search for correlations, with few adjustable parameters, which apply adequately over some range and which might have some mechanistic significance. The underlying premise is that there is not one single mechanism for CHF. The tentative conclusion is that at least two mechanisms appear operative, leading to two type of correlations, one local, the other nonlocal, with possible additional subdivisions, particularly in the nonlocal regime.

TABLE OF CONTENTS

1. INTRODUCTION

1. Background and Test Objective	1
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2. DESCRIPTION OF TEST FACILITY

2.1 Introduction	3
2.2 Test Facility Physical Description	3
2.2.1 Single Tube Test Loop for CHF Test Mode	3
2.2.2 Test Section	10
2.3 Test Matrix	12
2.4 Test Loop Operation	12

3. INSTRUMENTATION AND DATA ACQUISITION

3.1 Instrumentation	14
3.1.1 Instrumentation Philosophy	14
3.2 Data Acquisition System	18
3.2.1 Description of Data Acquisition System	18
3.2.2 Description of Data Acquisition Procedure	20
3.2.3 Description of Data Files	23

4. ERROR AND UNCERTAINTY ANALYSIS

4.1 Instrumentation Accuracy	24
4.1.1 Installation Errors	24
4.1.2 Measurement Uncertainties	24

4.2 Overall System Accuracy	27
4.2.1 Uncertainty in Absolute Pressure	28
4.2.2 Uncertainty in Differential Pressure Measurement	28
4.2.3 Uncertainty in Temperature Measurement	29
4.2.4 Uncertainty in Flowrate Measurement	29
4.2.5 Uncertainty in Test Section Voltage Measurement	30
4.2.6 Uncertainty in Test Section Current Measurement	30
4.2.7 Uncertainty in Test Section Dimensional Measurement	31
4.2.8 Uncertainty in Test Section Power Calculation	31
 5. RESULTS	
5.1 Experimental Results	32
5.2 Correlation of Experimental Results	40
5.3 A Simple Kinetic Model of Vaporization	43
5.4 Correlation of CHF Data from Literature	47
 6. RECOMMENDATIONS	55
 7. REFERENCES	58
 8. NOMENCLATURE	59
 APPENDIX A	

1. INTRODUCTION

1.1 Background

At the request of The Savannah River Laboratory, a program, Task Number 14, was initiated in December 1989 to measure CHF for vertical down-flow in single electrically-heated tubes. CHF was determined by gradually increasing power to the test section until a rapid rise in wall temperature, as detected by one or more of the wall thermocouples, exceeded a set limit causing the circuit breaker to open. All testing was performed on two tubes each with a heated length of 8 ft.. Early efforts to measure CHF failed because of flow instabilities resulting from the inability of the centrifugal pump to maintain steady flow to the test section at conditions far beyond the minimum (the so-called OFI point) in the demand curve, test section pressure drop versus flowrate plot. A new screw-type pump was purchased and installed in the loop but this pump was also proved inadequate to maintain steady flow. This pump was not effectively a positive displacement pump, but the high head of the pump might have been used to advantage by strongly throttling the pump discharge.

In March 1990, the first successful CHF tests were performed using the original centrifugal pump with a severely throttled output and no bypass, except for a modest flow to a mixing tee at the test section outlet to quench the steam generated. Flow stability was notably improved but most runs were still terminated by flow trips and only two valid CHF data points were obtained without experiencing flow instability. All of these runs were performed with an Inconel 600 tube with a 0.612" I.D. and 8 ft heated length. The test section was burned while obtaining the second CHF data point. A second centrifugal pump, identical to the first, was installed to provide quench flow to the mixing tee and permit the first pump to supply flow only to the test section with no bypass whatever. The remaining 26 data points were obtained with this configuration and an Inconel 625 tube with a 0.623" I.D. and 8 ft heated length.

1.2 Test Objective

The primary objective was to obtain Critical Heat Flux (CHF) data for a single, electrically-heated tube in vertical down flow over as wide a range of flow rates, inlet temperatures and exit pressures as time and the limitations of the test facility would permit. In this case, the ranges for heat flux, flow rate, inlet temperature, and exit pressure

were $0.77 - 1.80 \times 10^6$ Btu/hr/ft, 5.3 - 25 gpm, 66 - 173 deg F, 31 - 94 psig respectively. All data were obtained with two tubes of two different materials (Inconel 600 and Inconel 625) with approximately the same dimensions (8 feet long and approximately 0.62" ID). No CHF data were obtained for other diameter tubes because of time limitations.

2. DESCRIPTION OF TEST FACILITY

2.1 Introduction

All attempts to measure CHF in the single tube test facility prior to March 1990 failed because of flow instabilities resulting from the inability of the circulating pump to maintain steady flow to the test section. In March 1990, the method of operation was changed by closing the bypass valve to the tank and bypassing some of the flow from the pump to a mixing tee to quench the steam from the test section outlet. By severely throttling the flow to the test section inlet, the sensitivity of the test section flowrate to changes in test section pressure drop was greatly reduced. Two CHF points were obtained in this way but the first test section, 0.612" ID Inconel 600, burned out in the second of these tests.

A second pump was added to the loop in April, 1990 to supply flow to the mixing tee for quenching. The output from the circulating pump supplied only the test section flow. The remaining 26 CHF points were obtained with this configuration, which is shown in Figure 2.1, and with a 0.623" ID Inconel 625 uniform tube (the reference tube for the non uniform tube demand curve tests). The test section instrumentation for the 0.612" tube is shown in Figure 2.2 and for the 0.623" tube in Figure 2.3.

Power trips on flow and thermocouples were connected to protect the test section. The flow trip was set at approximately 4 gpm since values below 3 gpm could not be measured accurately with the 1" turbine flow meter. All of the thermocouples were connected to the Metrascope and the trip levels were set approximately 100 °F above the maximum wall temperature expected during stable operation and these values were adjusted for each CHF point.

2.2 Test Facility Physical Description

2.2.1 Single Tube Test Loop for CHF Test Mode

For these tests, data were recorded and stored in a transient mode. After steady state conditions of inlet temperature, exit pressure, surface heat flux, and test section flow were established, the power to the test section was gradually increased until power was tripped by one or more of the wall thermocouples.

The test apparatus consists of the test loop and the test section. Figure 2.1 presents a schematic of the complete single tube test apparatus. The pump was capable of supplying 250 gpm at a pump head of 75 psi. The test loop can be pressurized for a range of operating pressures up to a maximum of 150 psig which was the rated limit for the plate heat exchanger. Heat input to the test section was supplied by a generator which can deliver approximately 1.5 MW of DC power (240 V, 6500 A). This energy source was capable of delivering more than 3,000,000 Btu/hr-ft² surface heat flux to the 0.62 " inside diameter test section (resistance approximately 0.0334 ohm) employed in this program. All components in the flow loop were stainless steel or nickel plated. The water in the loop was maintained at a pH of slightly less than 7.

As shown in Figure 2.1, a 100 gallon accumulator supplies deionized and deaerated water to the pump inlet. System pressure was maintained by adjusting the liquid level and by changing the helium blanket pressure in the accumulator. The test section inlet temperature was controlled by adjusting the loop external heat rejection rate.

The pumps used in this test program were centrifugal pumps capable of providing a maximum flowrate of 250 gpm. Figure 2.4 presents the pump performance curve for these units. The flow to the test section was controlled by an air operated valve which was located upstream of the test section (see Figure 2.1). At CHF, the pressure drop across the test section was frequently around 22 psi which was a significant part of the total pressure drop of approximately 70 psi. Therefore the pressure drop across the control valve, although a major component of the total pressure drop, often was not the controlling factor in determining the flow to the test section especially when the fluctuations in test section pressure drop were very large (standard deviations up to 8 psi) and rapid as they frequently were under these conditions.

Downstream of the test section was a plate type heat exchanger used to remove energy from the water before it was returned to the accumulator (tank).

Two types of loop instrumentation were used. The primary instrumentation, which was used for data analysis, includes flow, temperature, absolute pressure and differential pressure transducers. These instruments have been calibrated against standards traceable

to the National Institute of Standards and Technology (NIST). They were routinely checked at the beginning of each day's operation and were constantly monitored during testing. Secondary loop instrumentation was used for controlling loop functions and also as back-up to the primary instrumentation. These instruments have also been calibrated but this calibration may not be traceable to NIST standards.

Figure 2.1 Flow Loop

Figure 2.2 T/S instrumentation 0.613"

TEST NO.: ST-8 TUBE NO.: 4.620-003I

MATERIAL : Inconel 600 ID: 0.61"

Figure 2.3 T/S instrumentation 0.625"

SRL - VOID FRACTION MEASUREMENT TEST SECTION INSTRUMENT ARRANGEMENT

TUBE NO.: 5.625-001IU MATERIAL: Inconel 625 ID: 0.623" OD: 0.763"

Figure 2.4 Pump head vs. flowrate for centrifugal pump

2.2.2 Test Section

The test section assembly was 126 inches in length. It was composed of a 96 inch heated test section and upstream and downstream 15 inch calming lengths which also serve as a connection to the power system. The calming lengths have an outside diameter of 1.5 inches and an inside diameter to accommodate the heater tubes. Two heater tubes of approximately the same size and of two different materials were used. Table 2.1 presents the specifications of the test sections used in the program. During the program, the first test section (Inconel 600, 0.612" ID) was burned out. This test section was constructed from commercial grade tubing which means that the nominal uniform tube wall thickness could vary by as much as 10%. The replacement tube was the custom made reference tube used for the non uniform tube tests (Task 5). This tube was specified to have a maximum variation in wall thickness of 5%. Three different methods were used to measure the tube inside diameter. Where gages were not available, the inside diameter was calculated from outside diameter and wall thickness measurements. In later sections of this report, the measured ID rounded to three decimals was used to identify the tube.

The test section construction was essentially the same for all units. The heated portion of the test section was brazed to nickel plated copper end pieces which provided flow calming length and also a connection to the power system. The inside diameter of the end pieces were gunned bored to match the inside diameter of the inconel piece. To eliminate any non-uniformity in the heated section, there were no penetrations made in the tube walls. Pressure measurement taps were located in the copper end pieces. These taps, which were 2.25 inches from the end of the heaters, were used for absolute and differential pressure measurements. Voltage taps were brazed at either end of the test sections. In addition these test sections had a third voltage tap brazed approximately 12 inches from the test section exit. This tap was not used in these tests because spurious power trips, resulting from variations in the tube resistivity, were common in the transient period following increases in test section power.

Test section instrumentation includes thermocouples for wall temperature measurement, taps and transducers for pressure drop measurement, and voltage

tap leads and shunts for power measurements. These instruments were also calibrated and traceable to NIST standards.

Power to the test section was provided by a single motor generator set capable of supplying 6,500 Amperes at 240 Volts DC. The voltage can be varied continuously to produce zero to full power. The voltage control was operated from the test area.

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

2.3 Test Matrix

The single tube uniformly heated tests covered the following ranges of test conditions:

Flow Rate:	5.3 - 25 gpm
Inlet Temperature:	66 - 173 °F
Exit pressure:	31 - 94 psig
Heat Flux:	770,000 - 1,800,000 Btu/hr-ft ²

2.4 Test Loop Operation

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

- 1) at the lowest point deionized deaerated water was added to the system until water reaches vacuum pump.
- 2) system bleed valves were opened selectively to remove any remaining air.
- 3) system was pressurized to 100 psia and leak check performed.
- 4) pumps were energized and nominal flowrate established to check for any remaining leaks.
- 5) loop operating pressures and temperatures will be established and maintained for 10 minutes to insure satisfactory operation of loop controls.

All CHF tests were performed by slowly raising the power until one or more of the thermocouples caused a power trip. The test section outlet pressure was adjusted by adding or dumping helium in the tank through solenoid operated valves (Figure 2.1, V14 and V20). More rapid reductions in pressure were made by dumping water through another, larger, solenoid operated valve (Figure 2.1, V21). The test section inlet temperature was controlled by varying the flow of cooling water to the plate type heat exchanger through air operated valves (Figure 2.1, V32 and V33) but these valves do not give sufficiently fine control to maintain this temperature constant over prolonged periods (more than minutes) particularly in tests such as these where the heat flux was gradually increased in small steps.

Test section flow rate, inlet temperature and outlet pressure were not varied intentionally during the course of the test, but these parameters do vary gradually as power was increased. No attempt was made to adjust flow, outlet pressure, or inlet temperature once the CHF run was initiated since the system was very unstable near CHF conditions and, with the existing equipment, it was very difficult to change these parameters in a smooth and controlled fashion.

The data were taken in the continuous scan and store mode where the results of each scan were continuously stored on tape then reduced off-line to engineering units and transferred to an IBM PC for analysis.

3. INSTRUMENTATION AND DATA ACQUISITION

3.1 Instrumentation

3.1.1 Instrumentation Philosophy

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

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

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

Table 3.1 List of instruments

Table 3-1

**SRL - UNIFORMLY HEATED SINGLE TUBE TEST
INSTRUMENTATION LIST**

Page 1

INSTRUMENT (Symbol)	TYPE OF SENSOR	HAND MANUFACTURER	LOCATION
Volt BB	Voltage		Bus to bus voltage
Volt TS*	Voltage		Test section voltage
Curr TS*	Current (shunt)		Test section current
Curr TS2	Current (shunt)		Test section current
PTI1*	Absolute pressure transducer	SENSOTEC	Inlet of test section
PTI2	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.)
PXI1	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
FS1	Turbine flowmeter	HOFFER	Bypass to tank (pump exit)

SRL - UNIFORMLY HEATED SINGLE TUBE TEST INSTRUMENTATION LIST

Page 2

INSTRUMENT	TYPE OF INSTRUMENT	UNIT	LOCATION
RTI1*	Resistance temperature detector	WEED	Inlet of test section
RTI2	Resistance temperature detector	WEED	Inlet of test section
RTO1*	Resistance temperature detector	WEED	Exit of test section
RTO2	Resistance temperature detector	WEED	Exit of test section
JX11	Ungrounded type J thermocouple	CGS	Inlet to heat exchanger
JXO1	Ungrounded type J thermocouple	CGS	Exit of heat exchanger
EW1 (95W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW2 (95E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW3 (72N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW4 (72S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW5 (48W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW6 (48E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW7 (24N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW8 (24S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW9 (13W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW10 (13E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW11 (10N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW12 (10S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW13 (7W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW14 (7E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW15 (4N)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW16 (4S)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW17 (1W)	Ungrounded type E thermocouple	CGS	Test section wall temp.
EW18 (1E)	Ungrounded type E thermocouple	CGS	Test section wall temp.
TCB1 (7W)	Grounded type K thermocouple	CGS	Test section wall temp.
TCB2 (4E)	Grounded type K thermocouple	CGS	Test section wall temp.
TCB2 (1S)	Grounded type K thermocouple	CGS	Test section wall temp.

*:Primary instrument

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

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

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

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

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

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

The basic instrumentation philosophy was to make all measurements by non-intrusive devices to avoid any flow disturbance. Based on this approach, thermocouples were attached to the exterior of the heater to obtain steady state thermal data. For a

uniformly heated tube, the hottest region will be near the exit of the test section. Therefore, thermocouples were heavily distributed near the exit of test section.

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

The arrangement of thermocouples for these test sections is shown in Figures 2.2 and 2.3.

3.2 Data Acquisition System

3.2.1 Description of Data Acquisition System

The data 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) was 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 was 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 3.1 shows the CCDAS schematically. Specifications of this subsystem are given in Table 3.2.

Figure 3.1 CCDAS schematic

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 was an on-line contact with the operator at the loop control area through one of its terminals. Depending on the option selected, the computer either initiates a scanning procedure and performs on-line data reduction to engineering units or scans and stores continuously with off-line data reduction. 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 were set to zero position and all channels were scanned using the computer program to determine zero shifts of the transducers. These values were used by the program to offset the readings of the transducers until new zero shifts were calculated. With the instruments in zero position, all channels were 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 was pressurized to 50 psig, and all instruments were scanned and reduced to engineering units to check the consistency of the data. The procedure was repeated with the loop pressurized to 20 psig.

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

When steady state conditions were achieved, the sequential scanning was manually interrupted using a scan default option. Then the latest 40 sequential scans were 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 was reduced to engineering units, stored on the magnetic tape, and printed on the printer. The following parameters were printed for each run:

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

In a typical transient operation, the system was first brought to a steady state with the desired conditions of flow, pressure, and temperature, the operator then initiates the scanning process and the data channels were scanned and the data stored on tape until the operator interrupts. During this time, the voltage was gradually increased until the power trips either because of low flow or temperature excursion. This process was repeated for each CHF point. Since the data reduction and data dumping was a relatively slow process, the data were reduced and dumped to an IBM PC, usually at the end of the day's testing. The format for these data files is given in Table 3. 3.

Table 3.2 Data Acquisition System Specification

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

3.2.3 Description of Data Files

Table 3.3 presents the format of the data files. Because of the size of these files no listing of the data is given. HTRF has sent these data to SRL on floppy diskette.

Table 3.3 Format for Data Files

The CHF files have the following format			
Column	Data	Description	Units
1	Scan	Number	
2	Time	Elapsed Time	Seconds
3	PTO1	Exit Pressure	Psig
4	TRT11	Inlet Temperature	Deg. F.
5	TRTO1	Exit Temperature	Deg. F.
6	FT11	Test Section Flow	GPM
7	FL11	Loop Flow	GPM
8	QUAL	Exit Quality	%
9	HFLX	Average Heat Flux	M.Btu/hr/ft ²
10	DPT1	Pressure Drop T.S.	Psi
11	DPT2	Pressure Drop T.S.	Psi
12	EW15E	Wall Temperature	Deg. F.
13	EW12N	Wall Temperature	Deg. F.
14	EW12S	Wall Temperature	Deg. F.
15	EW08W	Wall Temperature	Deg. F.
16	EW08E	Wall Temperature	Deg. F.
17	EW04N	Wall Temperature	Deg. F.
18	EW04S	Wall Temperature	Deg. F.
19	EW01W	Wall Temperature	Deg. F.
20	EW01E	Wall Temperature	Deg. F.
21	KW14.5N	Wall Temperature	Deg. F.
22	KW10S	Wall Temperature	Deg. F.
23	KW05N	Wall Temperature	Deg. F.
24	KW01.5S	Wall Temperature	Deg. F.

4. ERROR AND UNCERTAINTY ANALYSIS

4.1 Instrumentation Accuracy

The errors attributed to the measurement can be categorized into three main sources; namely, the errors due to installation procedures, the instrument errors, and the errors derived from the measurement data acquisition system. Most of the installation errors in these tests existed systematically as a fixed deviation.

4.1.1 Installation Errors

In order to eliminate possible power and flow disturbance, the pressure taps were installed on the copper end pieces 2.25" away from the top and bottom of the heater.

The installation errors for the fluid temperature measurement have not been considered in detail. The thermocouples for wall temperature measurement were installed in a way to minimize the installation errors. The thermocouples were installed on the exterior of the heater to eliminate any flow disturbance. A high thermal conductivity cement was used to minimize any possible effects 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 stem conduction effects. The overall installation error for the primary wall temperature thermocouples should be negligible. The errors in the brazed thermocouples resulting from the high electrical conductivity of the brazing material, were variable and unknown and these thermocouples can not be used for precise temperature measurements.

4.1.2 Measurement Uncertainties

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

4.1.2.1 Instrument Errors

Each instrument used in the tests has been calibrated prior to installation. In addition, all instruments used to provide data necessary for test data analysis have been

calibrated and certified to an NIST standard. Instruments which were used as backup to check the functioning of a primary instrument have been calibrated and were traceable to a NIST standard but may not have traceable certification.

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

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

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

All thermocouples used in these tests have been calibrated and certified to meet the special accuracy limits of error as recommended by ANSI MC96.1-1982. For the type E thermocouple, the special limits of error are 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 was 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 zeros 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 entrapped air.

4.1.2.3 Data Acquisition Errors

The measuring system errors include errors from various sources such as ripple in the power supplies of the data acquisition system, errors in gain of various amplifiers, drift due to temperature effects, and digital run-off errors. Detailed descriptions of such errors are discussed in the section of data acquisition system. The errors introduced by the data acquisition system were 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 variables. The errors included are in:

1. Absolute pressure measurement using pressure transducer.
2. Differential pressure measurement using pressure transducer.
3. Temperature measurement using RTD.
4. Flow rate using turbine flow meter.
5. Voltage measurement.
6. Current measurement.
7. Dimension measurements.
8. Power measurement (calculation).

In combining errors, the basic approach recommended by Kline and McClintock (1953) will be used. The uncertainty interval, dR , of a dependent variable, $R = r(v_1, v_2, \dots, v_n)$ is given by:

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

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

The magnitude of the estimated errors presented here is assumed to be a reasonable approximation of the largest error possible. More precisely, these errors are assumed to be equal to double the standard deviation of that which would be computed from a 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

The total error in pressure measured by the absolute pressure transducers consists of:

- a) Accuracy of the instrument and excitation voltage stated by the manufacturer as 0.112% of full scale (200 psi).
- b) Error in the line from the source to the multiplexer digitizer. This was measured to be 0.304% of the reading.
- c) Error in the multiplexer digitizer (0.005 V)

The following table presents the uncertainty in absolute pressure measurement:

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

4.2.2 Uncertainty in Differential Pressure Measurement

The total error in pressure measured by the differential pressure transducers consists of:

- a) Accuracy of the instrument and excitation voltage stated by the manufacturer as 0.112% of full scale.
- b) Error in the line from the source to the multiplexer digitizer measured to be 0.304% of the signal.
- c) Error in the multiplexer digitizer (0.005 V)

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

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

4.2.3 Uncertainty in Temperature Measurement

The total error in temperature measured by the RTDs consists of:

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

The following table presents the uncertainty in temperature measurement:

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

4.2.4 Uncertainty in Flowrate Measurement

The total error in flow rate measured by the turbine flowmeters consists of:

- a) Accuracy of the instrument and Anadex frequency converter stated by the manufacturer as 0.5106% of full scale (60 GPM).
- b) Error in the line from the Anadex output to the multiplexer digitizer measured to be 0.200% of the reading.
- c) Error in the multiplexer digitizer (0.005 V)

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

4.2.5 Uncertainty in Test Section Voltage Measurement

The total error in the test section voltage measurements consists of:

- a) Accuracy of the voltage divider stated by the manufacturer as 0.050% of the reading.
- b) Error in the line from the source to the multiplexer digitize, measured to be 0.304% of the reading.

The foll

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

4.2.6 Uncertainty in Test Section Current Measurement

Total error in test section current measurement consists of:

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

The following table presents the uncertainty in the current measurement:

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

4.2.7 Uncertainty in Test Section Dimensional Measurement

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

Test Section	ID	Heated length	Pressure Tap Separation
	(inch)	(inch)	(inch)
ST-9	0.0015	0.038	0.058

4.2.8 Uncertainty in Test Section Power Calculation

The uncertainty in the calculated power is directly related to the uncertainties in current and voltage. The uncertainty in the calculated heat flux relates to the uncertainties in calculated power and heat transfer area. The actual heat transfer area varies because of thermal expansion so all heat flux calculations are based on the area measured at room temperature.

5. RESULTS

5.1 Experimental Results

For the sake of brevity, the data points obtained in these tests are referred to as CHF points. Whether these data points represent CHF points or flow instabilities, they represent the maximum heat flux that was obtainable with the given conditions, equipment, and operational technique. It is not even clear that CHF and flow instability can always be separated. The results are summarized in Table 5.1.1 which presents the average values of the more important test parameters and in Table 5.1.2 which presents the standard deviations of these variables. The averages were taken over the 40 scans (approximately 3.86 seconds, 10.36 scans/sec) preceding the transient where the parameters were still practically steady. In all, 28 CHF points were obtained.

All runs were terminated by a thermocouple trip except for Test No. C0327A where physical burnout occurred at approximately 1" from the end of the heated length. A brazed K-type thermocouple was located within a few inches of the burnout point but failed to show a temperature excursion as can be seen from Figure A.2, Appendix A, page A.2. The more slowly responding E-type, cemented thermocouples do show the temperature excursion. One possible explanation is that the brazed thermocouples became detached from the tube wall at some point prior to burnout. Up to this time only three brazed thermocouples were connected to power trips. In all subsequent tests all thermocouples were connected to the Metrascopes and set to trip on a temperature excursion. Note that the very high (over 1200 °F) and very low (below 400°F) thermocouple readings indicate damaged thermocouples.

In another test, C0718C, a defective thermocouple caused a premature power trip and this point has been omitted. In almost all cases a sharp rise in one or more wall temperatures immediately precedes the power trip but in a few cases this temperature excursion is very small or barely perceptible and, in one case, imperceptible. Frequently, the flow drops at approximately the same time that the temperature excursion occurs.

Summary of CHF Test Results

Averages for Forty (40) Scans (10.36 scans/sec)

Test No. C0327A is First(A) CHF Test (C) on 03/27/1990, etc.

Test No.	Scan No.	Pout psig	Tin deg F	Tout deg F	Flow gpm	Quality %	MBtu/hr /sqft	del P1 psi	delP2 psi
C0320C	1371.5	52.4	66.3	291.3	15.17	0.85	1.44	18.31	18.48
C0327A	1457.5	43.3	73.6	273.7	20.11	-1.33	1.61	17.10	18.63
C0515A	659.5	62.4	67.0	295.4	5.34	23.57	0.93	22.61	30.07
C0515B	619.5	67.0	66.0	297.9	6.98	17.09	1.08	24.44	36.45
C0515C	200.5	60.7	73.9	299.2	13.61	1.61	1.30	18.14	19.41
C0515D	860.5	43.8	73.5	276.2	20.26	-0.81	1.64	21.24	22.47
C0525A	1240.5	69.7	73.7	297.6	7.63	17.05	1.16	25.06	38.71
C0525B	290.5	44.9	77.5	266.5	20.69	-2.09	1.56	12.24	13.29
C0525C	740.5	50.3	79.5	293.8	16.42	1.15	1.45	19.08	20.32
C0525D	565.5	55.3	71.5	294.7	12.66	3.23	1.27	19.74	22.05
C0525E	1220.5	53.8	114.1	299.1	18.31	1.16	1.39	21.48	22.44
C0525F	490.5	52.7	123.5	298.2	16.61	1.06	1.18	17.99	17.98
C0525G	1510.5	59.4	118.6	298.4	15.41	2.08	1.22	20.90	21.37
C0530A	320.5	53.7	101.5	294.4	14.96	1.64	1.23	17.23	0.00
C0530B	2180.5	71.1	106.7	295.6	5.80	25.83	0.98	24.67	0.00
C0530C	620.5	64.0	99.9	295.0	8.87	12.46	1.10	24.78	1.96
C0530D	920.5	54.8	101.9	296.8	17.38	1.36	1.42	21.00	1.84
C0530E	1160.5	46.2	103.0	288.3	23.18	0.17	1.71	24.83	0.47
C0530F	821.5	37.9	121.5	276.6	25.30	-0.29	1.55	24.65	0.44
C0530G	1600.5	37.9	92.7	273.4	25.03	-0.40	1.80	23.90	0.48
C0530H	980.5	31.0	74.0	265.7	17.38	0.80	1.39	19.58	0.25
C0530I	1370.5	49.0	69.0	263.1	6.01	20.49	0.96	24.11	0.39
C0530J	61.5	31.3	68.7	265.2	13.26	1.50	1.13	14.55	0.22
C0530K	665.5	31.2	75.5	268.1	21.98	0.22	1.71	24.49	25.90
C0718A	2910.5	55.3	158.1	259.3	6.12	20.79	0.77	25.38	0.00
C0718B	1190.5	57.0	167.5	259.9	9.65	11.32	0.87	25.51	0.00
C0718C	840.5	16.0	162.5	247.6	25.4	-0.03	0.85	20.0	0.00
C0718D	1520.5	59.0	169.0	261.4	8.93	13.47	0.87	25.21	0.00
C0718E	3620.5	93.6	173.0	318.1	8.87	17.44	1.05	24.36	0.00

Table 5.1.1. Summary of Average Values (of 40 scans) for CHF Tests.

Summary of CHF Test Results

Averages for Forty (40) Scans (10.36 scans/sec)

Test No. C0327A is First(A) CHF Test (C) on 03/27/1990, etc.

K07N = Type K Thermocouple, 7" from end of heated length, Orientation North

"Inconel 600 Tube, 0.612" ID"

	E13W	E13E	E10N	E10S	E07W	E07E	E04N	E04S	E01W	E01E	K07N	K04E	K01S
C0320C	688	704	695	598	654	696	688	1438	1517	745	711	740	0
C0327A	745	743	739	669	707	729	723	0	0	775	738	757	0

"Inconel 625 Tube, 0.623" ID"

	E15E	E12N	E12S	E08W	E08E	E04N	E04S	E01W	E01E	K14N	K10S	K05N	K01S
C0515A	655	663	654	647	64	64	639	565	644	712	645	660	756
C0515B	720	723	714	705	64	64	700	618	701	773	705	720	839
C0515C	782	793	779	766	64	64	761	703	763	829	783	792	909
C0515D	867	867	855	844	64	64	839	762	849	905	846	871	1019
C0525A	746	741	737	732	104	706	728	683	735	768	729	754	877
C0525B	837	853	845	830	64	799	828	770	836	858	846	857	1000
C0525C	818	828	815	801	101	773	798	741	807	830	816	829	965
C0525D	758	769	760	754	96	725	748	682	757	778	756	786	905
C0525E	802	813	802	795	177	766	790	741	798	826	802	822	951
C0525F	745	742	730	731	140	704	723	674	730	767	729	757	786
C0525G	767	766	755	754	161	724	746	706	751	782	751	772	798
C0530A	751	746	739	739	186	705	728	689	733	786	733	784	805
C0530B	681	685	682	680	100	655	675	640	682	697	677	708	747
C0530C	740	735	727	722	105	690	712	674	714	752	714	735	757
C0530D	815	816	809	801	312	764	791	755	795	839	810	842	854
C0530E	888	886	878	880	87	840	870	838	873	902	869	910	925
C0530F	833	841	826	826	109	788	818	788	818	758	822	366	869
C0530G	898	910	899	889	65	847	881	846	889	929	888	358	934
C0530H	768	772	771	758	125	721	745	709	753	391	763	308	469
C0530I	658	661	658	654	72	625	644	616	648	562	653	275	425
C0530J	693	696	693	690	89	659	679	640	691	460	689	270	421
C0530K	856	862	858	841	154	799	825	786	844	843	851	327	490
C0718A	607	597	600	602	64	546	589	596	590	305	680	666	698
C0718B	649	641	643	645	64	64	632	632	630	62	725	705	975
C0718C	609	614	608	613	64	64	602	601	598	62	696	680	1528
C0718D	654	652	648	649	64	64	640	639	636	68	726	710	1552
C0718E	712	713	704	707	64	64	696	697	691	801	765	786	2499

Table 5.1.1(cont'd). Summary of Average Values (of 40 scans) for CHF Tests.

Summary of CHF Test Results

Standard Deviations for Forty (40) Scans (10.36 scans/sec)
Test No. C0327A is First(A) CHF Test (C) on 03/27/1990, etc.

Test No.	Scan No.	Pout psig	Tin deg F	Tout deg F	Flow gpm	Quality %	MBtu/hr/sqft	del P1 psi	delP2 psi
C0320C	11.7	4.1	0.3	4.4	0.30	0.66	0.027	2.5	4.9
C0327A	11.7	7.4	0.2	0.2	0.02	0.92	0.012	8.1	12.0
C0515A	11.7	10.9	0.1	2.9	0.16	1.84	0.004	5.4	13.5
C0515B	11.7	11.8	0.2	2.1	0.26	1.84	0.004	2.7	14.1
C0515C	11.7	5.1	0.3	0.4	0.34	0.88	0.009	4.6	5.6
C0515D	11.7	4.7	0.2	0.4	0.11	0.60	0.008	4.4	5.4
C0525A	11.7	9.8	0.3	2.3	0.26	1.97	0.010	1.9	11.4
C0525B	11.7	6.1	0.0	0.2	0.02	0.74	0.013	8.3	11.8
C0525C	11.7	3.3	0.1	1.8	0.35	0.50	0.012	3.7	4.8
C0525D	11.7	5.1	0.0	0.2	0.15	0.64	0.008	5.0	8.6
C0525E	11.7	2.2	0.2	0.4	0.06	0.25	0.009	2.9	4.2
C0525F	11.7	2.3	0.1	0.2	0.11	0.30	0.009	3.1	3.9
C0525G	11.7	3.7	0.2	0.3	0.04	0.47	0.008	3.4	6.1
C0530A	11.7	3.7	0.0	4.8	0.43	0.63	0.009	3.5	0.0
C0530B	11.7	11.1	0.2	2.8	0.26	2.36	0.011	1.6	0.0
C0530C	11.7	8.2	0.2	1.3	0.07	0.91	0.011	2.4	0.1
C0530D	11.7	3.4	0.2	0.2	0.15	0.47	0.011	2.9	0.1
C0530E	11.7	2.6	0.0	0.9	0.09	0.37	0.012	1.0	0.0
C0530F	11.7	2.0	0.0	0.2	0.04	0.28	0.015	1.4	0.0
C0530G	11.7	3.4	0.5	1.1	0.08	0.46	0.013	2.6	0.0
C0530H	11.7	1.8	0.0	0.2	0.12	0.43	0.014	3.0	0.0
C0530I	11.7	12.8	0.1	0.7	0.13	1.87	0.011	3.1	0.0
C0530J	11.7	2.3	0.2	0.4	0.08	0.38	0.011	4.0	0.0
C0530K	11.7	2.1	0.2	0.3	0.11	0.35	0.014	1.4	3.2
C0718A	11.7	6.3	0.2	4.0	0.08	0.67	0.005	1.7	0.0
C0718B	11.7	5.1	0.1	4.6	0.27	0.96	0.005	0.9	0.0
C0718C	11.7	0.4	0.0	0.2	0.05	0.09	0.007	2.3	0.0
C0718D	11.7	4.6	0.1	4.3	0.13	0.63	0.005	1.9	0.0
C0718E	11.7	15.7	0.0	1.7	0.50	2.52	0.005	4.5	0.0

Table 5.1.2. Summary of Standard Deviations (of 40 scans) for CHF Tests.

Summary of CHF Test Results

Standard Deviations for Forty (40) Scans (10.36 scans/sec)

Test No. C0327A is First(A) CHF Test (C) on 03/27/1990, etc.

K07N = Type K Thermocouple, 7" from end of heated length, Orientation North

	E13W	E13E	E10N	E10S	E07W	E07E	E04N	E04S	E01W	E01E	K07N	K04E	K01S
C0320C	1	2	2	1	1	2	2	27	30	13	10	12	0
C0327A	1	1	1	1	1	1	1	0	0	7	10	8	0
	E15E	E12N	E12S	E08W	E08E	E04N	E04S	E01W	E01E	K14N	K10S	K05N	K01S
C0515A	1	1	1	1	0	0	1	2	1	7	5	6	5
C0515B	1	2	2	1	0	0	1	2	3	6	6	5	5
C0515C	1	1	1	2	2	0	2	1	2	7	7	7	7
C0515D	1	2	1	1	0	0	1	2	1	6	4	4	4
C0525A	1	2	1	1	32	1	1	1	3	6	7	7	7
C0525B	2	1	1	1	0	1	1	1	1	7	6	6	3
C0525C	1	2	1	1	42	1	1	1	1	9	6	7	8
C0525D	1	2	1	1	8	1	1	1	1	10	9	9	8
C0525E	1	2	1	1	13	1	1	1	1	8	9	9	7
C0525F	1	2	0	1	12	1	1	1	1	9	8	9	8
C0525G	1	2	1	1	11	1	1	1	1	7	7	8	6
C0530A	3	3	3	2	82	2	2	1	3	13	5	13	9
C0530B	1	2	1	1	44	1	1	1	1	8	6	10	27
C0530C	1	2	0	1	46	0	1	1	1	7	6	9	5
C0530D	1	2	1	1	20	1	1	1	1	8	7	9	5
C0530E	1	2	1	1	15	1	1	1	1	7	5	6	5
C0530F	1	1	1	0	16	1	1	1	1	109	5	1	5
C0530G	1	2	0	1	2	1	1	1	1	9	6	1	4
C0530H	1	2	1	1	18	1	1	1	2	190	8	1	1
C0530I	1	1	1	0	18	0	1	1	2	145	5	2	2
C0530J	1	2	1	0	18	1	1	1	1	188	9	1	2
C0530K	2	2	1	1	16	1	1	1	1	45	11	1	2
C0718A	1	1	1	1	0	1	1	1	1	83	7	7	7
C0718B	0	0	1	0	0	0	0	1	0	0	7	9	7
C0718C	1	1	1	0	0	0	1	1	0	1	7	8	9
C0718D	0	0	0	0	0	0	0	0	0	15	7	7	7
C0718E	0	0	0	0	0	0	0	2	0	147	8	9	0

Table 5.1.2(cont'd). Summary of Standard Deviations (of 40 scans) for CHF Tests.

Test No.	Scan No. at				TC with Max Temp	Temp. oF		Relative to Power Trip Scan No. of		CHF MBtu/hr /sqft
	Avg. of 40 scans	Power Trip	Flow Min.	Max. Temp		40 scan average	Max	Flow Min	Max Temp.	
C0320C	1371.5	1442	1435	1446	K07N	711	1434	-7	4	1.44
C0327A	1457.5	1553	1553	1553	E04N	723	887	0	0	1.61
C0515A	659.5	694	687	693	K01S	756	942	-7	-1	0.93
C0515B	619.5	662	652	661	K01S	839	1072	-10	-1	1.08
C0515C	200.5	252	249	251	K01S	909	1180	-3	-1	1.30
C0515D	860.5	911	911	910	K01S	1019	1051	0	-1	1.64
C0525A	1240.5	1277	1274	1276	K01S	877	1091	-3	-1	1.16
C0525B	290.5	322	319	318	K01S	1000	1016	-3	-4	1.56
C0525C	740.5	804	802	802	K01S	965	1134	-2	-2	1.45
C0525D	565.5	681	679	680	K01S	905	1238	-2	-1	1.27
C0525E	1220.5	1278	1273	1278	K01S	951	1259	-5	0	1.39
C0525F	490.5	662	657	666	K01S	786	1060	-5	4	1.18
C0525G	1510.5	1715	1711	1719	K01S	802	1043	-4	4	1.22
C0530A	320.5	405	400	406	K05N	793	995	-5	1	1.23
C0530B	2180.5	2207	2206	2209	K01S	747	1068	-1	2	0.98
C0530C	620.5	695	691	701	K01S	757	1142	-4	6	1.10
C0530D	920.5	979	974	980	K05N	842	1106	-5	1	1.42
C0530E	1160.5	1248	1243	1250	K14N	905	1210	-5	2	1.71
C0530F	821.5	940	934	941	K01S	869	1113	-6	1	1.55
C0530G	1600.5	1705	1699	1707	K14N	929	1270	-6	2	1.80
C0530H	980.5	1073	1067	1078	K10S	763	836	-6	5	1.39
C0530I	1370.5	1438	1425	1455	E01E	648	1148	-13	17	0.96
C0530J	61.5	170	167	186	E01E	691	738	-3	16	1.13
C0530K	665.5	727	721	730	K14N	826	1068	-6	3	1.71
C0718A	2910.5	2941	2940	2939	K01S	698	704	-1	-2	0.77
C0718B	1190.5	1255	1249	1254	K01S	975	1680	-6	-1	0.87
C0718D	1520.5	1623	1599	1624	K05N	710	1586	-24	1	0.87
C0718E	3620.5	3709	3699	3732	E01W	697	1007	-10	23	1.05

Table 5.1.3. Notes on CHF Transients.

It is also possible that some of the power trips were caused by either noise or erratic thermocouples. However, all points are included unless there was good cause for exclusion (as in the case of C0718C which was strongly suspected to be erroneous at the time of the test). In any case, the "CHF" values would be conservative lower limits.

Appendix A contains graphs showing heat flux, flow rate, quality (which is calculated from heat flux, flow rate, inlet temperature, and pressure), and four wall thermocouples for scans immediately preceding (including the scans used for averaging) and following the power trip. Where possible, the brazed K-type thermocouples (which have the faster response times) are displayed, but the severe conditions of these tests caused damage to a number of thermocouples.

Some of the graphs in Appendix A show features worth examining in more detail. In many, but not all, cases, the flow drops abruptly just prior to the power trip and at approximately the same time as the thermocouple excursions. In a significant number of tests this flow recovers, or starts to recover, before the power trip. Some tests show steady oscillations in flow rate and other parameters. These phenomena appear most clearly in Test No. C0718D (Figures A.27 and A.28). In this test the flow rate increases 24 scans (2.3 seconds) before the power trip. Corresponding to the flow increase, the outlet pressure decreases, the fluid outlet temperature decreases, and some thermocouples show a dramatic rise in wall temperature as if heat transfer were reduced practically to zero. It appears that part of the tube wall has been blanketed with an insulating layer of steam while the water flows down the center of the pipe. The cause of the oscillations in flow, exit temperature, etc., are not known but a plausible conjecture is that they are a result of fluctuations in steam production caused by partial blanketing of the tube wall by steam, followed by rewetting of the wall, followed by blanketing again, etc..

A brief summary of the sequence of events for each run is shown in Table 5.1.3. The scan number at which the minimum flow occurs relative to the scan number at which the power tripped is shown in this table. None of these numbers is positive indicating that the minimum flow occurred at or before the power trip. In some cases the time interval is substantial, 10 or more scans (10.4 scans/sec). The maximum temperature generally occurs close to the power trip for the brazed (type K) thermocouples and significantly later for the slower, cemented (type E) thermocouples. In most cases, the maximum temperature is at the end of the heated length but, in a few runs the maximum temperature is 14" from the end.

In Table 5.1.1, the pressure drops across the test section, measured by DPT1 and denoted by ΔP_1 , average 21.5 psi with a standard deviation of 3.6 psi. This is a result of saturation of the pressure transducer. This particular transducer was set on a 20 psi scale and cuts off at pressure drops greater than 25 psi. The column labeled ΔP_2 shows the readings of the backup differential pressure transducer, DPT2, and indicates pressure drops up to 39 psi but this transducer was not operational after 5/25/90; i.e., for runs numbers C0530A and beyond, with the exception of run number C0530K. Not all test parameters were stored in the transient mode of operation and, in particular the test section inlet pressure was not stored. Consequently the pressure drop can not be determined reliably for most runs beyond C0525G.

The fluid outlet temperatures, as measured by RTDs, are from 2 to 45 °F less than the saturation temperatures even though in many cases the thermodynamic outlet quality is positive. Since the RTDs are known to be accurate to at least one degree Fahrenheit these measured values must relate to the temperature of something. The most plausible hypothesis is that the RTD is indicating the temperature of the condensed phase (liquid water). It is known that OSV occurs at negative equilibrium qualities where the bulk average equilibrium temperature is well below saturation. In other words, these systems are far from equilibrium. For a tube of this size (0.61" ID, 96" heated length), both from direct experimentation¹ and from the Saha-Zuber correlation², OSV is known to occur when

$$\begin{aligned} q''_{\text{sat}}/q''_{\text{osv}} &= 1 + D/4LS \\ (T_s - T_i)/(T_o - T_i) &= 1.24 \end{aligned}$$

where S represents the value of the Stanton number at OSV ($S = 0.0065$ for Peclet number $> 70,000$), T represents the temperature, and the subscripts o , s , and i represent outlet, saturation, and inlet, respectively. For an inlet temperature of 77 °F and a saturation temperature of 298 °F (50 psig), the calculated outlet temperature is 255 °F, which represents 43 °F sub cooling. Thus steam is produced when the bulk average water temperature is 43 °F below saturation, so our hypothesis is not at all unreasonable.

Apart from the sources of uncertainty discussed earlier in Chapter 4 of this report, there are other sources of error worth mentioning. The two major problems relate to the heat flux and to the flow rate. The heat flux is calculated from the measured voltage,

current, and heat transfer area. This assumes that all of the energy input is delivered to the fluid. No correction was made for heat losses. Judging from steady state measurements in single phase flow where accurate heat balances can be determined, a reasonable estimate of heat loss would be less than two percent. No corrections were made for thermal expansion. The heat transfer area was calculated from dimensions measured at room temperature. Since the power in these tests was gradually increased at a rate corresponding to approximately 0.1 MBtu/hr/sqft each minute, the energy stored in the heater tube is not exactly constant. These errors would make all of the heat flux values high by possibly four percent. However since the heat flux steps are not negligible, the last stable condition might be at a heat flux value from 0 to 5 percent lower than the true CHF.

One of the greatest sources of error is the flow rate, both because of the measurement uncertainty and the uncertainty in determining the flow rate at which CHF occurs and in the corresponding value of q''_{sat} . The error in the flow rate is the dominant contribution to the error in q''_{sat} . The measurement uncertainty (0.32 gpm) alone represents an uncertainty of 1 to 6 percent which gives rise to a similar uncertainty in q''_{sat} .

5.2 Correlation of Experimental Results

The data are correlated reasonably well (std. dev. = 0.062) by the equation

$$q''_{CHF} = m \cdot q''_{sat} + b \quad (m = 0.587, b = 0.632) \quad (5.2.1)$$

where q''_{CHF} is the critical heat flux and q''_{sat} is the heat flux required to bring the fluid to saturation at the test section outlet pressure, both in MBtu/hr/ft². This fitted line and the data are shown in Figure 5.2.1 and summarized in Table 5.2.1. A standard deviation of 0.062 is probably as good as can be expected for this data.

HTRF Data, 28 points, L = 96 in., 46 to 109 psia, 1.3 to 6.9 Mlb/hr/sqft
Inlet Subcooling = 136 to 249 Btu/lb, Exit Quality = -2.1 to 26.6%

Figure 5.2.1. Low Pressure HTRF Data for Water in Vertical Down-Flow.

	Test	Pout psig	Tin deg F	Flow gpm	Tsat deg F	Heat Flux q'' , MBtu/hr/sqft			
						sat	meas	calc	diff
1	C0320C	52.4	66.3	15.17	300.1	1.39	1.44	1.45	-0.01
2	C0327A	43.3	73.6	20.11	290.5	1.71	1.61	1.63	-0.02
3	C0515A	62.4	67.0	5.34	309.3	0.50	0.93	0.92	0.01
4	C0515B	67.0	66.0	6.98	313.3	0.66	1.08	1.02	0.05
5	C0515C	60.7	73.9	13.61	307.9	1.22	1.30	1.35	-0.05
6	C0515D	43.8	73.5	20.26	291.2	1.69	1.64	1.63	0.01
7	C0525A	69.7	73.7	7.63	315.5	0.71	1.16	1.05	0.11
8	C0525B	44.9	77.5	20.69	292.4	1.71	1.56	1.63	-0.08
9	C0525C	50.3	79.5	16.42	298.0	1.38	1.45	1.44	0.01
10	C0525D	55.3	71.5	12.66	302.8	1.13	1.27	1.29	-0.02
11	C0525E	53.8	114.1	18.31	301.5	1.31	1.39	1.40	-0.01
12	C0525F	52.7	123.5	16.61	300.3	1.12	1.18	1.29	-0.11
13	C0525G	59.4	118.6	15.41	306.7	1.08	1.22	1.26	-0.04
14	C0530A	53.7	101.5	14.96	301.3	1.12	1.23	1.29	-0.05
15	C0530B	71.1	106.7	5.80	316.7	0.47	0.98	0.91	0.07
16	C0530C	64.0	99.9	8.87	310.8	0.72	1.10	1.05	0.05
17	C0530D	54.8	101.9	17.38	302.4	1.34	1.42	1.42	0.00
18	C0530E	46.2	103.0	23.18	293.7	1.69	1.71	1.63	0.08
19	C0530F	37.9	121.5	25.30	284.4	1.57	1.55	1.55	-0.01
20	C0530G	37.9	92.7	25.03	284.3	1.84	1.80	1.71	0.09
21	C0530H	31.0	74.0	17.38	275.5	1.34	1.39	1.42	-0.03
22	C0530I	49.0	69.0	6.01	296.6	0.53	0.96	0.94	0.02
23	C0530J	31.3	68.7	13.26	276.0	1.06	1.13	1.25	-0.12
24	C0530K	31.2	75.5	21.98	275.9	1.69	1.71	1.62	0.08
25	C0718A	55.3	158.1	6.12	302.8	0.34	0.77	0.83	-0.06
26	C0718B	57.0	167.5	9.65	304.4	0.50	0.87	0.93	-0.06
27	C0718D	59.0	169.0	8.93	306.3	0.46	0.87	0.90	-0.03
28	C0718E	93.6	173.0	8.87	333.0	0.54	1.05	0.95	0.10

Table 5.2.1. Correlation of Critical Heat Flux with q''_{sat} .

At first glance this equation appears to specify non-local dependence for CHF because of the dependence on the inlet temperature which appears in q''_{sat} . However this result can be rearranged into the equivalent form

$$q''_{\text{CHF}} = A - B \cdot H_{\text{fg}} \cdot G \cdot X \quad (5.2.2)$$

where G is the mass flux, H_{fg} is the heat of vaporization, and X is the thermodynamic quality, and A and B are related to b and m by

$$m = l/(1 + l) \quad b = A(1 - m) = A/(1 + l) \quad (5.2.3)$$

where $l = 4BL/D$, L is the heated length and D is the inside diameter. If A and B depend on local variables only then this correlation is a local correlation and b and m must depend on length as specified in equation 5.2.3. If B is negative then upstream burnout must occur unless B decreases with increasing length. Assuming that upstream burnout does not occur in uniform tubes, then, it is necessary, but not sufficient, that B be positive to obtain a local correlation. Note that requiring that B be a positive number requires that the slope, m , be between 0 and 1. A stronger upper bound for m is given in the next section. Upstream burnout in a uniform tube would appear to be very improbable in vertical upflow, although conceivable in vertical downflow. In any case, it is unlikely that such a phenomenon would be governed by a local correlation. This form of the equation is best suited for physical interpretation but not well suited for data analysis since the variable X is not an independent variable.

Equation 5.2.2 suggests that CHF is primarily determined by the mass flux of steam generated. Although this interpretation might appear reasonable for positive exit qualities, such an interpretation appears more dubious in general since the equilibrium quality, X_e , is not a direct measure of the true mass quality, X_t . A simple kinetic model is presented below, in section 5.3, which yields a linear relation between $G \cdot X$ and $(G \cdot X_e)^{1/2}$ for small values of X_t .

Since only one length of tube was employed, it is not possible, from these data, to determine whether the correlation is local or nonlocal. Because of the limited amount of data and the limited range of exit pressures, the exact dependence on pressure is difficult to ascertain. The correlation of the data indicates that, except for the effect of pressure on q''_{sat} (effect on saturation enthalpy) the effect of pressure is small in this low pressure region. Comparison of these data with Swedish data at low pressures (section 5.4 of this report) sheds some light on these questions but does not settle these issues.

5.3 A Simple Kinetic Model of Vaporization

The correlation developed in this investigation suggests that CHF is determined principally by the local mass flux of steam at the point of CHF. Consistency with this interpretation, requires that the present correlation be written in the form

$$q''_{\text{CHF}} = \alpha - \beta \cdot H_{\text{fg}} \cdot G \cdot (X - X_{\text{OSV}}) \quad (5.3.1)$$

The Saha-Zuber correlation² (a local correlation) yields, for Peclet number greater than 70,000,

$$q''_{\text{CHF}} = -S \cdot H_{\text{fg}} \cdot G \cdot X_{\text{OSV}} \quad (5.3.2)$$

where $S = 0.0065$ is the value of the Stanton number at OSV. Stanton number and Peclet number are defined as

$$\text{St} = q'' / (G \cdot (H_{\text{sat}} - H_{\text{f}})) \quad \text{Pe} = G \cdot D \cdot c_{\text{pf}} / k_{\text{f}} \quad (5.3.3)$$

These equations can be rearranged into the equivalent form (given above)

$$q''_{\text{CHF}} = A - B \cdot H_{\text{fg}} \cdot G \cdot X \quad (5.3.4)$$

where

$$A = \alpha / (1 + \beta/S) \quad B/S = (\beta/S) / (1 + \beta/S) \quad (5.3.5)$$

If β is positive then B must be less than S which yields for the slope, m , in equation (5.2.1) an improved upper limit.

$$0 < m < (1 + D/4LS)^{-1} < 1 \quad (5.3.6)$$

A second inference is that this simple form might not apply for Peclet numbers less than 70,000 which, for a particular pressure (or saturation temperature) places a lower limit on the admissible flow rates. Although equation (5.3.1) is the more fundamental form of the correlation, it is poorly suited to data analysis. Equation (5.3.4) is preferable for data analysis, but equation (5.2.1) is better yet.

For all values of Peclet number, the Saha-Zuber correlation yields

$$q''_{\text{CHF}} = -S \cdot H_{\text{fg}} \cdot G \cdot X_{\text{OSV}} / \{ \text{Pe} / 70000 \} \quad (5.3.9)$$

where the brackets signify

$$\begin{aligned} \{x\} &= x \text{ for } x \leq 1 \\ &= 1 \text{ for } x > 1 \end{aligned} \quad (5.3.10)$$

and thus

$$A = \alpha / (1 + \beta \cdot \{ \text{Pe} / 70000 \} / S) \quad B/S = (\beta/S) (1 + \beta \cdot \{ \text{Pe} / 70000 \} / S) \quad (5.3.11)$$

Whether this modification yields any improvement in the goodness of fit is not known at this time.

The results of this investigation suggest that CHF is determined principally by the local mass flux of steam at the point of CHF. Even if, as seems plausible, CHF is determined by local conditions at the point where CHF occurs, these local conditions might not be related in any simple way to the directly determinable experimental parameters. In fact, these local conditions might not depend on these parameters in a local manner. To elucidate these points and to test the hypothesis that the local steam mass flux is the principal variable determining CHF, it is necessary to make some estimate of the true mass flux of steam.

The initial attempt in this direction used the relationship proposed by Kroger and Zuber³ and the results were encouraging. The Kroger-Zuber correlation relates the true mass fraction of steam, X_t , to the equilibrium quality, X , and, X_{OSV} the quality at OSV (which was obtained from the Saha-Zuber correlation).

$$X_t = [X - X_{OSV} \cdot \exp(-1 + X/X_{OSV})] / [1 - X_{OSV} \cdot \exp(-1 + X/X_{OSV})] \quad (5.3.12)$$

There are three important limitations to this approach: (1) the Saha-Zuber correlation has not been tested at pressures above 1500 psia and appears to fail at very high pressure; (2) the Kroger-Zuber relation does not yield a direct relationship between $G \cdot X$ and $G \cdot X_t$ for small values of X_t ; (3) the Kroger-Zuber relation is a static, rather than kinetic correlation and consequently can not deal with conditions where the inlet quality, although less than zero, is greater than X_{OSV} , since inlet quality does not appear in that relation which, consequently, predicts a non zero value for X_t at the tube inlet.

The simple kinetic model proposed here is based on the following assumed equation for the rate of vaporization:

$$H_{fg} \cdot dM_v = S \cdot G \cdot (H_f - H_{OSV}) \cdot \pi \cdot D \cdot dz \quad (5.3.13)$$

where M_v represents mass flow rate of vapor and z represents distance along the tube. This equation is purely a hypothesis and must be judged on its value in interpreting experimental results, but it has not been chosen arbitrarily and is closely related to the Saha-Zuber correlation for OSV, which is the reason that the rate constant is denoted by the same symbol "S", the Stanton number at OSV.

Assuming that the specific enthalpy of the steam is constant at its saturation value and using the usual conservation laws, the following pair of coupled non linear differential equations are obtained:

$$dX_t/dX = \Theta \quad \Theta = (H_f - H_{Osv})/(H_g - H_{Osv}) \quad (5.3.14)$$

$$(1 - X_t) * d\Theta/dX + (1 - \Theta - 1/X_{Osv}) * dX_t/dX = -1/X_{Osv} \quad (5.3.15)$$

For simplicity, only the case where the inlet quality is less than X_{Osv} is considered here. In that case, the appropriate initial conditions are

$$\Theta = 0, X_t = 0, \quad \text{for} \quad X = X_{Osv} \quad (5.3.16)$$

The solution is found to be

$$-\ln(1-t) = [\ln(1+X_{Osv}*V) + X_{Osv}*\ln(1+V/X_{Osv})]/[1 + X_{Osv}] \quad (5.3.17)$$

where

$$t = (X - X_{Osv})/(1 - X_{Osv}) \quad V = (t - X_t)/(1 - X_{Osv}) \quad (5.3.18)$$

Calculation of X_t from X using this equation is very cumbersome and makes data analysis difficult. A simpler expression, that gives a practically indistinguishable result and which has the same behavior in the limits as X approaches X_{Osv} and 1, is the following

$$X_t = a_1 * [\exp(-t) - 1 + t] / [1 + a_2 * t + a_3 * t * (1 - t) * \exp(-t * (1 - t))] \quad (5.3.19)$$

where

$$\begin{aligned} a_1 &= -(1 - X_{Osv})^2 / X_{Osv} & a_3 &= a_1 * (a_4 + 2 - e) / e - 1 \\ a_2 &= a_1 / e - 1 & a_4 &= 1 - X_{Osv} \quad \text{for } -X_{Osv} < 1 \\ & & a_4 &= 1 - 1/X_{Osv} \quad \text{for } -X_{Osv} > 1 \end{aligned} \quad (5.4.19)$$

As X approaches X_{Osv} (t approaches 0), X_t approaches zero as

$$X_t/X_{Osv} = (1 - X/X_{Osv})^2/2 \quad (5.3.20)$$

For the Kroger-Zuber correlation this limit is

$$X_t/X_{OSV} = (1 - X/X_{OSV})^2/[2*(1 - X_{OSV})] \quad (5.3.21)$$

Substituting into equation 5.3.1 the expression for $X - X_{OSV}$ obtained from equation 5.3.21 and using the Saha Zuber relation to eliminate X_{OSV} yields

$$q''_{CHF} = \alpha - (\beta/S)*[2*H_{fg}*G*X_t*q''_{CHF}]^{1/2} \quad (5.3.22)$$

which clearly demonstrates the functional dependence of q''_{CHF} on the variable $G*X_t$ for small X_t . Solving this quadratic equation for q''_{CHF} makes this dependence explicit (or more simply replace q''_{CHF} in the square root by α).

5.4 Correlation of CHF Data from Literature

In order to better understand the effects of pressure, length, and inlet conditions, an extensive survey and analysis of the data available in the literature was performed. To date thousands of data points have been analyzed over a wide range of pressures, flow rates, lengths, diameters, and inlet subcoolings. This work is not yet complete but even the results obtained so far would require a considerable amount of time and space to present in a coherent fashion. The results, when complete, will comprise part of a doctoral thesis to be submitted to Columbia University by T. Jafri. Only a brief summary of some of the more interesting and pertinent results will be discussed here.

It is convenient to separate the data into three regimes of pressure: low pressure (50 - 500 psia); medium pressure (500 - 1700 psia), and high pressure (1700 - 3000 psia). The low pressure regime, which is the most pertinent to the present work, will be considered in greatest detail. In the low and medium pressure regimes, OSV can be determined with reasonable reliability from the Saha-Zuber correlation and CHF occurs at exit qualities greater than the quality at which OSV is predicted by the Saha-Zuber correlation to occur. At high pressures this is not always the case. Thus, either the Saha-Zuber correlation is not accurate at high pressure, or some of the high pressure data is not reliable, or both. The remaining possibility is that, at high pressure, CHF can sometimes occur prior to the onset of significant void generation, although this would appear to be unlikely. In the low pressure region, there is little explicit dependence of CHF on pressure;

i.e., the effect of pressure appears principally in the saturation enthalpy. The explicit pressure dependence is stronger in the medium pressure region where the coefficient of G^*X ; i.e., B^*H_{fg} is almost directly proportional to pressure. It should be noted that $H_{fg}^*V_l/V_g$ is, to a very high degree of accuracy, directly proportional to pressure up to 2700 psia, then falling sharply to zero at the critical point.

For all pressures there are extensive regions where q''_{CHF} is a linear function of q''_{sat} . In fact, frequently there appear to be two linear regions, one at low values of q''_{sat} and another at higher values of q''_{sat} . Thus the data can be correlated over a wide range by the two linear equations:

$$q''_{CHF} = M^*q''_{sat} \quad M > 1 \quad q''_{sat} \leq q_1^* \quad (5.4.1)$$

$$q''_{CHF} = b + m^*q''_{sat} \quad b > 0, \quad 0 < m < 1 \quad q''_{sat} \geq q_2^* \quad (5.4.2)$$

Usually, but not always, the limiting values q_1^* and q_2^* are equal and these regions form a continuous curve. Under some conditions these domains overlap and the curves cross. The transition from one regime to the other is more or less gradual. In the low pressure regime, the parameters in these equations are only slightly dependent on pressure. The parameter M is practically independent of length and equation (5.4.1) represents a nonlocal correlation. The parameters b and m depend on length (i.e., L/D) as expected for a local correlation. In the medium pressure regime the pressure dependence is stronger. The range of variables in which this type of behavior obtained is at present uncertain since complete sets of data covering wide ranges of flow rates, subcoolings, tube lengths, and diameters are not available in abundance. It should be understood that the above remarks are generalizations which need not always apply at extreme values of flow rates, subcoolings, and tube dimensions.

Of course these equations can be expressed as linear functions of G^*X , as in equation 5.2.2.. In this form the local or nonlocal character is more obvious. The slope of the G^*X curve, $-B$, is positive when m , the slope of the q''_{CHF} vs. q''_{sat} line, is greater than one and negative when that slope, m , is less than one. A positive slope in the q''_{CHF} vs. G^*X plot of necessity implies a nonlocal correlation (assuming that upstream burnout does not exist) and the slope must decrease with increasing tube length, and this is observed to be the case. A negative slope is not necessarily local or nonlocal and the

correlation is local only if B (and, of course, the intercept A also) is independent of tube length, as it usually is when the slope is negative.

It is frequently observed that CHF is practically independent of inlet subcooling for low inlet subcoolings, depending principally on the mass flux, G , for a given tube and pressure, yielding a nonlocal correlation of a peculiar type, since mass flux is constant along the tube length. This generally occurs only for inlet subcoolings less than 100 °F but subcooling less than this does not necessarily give this behavior. The precise limits have not yet been determined for different pressures and tubes.

Figure 5.4.1 shows the low pressure Swedish⁴ CHF data for their tube with the largest I.D. (17.5 mm, 0.69 in.) plotted versus q''_{sat} . The Swedish report contains data for larger I.D. tubes exist but not in the low pressure range. The tube length was 2.50 m (98 in.). The data obtained in this investigation (0.61 in. I.D., 96 in. length) are plotted on the same graph for comparison. Figure 5.4.2 shows all of the low pressure Swedish data for their tubes with the next largest I.D. (13 mm, 0.51 in.) plotted, along with the HTRF data, versus q''_{sat} . Several interesting points emerge from these figures. Firstly, the HTRF and Swedish data complement each other very well. Secondly, the Swedish data for the 13 mm I.D. tubes contains 543 data points, for a range of pressures of 100 to 520 psia and tube lengths of 0.6 - 3.0 m (24 - 120 in.), all of which lie nearly on a single curve with slope, m , almost always greater than one. It is clear that this correlation for the Swedish data is nonlocal. The same type of behavior is found for all of the low pressure Swedish data. The HTRF data lie mostly at higher values of q''_{sat} and the slope is generally less than one.

This approach was also applied to previously published data in the medium pressure range (Swedish⁴, Griffel⁵, Lee and Obertelli⁶, USSR⁷) with reasonable success. Collectively, these data covered a wide range of tube lengths, diameters, flow rates, and inlet subcoolings. Unfortunately, the USSR data does not include important information, such as tube length and inlet subcooling, needed to determine the limits of local behavior and to calculate q''_{sat} , therefore it is necessary to assume a local correlation. The Swedish, Griffel, and Lee-Obertelli data do contain this information and in these cases the local or nonlocal character of the correlation can be determined. The Griffel and Lee-Obertelli data are practically all in the local range so only the Swedish data can be used to illustrate nonlocal behavior. Fig. 5.4.3 shows some of the Swedish data plotted versus q''_{sat} which exhibits both local and nonlocal behavior. A similar plot for the USSR data can not be

made since information relating to tube length and inlet subcooling is not available. Figure 5.4.4 shows all of the USSR data (8 mm I.D.) for the medium pressure range as a function of $(PGX_t)^{1/2}$ which yields what appears to be a universal curve which is linear for small values of this variable.

At present, it is not possible to calculate X_t with any confidence, for pressures above 1500 psia. At pressures above 1700 psia, the exit quality at CHF is sometimes less than X_{OSV} as calculated from the Saha-Zuber correlation. In order to avoid such problems it is necessary to assume that S , the value of the Stanton Number at OSV, decreases with increasing pressure above 1700 psia. The fit is poor even if the value of S is treated as an adjustable parameter. Of course, correlation with q''_{sat} and GX is still possible where the needed data are available but this restricts the analysis to the linear range.

HTRF Data: 28 points, L = 96 in., ID = 0.61 in., 46-109 psia
Swedish Data: 18 points, L = 98 in., ID = 0.69 in., 450 psia

Figure 5.4.1. Comparison of HTRF data with Swedish Data for a Similar Size Tube in Low Pressure Range (50 - 500 psia).

HTRF Data: 28 points, L = 96 in., ID = 0.61 in., 46-109 psia
 Swedish Data: 543 points, L = 24-118 in., ID = 0.51 in., 126-558 psia

Figure 5.4.2. Comparison of HTRF data with Some Swedish Data in Low Pressure Range (30 - 500 psia).

Swedish Data: 30 points, L = 39 in., ID = 0.24 in., 1030 psia

Figure 5.4.3. Some Swedish Data in Medium Pressure Range (500-1500 psia) Showing Both Local and Non Local Correlations.

USSR Data, Medium Pressure Range, 428-1421 psia

Figure 5.4.4. USSR Data as Function of Steam Mass Flow Rate and Pressure for Medium Pressure Range.

6. RECOMMENDATIONS

Measurement of CHF in single tubes requires a fluid delivery system capable of maintaining a constant flow rate to the test section for conditions where the test section pressure drop might be very large and fluctuating strongly. Furthermore the system must be capable of maintaining an adequate and constant rate of flow to the mixing tee to condense the steam produced in the test section. This second requirement also suggests that some effort be made to determine the optimum flow for quenching. The existing system utilized a centrifugal pump with the outlet strongly throttled in an attempt to make the pressure drop across the test section small compared to the total loop pressure drop. However the pump head is only 70 psi and the pressure drop at CHF can be close to this value, so this condition was not completely satisfied. Furthermore operating this high capacity pump (250 gpm) at such low flows (5 to 25 gpm) places severe strains on the pump, particularly the pump seals. All factors contributing to loop instabilities should be considered. Some factors generally considered to be important are inlet and outlet flow restrictions, compressibility in various parts of the loop, pump characteristics, etc..

During a typical CHF test, conditions can be so close to instability that it is often difficult to make adjustments in operating conditions without inducing a flow instability, therefore these conditions were recorded but no attempt was made to change them in the neighborhood of CHF. Some method of automatic control which could make smooth and gradual adjustments to maintain fixed operating conditions would definitely be of help, if such a system could be devised. In an experimental facility designed to handle test sections of different dimensions and where conditions are varied over wide ranges, it is difficult to obtain optimum performance.

Since all CHF data are determined in tests which terminate by thermocouple trips, it would be advantageous to have a system which automatically adjusts the set point to be about 100 °F above the wall temperature. Of course the response time of this adjustment, must be longer than the response time of the thermocouples, which is typically less than one second. Alternatively, a trip based on rate of rise of temperature could be used but would still require attention to response time and effects of noise. At present, these adjustments are made manually at the start of each run and it is not practical to reset the trip levels during the course of the run since the setting for each thermocouple must be made individually. Since wall temperatures can increase dramatically, the tube can become very hot if the set point is too high. If the set point is too low, spurious trips can result

from noise or temporary excursions as power is increased. Very high wall temperatures frequently cause damage to the thermocouples. At least the system should be modified to simplify the method of raising the trip point; e.g., a single adjustment that raises the set points for all thermocouples simultaneously.

Since all CHF tests were run in a continuous scan mode, it was not possible to ascertain exactly what occurred in these tests until the data were transferred from the HP tape to the IBM pc. Some information was available immediately. Inlet temperature, flow rate, exit pressure, voltage, current, and wall temperatures (displayed as bar graphs on the Metrascope) were displayed in the control room, but the transient was very fast and this information was not easily assimilated. It was possible to review the results immediately after the test but, at present, this process is time consuming and inconvenient and should be improved.

Attempts to measure void fraction during the CHF tests were not successful, however more recent work has revealed interesting relationships between fluctuations in void fraction and velocity in both steady state⁷ and transient conditions⁸. Of particular interest in connection with the present investigation, measurements of void fraction for air-water mixtures in vertical down flow in a 2" tube showed large hysteresis effects in many cases. These hysteresis effects were not observed for the same system in vertical upflow⁷, nor in an annular test section with diameters of 2.00 and 2.50 " (0.25" gap), neither in upflow nor in downflow. Upstream burnout in downflow must be considered at least as a possibility. Void fraction measurements might shed some light on the different types of behavior in the various regions of CHF such as the different regimes of pressure, q''_{sat} , and inlet subcooling. In addition, the relation between X , X_t , and X_{OSV} would be particularly worthy of investigation.

Even the limited results obtained in this investigation show how a careful study of the transient behavior immediately preceding and following the power trip can shed light on the mechanism of CHF. A complete analysis of the data already obtained, which would be very complex and time consuming, has still not been performed. The variation of wall temperatures and heat transfer coefficients in space and time should be examined more carefully. In some runs the temperature excursion appears to begin somewhat before the end of the heated length, raising the question of possible upstream burnout. The range of inlet temperatures should be expanded to include values much closer to saturation since this is known to be a region of anomalous behavior. The effects of tube length, tube

diameter, and power profile were not investigated at all. More subtle factors, such as flow loop effects, should be examined. For example, the effect of varying quench flow, which changes the pressure drop from the test section outlet to the tank, might affect pressure and flow oscillations in the test section which in turn affect heat transfer rates.

It is surprising that the results obtained in this work, and much of the published data for CHF in uniform tubes, can be correlated so well with such simple equations. On the basis of the present, very limited, series of tests no very definite conclusions could be drawn about the mechanism of the CHF transient. The consistency of these results with published data for CHF in upflow is encouraging but it can not be assumed that this agreement will hold for all conditions. Probably the most important subjects for future study is the effect of pressure on CHF particularly in this low pressure range and the limits of the region of local behavior. Although the pressure range covered in this study was not very large, the relative insensitivity to pressure is, nevertheless, surprising considering the large variations in vapor density, although this finding is compatible with existing knowledge. In this connection, void fraction measurements would be most desirable.

In summary, there appears to be a significant need for more extensive and thorough investigation of CHF at low pressures both in tubes and in annuli, particularly for vertical downflow. Some of the questions to be answered are: whether upstream burnout is possible with uniform heating; under what conditions CHF is a local phenomena; and whether CHF in uniform tubes can be related to CHF in non uniform tubes and in other geometries. Of course, these are not new questions and a great (but nevertheless inadequate) amount of information is already available for upflow. In addition to the need for experimental studies of the details of the CHF transient, there is an equally great need for correlations which not only reproduce a particular set of data reasonably well but apply to a range of pressures, fluids, and geometries and which hopefully would have some reasonably clear physical interpretation. Such correlations are unlikely to apply over the entire range of flow rates, subcoolings, dimensions, etc., since it is unlikely that the detailed mechanism of CHF is the same for all conditions. There is no shortage of CHF correlations but most appear to have as their goal the accurate reproduction of as large a body of data as possible and consequently these correlations are very complex, containing many adjustable parameters, and not very amenable to generalization, interpretation, or extrapolation.

7. REFERENCES

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8. NOMENCLATURE

Symbol	Description	Units
A	parameter in CHF correlation	Btu/hr/ft ²
B	parameter in CHF correlation	none
D	tube diameter	ft
H	specific enthalpy	Btu/lb
L	tube length	ft
M	mass flow rate	lb/hr
M	parameter in CHF correlation	none
P	pressure	lb/in ²
S	Stanton Number at OSV	none
T	temperature	°F
G	mass velocity	lb/hr/ft ²
V	specific volume	ft ³ /lb
V	function of X_t	none
X	thermodynamic quality	none
a	parameter in CHF correlation	Btu/hr/ft ²
a ₁ , a ₂ , a ₃ , a ₄	parameters in mass fraction equation	none
b	parameter in CHF correlation	Btu/hr/ft ²
c	heat capacity	Btu/lb/°F
e	base of natural logarithms = 2.714	none
k	thermal conductivity	Btu/hr/ft/°F
l	dimensionless length	none
m	parameter in CHF correlation	none
q*	a limiting heat flux	Btu/hr/ft ²
q"	heat flux	Btu/hr/ft ²
t	function of X	none
z	distance along tube	ft
Θ	dimensionless enthalpy	none
α	parameter in CHF correlation	Btu/hr/ft ²
β	parameter in CHF correlation	none
μ	viscosity	lb/hr/ft
π	pi = 3.1416	none
ρ	density	lb/ft ³

Nu	Nusselt number, $Nu = St \cdot Pe$, $[q''D/k\Delta T]$	none
Pe	Peclet number, $Pe = Re \cdot Pr$, $[DGc_p/k]$	none
Pr	Prandtl number, $[c_p\mu/k]$	none
Re	Reynolds number, $[DG/m]$	none
St	Stanton number, $[q''/Gc_p\Delta T]$	none

Subscripts

c	critical condition
f	fluid
f	flow
g	gas
h	heat transfer
i	inlet
o	outlet
t	true (mass fraction)
V	vapor
sat	saturation
osv	onset of significant vaporization
chf	critical heat flux

Appendix A. Plots of CHF Transients

Figure A.1 CHF Test No. C0320C, 0.612" ID Inconel 600

Figure A.2 CHF Test No. C0327A, 0.612" ID Inconel 600

Figure A.3 CHF Test No. C0515A, 0.623" ID Inconel 625

Figure A.4 CHF Test No. C0615B, 0.623" ID Inconel 625

Figure A.5 CHF Test No. C0515C, 0.623" ID Inconel 625

Figure A.6 CNF Test No. C05150, 0.623" ID Inconel 625

Figure A.7 CHF Test No. C0525A, 0.623" ID Inconel 625

Figure A.8 CHF Test No. C05258, 0.623" ID Inconel 625

Figure A.9 CHF Test No. C0525C, 0.623" ID Inconel 625

Figure A.10 CHF Test No. C05250, 0.623" ID Inconel 625

Figure A.11 CHF Test No. C052SE, 0.623" ID Inconel 625

Figure A.12 CHF Test No. C0525F, 0.623" ID Inconel 625

Figure A.13 CHF Test No. C0525G, 0.623" ID Inconel 625

Figure A.14 CHF Test No. C0530A, 0.623" ID Inconel 625

Figure A.15 CHF Test No. C05308, 0.623" ID Inconel 625

Figure A.16 CHF Test No. C0530C, 0.623" ID Inconel 625

Figure A.17 CHF Test No. C0530D, 0.623" ID Inconel 625

Figure A.18 CHF Test No. C0530E, 0.623" ID Inconel 625

Figure A.19 CHF Test No. C0530F, 0.623" ID Inconel 625

Figure A.20 CHF Test No. C0530G, 0.623" ID Inconel 625

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Figure A.21 CHF Test No. C0530H, 0.623" ID Inconel 625

Figure A.22 CHF Test No. C05301, 0.623" ID Inconel 625

Figure A.23 CHF Test No. C0530J, 0.623" ID Inconel 625 :

Figure A.24 CHF Test No. C0530K, 0.623" ID Inconel 625

Figure A.25 CHF Test No. C0713A, 0.623" ID Inconel 625

Figure A.26 CHF Test No. C07188, 0.623" ID Inconel 625

Figure A.26 CHF Test No. C0718B, 0.623" ID Inconel 625

Figure.A.27 CHF Test No. C0718D, 0.623" ID Inconel 625

Figure A.28 CHF Test No. C0718D, 0.623" ID Inconel 625

Figure A.29 CHF Test No. C0718E, 0.623" ID Inconel 625

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