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FLOW REVERSAL AND THERMAL LIMIT IN A HEATED RECTANGULAR CHANNEL

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ABSTRACT

The thermal limit in a vertical rectangular channel was determined in a series of experiments whereby the internal coolant underwent a change in flow direction from forced downflow to upward natural circulation. The tests were designed to simulate the flow reversal transient in the High Flux Beam Reactor. A number of parameters were varied in the flow reversal experiments to examine their effects on the thermal limit. Among the parameters varied were the rate of flow coastdown, inlet subcooling, water level in the upper plenum, bypass ratio (ratio of initial flow through the heated section to initial flow through the bypass orifice), and single- verses double-sided heating.

INTRODUCTION

A series of experiments has been conducted to determine the thermal limit in a vertical rectangular channel when the internal coolant undergoes a change in flow direction from forced downflow to upward natural circulation. These tests were designed to simulate the flow reversal transient in the High Flux Beam Reactor (HFBR) under postulated emergency shutdown conditions at near atmospheric pressures.

The HFBR at Brookhaven National Laboratory (BNL) is a research reactor which is fueled by 93% enriched uranium and is cooled, moderated, and reflected by heavy water. The core is composed of 28 fuel elements with each element made up of 18 fuel plates in a parallel plate array. The aluminum cladded fuel plates are 0.05 inch thick and are spaced to provide coolant channels about 0.1 inch thick and 2.5 inch in width. During normal operation the coolant flow direction, as indicated in Figure 1, is downward through the core. For emergency shutdown heat removal, the HFBR employs a scheme that provides a low resistance return path around the core so that natural circulation cooling can be established. The return path is provided by the opening of four spring-loaded flow reversal valves. These valves are held closed during normal operation by the head developed across any one of the two primary and shutdown coolant pumps. When pump power is lost, the reactor scrams automatically and flow coastdown begins. The reactor vessel is also automatically depressurized through a vent valve. The flow reversal valves open automatically when the head developed by the pumps can no longer maintain the valve springs in tension. When the downward core flow reaches a value at which the thermal buoyancy head is comparable to the friction losses in the core, flow reversal occurs.

The reliance on flow reversal to establish natural circulation cooling is not uncommon for research reactors. Flow reversal experiments have been conducted in the Belgian engineering test reactor BR2 (Stiennon et. al., 1965) and the Advanced Test Reactor (ATR) at INEL (Hanson et. al., 1970). These in-reactor tests were essentially single-phase experiments because the heat fluxes used were relatively low and there was no boiling after the flow reversal.

The limiting shutdown heating rate for the HFBR was established for the original design power level of 40 MW in a series of flow reversal tests (Tichler and Hill, 1963) during the reactor design period (1958-1963). These tests were simple, go, no-go tests in which the success criterion was the absence of rapid temperature excursions in the test section. In 1982 after a number of plant modifications were made the reactor power was increased to 60 MW. During the period of 1989-1991 reviews by the Department of Energy (DOE) have raised the issues of the prototypicality and the applicability of these earlier tests to the 60

MW operation of the HFBR. Subsequently a more conservative heat removal limit was formulated for the HFBR based on the flooding limit (Tichler et. al., 1991). The nominal operating power level corresponding to this limit is 30 MW.

In an effort to provide a more realistic and defensible estimate of the flow reversal heat removal limit and thereby increase the HFBR power level, a series of flow reversal tests were conducted for the BNL at the Heat Transfer Research Facility (HTRF) of the Columbia University. The objective of these tests was to determine the thermal limit during flow reversal. The thermal limit is defined as the channel power level below which flow reversal will proceed safely to natural circulation without excessive temperatures occurring in the heated wall(s) of the coolant channel. These tests have provided quantitative measures for the determination of thermal limits in a narrow rectangular channel.

THE TEST LOOP

The test loop was constructed to simulate the transition from forced downward flow to natural circulation in the HFBR. The tests were performed with an electrically heated section representing the core, an orifice representing the flow reversal valves, a variable speed pump to simulate the flow coastdown, and auxiliary piping and equipment to simulate other pertinent structures in the reactor vessel. Figure 2 shows the various components of the test loop and their general arrangement. The test loop was set up to preserve the vertical height of the natural circulation flow path in the HFBR vessel. The heated section was a full-size mockup of a typical channel in a HFBR fuel element. The flow areas of the test loop were scaled to correspond to a typical coolant channel in the HFBR. The scaling criteria for the test loop were based on the similarity rules derived by Ishii and Kataoka (Ishii and Kataoka, 1984). The following assumptions were used in establishing the scaling criteria:

1) Identical coolant channel dimensions.
2) Dynamic similarity (inertia and pressure loss) preserved for the natural circulation loop;
3) Similar thermal inertia, particularly in the lower plenum/reflector region and the upper plenum region.

The dimensions of the test loop components are summarized in Figure 2. The top of the upper plenum region was open to the atmosphere. Demineralized water was the working fluid of the test loop.

The fuel plates were simulated in the test by 6061 aluminum plates of similar thickness and powered by direct DC heating. The heated section was 2 feet in height. Two separate heater arrangements were used in the experiments. The single-sided arrangement had one heater plate and a transparent Plexiglas separated by the coolant gap. The double-sided heater had a heater plate on each side of the coolant gap. The cross-sectional view of the single-sided heater is shown in Figure 3. The channel gap was maintained by two spacer rails installed along the side edges of the channel, overlapping the heater plate(s) by ~0.05 inch. The dimensions of the two heated sections (in inches) were:

	Single Sided Heater	Double-Sided Heater
Width of channel	2.160	2.160
Channel gap	0.10-0.113	0.098-0.116
Channel length	24.00	24.00
Heated length	22.750	22.750
Heated plate thickness	0.050	0.025
Width of heater	2.250	2.250

The heated section was powered by a set of direct current generators. The low electrical resistance of aluminum resulted in a voltage drop of only ~2 volts across the length of the heater plates. At low voltages the generator output was prone to drift. A ballast, made up of a twenty-foot length of water cooled stainless steel pipe, was installed in series with the heater plates(s) to raise the total resistance seen by the generator and stabilize the output voltage.

An orifice was used to simulate the flow impedance of the four flow reversal valves in the reactor. The nominal flow condition of four open valves was simulated by a 0.199 inch diameter orifice. The nominal flow split between the heated section and the bypass was 2:1. Additional tests were done with a smaller orifice 0.129 inch in diameter to examine the effects of a more restrictive return flow path. The smaller orifice gave a nominal flow split of 5:1.

The initial flow through the heated section and the bypass orifice was provided by an eccentric screw pump which has the characteristics of a positive displacement pump. The pump capacity is 10 gpm. The effect of flow coastdown was created by using a programmable speed controller to vary the rotational speed of the pump motor.

INSTRUMENTATION

The layout of instrumentation is shown in Figure 4. The test loop was instrumented to monitor the temperature, pressure, and flow rate of the coolant. Each heater plate was monitored for current, voltage, and wall temperatures at nine locations. All data were collected digitally by a computer controlled data acquisition system. In addition, video recordings were made for all the single-sided heater tests.

The total loop flow was measured by a 0.5-inch turbine flowmeter (FLI1) located downstream of the circulation pump discharge. Two bi-directional turbine flowmeters were installed in the bypass line and the reflector section to measure the bypass flow (FBP) and the test section flow (FRE). The turbine flowmeters were calibrated in place for single-phase water flow in the range of 0.2 - 3.0 gpm. In case of two-phase flow or high frequency flow oscillation both the flow rate and the directional signals from the flowmeters became difficult to interpret. A differential pressure transducer (DO1) was installed across the bypass orifice plate as a backup for the bypass flow measurement. A similar transducer (DRE) was installed across the reflector turbine flowmeter (FRE).

Three pressure transducers were used to measure the absolute pressure at the inlet section (PTIB), the lower plenum (PTOB), and the upper plenum (PTP1). Five differential pressure transducers were used to measure the pressure drop along the heated section. One transducer measured the pressure drop in each quarter of the heated section (DT1, DT2, DT3, DT4), and one was for the overall heated section pressure drop measurement (DT5). The five pressure taps were located on the narrow side of the heated channel. The differential pressure indications did not include the hydrostatic head because the zero reading was taken when the test loop and the pressure lines were filled with water. Hence, the differential pressure transducers only measured the frictional and acceleration pressure drop.

The water temperature was monitored by two types of sensors, namely, iron-constantan thermocouples and resistance temperature detectors (RTD). Test section inlet and exit temperatures were measured by RTD's located in the inlet section (RTI1) and the lower plenum (RTO1). In addition, two thermocouples (JTI1 and JTO1) were installed at the same locations as backup measurements. Two other RTD's were located in the upper plenum (RTP1) and the reflector region (RTR1) to monitor the trend of temperature variation during the course of flow reversal and natural circulation. For the same purpose, two additional thermocouples were used in the lower plenum (JRB1) and at the junction, upstream of the pump suction, where the fluid streams from the reflector and the bypass sections recombined (JRP1).

The wall temperatures of the heater plates were measured by 0.064-inch thermocouples. Each thermocouple was installed through an eyelet pinned directly to the heater plate. Nine thermocouples were evenly distributed along the middle of the heater plate at 2.75 inches interval. They were identified from top to bottom by numbers EW01 to EW09 for the single-sided heater, and EW101 to EW109 for the first plate and EW201 to EW209 for the second plate of the double-sided heater.

The heater plates were protected from overheating during the flow reversal experiments by two types of power trips, a temperature trip and a voltage trip. Depending on the power level, all wall temperature trips were set at a temperature of about 30 - 40 degrees F above the test section exit saturation temperature. Typical temperature trip setpoint was between 260 to 280 °F. There was an increase in the electrical resistance of the aluminum plates as their temperatures rose during the course of the flow reversal transient. The upward drift in voltage was about 5 - 7 % for a coolant temperature rise from 130°F to saturation. The voltage trip was set at 10 % above the initial operating voltage. This setting was found to be high enough to avoid spurious trips while protecting the heater plates from overheating.

Power to the test section was calculated from the measured current and voltage applied to the heater plates. The current was measured separately by two calibrated shunts. The test section voltage was measured by two separate calibrated voltage divider setups. For the double-sided heater the two heater plates were installed in series. An excursion in the wall temperature or an over-shoot in the voltage across a heater plate would result in an automatic power cut off to the heated section. This was used as an indication that the thermal limit had been exceeded.

THE FLOW REVERSAL TESTS

In each test, flow reversal in the heated section was initiated by a reduction in the forced flow provided by the circulation pump. The pump flow was ramped down linearly in time to simulate the coastdown of the primary pumps in the HFBR. A number of parameters were varied in the tests to examine their effects on the thermal limit. Among the parameters varied were the rate of flow coastdown, inlet subcooling, water level in the upper plenum, bypass ratio (ratio of initial flow through the heated section to initial flow through the bypass orifice), and single verses double-sided heating. The baseline test conditions were:

Mode of heating: single-sided
Water level: 14 feet above the top of the inlet section
Inlet temperature: 130 °F, entering the heated section
Coastdown time: 40 seconds
Bypass ratio: 2:1

For a given set of test conditions the flow reversal experiment was repeated at increasing power levels to the heated section until the thermal limit was bracketed within a 0.5 kW interval. The power was maintained at the specified level throughout each test run. However there was a small upward drift in power due to the changing electrical resistance of the heated section as the temperature increased. A successful flow reversal was defined as a test where natural circulation cooling was sustained without a power trip for more than 120 seconds after pump shut off.

The initial pump flow for all tests was 3 gpm. After reaching the desired flow rate, the differential pressure transducers which measured the pressure gradient along the heated section were used to cross check each other and verify the uniformity of the flow channel geometry. Channel dimensional checks had been performed after assembly of the heated section. However the design allowed for thermal expansion of the heater plates and therefore the differential pressure measurements were used to ensure that unexpected changes in the channel geometry would be detected.

The test results for the single-sided and double-sided heater are presented in Tables 1 and 2 respectively.

DISCUSSION OF RESULTS

Test #1 represents the base case of the flow reversal experiments. For the base-line test conditions, flow reversal occurred at a power level of 7.3 kW. The test operated for about 170 seconds and ended with a manual power trip. Flow reversal is clearly demonstrated in Figure 5 by the increase and then stabilization of the water temperature (RTI1) in the channel top (inlet tube section). Concurrently, the water temperature (RTO1) in the channel bottom (below the bottom of the heated section) begins to drop. In addition, the wall thermocouple reading (EW01) in Figure 6 does not indicate any temperature excursion.

Figure 7 is a plot of the flow rate through the heated channel as recorded by the flowmeter (FRE). The positive flow direction, also the initial flow direction, is downward. Figure 7 shows that flow coastdown started at about 5 second and the first change in flow direction occurred at about 40 second. The pump flow did not stop until about 45 second. The flowmeter indicated that there were flow fluctuations after flow reversal. The bypass flow (FBP) is shown in Figure 8. It is observed in Figure 8 that flow reversal is preceded by an increase in the bypass flow. In both Figures 7 and 8 there appears to be a dead band in the flowmeter for flow rates between plus and minus 0.25 gpm. This anomaly was due to the fact that the calibration constants for the turbine flowmeters were valid only for flows above 0.2 gpm in either direction. The application of the same constants for flows below 0.2 gpm would then result in erroneous readings.

The base-line case experienced a power trip at 7.95 kW in test #2. The wall temperature in Figure 9 shows that an excursion occurred at about 40 second. In Figure 10, the water temperature in the channel top was still in an upward trend when the power was tripped. This was an indication that the coolant had not completed its reversal in flow direction in the channel. The flowmeter readings in the reflector and the bypass regions are shown in Figures 11 and 12 respectively.

It was observed during the experiment that steam generation in the heated section provided the first indication of an impending flow reversal. The steam soon expanded to cover most of the heated section. At this point water began to enter the heated section from below. The boiling boundary continued to move up and down the heated section. The flow regime was best described as churn-turbulent/annular with steam occupying the wide span of the flow channel and water in the form of a thin film on the narrower sides of the rectangular channel. For all the tests that ended by a power trip from thermal excursion, the heated section was almost completely voided when the trip occurred.

The test results also show the significant effect of the pump coastdown period on the thermal limit. A shorter coastdown period results in a higher flow reversal power limit. For instance, in test #1 with a coastdown of 40 seconds the power limit for flow reversal is 7.3 kW. Decreasing the period to 30 seconds in test #3 increases the power limit to 7.9 kW. For the same test conditions, a pump trip in test #5 effectively decreased the pump flow to zero in 1.5 seconds. The pump trip case allows flow reversal without temperature excursion up to a power level of 10.85 kW.

Two water levels were investigated in the test, 14 feet and 3.67 feet above the top of the inlet section. The 14 feet corresponds to the normal water level in the HFBR and the 3.67 feet represents a low water level as postulated in a loss of coolant accident. The test shows that water level has a negligible effect on the power at which sustained flow reversal is possible.

Three inlet temperatures were used in the tests, 130, 110 and 150 °F. As expected, lowering the test section inlet temperature increases the power threshold for sustained flow reversal.

Several tests were conducted to determine the effect of the flow split between the test section and the bypass line. Results in Tables 2 and 3 indicate a slight increase in flow reversal power level when the bypass ratio (ratio of test section to bypass flow) is increased.

The experiments also looked at the effect of single versus double-sided heating. The single-sided heating tests allowed for visual observation of the flow reversal transients. The double-sided heating tests provided a better simulation of the real boundary condition in the reactor, namely, heating from both sides of a coolant channel. For similar test conditions, the double-sided heater always resulted in higher thermal limits during flow reversal.

CONCLUSIONS

This series of flow reversal experiments has provided quantitative results for the determination of thermal limits in a narrow vertical rectangular channel. The effects from varying several initial and boundary conditions have also been studied. The data show that a shorter coastdown time or a lower inlet temperature results in a higher power level for sustained flow reversal. A higher power threshold is also achieved by double-sided heating rather than single-sided heating. The measured power threshold of about 7 kW for the base-line case is approximately twice as high as the thermal limit imposed on the HFBR by the flooding limited criterion.

ACKNOWLEDGEMENTS

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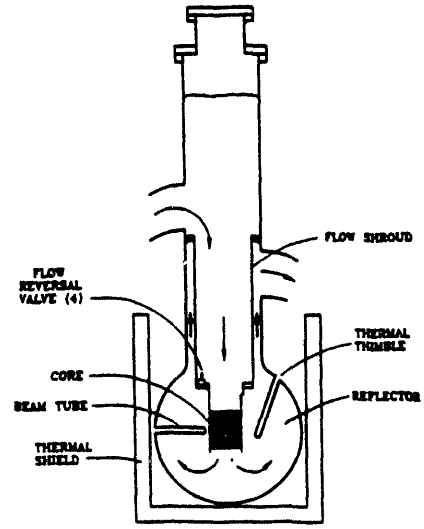


Figure 1. HFBR vessel showing normal flow direction.

TABLE 1

SINGLE HEATER FLOW REVERSAL TESTS

TEST NO.	NOMINAL POWER (kW)	FLOW REVERSAL POWER (kW)	TRIP POWER (kW)	WATER LEVEL (ft)	INLET TEMPERATURE (°F)	PUMP COASTDOWN (sec.)	BYPASS RATIO
1	7.0	7.3		14.43	130	40	2:1
2	7.5		7.95	14.00	130	40	2:1
3	7.5	7.9		14.00	130	30	2:1
4	8.0		8.70	14.00	130	30	2:1
5	10.5	10.85	11.05*	14.00	130	pump trip	2:1
6	10.0	10.40	10.65*	14.00	130	pump trip	2:1
7	8.0	8.65	9.2*	14.00	110	40	2:1
8	9.0		9.5	14.00	110	40	2:1
9	7.0	7.15		3.67	130	40	2:1
10	7.5		8.10	3.67	130	40	2:1
11	7.5	8.10		14.00	130	40	5:1
12	8.0		8.95	14.00	130	40	5:1

TABLE 2

DOUBLE HEATER FLOW REVERSAL TESTS

TEST NO.	NOMINAL POWER (kW)	FLOW REVERSAL POWER (kW)	TRIP POWER (kW)	WATER LEVEL (ft)	INLET TEMPERATURE (°F)	PUMP COASTDOWN (sec.)	BYPASS RATIO
13	8.0	8.7		14.00	130	40	2:1
14	8.5		9.4	14.00	130	40	2:1
15	10.5	11.4	12.0*	14.00	130	pump trip	2:1
16	7.0		7.7	14.00	150	40	2:1
17	6.5	6.7		14.00	150	40	2:1
18	7.0		7.85	14.00	130	60	2:1
19	6.5	7.3		14.00	130	60	2:1
20	8.5	9.35		14.00	130	40	5:1
21	9.5		10.05	14.00	130	40	5:1

* Trip occurred after natural circulation had been established.

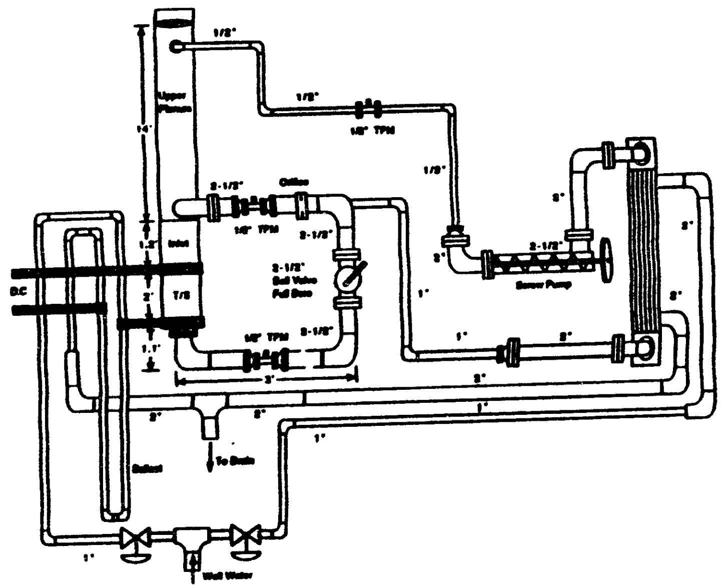


Figure 2. Schematic of the flow reversal test loop.

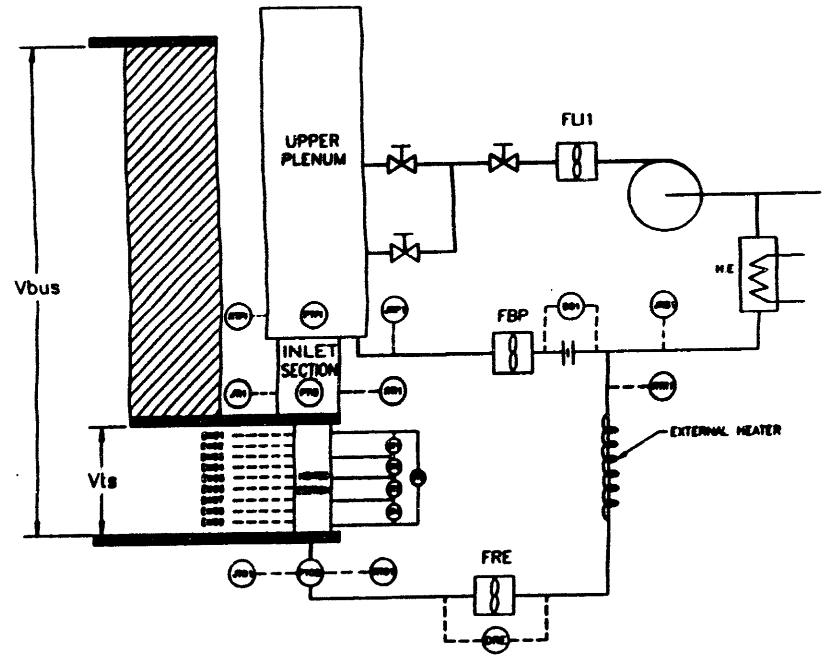
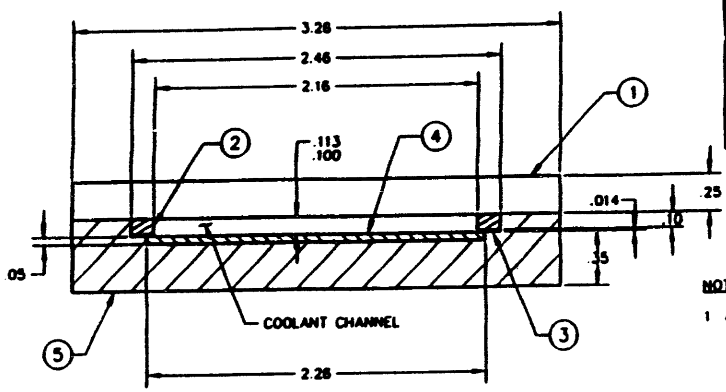


Figure 4. Schematic of instrumentation for the test loop.



ITEM NO.	QTY	DESCRIPTION
1	–	PLEXIGLAS
2	–	SIDE RAIL (ASBESTOS PHENOLIC)
3	–	KAPTON TAPE (4 LAYERS)
4	–	ALUMINUM HEATER STRIP (WIDTH = 2.25)
5	–	INSULATOR (PEEK)

NOTE:

1 ALL DIMENSIONS ARE NOMINAL VALUES AND IN INCHES

Figure 3. Cross-section of the single-heater test section.

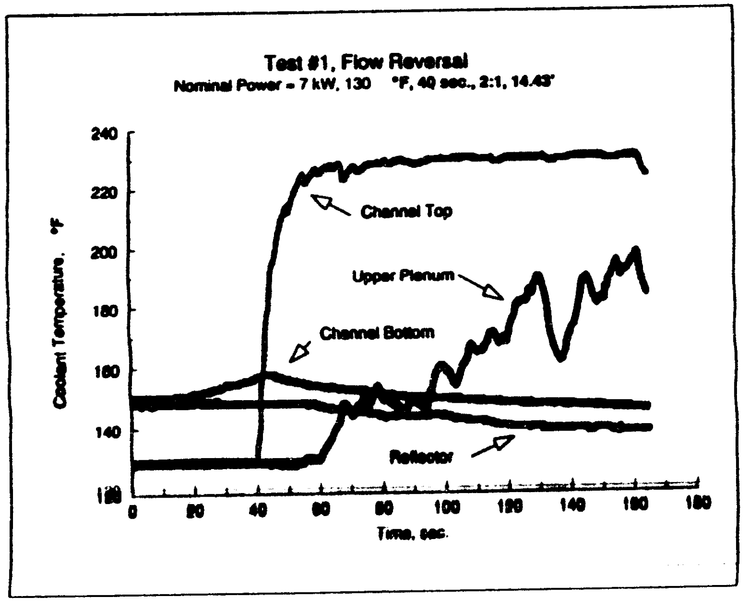


Figure 5. Coolant temperatures in Test #1

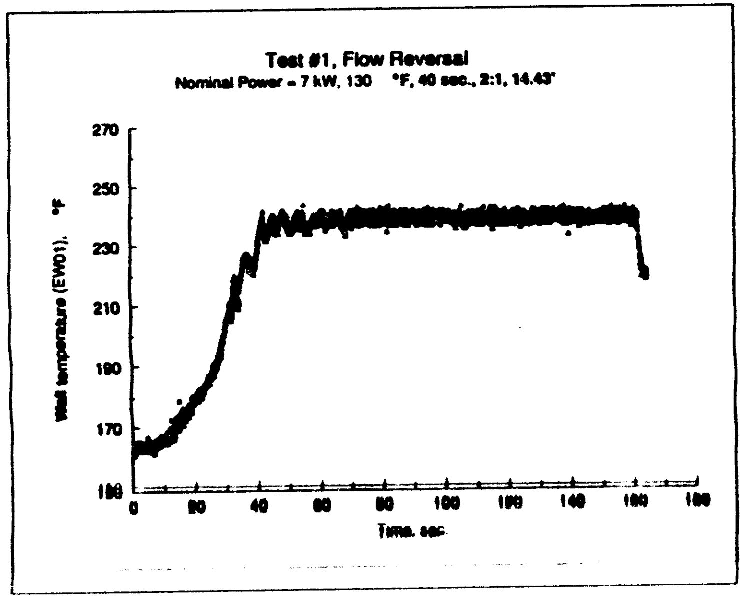


Figure 6. Wall temperature in Test #1

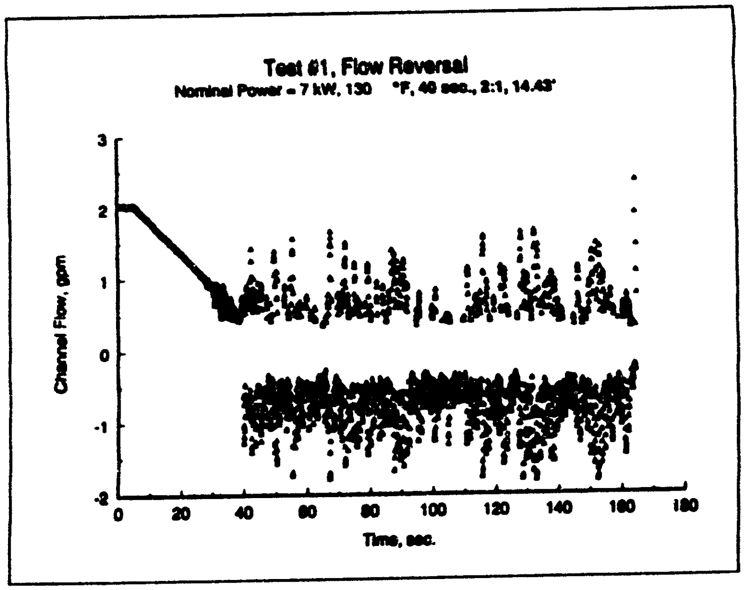


Figure 7. Channel flow rate in Test #1

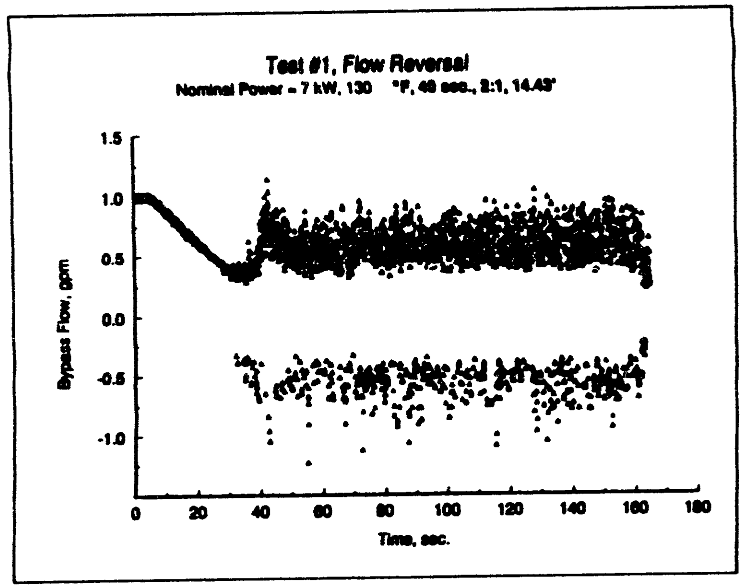


Figure 8. Bypass flow rate in Test #1

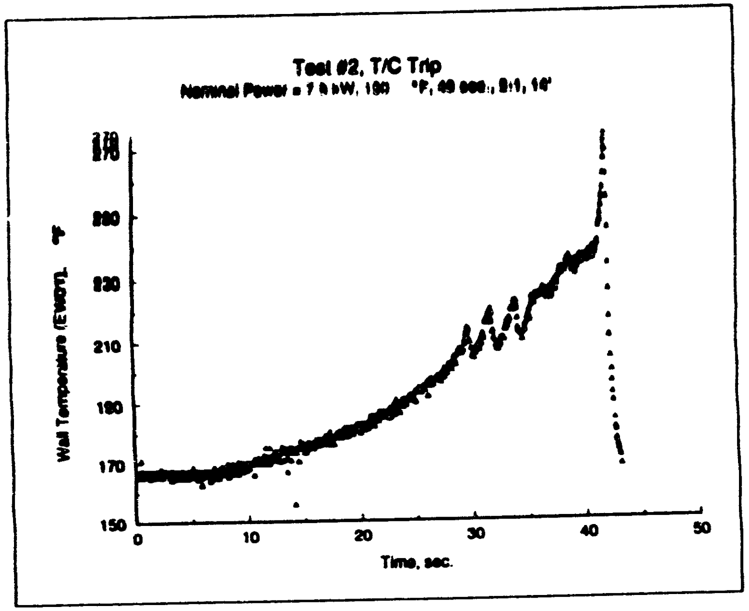


Figure 9. Wall temperature in Test #2

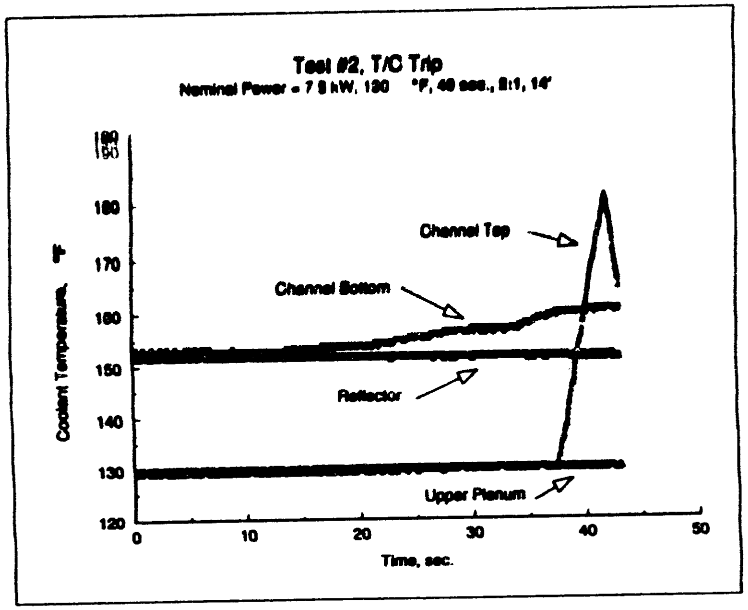


Figure 10. Coolant temperatures in Test #2

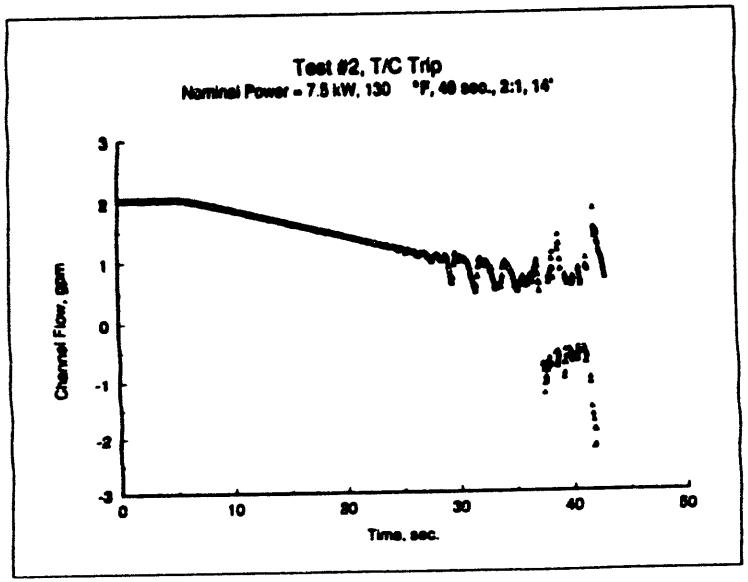


Figure 11. Channel flow rate in Test #2

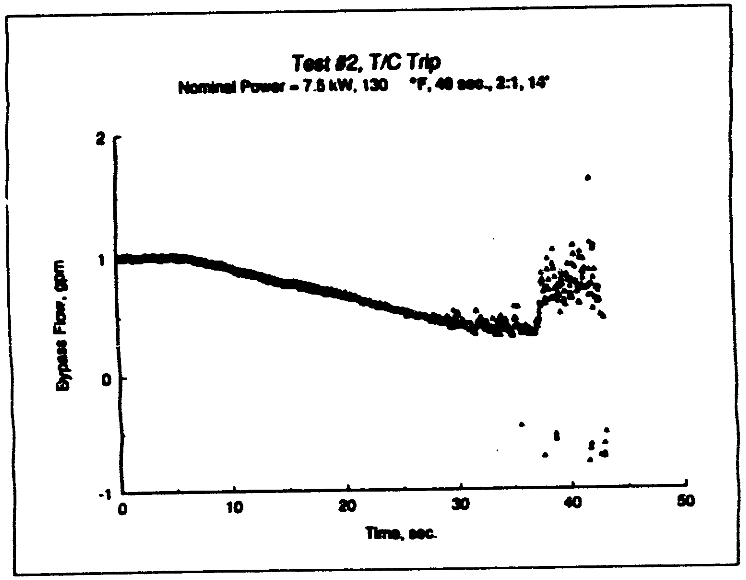


Figure 12. Bypass flow rate in Test #2

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