AN ABSTRACT OF THE THESIS OF

Ross D. Snuggerud for the degree of Master of Science in Nuclear Engineering presented on January 22, 1993.

Title: Ultralite Copper Reflux Tube Life Test and Ceramic Fabric Wicking Rate Experiments.

Redacted for Privacy

Abstract approved: ______________________
Andrew C. Klein

This thesis covers two topics. The first subject involves tests run on a ultralite reflux tube supplied by Battelle Pacific Northwest Laboratories (PNL). The second topic involves tests to determine the relative wicking rates of several different fabrics.

The ultralite reflux tube supplied by PNL was constructed of copper and Nextel 312. It had a 10 mil thick copper evaporator and a 10 mil thick copper condenser end cap. The bulk of the condenser was 2 mil thick copper covered by a one inch diameter Nextel 312 woven hose. A life test was run within the Heat Pipe Test Facility, a chamber used to simulate low earth orbit. The life test lasted for over 800 hours, during which time the reflux tube operated steadily with no drop in performance. At the end of the test the reflux tube was removed and observed. The only noticeable change was a slight discoloration of the Nextel 312 used to cover the condenser. This discoloration

was consistent with previously observed phenomenon.

The second topic, fabric wicking rate studies were done as a follow up study to the dry uptake tests previously conducted at Oregon State University. The purpose of the tests were to get a relative feel for the ability of different fabrics to wick water. This was achieved using a drop test in which the fabrics were laid out on a bridge connecting two containers. One of the containers was elevated above the other. The fabrics were allowed to wick water from the upper container to the lower container and the rate at which this was accomplished was measured. The fabrics were all able to move significant amounts of water. The stiffer fabrics seemed to perform better. The major transport mechanism was transport between fabric layers and the fabric and the bridge.

Ultralite Copper Reflux Tube Life Test and Ceramic Fabric Wicking Rate Experiments

by

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I. INTRODUCTION.

Heat pipes, reflux tubes, and thermal siphons have been used in many different applications. These applications range from heating roads to cooling circuitry. All three devices operate using the same principles and accomplish the same goal; moving large amounts of heat through a limited cross sectional area with marginal temperature drop. This is accomplished by using the large amounts of heat necessary to cause a change in state of a working fluid and then letting the vaporized working fluid be transported to the location were cooling occurs.

The concept for a heat pipe was first described in 1942 by R. S. Gaugler and patented in 1944 [1]. However the device was never used. In 1963 G. M. Grover and his co-workers independently reinvented the device at Los Alamos Scientific Laboratory [2]. By building prototypes and testing them, they did the work that got heat pipes moving. It was also Grover that coined the term 'heat pipe', which has been carried through to later work.

A reflux tube, or thermal syphon, is a device consisting of a tube that is evacuated, charged with a working fluid, and then sealed. The lower end of the tube, known as the evaporator section, is heated causing the working fluid to vaporize. The vapor then moves up the tube to the condenser end. The condenser end is cooled by an outside heat sink and causes the vapor to condense on the inside wall of the tube. Once the vapor has condensed, gravity causes it flow back down to the evaporator section. The condenser and the evaporator sections can be separated by an adiabatic section that is insulated.

Reflux tubes or thermal siphons have been used in many applications. They are used to prevent the thawing of the permafrost around the supports of the Trans-Alaska pipeline [1]. These reflux tubes remove heat from the ground and rejects it into the air. Reflux tubes can also be used to recover heat lost in ventilation systems [2]. By connecting the outlet and the inlet ducts with reflux tubes, heat that would normally be lost to the environment can be recovered.

A heat pipe uses the same method as a reflux tube to move heat, but does not rely on gravity to return the working fluid to the evaporator section. Instead a wicking structure is used to move the working fluid back to the evaporator by capillary action. This wick can take several different forms including; metal screens, axial grooves, metal felts, or a combination of these.

Previously work has been done at Oregon State University to support the development of fabric composite heat pipes. These heat pipes are similar to the ultralite reflux tubes, with the exception of employing an internal wick. Work done by Tim Marks [3] researched the dry uptake rates of several different fabrics being considered for use as wicks. Zubida Gulsha-Ara has looked into the 'effective' emissivities of fabric and metal composites [4]. These materials show increased performance over the heat rejection capacities of the individual materials. Fabric composite heat pipes have been successfully built and tested by William Kiestler [5]. This work showed the promise of increased performance and lighter weights that the new designs could achieve.

Experiments and testing were performed at Oregon State University to support the development of fabric composite (also known as ultralite fabric) reflux tube heat rejection radiators. These heat rejection systems are being designed for application on the lunar and martian surfaces. Because of the local gravity the internal wick of a heat pipe design is not necessary for this application. The goal of the design work is to develop a systems that can be used to reject waste heat from power systems and habitation modules. Two primary sets of experiments were conducted. The first was a series of tests conducted using a Battelle Pacific Northwest Laboratory (PNL) designed, developed, and constructed reflux tube in the OSU Fabric Composite Heat Pipe Test Facility. This facility has an inner vacuum chamber length of 40 inches, with a diameter of 5.5 inches, and can be maintained at a moderate vacuum for extended periods of time. The test chamber also is surrounded by a cooling jacket that is filled with a chilled ethylene glycol and water mixture capable of maintaining the inside chamber wall surface below 0 °C. These tests included transient, start-up and shutdown testing of the PNL supplied reflux tubes, and a "life" test of over 800 hours. The second series of tests involved wicking rate tests for PNL supplied ceramic fabric samples and other fabrics samples that were readily available. These tests were performed using a drop test in which the fabrics were allowed to wick water from an elevated tray to a lower collection tray.

II. REFLUX TUBE OPERATION TESTS.

A. Experimental Setup and Procedures.

An Ultralite copper reflux tube was supplied by Battelle Pacific Northwest Laboratory. This reflux tube was constructed of copper and Nextel 312, an aluminum borosilicate glass fabric. The reflux tube has an overall length of 1 meter and a diameter of 2.54 cm. The evaporator section is approximately 15 cm, and the fabric covered condenser section is approximately 81 cm, with approximately 4 cm of uncovered condenser. Both ends of the reflux tube are rounded. The condenser end has a 0.32 cm fill and evacuation line that is an integral part of the tube.

The evaporator section is bare copper with a wall thickness of 0.305 mm. Inside the reflux tube there is a 15 cm long piece of braided Nextel 312 wick. This wick is not anchored within the tube and is free to move around inside the reflux tube when the reflux tube was shifted. This in fact has been observed. The purpose of the wick is to maintain a more even distribution of working fluid over the length of the evaporator section. This is necessary because there is very little working fluid in the reflux tube during normal operation.

The condenser section consists of a copper wall with a thickness of 0.0508 mm covered by another braided Nextel 312 hose. This ceramic fabric only covers about 81 cm of the reflux tube leaving approximately 4 cm of bare copper at the top of condenser. The uncovered end piece of the condenser is 0.305 mm thick, like the evaporator, and acts as one of the anchor points for the outer cover of Nextel 312. The other anchor point is at the top of the evaporator section. The Nextel 312 covering is anchored through a special crimping method developed at Battelle Pacific Northwest Laboratory which adequately holds the fabric without adding significant stress points to the liner.

At the top of the reflux tube, on the evacuation line are several fittings, these fittings are used to feed an internal thermocouple into the reflux tube, attach a pressure transducer, attach a 1/3 psi check valve, and allow the reflux tube to be evacuated and charged with working fluid.

In order to evaluate the performance of fabric composite heat pipes and reflux tubes, a test facility was designed and built to accommodate a variety of fabric composite designs. This facility, called the Heat Pipe Test Facility (HPTF), was originally designed to be used to evaluate single heat pipe or multiple heat pipes in a vacuum at low temperatures. By reorienting the facility on its end it has been used to test reflux tubes. The Heat Pipe Test Facility was previously Described by William Kiestler [5]. His description has been modified to more accurately describe the HPTF in the orientation used in this application. This section provides a detailed description of the HPTF, the reflux tube, testing principles and procedures.

The Heat Pipe Test Facility consists of two mild steel concentric cylinders (15 and 25 cm ID) welded together to form an outer cooling jacket and an inner vacuum chamber. The inner vacuum chamber is 101 cm (40 in.) deep. The cooling jacket is insulated with 5 cm (2 in.) of highly compressed, rigid fiberglass insulation. To accommodate the PNL supplied reflux tube a 15.24 cm (6 in.) steel pipe extension was attached to the open end of the facility and sealed using an O-ring seal. The extension was insulated with flexible blister pack insulation. A recirculating bath chiller is used to circulate a 50% aqueous ethylene-glycol coolant, at temperatures as low as -20°C, through the cooling jacket. The extension to the vacuum chamber is not directly cooled. The interior of the inner cylinder is smooth and painted black to allow for improved radiation heat transfer. The test chamber is sealed by a teflon end piece with an O-ring seal. The teflon end piece contains leads for heater power input and thermocouples, the reflux tube evacuation and charging line, and a line for drawing a vacuum on the test chamber. The evacuation and charging line is fitted with a DC pressure transducer for monitoring the reflux tube operating pressure, and has a four-way valve that can be positioned for evacuating the reflux tube, charging the reflux tube with working fluid, or isolation. A schematic diagram of this facility is shown in Figure 1.

With the Heat Pipe Test Facility on its end the reflux tube was allowed to rest on the bottom of the chamber and be supported by the charging line. The reflux tube heater was insulated in an attempt to reduce the direct loss of heat from the heaters to the cooling jacket. This insulation was made of three alternating layers of aluminum foil and stove pipe insulation. It covered the entire length of the evaporator end and was wrapped around the bottom of the reflux tube. An additional piece of stove pipe insulation was laid on the bottom of the HPTF before the reflux tube assembly was inserted into the HPTF.

The HPTF is cooled with a PolyScience Model 900 constant temperature circulator. The chiller circulates coolant between the HPTF cooling jacket and a 5 liter internal bath. A dual speed centrifugal pump provides flow of up to 15 l/min, depending on the coolant viscosity and system head. Under the conditions for the tests conducted, the slow pump speed corresponded to a flow rate of approximately 3.8 l/min (1 gpm), and the high speed provided approximately 7.6 l/min (2 gpm). The chiller is rated at 240 W at -20°C. During these tests an inlet temperature of approximately -10°C was maintained.

Pressure in the vacuum chamber is monitored using a standard bellows type gage. The gage is capable of

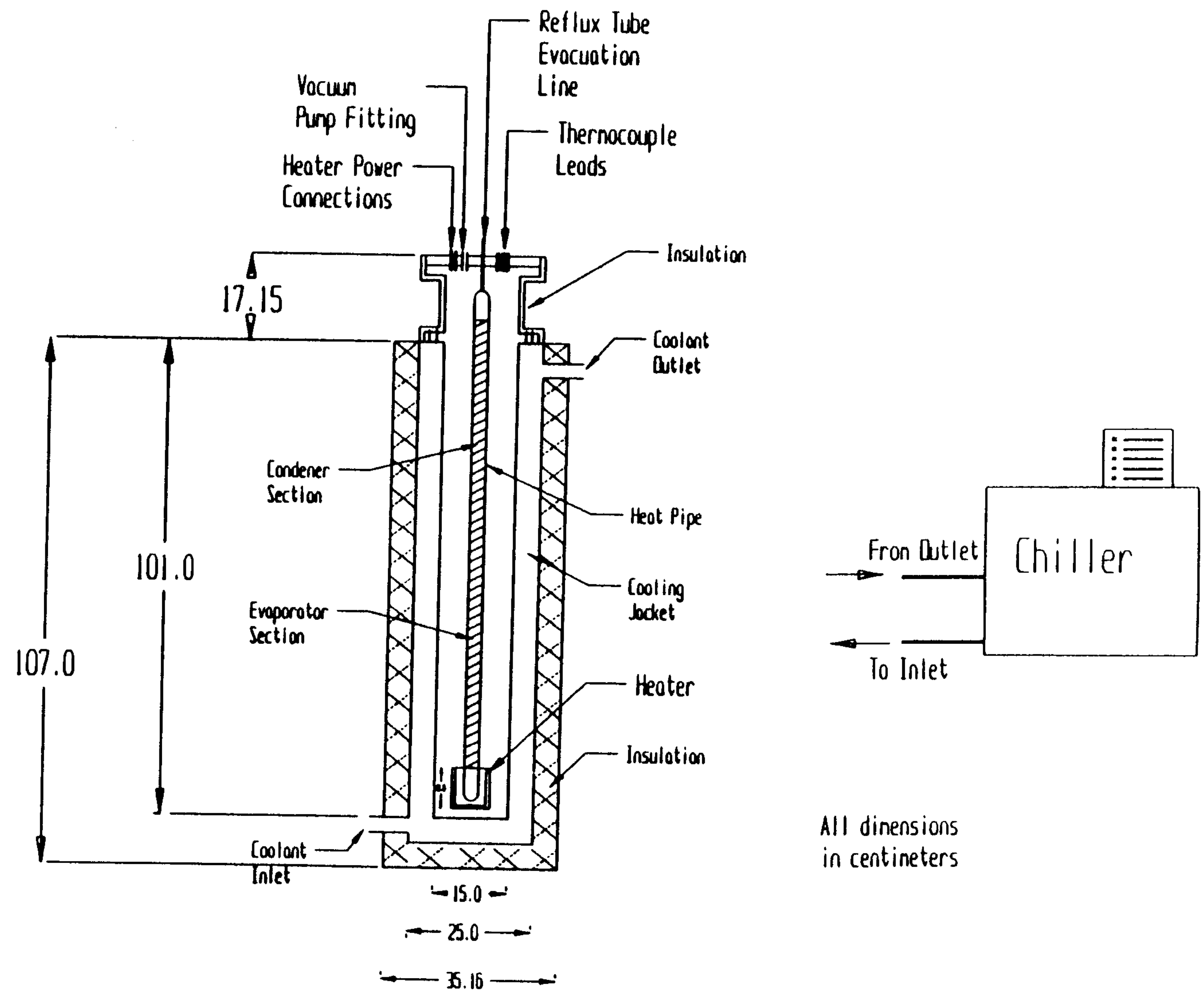


Figure 1. The Schematic Diagram of the Heat Pipe Test Facility in the Reflux Tube Configuration.

measuring the pressure over a range of -100 to 200 kPa (30 in Hg vac. to 30 psig). The vacuum chamber pressure is not monitored or recorded by the data acquisition system. It must be checked visually periodically during testing to verify the vacuum in the test chamber. If the pressure rises in the test chamber, the vacuum can be easily redrawn with a vacuum pump.

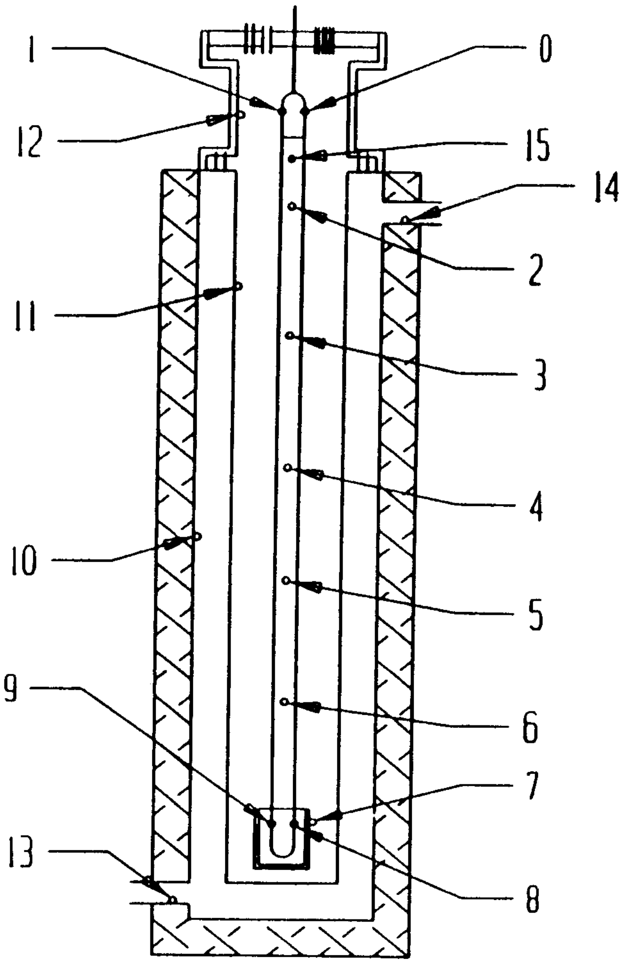
The volumetric flow rate of the coolant is measured by an Omega acrylic rotameter. The flow meter uses a guided stainless steel float to measure flow from 0 to 5 gpm. The rotameter is accurate to within 4% of full scale, but is calibrated for fluids having a specific gravity equal to 1.0. Thus, the uncertainty in the properties of the aqueous ethylene-glycol mix contributes to an appreciable overall uncertainty in the measurement of the coolant flow rate. Fortunately for this experiment this was not an important measured parameter.

An Omega PX300-500G-V 10 volt DC pressure transducer is used to continuously monitor the pressure in the reflux tube. The pressure transducer operates over a range of 0 to 500 psi and provides a linear signal from 0 to 30 mV. The output is coupled to the data acquisition system through an Omega signal amplifier, which has a maximum output voltage of $\pm$ 9 Vdc. The gain of the amplifier (10x, 100x, or 1000x) is set to provide a signal within the $\pm$5 Vdc analog input range of the data acquisition system.

Heat is provided to the reflux tube evaporator end by a 7.6 cm (3 in) band heater. Power to the heater is controlled by a 0-120 V variable transformer. An ammeter in line with the heater wire provides for the measurement of the current to the heaters. The voltage and current are used to determine the power delivered to the reflux tube.

Chromel-Alumel (K-type) thermocouples are used to measure the temperatures associated with the reflux tube and HPTF. A single Iron-Constantan (J-type) sheathed thermocouple was used to monitor the internal temperature of the reflux tube. A total of 16 channels were used for temperature measurements. Figure 2 summarizes the location of the thermocouples assigned to each of the 16 channels.

An 8088 personal computer and Omega DAS-8 analog/digital interface board were used to provide continuous monitoring and recording of the reflux tube and HPTF parameters [6]. The DAS-8 system contains eight single ended analog input channels, and uses a 12-bit successive approximation analog to digital converter with a nominal conversion time of 25 μsec. Two Omega Model EXP-16 Analog Input Multiplexers were used to provide up to 32 channels of monitoring on one DAS-8 channel, however only 17 were used during the reflux tube tests [7]. Sixteen channels were used to measure the temperatures, and one channel was used to monitor the internal pressure of the reflux tube. The DAS-8 is controlled using programs written in Microsoft



Channel #	Location of Thermocouple
0,1	Reflux tube condenser end cap surface
2-6	Reflux tube condenser fabric surface
7	Exterior surface heater insulation
8-9	Reflux tube evaporator surface
10-11	Vacuum chamber walls
12	Coolant inlet
13	Coolant outlet
14	Extension wall
15	Reflux tube interior

Figure 2. Thermocouple Locations.

QuickBASIC [8]. A copy of the program used to collect data can be found in the master's thesis of William Kiestler [5].

The reported data is based on the average of the collected data over the last recording interval. The data recording rate can be adjusted by setting the upper integer value for a data sampling loop. The data is then taken and displayed on the PC screen for each step of the sampling loop, but it is not written to the output file until the loop count reaches the upper integer value. This data averaging is used to correct problems with thermocouple voltage fluctuations and may account for some of the short term erroneous signals obtained from particular thermocouples when the recording interval is short.

Due to the length of the test, constant monitoring was not possible. Therefor to insure that the reflux tube was protected against severe transients and that the test facility was operated safely, two precautionary devices were add to the facility. The first was a switch that tripped off in the event of a power outage. This breaker would insure that the power remained off if a power outage occurred while the experiment unsupervised. This allows time to reset the control devices and restart the data acquisition equipment. The power to the heater was regulated by the second device, a temperature controller that was connected to one of the two thermocouples located underneath the heater on the evaporator surface. This allowed a high temperature cutoff to be set that would cut power to the heaters if the temperature on the surface of the evaporator exceeded 175° C. This was a semi-arbitrary limit set to insure that the controller did not trip during normal operation, but would trip if something unexpected happened and the evaporator temperature reached too high of a temperature.

Preparing the reflux tube for testing was a difficult task. This work was extremely delicate due to the fragile nature of the reflux tube. Great care had to be taken to insure that the reflux tube was not stressed in its preparation for testing. In the first attempt to prepare one of the two reflux tubes that had been supplied by Battelle Pacific Northwest Laboratory the reflux tube was destroyed.

This accident occurred in an effort to attach the cylindrical clamp heater to the evaporator end of the reflux tube. The procedure involved one individual holding the condenser end of the tube by the evacuation and fill line and letting the evaporator end hang down as the heater was attached by another individual. While trying to secure the clamp the bottom end of the tube moved sideways while the top was held stationary. This caused the reflux tube to crease in a location that had been previously dented, prior to the arrival of the reflux tube to OSU, and created a pinhole rupture. This procedure was changed for the second reflux tube, one that had not been previously used by PNL. For this reflux tube the heater was attached by holding the evaporator end up while allowing the condenser end to hang free. This protected the reflux tube from the type of stress that occurred on the first pipe.

Several steps then had to be taken to prepare the reflux tube for testing. The first step was to attach thermocouples to the evaporator end of the reflux tube. Two thermocouples were attached about half way up the evaporator section, one on each side of the tube. These thermocouples were attached using small thermocouple adhesive tabs. The second step was to attach a 7.62 cm (3 in.) cylindrical clamp heater to the evaporator end. In order to get this heater to clamp on to the evaporator section several layers of aluminum foil were wrapped around the reflux tube. After the heater was attached, it was wrapped in insulation. This insulation consisted of two layers of stove pipe insulation separated by a layer of aluminum foil, and covered inside and out by layers of aluminum foil. The insulation was secured to the heater with steel wire.

Once the heater was attached, the rest of the thermocouples were mounted to the reflux tube using the same adhesive tabs used to secure the thermocouples placed under the heaters. When this was completed the reflux tube was ready to be placed into the HPTF. The evaporator end of the reflux tube was lowered into the facility, followed by the rest of the assembly. After this was completed the evacuation/fill line was connected to the reflux tube and then all of the thermocouples were connected to the HPTF lid. Next, the heater power lines were connected to the feed throughs in the lid. The last step was to secure the lid to the test facility.

A vacuum was then drawn in the test chamber. During this period of time the evacuation line to the reflux tube was left open to the atmosphere to ensure that the pressure inside the reflux tube was greater than that of the test chamber. This procedure precluded collapsing the condenser end of the reflux tube. After the vacuum had been drawn on the chamber it was allowed to sit over night. This provided time for the vacuum to drop if a poor seal had been achieved. Once the vacuum had been verified the chiller was turned on and allowed to bring the temperature of the test facility down to approximately -10° C. When the HPTF was cooled down, a vacuum was drawn on the reflux tube. This vacuum was then used to vacuum draw 25 ml of deionized water into the reflux tube. After the water was loaded into the reflux tube the data acquisition system was turned on and the heater was set to a low voltage. As the temperature in the reflux tube rose, more voltage was supplied to the heater until the condenser end of the reflux tube reached a temperature between 85° C and 90° C, this was the temperature range specified by PNL.

During the life test very little had to be done to keep the experiment running. A daily check of the reflux tube temperatures was made to insure that the tube was operating within the required limits. Periodically the vacuum had to be redrawn on the vacuum chamber, and the data collection system had to be stopped and restarted to allow the intermittent retrieval of data from the collecting computer.

B. Results and Discussion.

Two particular tests were conducted on the Ultralite Fabric Reflux Tube. These were a life test conducted for over 800 hours with a steady state total power input of 78.1 Watts, and two subsequent start up and shutdown tests. The 800 hour life test provided a significant amount of operational data. The test was conducted very smoothly and was terminated in order to make visual observations of the reflux tube at the request of the PNL Technical Contact. There is no reason to believe that the reflux tube would not have continued to perform for a much longer period of time. Data from one of the start up tests was lost, however the reflux tube operated as expected, and a second start up was conducted in order to collect adequate data. Figures 3 through 30 show the complete operational history of the reflux tube. Each figure includes a trace for thermocouples 1, 4, 5, and 15 and the "absolute" pressure inside the reflux tube. The "absolute" pressure was not measured but gage pressure was. To get absolute pressure 101 kPa were added to the gage pressure. Therefor this is not the exact absolute pressure, but a reasonable normalized approximation. Various lengths of collection intervals were used throughout these tests. Table 1 lists the start and stop times and the associated collection intervals for all of the data collected. Long time intervals were used during the life test, from 1 to 5 minutes, in order to reduce the amount of data collected over some long time periods. Short collection intervals, from 0.3 to 9.5 seconds, were used to observe interesting features during start up, shut down, and the life test.

The operational data in general showed no signs of deterioration in the performance of the reflux tube. However toward the end of the testing the internal thermocouple did have periods in which it was not functioning properly. During such a failure the temperature reported by the thermocouple dropped drastically and then later returned to normal. The exact cause of these failures is not known but a short in that channel may have been the cause. A loose connection was found and there have been no more occurrences of this problem.

There were two particularly interesting phenomena observed during the life test. The first was a cycling of the temperatures and pressure inside the reflux tube during

Table 1. Table of Start and Stop Times with Associated Collection Intervals.

Start Date & Time		Stop Date & Time		Collection Interval
11/17	16:03:07	11/18	08:42:43	5 min.
11/18	08:57:24	11/18	11:03:12	6 sec.
11/18	11:07:18	11/18	14:31:18	1 min.
11/18	14:34:17	11/19	11:35:05	5 min.
11/19	11:45:12	11/23	13:24:54	5 min.
11/23	13:33:42	11/24	12:22:30	5 min.
11/24	12:25:21	11/24	14:29:15	6 sec.
11/24	14:31:18	11/25	08:39:24	5 min.
11/25	08:44:12	11/25	09:27:48	0.3 sec.
11/25	09:19:56	11/25	15:46:38	30 sec.
11/25	15:54:50	11/30	08:49:44	5 min.
11/30	08:55:26	12/01	12:39:37	5 min.
12/01	12:44:45	12/01	13:35:08	1.5 sec.
12/01	13:38:19	12/03	14:03:22	5 min.
12/03	14:42:30	12/03	15:43:12	4 sec.
12/03	15:45:24	12/04	08:19:06	1 min.
12/04	08:21:24	12/06	09:47:00	5 min.
12/06	09:49:48	12/06	10:24:08	1.5 sec.
12/06	10:26:03	12/09	11:25:40	5 min.
12/09	11:28:14	12/09	14:35:46	9.5 sec.
12/09	14:37:46	12/14	08:50:20	5 min.
12/14	08:54:40	12/15	09:42:22	5 min.
12/15	09:46:09	12/15	10:27:07	1.5 sec.
12/15	10:29:46	12/18	10:34:46	5 min.
12/18	10:38:09	12/18	11:14:20	1.5 sec.
12/18	11:15:59	12/22	08:07:52	5 min.
12/22	08:10:14	12/22	09:24:24	9 sec.
12/22	09:26:00	12/22	09:47:33	9 sec. **
12/22	17:37:09	12/22	19:42:51	6 sec.

All graphs show thermocouples 1,4,8,15 and the absolute pressure.
** Time period not plotted.

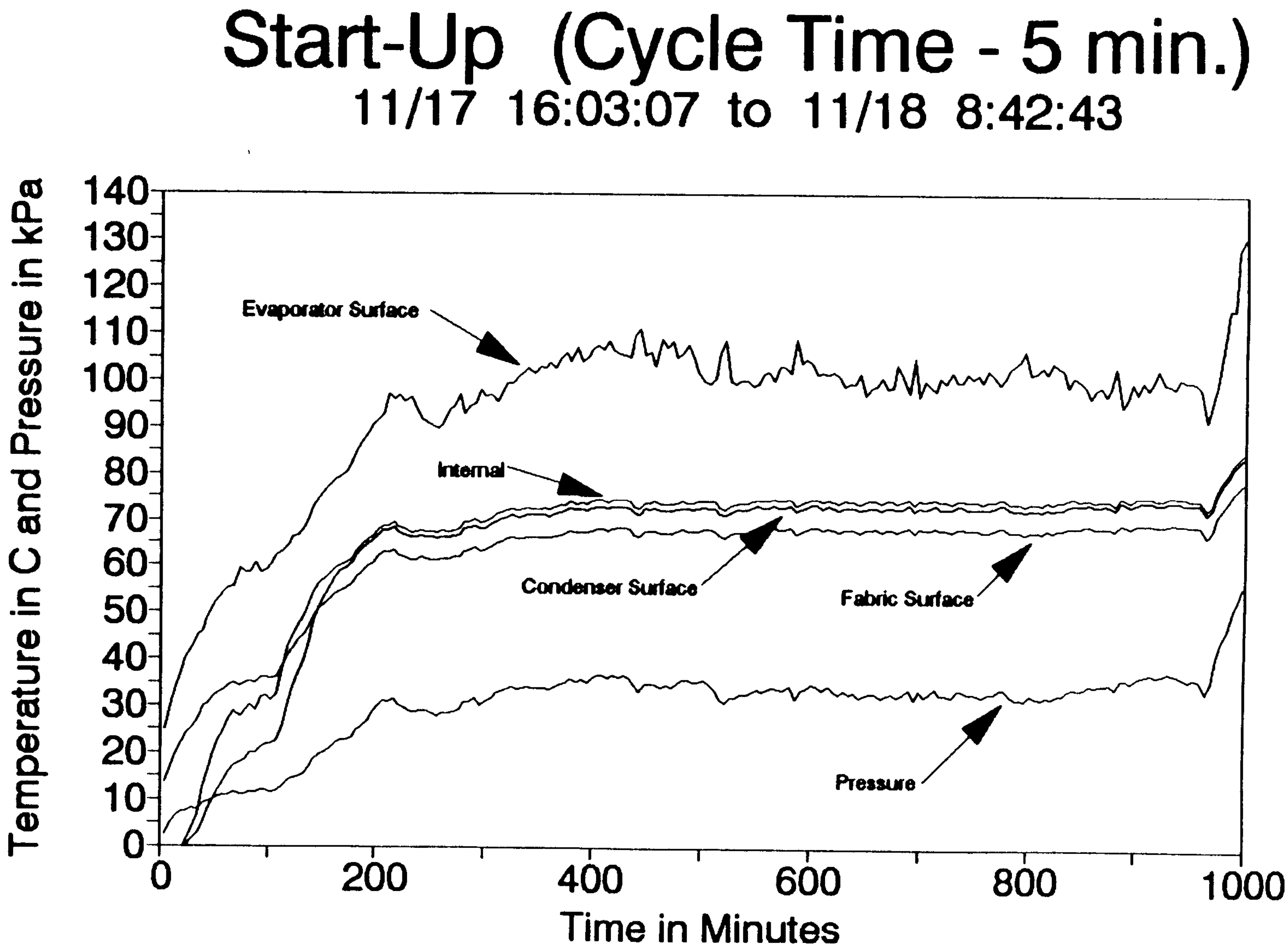


Figure 3. Data From Reflux Tube Operation.

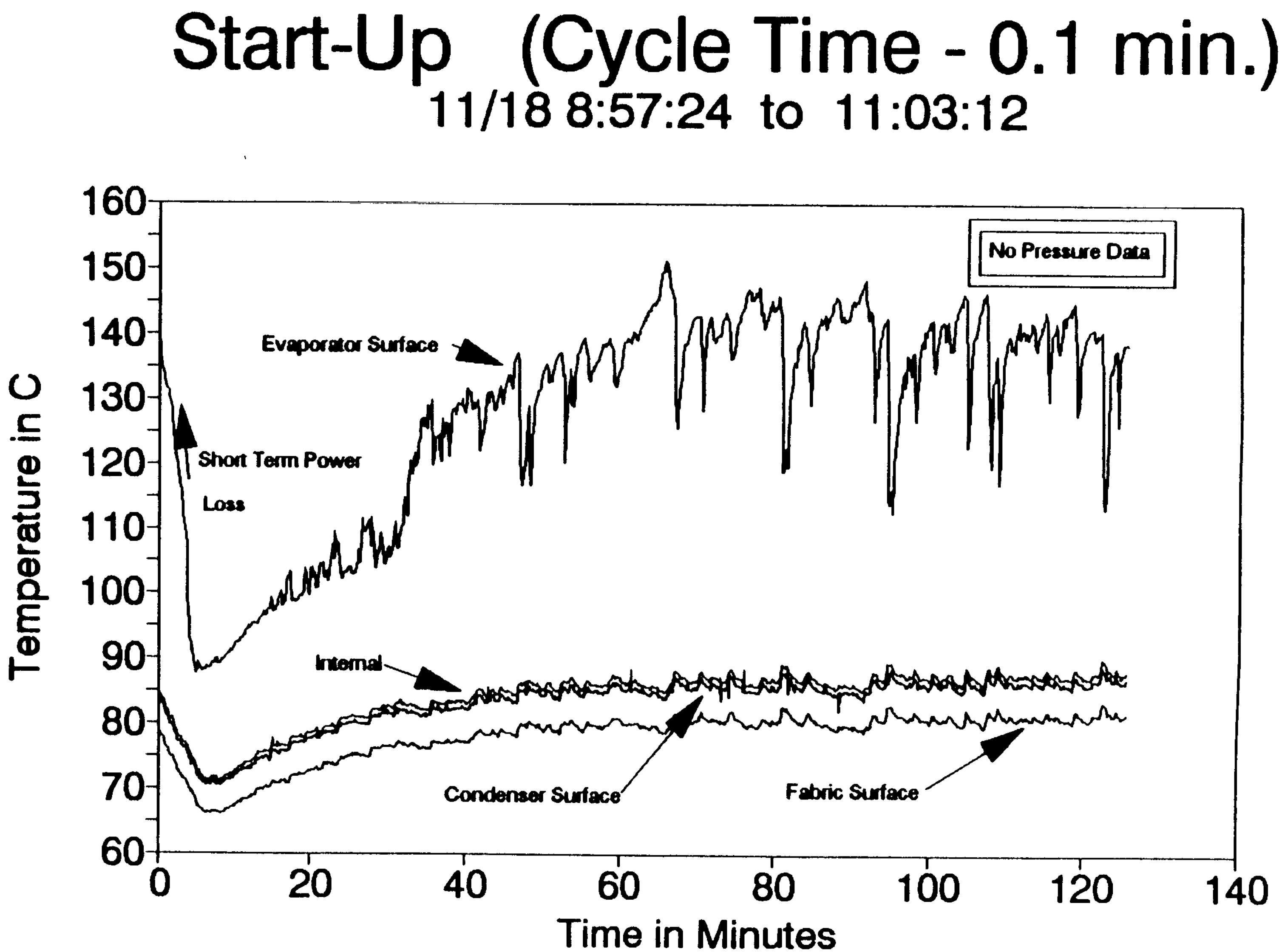


Figure 4. Data From Reflux Tube Operation.

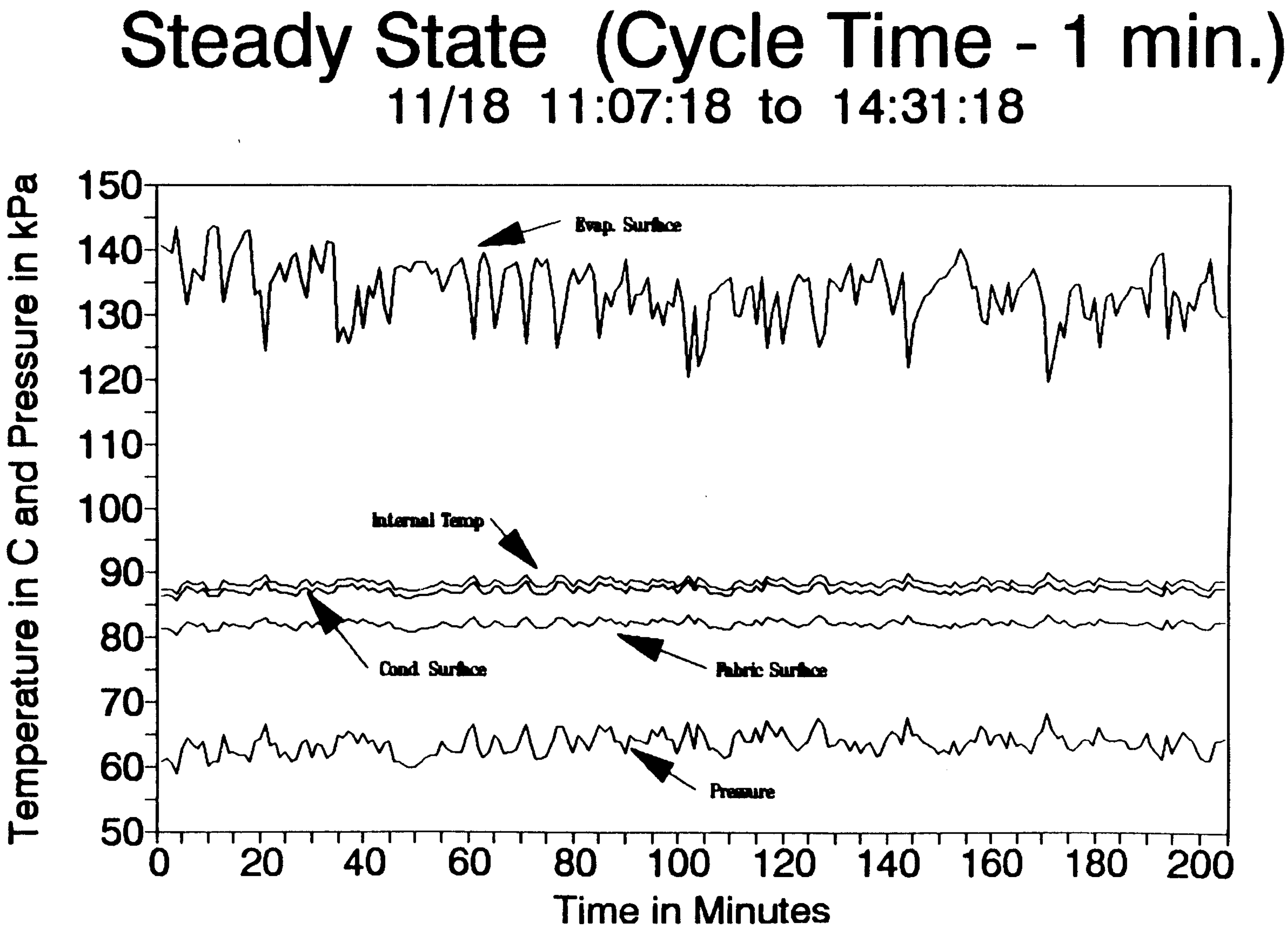


Figure 5. Data From Reflux Tube Operation.

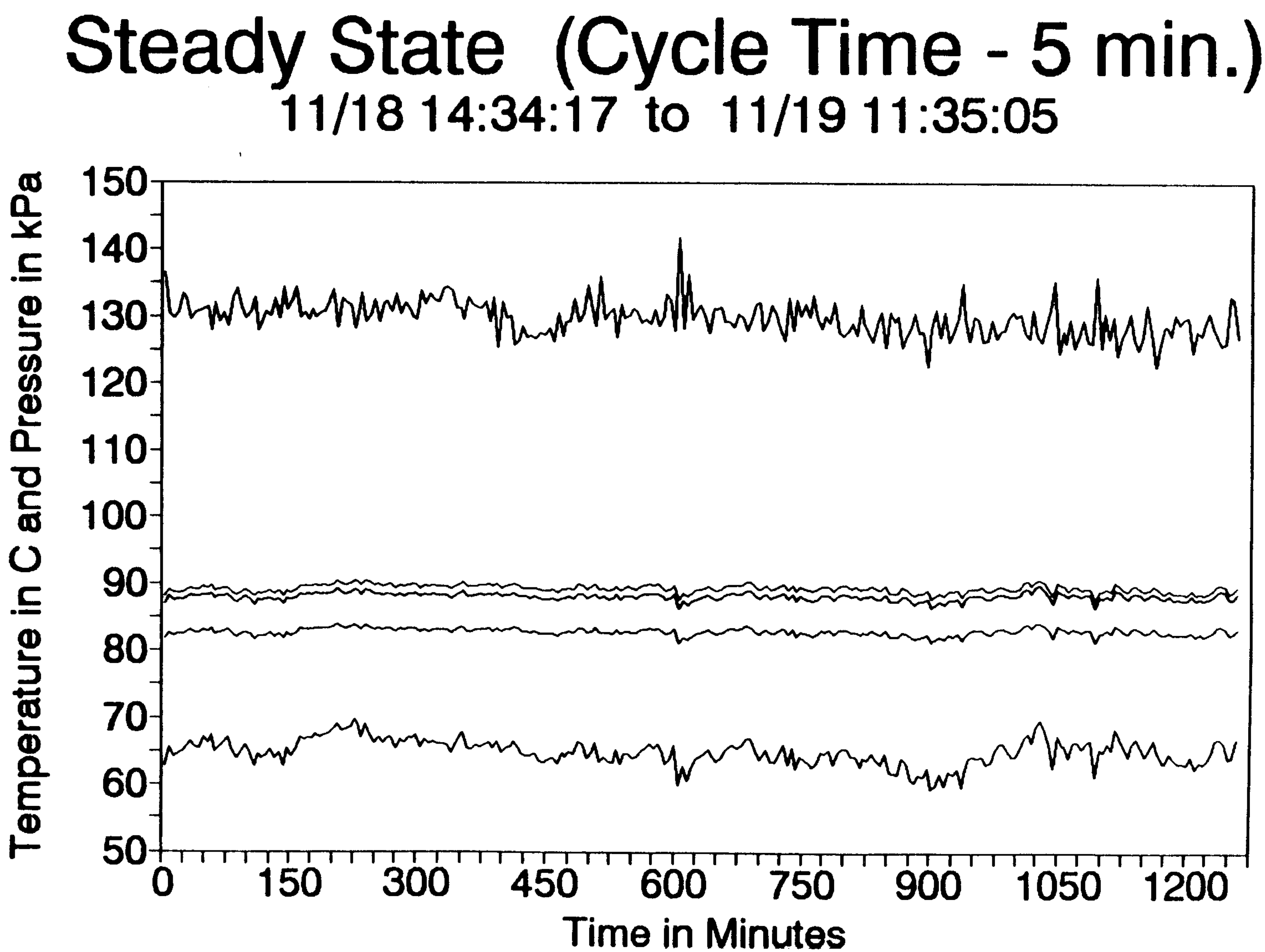


Figure 6. **Data From Reflux Tube Operation.**

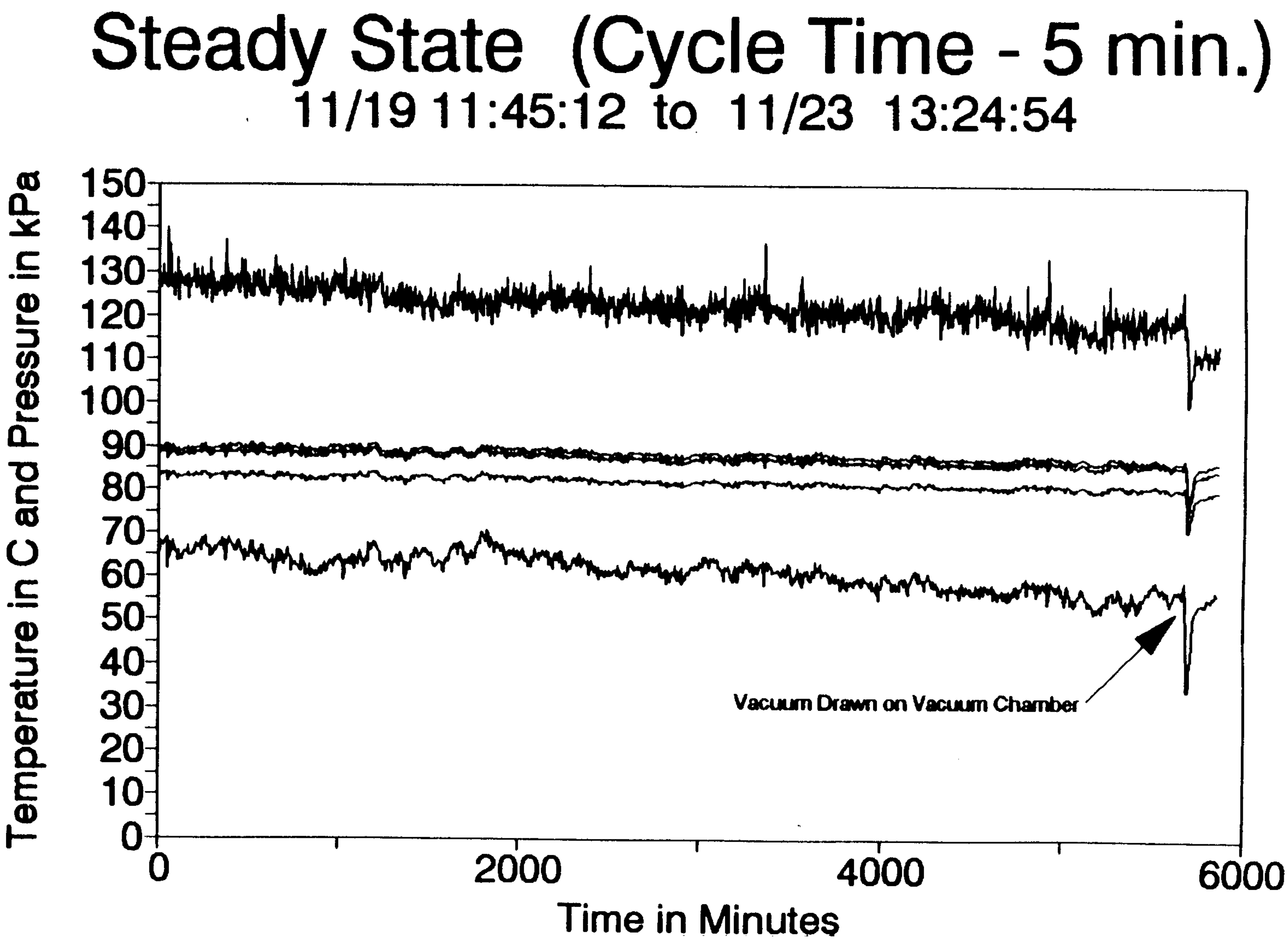


Figure 7. Data From Reflux Tube Operation.

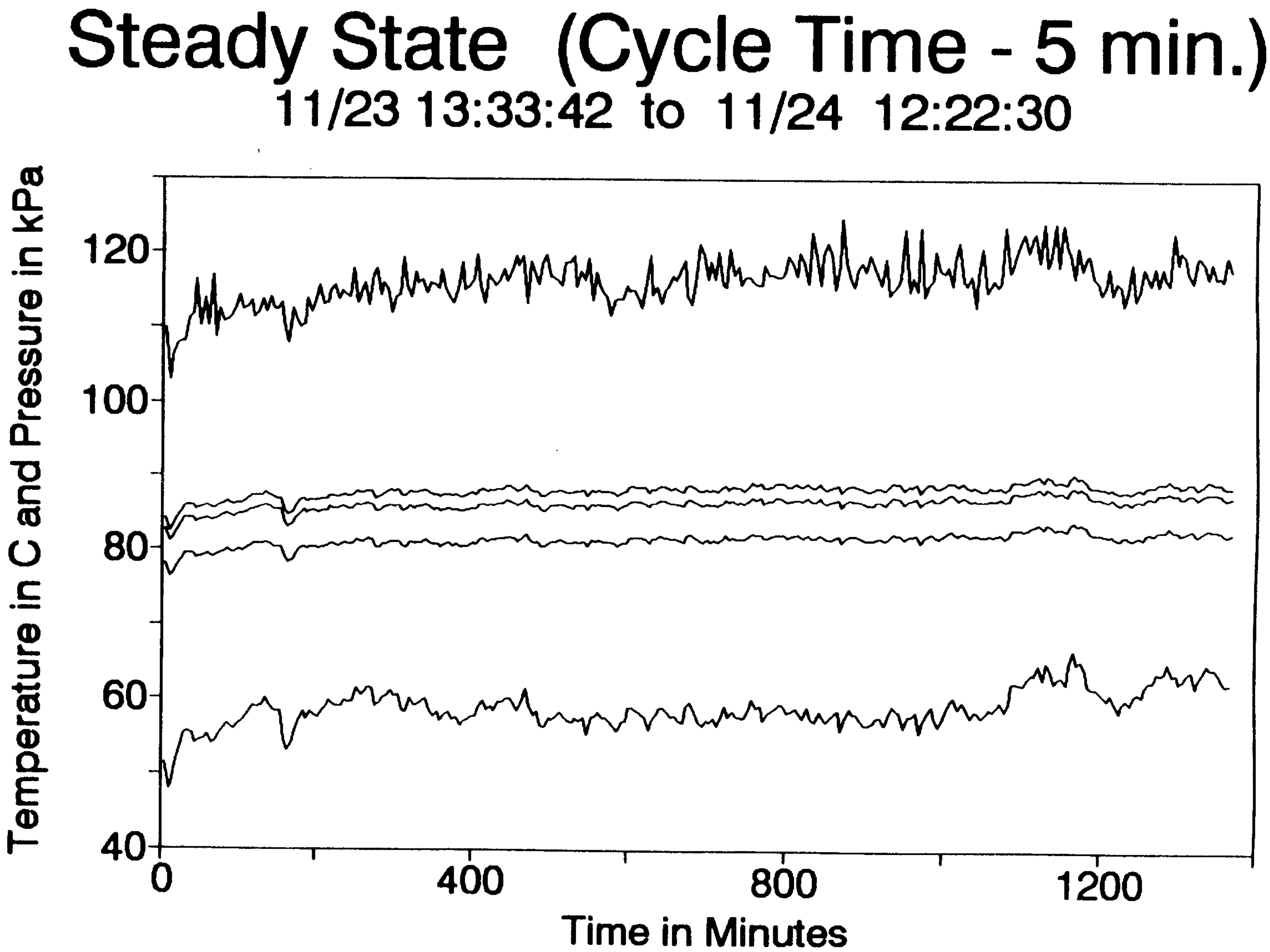
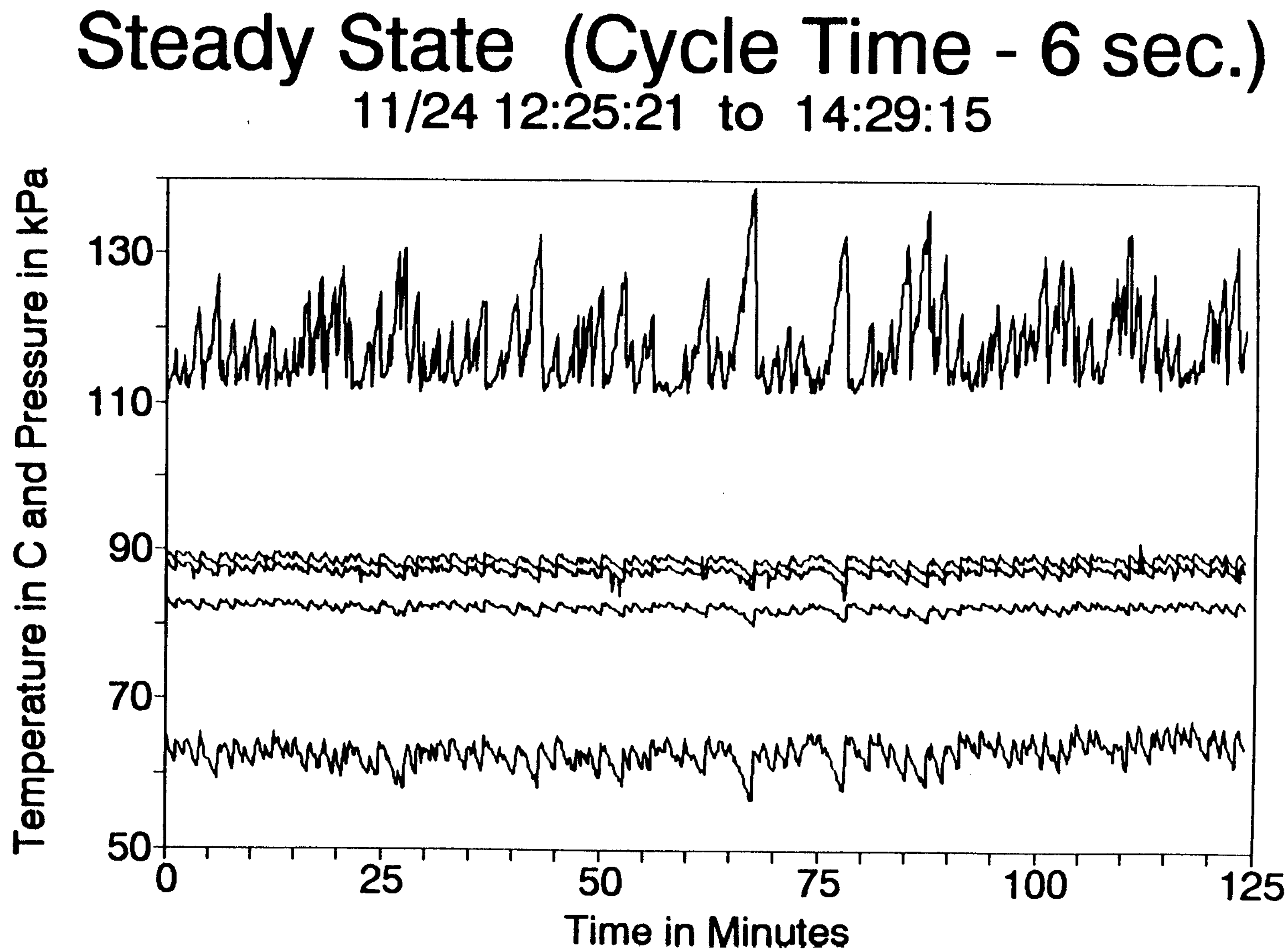


Figure 8. Data From Reflux Tube Operation.



Figuer 9. Data From Reflux Tube Operation.

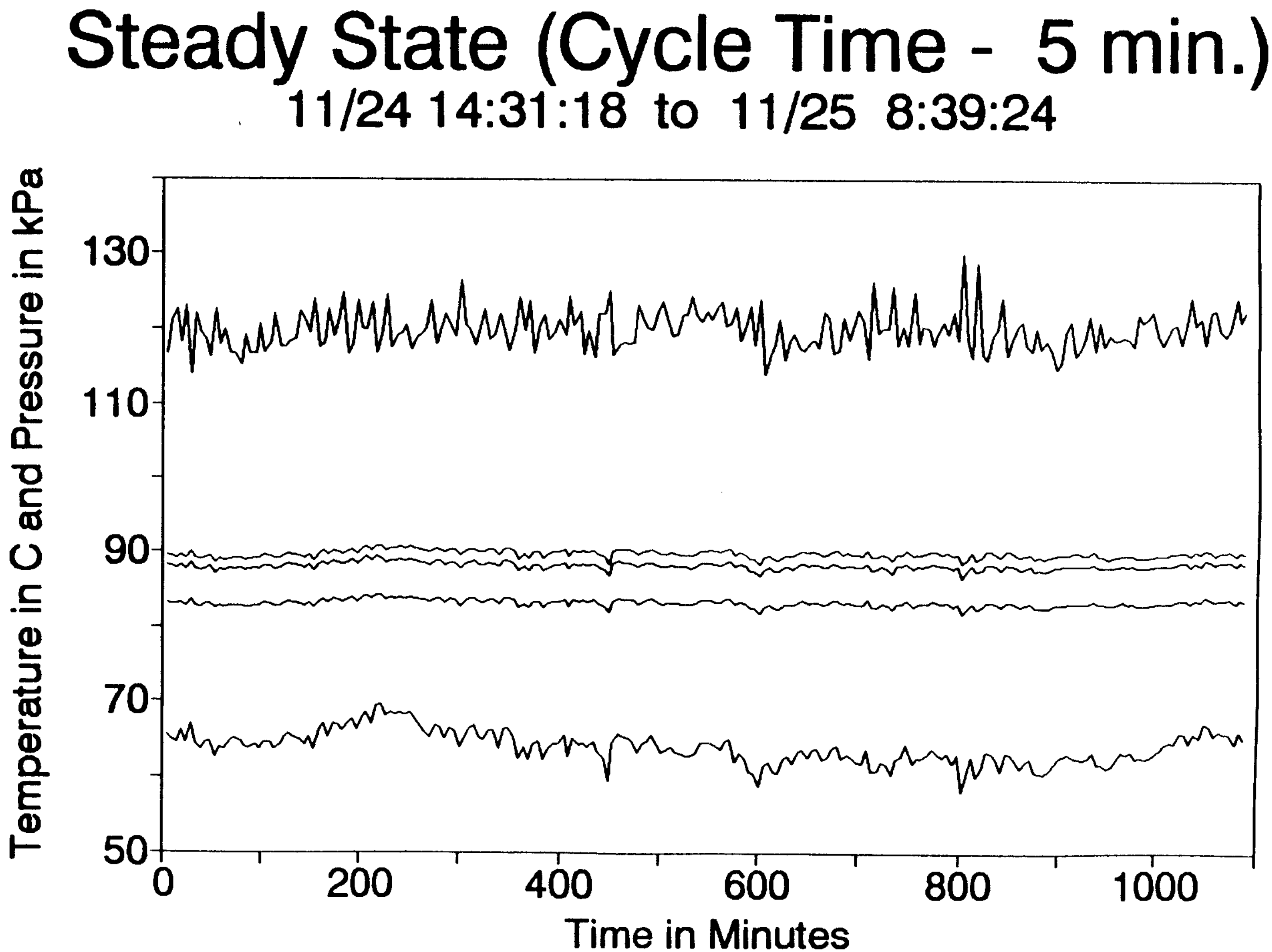


Figure 10. Data From Reflux Tube Operation.

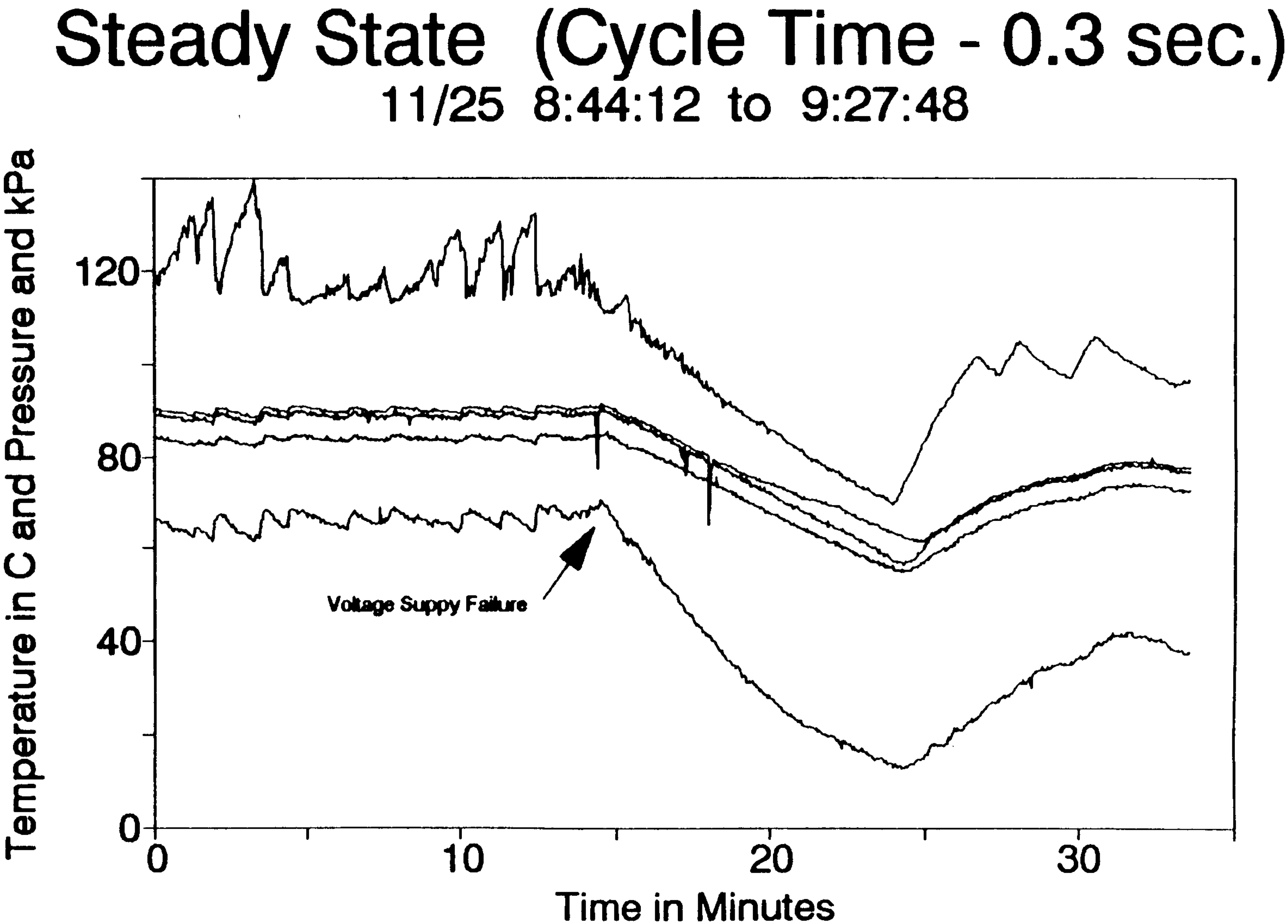


Figure 11. Data From Reflux Tube Operation.

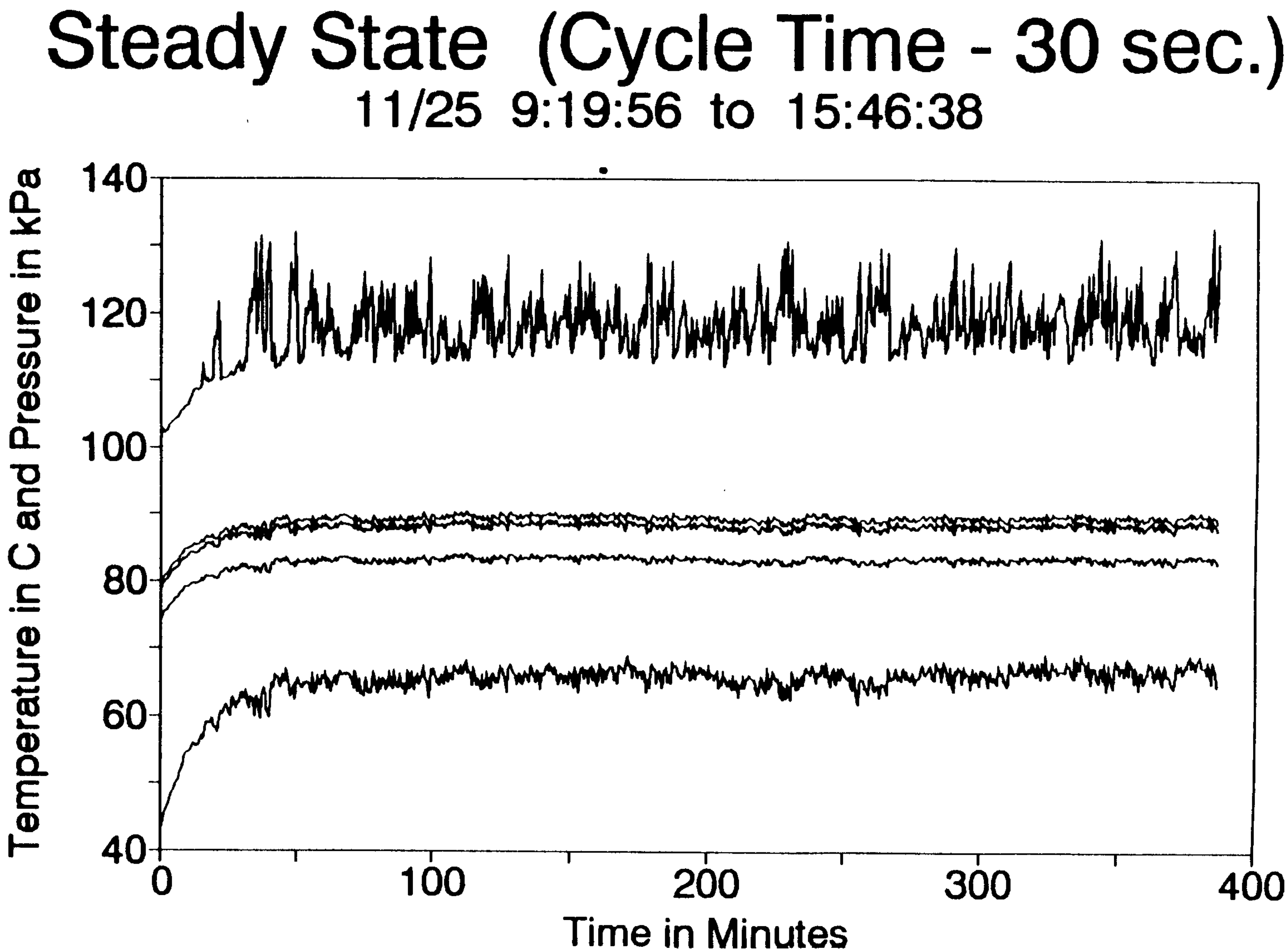


Figure 12. Data From Reflux Tube Operation.

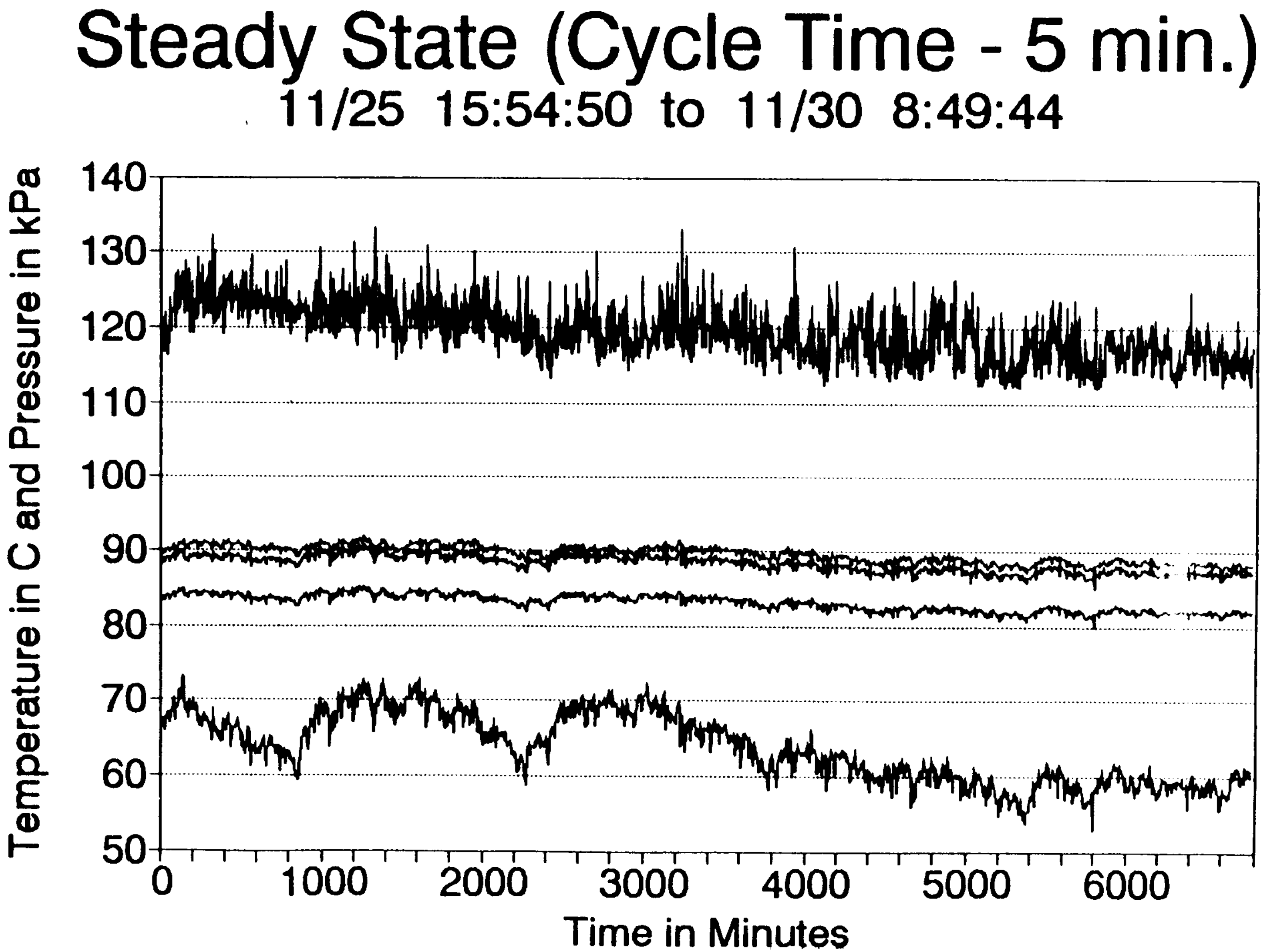


Figure 13. Data From Reflux Tube Operation.

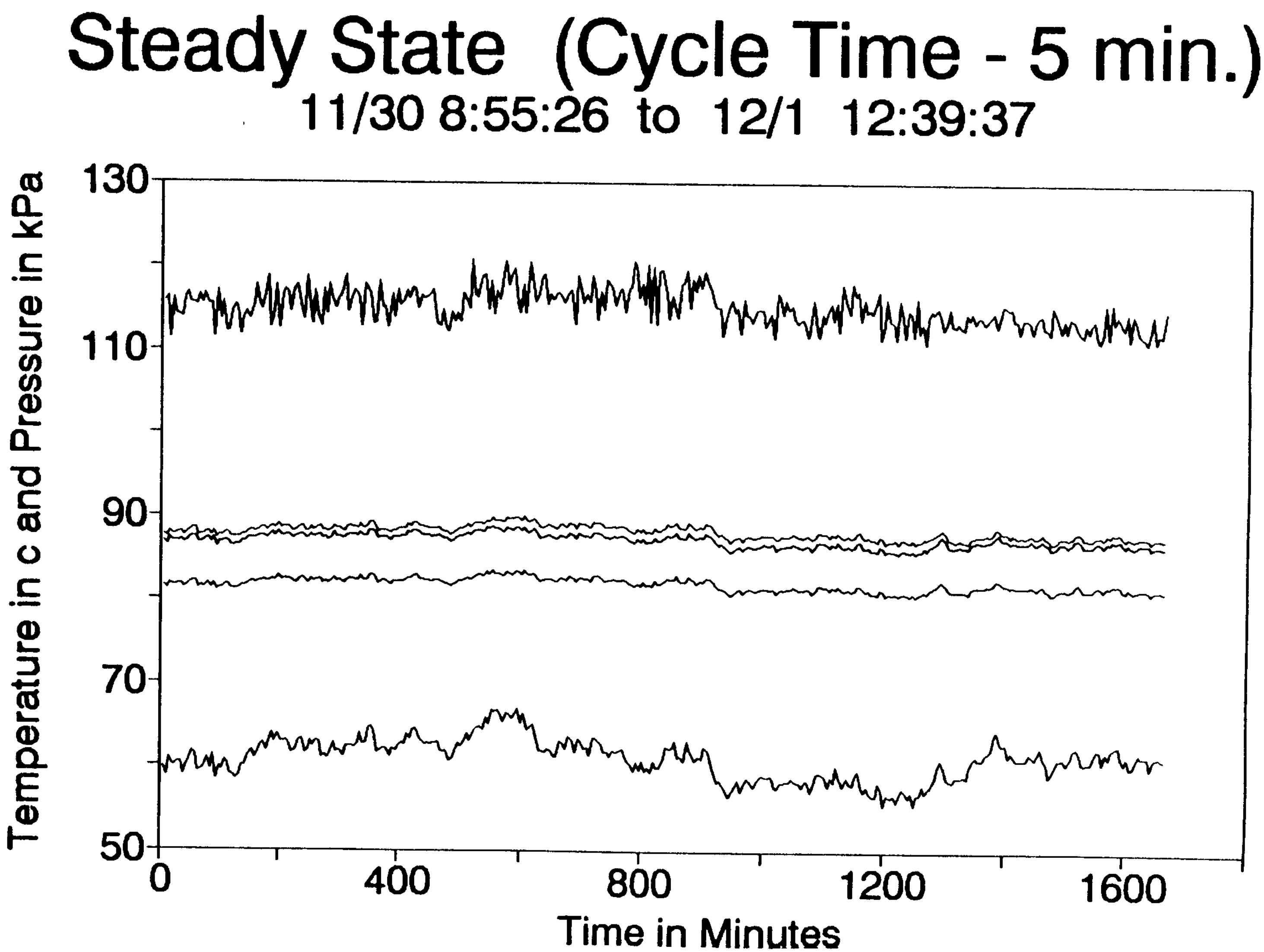


Figure 14. Data From Reflux Tube Operation.

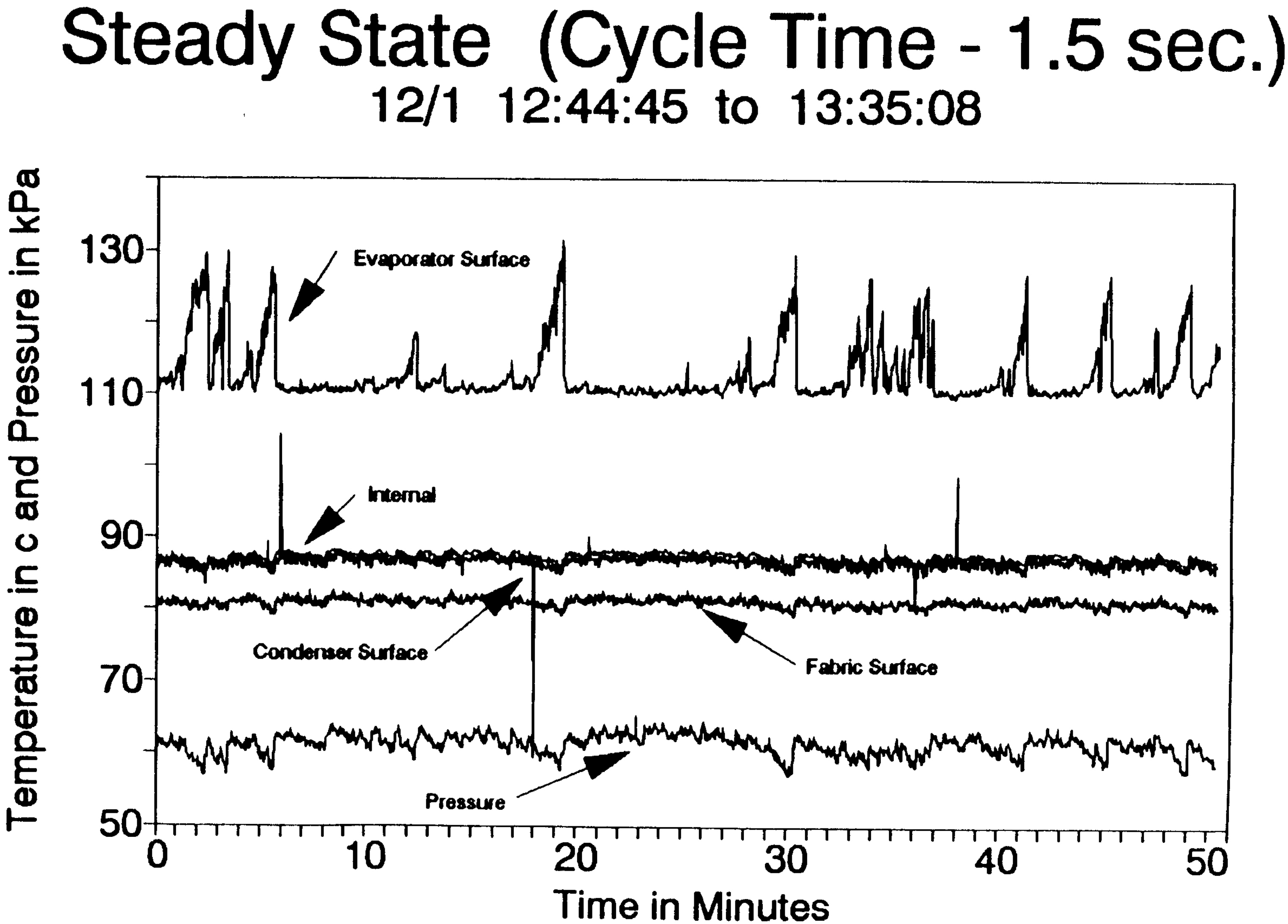


Figure 15. Data From Reflux Tube Operation.

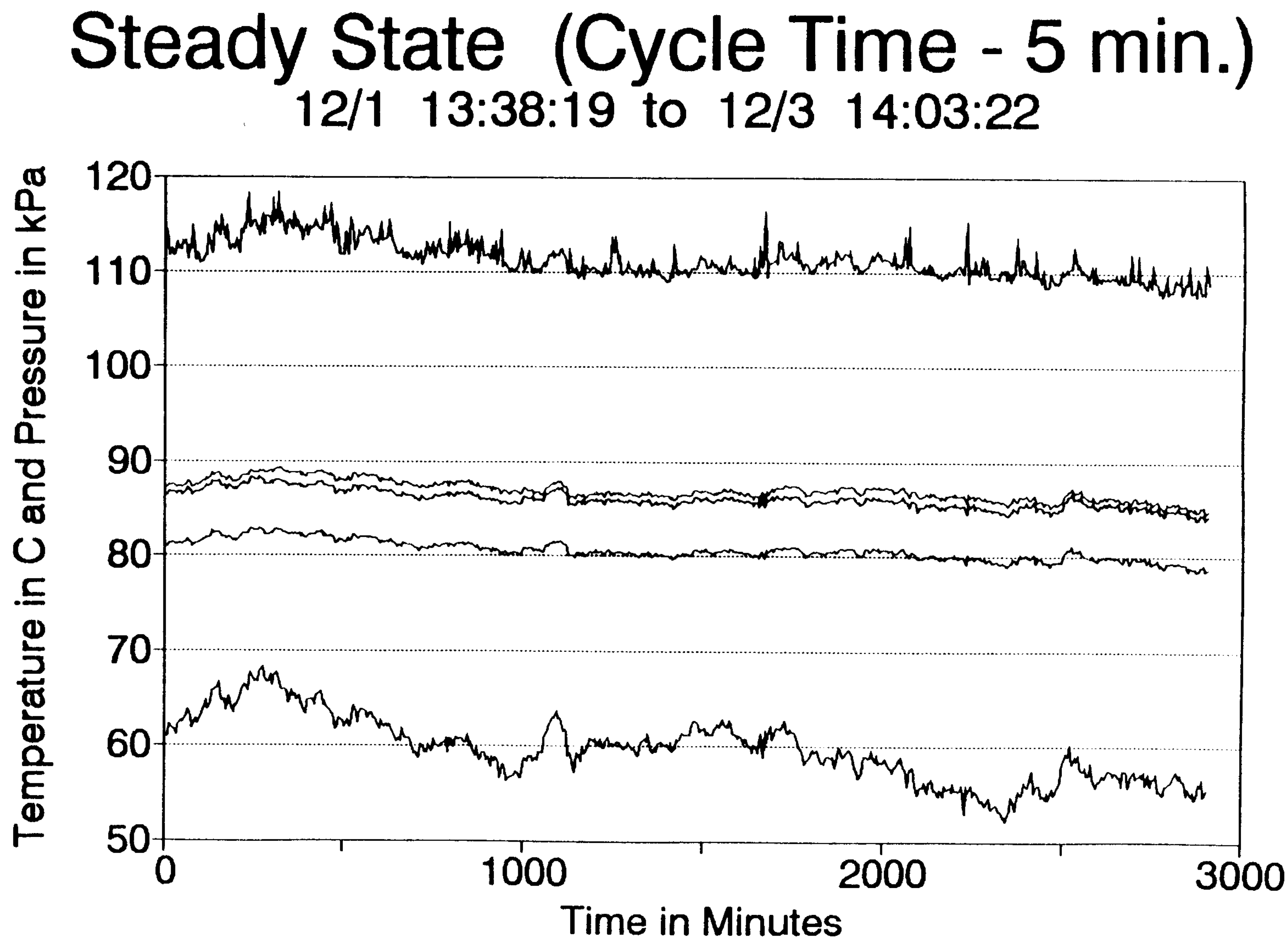


Figure 16. Data From Reflux Tube Operation.

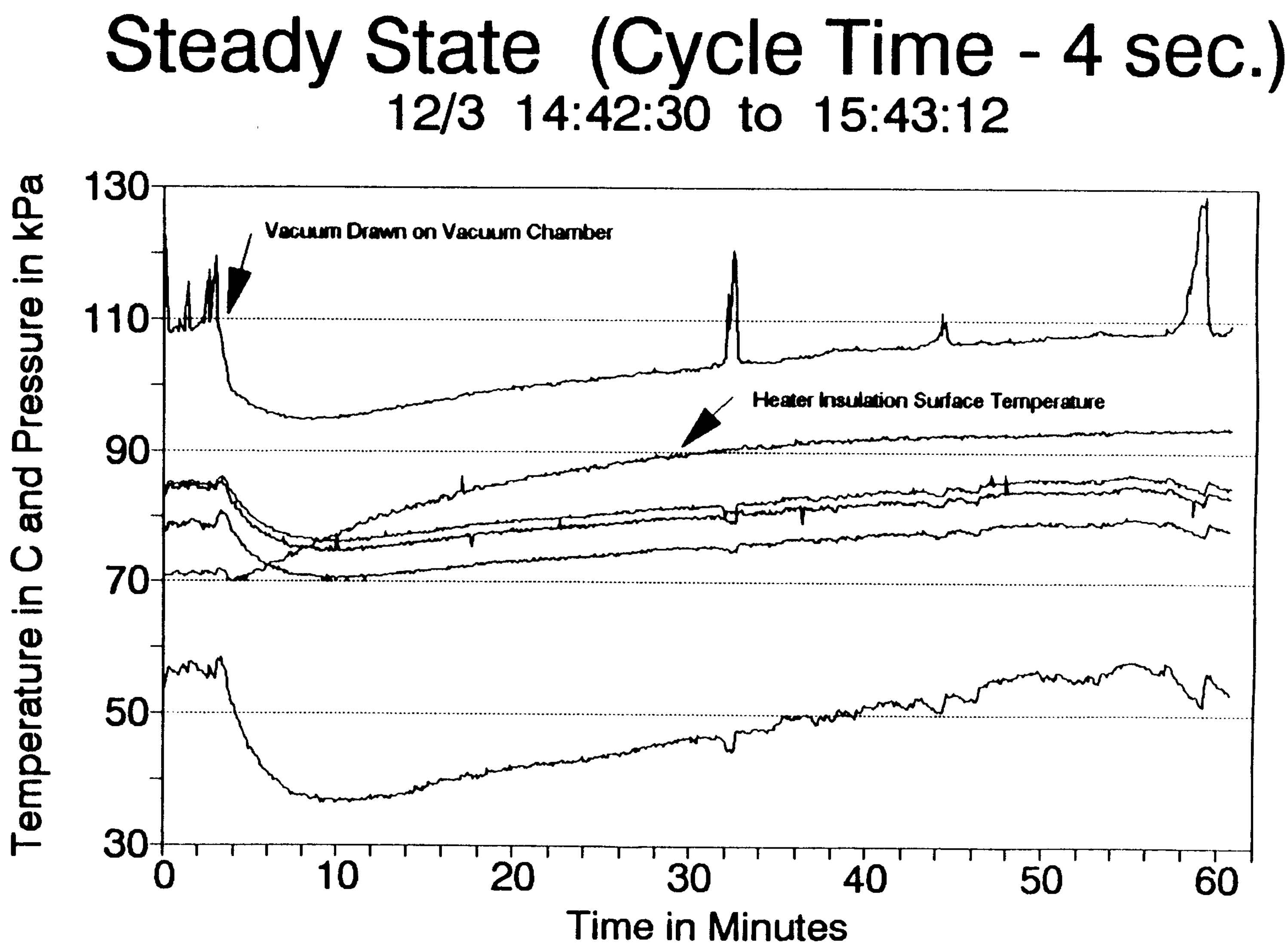


Figure 17. Data From Reflux Tube Operation.

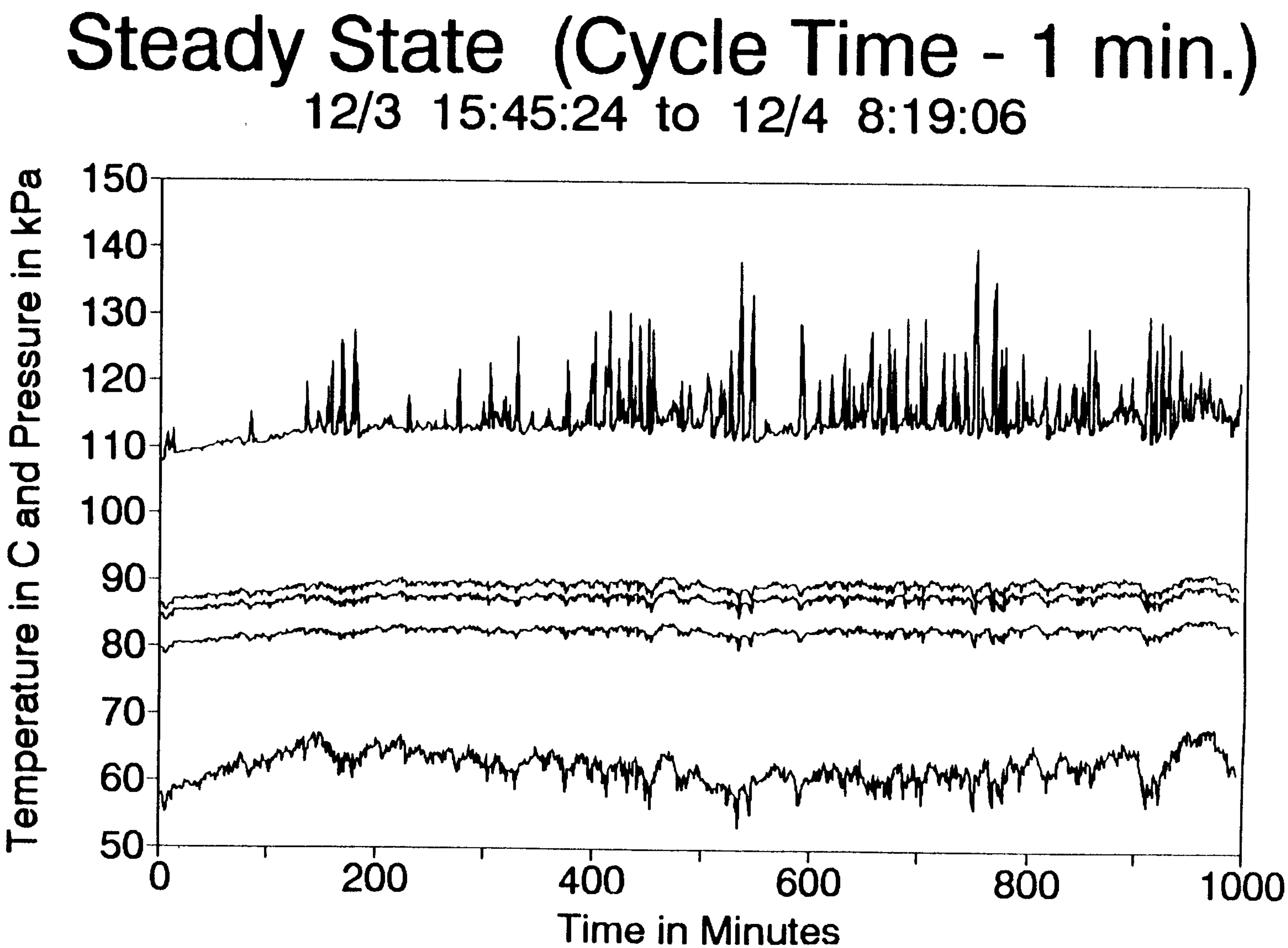


Figure 18. Data From Reflux Tube Operation.

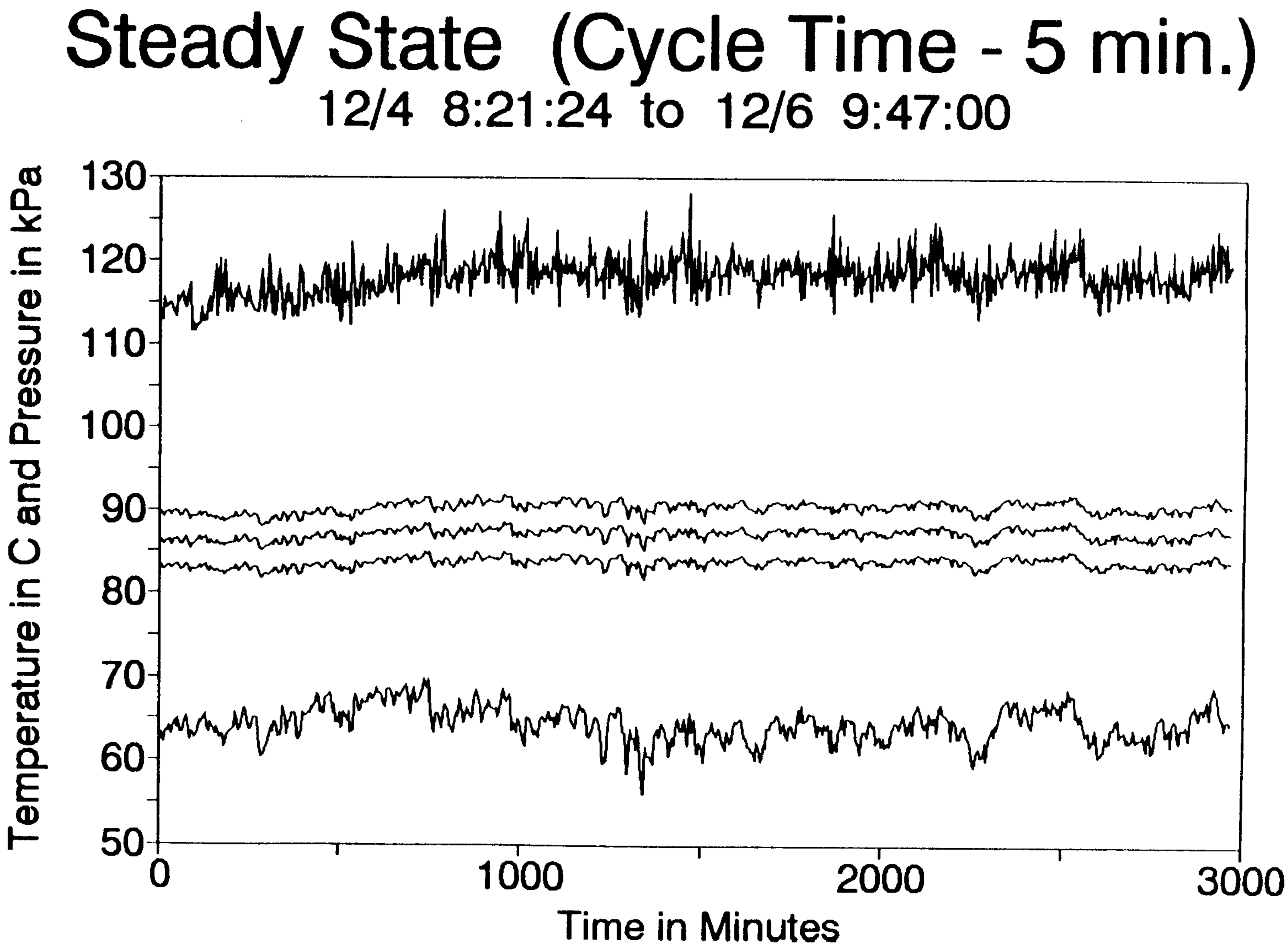


Figure 19. Data From Reflux Tube Operation.

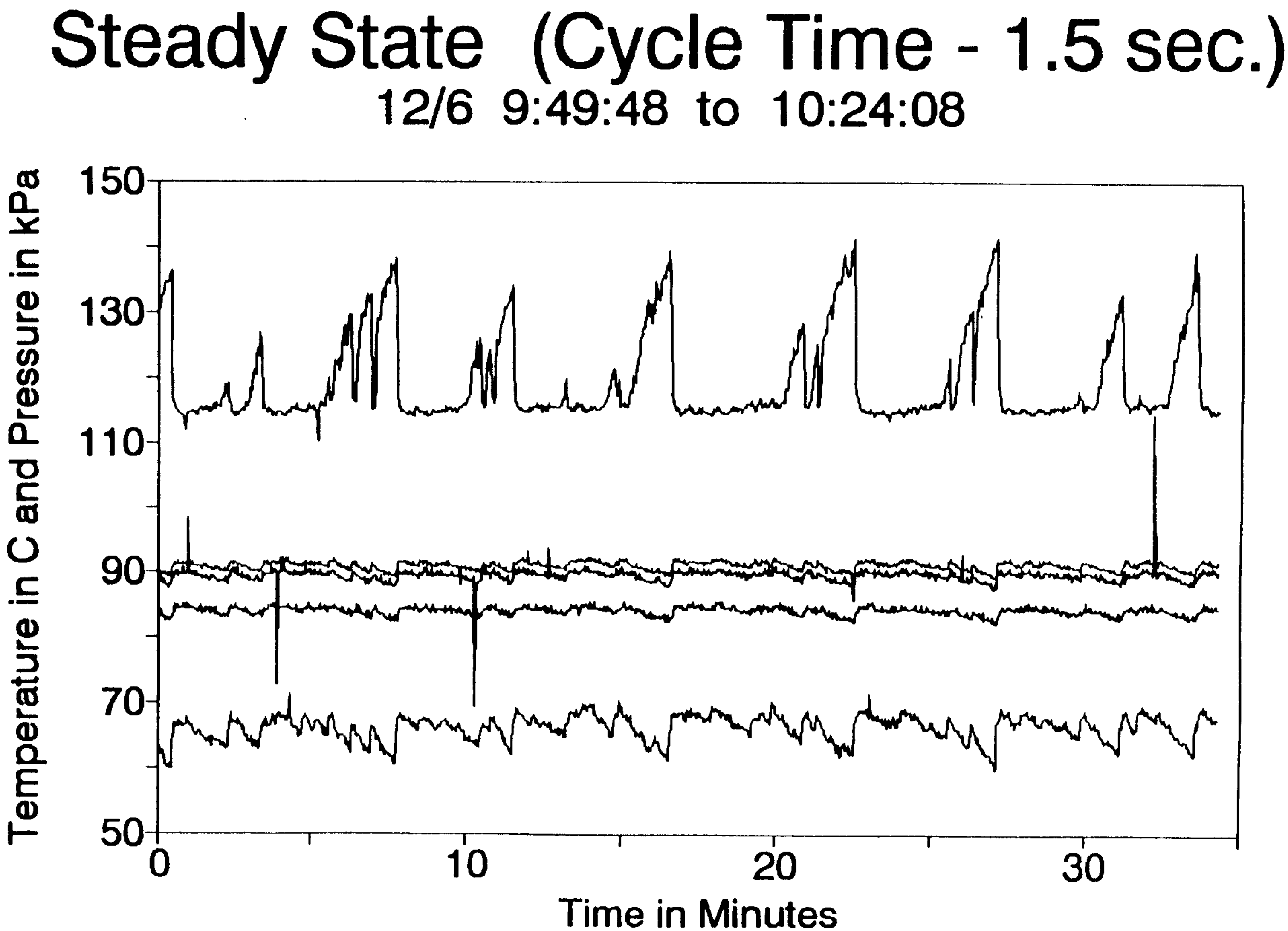


Figure 20. Data From Reflux Tube Operation.

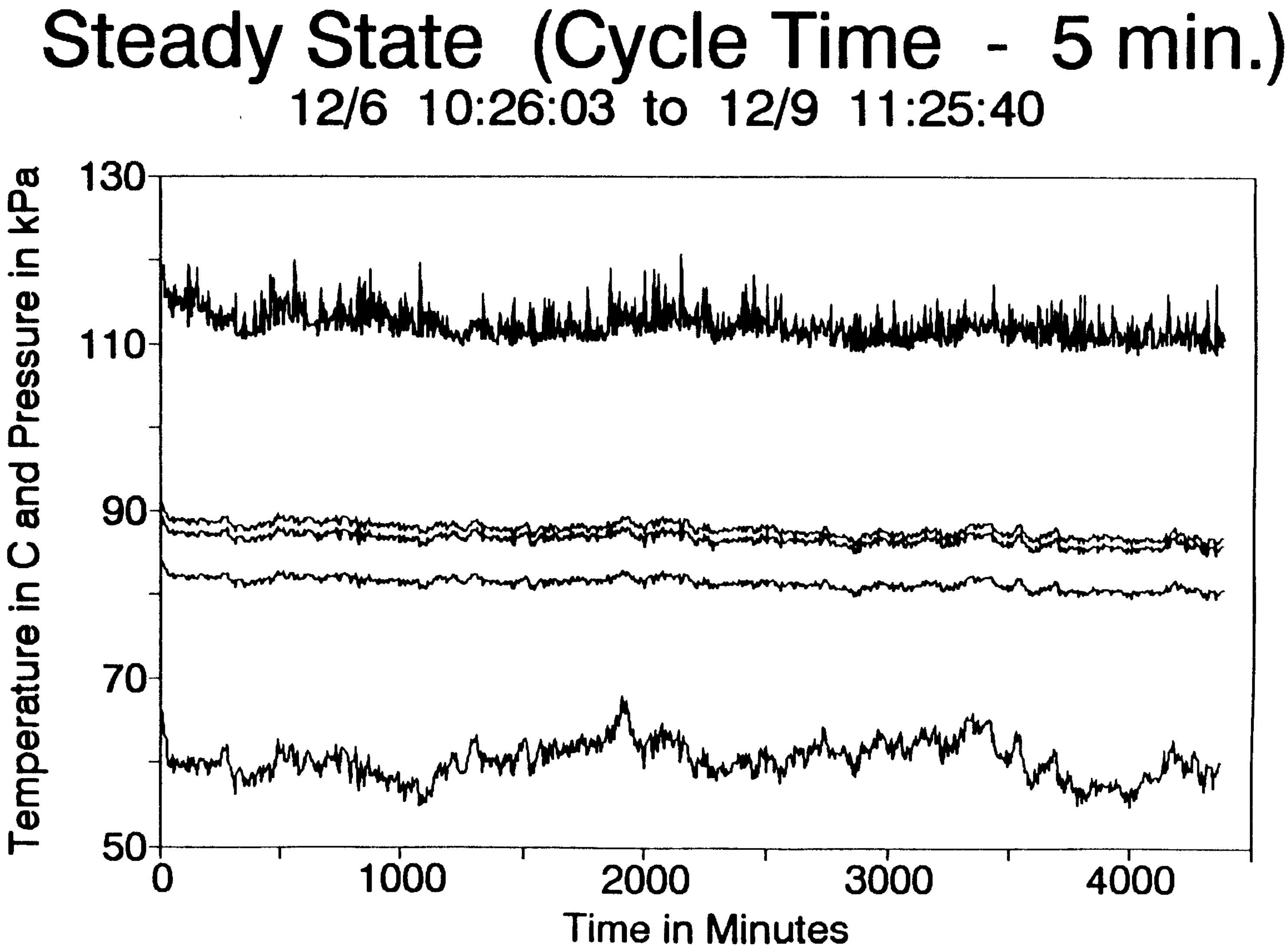


Figure 21. Data From Reflux Tube Operation.

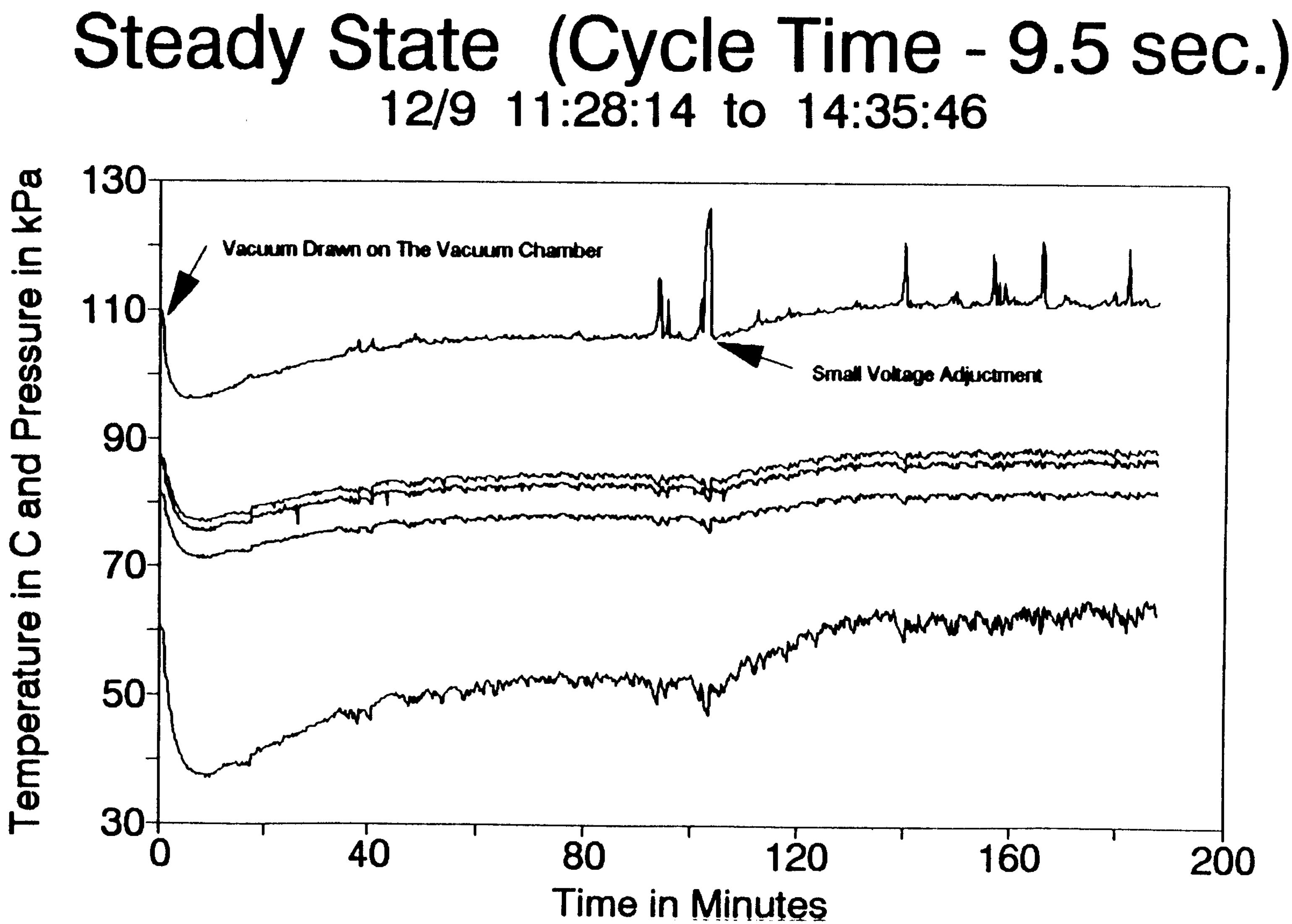


Figure 22. Data From Reflux Tube Operation.

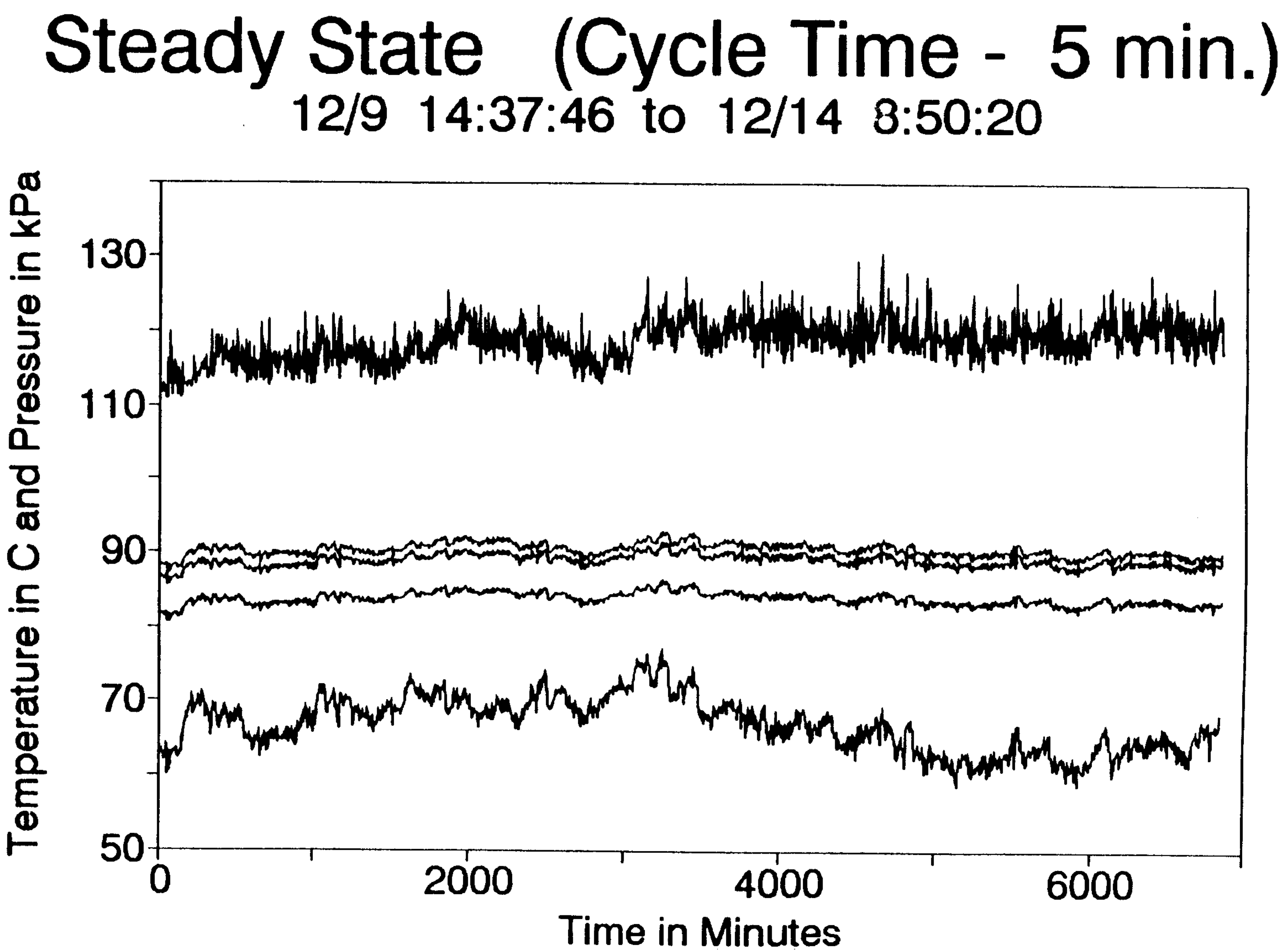


Figure 23. Data From Reflux Tube Operation.

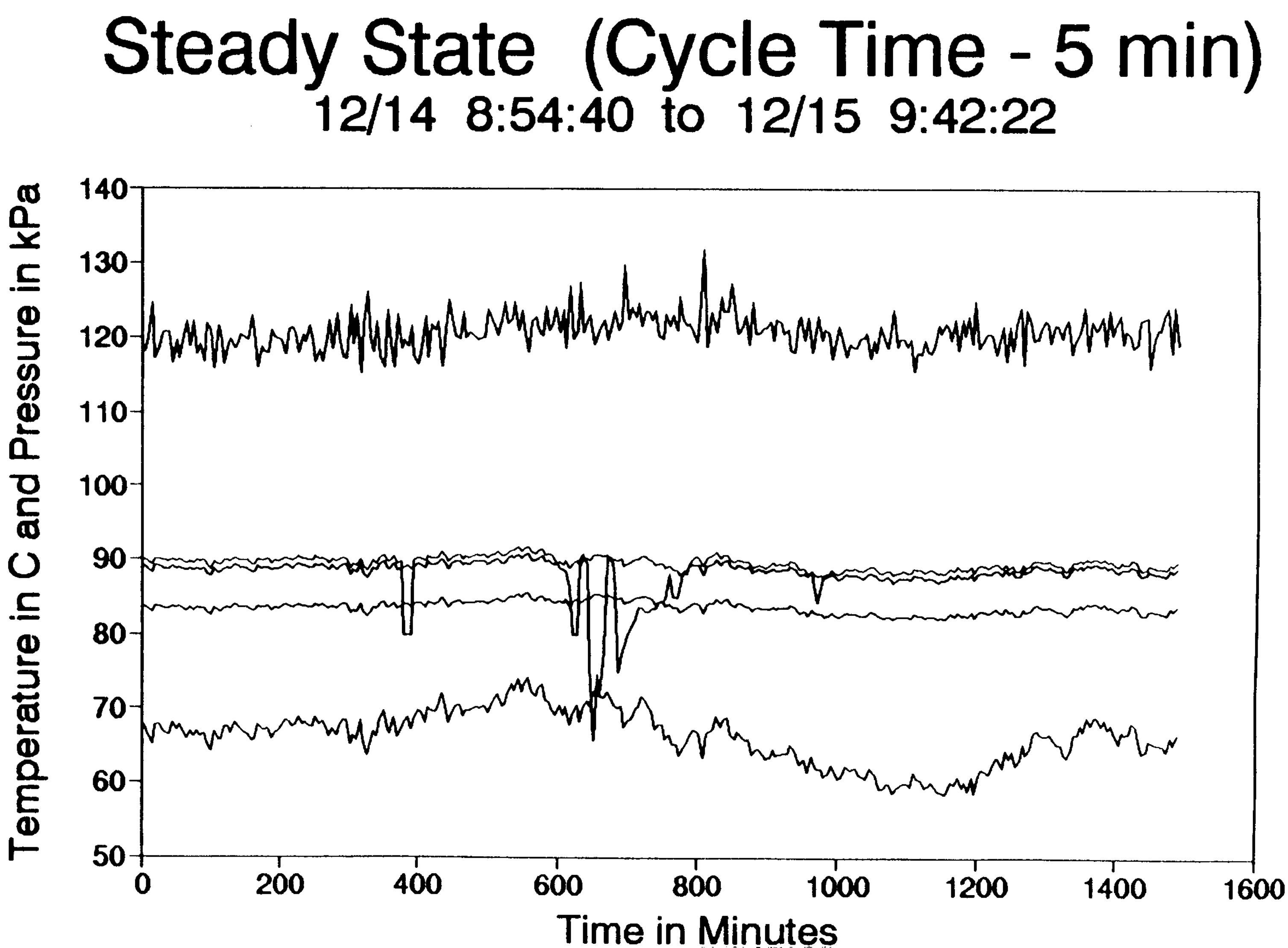


Figure 24. Data From Reflux Tube Operation.

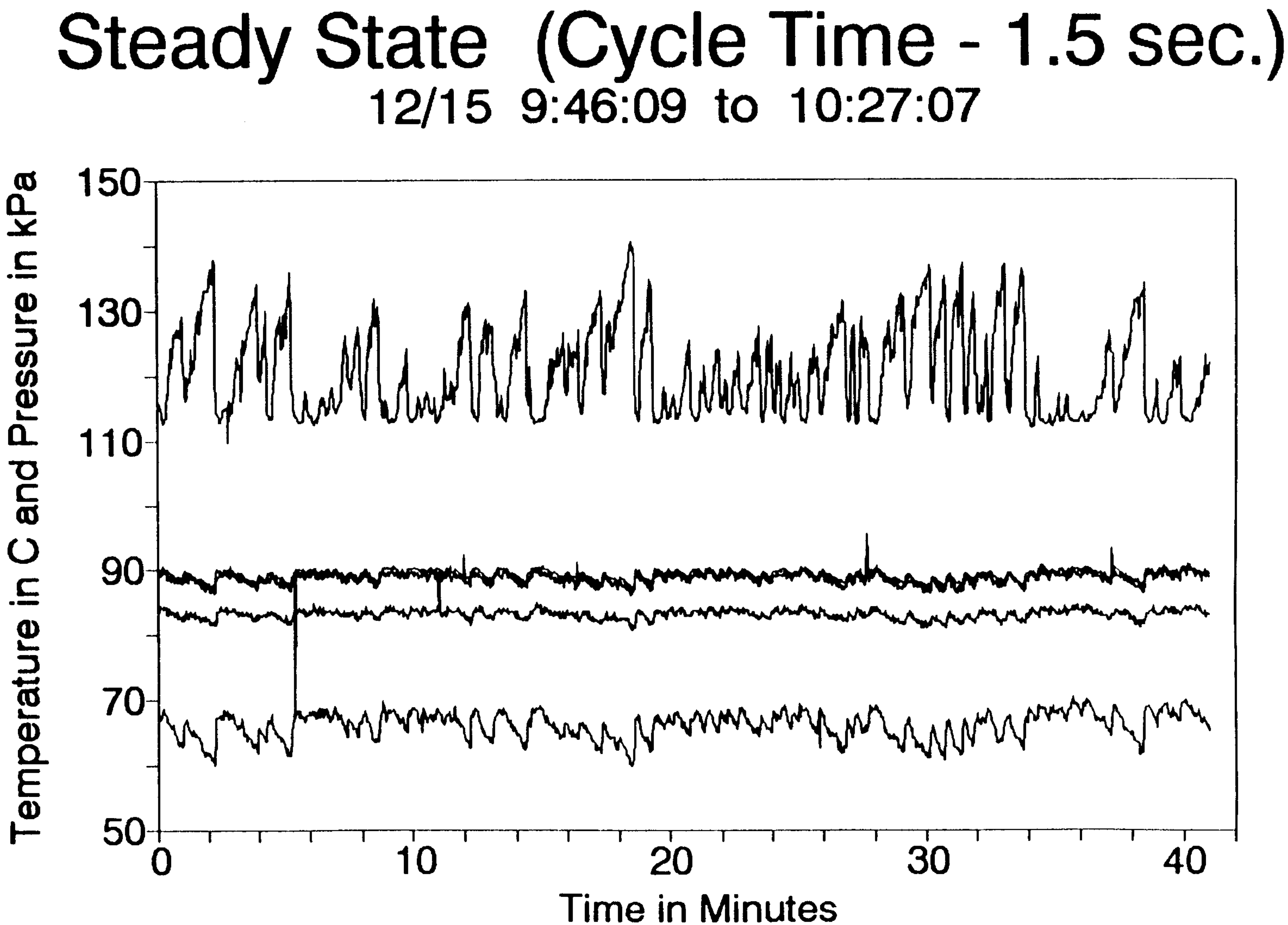


Figure 25. Data From Reflux Tube Operation.

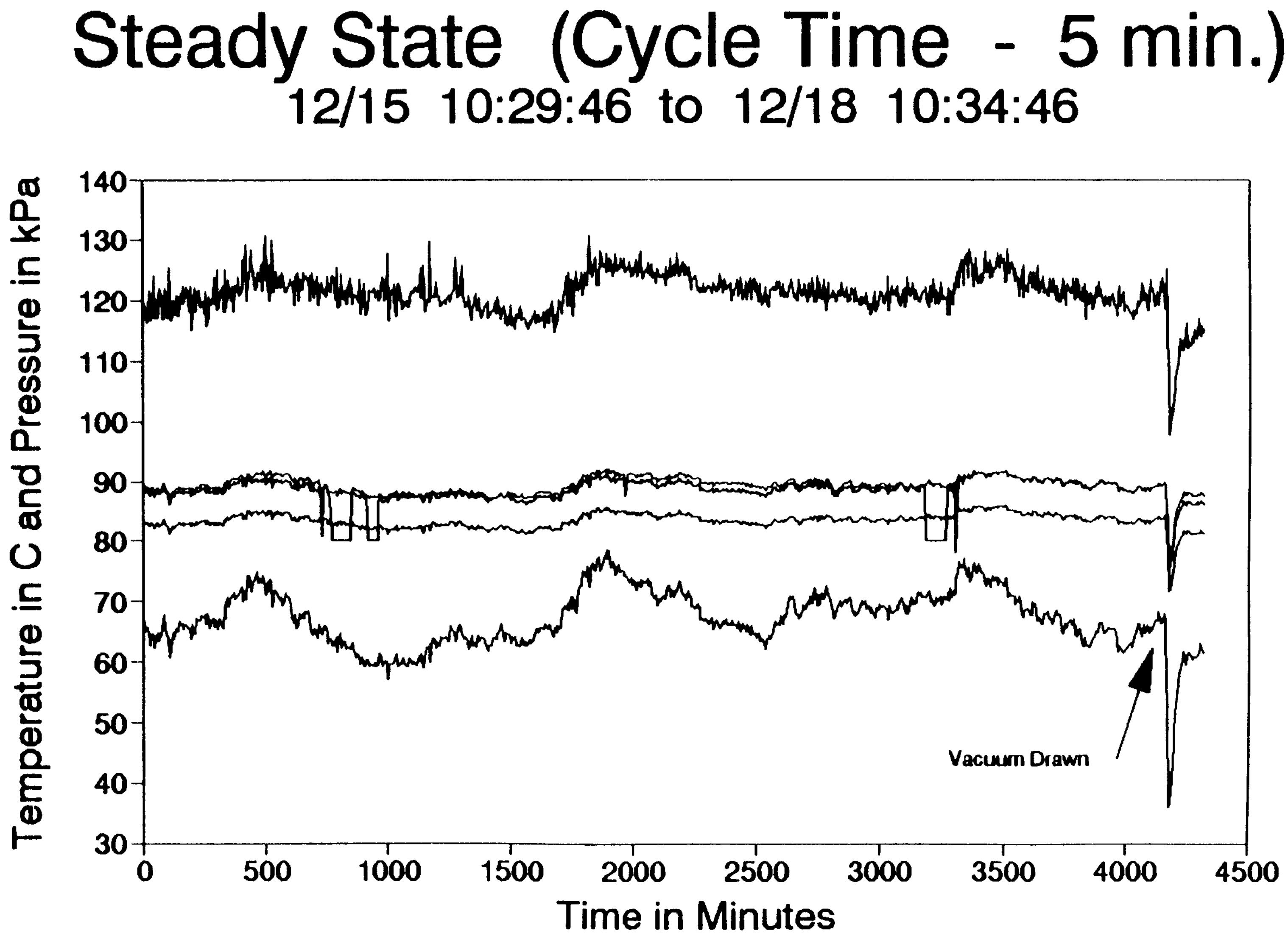


Figure 26. Data From Reflux Tube Operation.

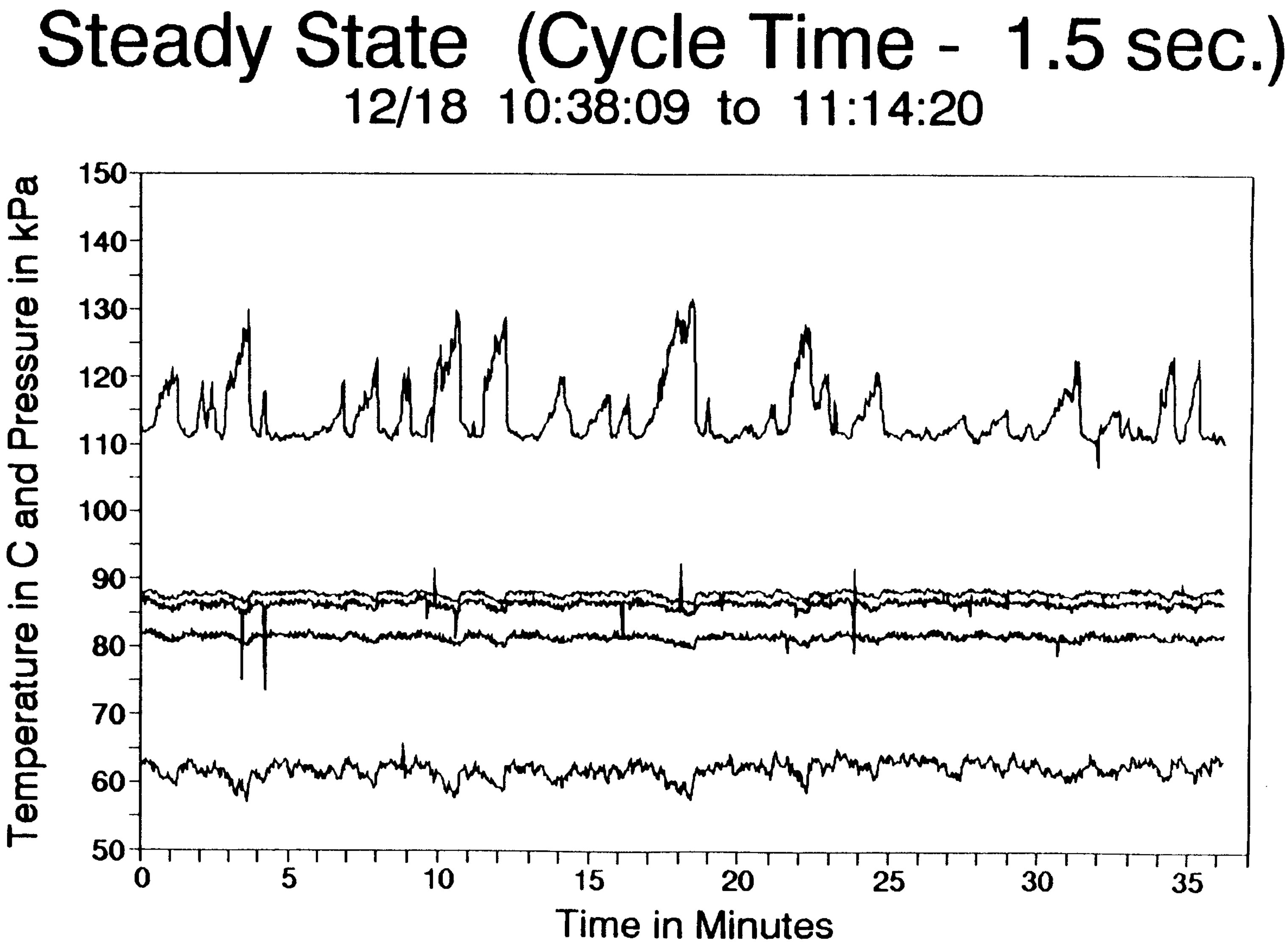


Figure 27. Data From Reflux Tube Operation.

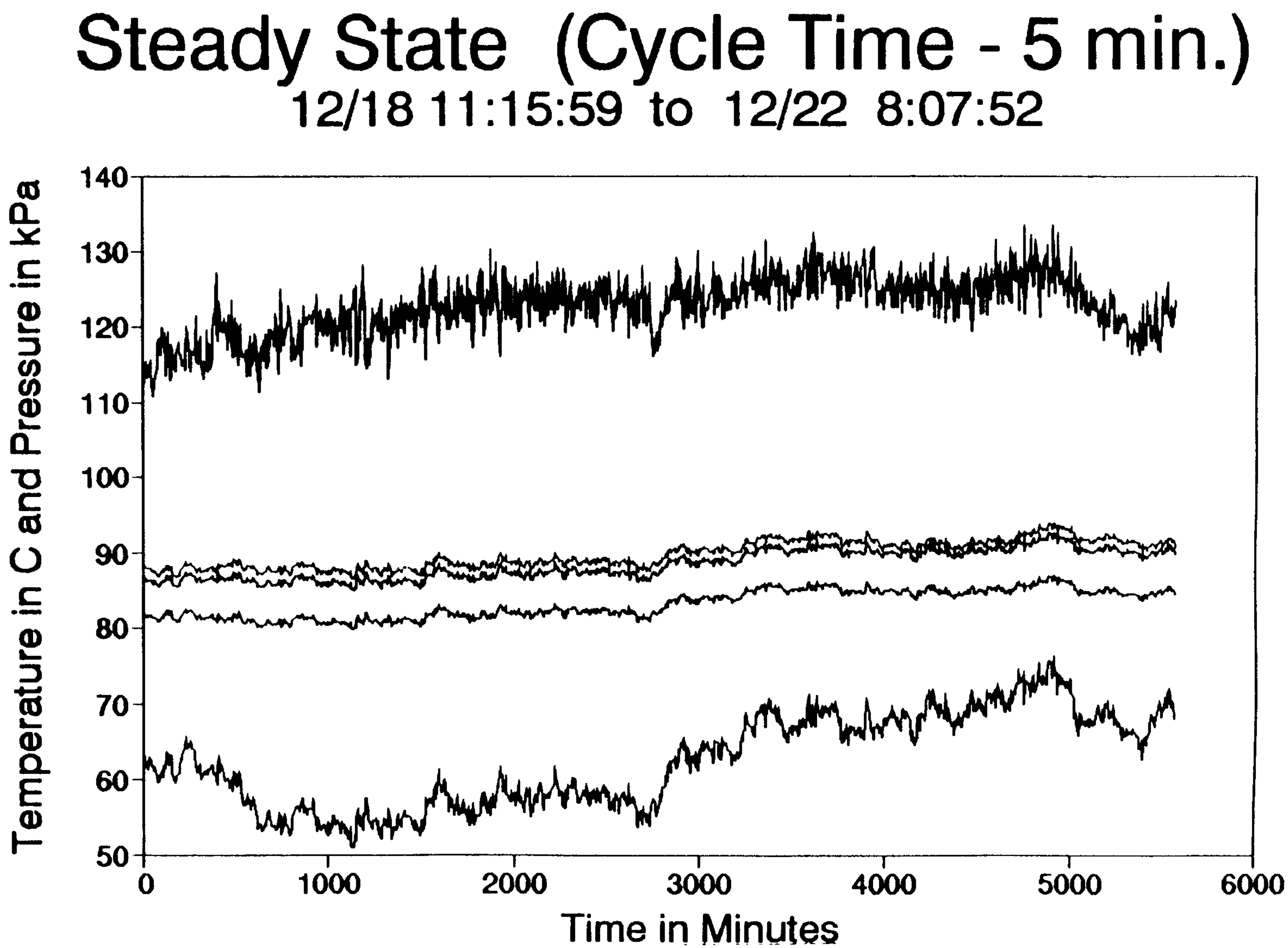


Figure 28. Data From Reflux Tube Operation.

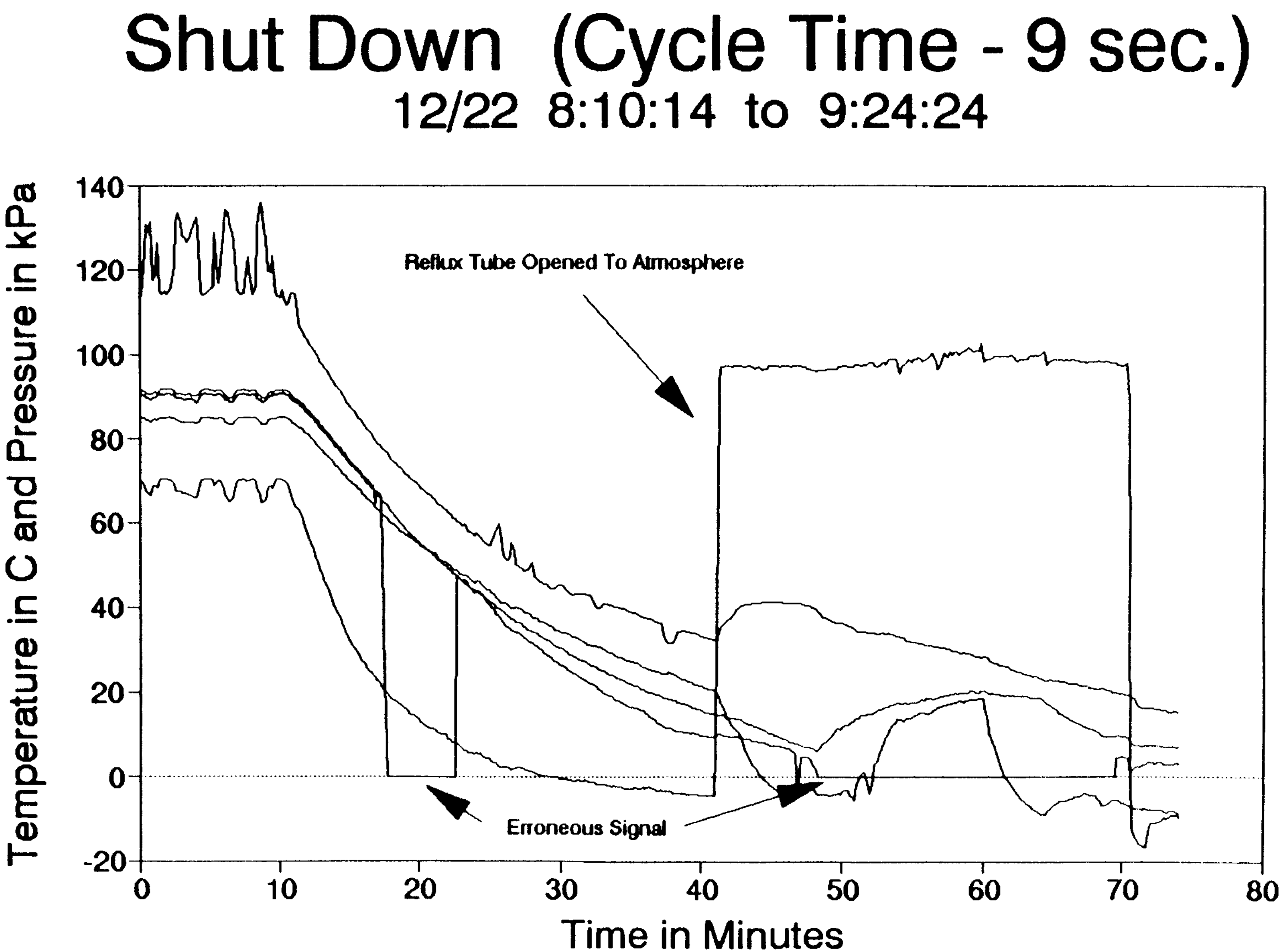


Figure 29. Data From Reflux Tube Operation.

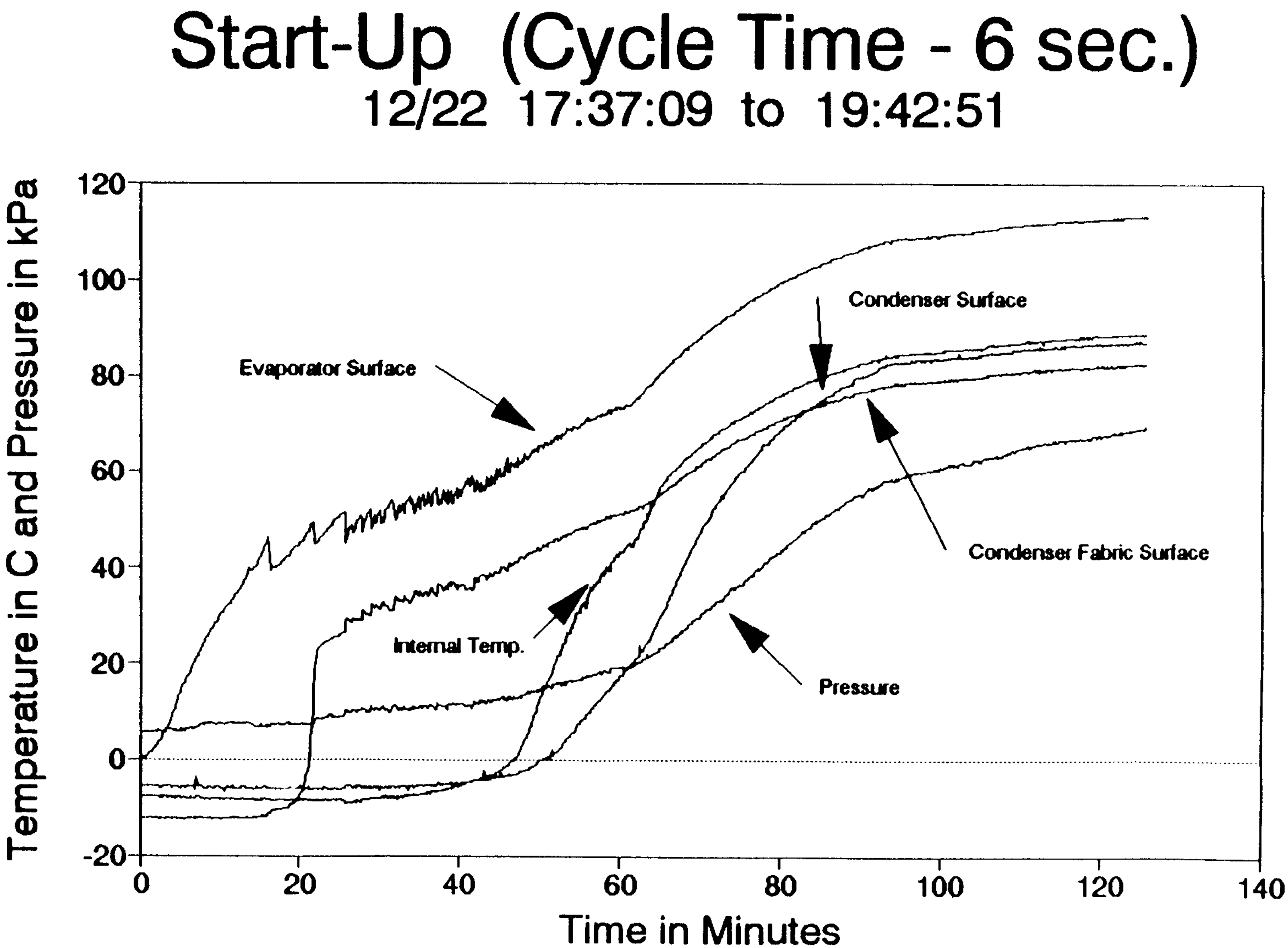


Figure 30. Data From Reflux Tube Operation.

steady state operation. As demonstrated in Figure 20, this cycling involved only a few degrees change within the reflux tube and its condenser, but a much larger change in temperature at the evaporator end. The second phenomenon that was observed took place when the vacuum was redrawn on the vacuum chamber, as seen in Figure 17. Because of the length of the test and the quality of the vacuum chamber seal, the vacuum had to be boosted periodically throughout the test. This was typically done about once a week, over which time the chamber had lost approximately 10 kPa. When the vacuum was boosted a drop in pressure and temperature was observed within the reflux tube. Following the drop the reflux tube took approximately 40 minutes to regain its former operating conditions.

The cycling of the temperature within the reflux tube can only be observed when the data cycle time is short. Therefor it is not evident on graphs in which the data cycle time was 5 minutes. However when the data collection cycle time was 30 seconds or less the cycling of the reflux tube is pronounced. During a typical cycle the reflux tube interior temperature, condenser temperature, and pressure all start to drop. At the same time the temperature in the evaporator section begins to rise. These temperatures and the pressure continue in these directions at a steady slope for about 1 minute. Then, abruptly they reverse direction, i.e. the condenser temperature, internal temperature, and pressure rise and the condenser surface temperature drops. This returns the heat pipe to its original working conditions in less than 2 seconds. The period and size of these cycles has varied throughout the test. The cycle time appears to be inconsistent and has a range of from approximately 1 to 5 minutes. The size of the temperature variations have been more consistent. On the evaporator end the temperature rise is about 20 °C, and on the condenser end the drop is approximately 2 to 3 °C.

The drop in the pressure of the reflux tube and the rise in the temperature of the evaporator both point to a short term dry out of the evaporator section. The evaporator drys out when the condensate on the wall of the reflux tube does not drip back down to the evaporator section. Only 25 ml of water were originally introduced into the reflux tube. Three to 5 ml of this water is probably held up in the charging and evacuation line. The very bottom of the reflux tube is not in contact with the heater. It is possible that as much as 10 ml of water could be down at the bottom without being in contact with the heaters. This means that 10 ml of water would have to be held up on the wall of the reflux tube in order to cause dry out. This is equivalent to about .02 ml/cm^2 of wall surface.

Once the evaporator section has dried out the temperature on the wall starts to increase because it has lost its heat sink. The pressure starts to drop because the vapor in the reflux tube continues to condense while little additional vapor is generated. The temperature of the condenser drops due to a drop in the amount of heat being transported to it. When a drop of water does make it down the wall or drips off of the internal thermocouple this water reaches the evaporator, which is now much hotter. This causes the drop to flash to steam and removes the heat that has built up in the evaporator section. At the same time it drives the pressure up and increases the condenser wall temperatures.

It is important to note that the dry out is not just a local phenomenon within a portion of the wick. The thermocouples on opposite sides of the evaporator section follow the same temperature cycles. It is also necessary that the entire evaporator section be dry due to the fact that very little water needs to change into steam to keep the system at equilibrium.

A satisfactory explanation of why the pressure within the reflux tube drops when a vacuum is drawn on the vacuum chamber has not been found. One obvious answer, a leak from the reflux tube, does not make sense. After over 800 hours of operation the reflux tube would certainly have completely dried out if a significant leak was present. A leak also does not explain why the reflux tube recovers to its steady state condition. If there were a leak having the vacuum pump running should not effect the leak rate. Once a vacuum has been fully established within the vacuum chamber the leak would continue to release steam and drop the temperature of the reflux tube. Instead, shortly after the vacuum pump has been shut down the reflux tube begins a steady recovery.

Analysis of the pressure drop was done to determine if changes in the reflux tube volume, associated with expansion caused by an external pressure drop, could be responsible for the pressure drop inside the reflux tube. In order for this to be the case the volume of the reflux tube would have to increase by 46%. This is significantly more than can be accounted for by the small change in exterior pressure.

The best explanation to date for these changes is that a combination of the small expansion of the reflux tube and the vibrations created by the vacuum pump cause the water which is held up on the wall and trapped in the evacuation line to drop to the bottom of the reflux tube. The water in the evacuation line is much cooler than the reflux tube operating temperature and acts as a spray, condensing significant amounts of steam within the reflux tube. The water on the wall of the reflux tube dropping to the bottom with the cool water from the evacuation line cools the pool of water at the evaporator end. This pool then becomes subcooled and stops producing steam. The condenser wall, having lost its layer of droplets would provide a more receptive surface for condensation. This explanation does explain the observations, but there is no direct evidence that water condensing in the evacuation line does actually drop because of the evacuation of the vacuum chamber.

The reason for the long time period associated with the recovery can be explained. The total amount of heat being supplied to the system does not go directly to the reflux tube. It is split almost evenly between heating the reflux tube and escaping through the heater insulation. Unfortunately the insulation used to isolate the heater is not very effective. When the reflux tube temperature drops, the reflux tube becomes a larger resistance to heat flow, because heat is radiated less effectively at lower temperatures. With the two heat paths being in parallel the heat takes the path of least resistance and escapes through the insulation, leaving less heat to go towards reheating the reflux tube. This is why the recovery period is extended to 40 minutes. This hypothesis is substantiated by a plot of the temperature on the surface of the heater insulation. Figure 17 shows that the heater insulation temperature starts to rise as soon as the temperature in the reflux tube starts to drop.

The internal wick does not appear to be serving any significant purpose. The surface temperature of the evaporator section is much higher than it would be if it were in direct contact with a pool of water or a film of water provided by the wick. The elevated temperature in the evaporator can be explained when the location of the thermocouples with relation to the probable water level is recognized, but only if the wick is not providing a water to the entire evaporator section. The wick may prove to be more useful at higher power ratings or large working fluid inventories. However for applications of the reflux tube that involve the temperatures used in this experiment it is most likely unnecessary.

The tube life test was terminated to remove the reflux tube from the test chamber and allow visual observations to be made after more than 800 hours of operation. No significant changes were observed in the reflux tube, except for a discoloration of the Nextel fabric. This copper colored discoloration was uniformly distributed along the entire length of the reflux tube. No significant end effects were observed. The discoloration is consistent with observations made on a stainless steel heat pipe previously operated in the HPTF [5]. This slight discoloration may contribute to a change in the reflux tube's emissivity over a long term test such as the one conducted. It did not significantly affect the performance of the reflux tube, and did not prevent the re-start of the tube.

C. Recommendations for Future Work.

The life test of the reflux tube has been completed, but further testing can still be done to give valuable insight into the characteristics of this thin walled reflux tube. The 30 to 40 watt reflux tube heat input used in this test is far below the maximum performance capacity. This is evident by the fact that the pressure within the tube stayed at about 65 kPa during the test, just 60% of an atmosphere. Tests performed at PNL to determine the type of pressures that the fabric composite is capable of containing have been observed into the 10 MPa range [9]. It would be interesting to run the reflux tube under much higher input power conditions. The heater that is currently attached to the reflux tube is only capable of 225 watts output. With approximately half of that escaping through the heater insulation this means that under current conditions it may only be possible to reach a power of 110 watts input to the reflux tube. To get to higher power levels it will be necessary to replace the heater or improve upon its insulation, the latter of these two choices being the most reasonable course of action. The insulation used was not as efficient as expected and an improvement should not be that difficult to obtain.

Another set of tests could be done using the current setup to look at frozen start-ups. These tests would provide data on the amount of time it takes for the reflux tubes to come up to power after a shut down. This information would be useful if the reflux tubes were ever employed and would provide a set of data for future improvements on the present design.

Finally, some tests should be run to determine how the reflux tube responds to ramping and step changes in power. The relatively low thermal mass of the reflux tube should make it very responsive to transients. This responsive behavior was observed to some extent in the life test, but on a whole the changes in power were to small to perform studies of the results.

As stated in the discussion of the higher power tests, improvements should be made to the heater insulation. In this way the researcher will be able to have a more exact knowledge of how much power is being delivered to the reflux tube. This would be especially useful in the transient tests. It would also allow the investigator to calculate the reflux tube's emissivity for comparison with those values previously observed.

III. FABRIC WICKING RATE TESTS.

A. Experimental Setup and Procedures.

Several ceramic fabrics have previously been tested for wicking velocity in a dry fabric at Oregon State University [3]. The experiments discussed in this section were run in an effort to determine the wicking capacity of similar fabric materials. The amount of liquid that a particular fabric is able to return to the evaporator end of a heat pipe is important in determining the maximum operating conditions [1].

The original attempts at collecting this data provided significant insight into the development of the final test set-up used to collect the data that is presented. The first experiment involved hanging a piece of s-glass 5 cm wide and 0.09 cm thick, out of a container filled with water. The fabric was allowed to hang down approximately 20 cm. Below the end of the fabric was a dish for collecting any liquid that dripped off the end of the fabric. This fabric was allowed to sit for 12 hours.

At the end of the test only the top half of the fabric was moist and the rest was dry. This test set up was dropped and a new test was developed in which the fabric was draped from one container to another and supported by a metal bridge. The bridge was intended to aid in transporting the liquid and simulate actual working conditions. The original bridge was constructed of aluminum and created a drop of 15 cm. To start these experiments the fabric was soaked in a water bath, then draped over the bridge from one pan to the other. These tests were allowed to run for several hours, at the end of which the transferred water was collected and measured. The results of these tests were disappointing. The small amounts of liquid that were actually transferred were inconsistent and probably distorted by the amount of liquid that evaporated during the tests.

To obtain values that were easier to measure, two changes were made. First, thicker fabric samples were used. This increased the cross sectional area that the liquid had to flow through. Second the material of the bridge was changed from aluminum to copper. This was done because previous work had reported that a short aluminum bridge had to be scored to increase the wetability of the metal [3].

With these changes the amount of liquid transferred became much easier to work with. Tests were run in which the individual fabrics were allowed to transport liquid from one container to another for 30 minutes to an hour. These tests were run for a couple weeks until it became apparent that the rate at which the liquid was being transported changed from the start of the test to the end of the test. This change was caused by the lowering of the water level in the upper dish. When this liquid level dropped it forced the fabric to wick the water up a longer grade before dropping down the bridge and into the collection dish.

In an effort to determine the change in rate, a better test format was developed. The first step was to build larger trays for the top liquid container. This made the liquid level in the top tray more constant over the duration of the test. The other improvement involved acquiring a low intensity vacuum extractor (turkey baster). This allowed the transported liquid to be removed from the collection dish, measured, and returned to the top tray, allowing continuous monitoring of the flow rate. All results presented were gathered in this way. Figure 31 shows a schematic diagram of the final, as tested arrangement.

Fabric strips were prepared especially for the final test procedure. The ceramic materials were heat treated to remove any sizing. These heat treatments varied for the different materials tested. The s-glass and silicon carbide were heated to 400° C for 8 hours. The Nextel fabrics 312 and 440 were baked at 550° C for 12 hours. Kevlar was not heat treated because of its low melting point. Instead the material was soaked in deionized water and detergent for 2 weeks. The Kevlar was treated in this way so that it would be consistent with the methods used in the dry uptake rate experiments. After the materials were treated they were cut into strips 6.5 cm wide. The outer 0.25 cm of fabric was impregnated with a silicon gel used for sealing aquariums.

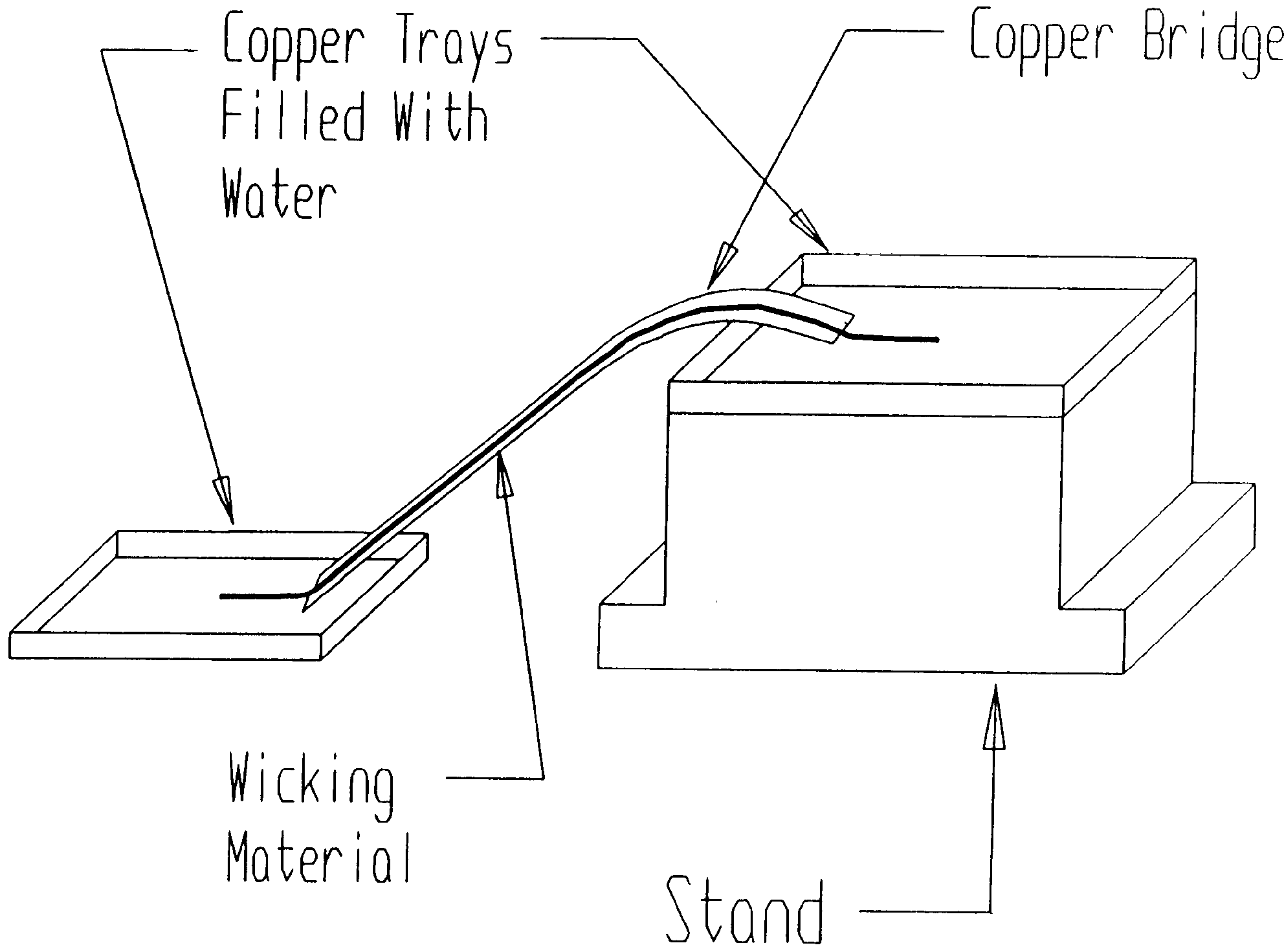


Figure 31. Schematic Diagram of the Wicking Rate Test Equipment.

This gel was used to make sure that the fabric did not unravel.

To run a test the upper container was partially filled with deionized water. The fabric that was to be tested was moistened and laid out across the bridge connecting the two trays. The upper container was then filled to the top and the material was given 10 to 15 minutes to establish a consistent and complete flow pattern. When time was not given to the material to settle down into a consistent flow pattern the first two or three data points did not match those of the rest of the run. At the end of this set-up time the liquid in the lower reservoir was removed and returned to the upper reservoir and the test began. When approximately 100 to 150 ml of water had been transferred from the top to the bottom reservoir the water was removed from the lower reservoir, measured and returned to the upper reservoir. These tests lasted anywhere from 30 minutes to 4 hours.

The fabrics chosen were all plain weaves of approximately the same thickness. However the weave densities of the individual weave patterns differs more than would have been preferred. The differences come from the fact that the fabrics were not intended to be used as wicks and their weave densities reflect their established uses. For the fabrics used Kevlar was the most dense and the silicon dioxide was the least dense. The Nextel fabrics and the silicon carbide had similar weave densities.

B. Results.

Each fabric was tested in four different set-ups. They were each tested as a single layer of fabric and as two layers together. They were also tested over a drop of 14 cm and a drop of 7 cm. For each one of these four situations the set-up was run four times. The Nextel 440 was also tested on a tall aluminum bridge for comparison with the copper bridge data. The flow rates within each individual test were very consistent, however the flow rates between separate tests with the same set-up were different by as much as a factor of 5.

The average of each individual run along with the average of all the runs put together is shown in Tables 2 through 7. This is done so that the large difference between individual tests of the same set-up can be seen clearly. The data has been normalized by the cross sectional area of the fabric to put the fabrics on more even terms. It is believed that some of this inconsistency is due to the way in which the data was acquired, however the nature of the physical phenomenon investigated does not lend itself to a consistent average. Figure 32 shows a bar graph of the normalized flow rates for the five fabrics tested in the four different set-ups.

Table 2. Wicking flow rates for s-glass at room temperature and pressure. Flow rates normalized by the fabric cross sectional area, mL/cm^2-hr. Each layer is 0.014 cm thick.

Layers	Trial 1	Trial 2	Trial 3	Trial 4	Average
Single 7 cm.	1190	5393	2024	3560	3042
Single 14 cm.	1536	3738	3083	2512	2717
Double 7 cm.	2173	48810	3857	3131	3510
Double 14 cm.	786	1446	952	6018	2301

Table 3. Wicking flow rates for Kevlar at room temperature and pressure. Flow rates normalized by the fabric cross sectional area, mL/cm^2-hr. Each layer is 0.0254 cm thick.

Layers	Trial 1	Trial 2	Trial 3	Trial 4	Average
Single 7 cm.	4403	1942	2106	12093	5136
Single 14 cm.	3150	1818	1293	5945	3051
Double 7 cm.	3087	5174	4419	7710	5098
Double 14 cm.	5984	2854	2218	3465	3630

Table 4. Wicking flow rates for silicon carbide at room temperature and pressure. Flow rates normalized by the fabric cross sectional area, mL/cm^2-hr. Each layer is 0.028 cm thick.

Layers	Trial 1	Trial 2	Trial 3	Trial 4	Average
Single 7 cm.	5179	4214	4869	4881	4786
Single 14 cm.	3929	4232	4881	4833	4469
Double 7 cm.	10030	6661	5750	7705	7536
Double 14 cm.	4649	6414	21991	5327	9595

Table 5. Wicking flow rates for Nextel 312 at room temperature and pressure. Flow rates normalized by the fabric cross sectional area, mL/cm^2-hr. Each layer is 0.036 cm thick.

Layers	Trial 1	Trial 2	Trial 3	Trial 4	Average
Single 7 cm.	1868	1384	1574	1892	1680
Single 14 cm.	951	1330	1005	2032	1330
Double 7 cm.	2847	2095	2523	2074	2384
Double 14 cm.	2523	2431	1927	2760	2411

Table 6. Wicking flow rates for Nextel 440 at room temperature and pressure. Flow rates normalized by the fabric cross sectional area, mL/cm^2-hr. Each layer is 0.043 cm thick.

Layers	Trial 1	Trial 2	Trial 3	Trial 4	Average
Single 7 cm.	4256	1781	2035	1876	2487
Single 14 cm.	1953	1942	2695	2531	2280
Double 7 cm.	2432	2374	2355	2742	2476
Double 14 cm.	4116	4326	3760	3992	4048

Table 7. Wicking flow rates for Nextel 440 at room temperature and pressure on Aluminum. Flow rates normalized by the fabric cross sectional area, mL/cm^2-hr. Each layer is 0.043 cm thick.

Layers	Trial 1	Trial 2	Trial 3	Trial 4	Average
Single 14 cm.	2502	1954	1591	1906	1988
Double 14 cm.	3845	2302	2202	1688	2510

C. Discussion.

There are several possible explanations for the differences between the separate test runs with the same set-up. One important explanation is that the test apparatus had to be reset before each run. This leads to small inconsistencies in the angle of descent, height of the test, contact between the fabric and the metal bridge, and the height of the water in the upper reservoir. A possible contributing factor to the discrepancies may have been that water traveled between the fabric and the metal, or between the fabric layers. Because of the way the fabric is made it is possible for the flow pattern from the top to the bottom of the bridge to be quite different in each case. If, because of the set-up, several fairly straight and clear arteries formed from the top to the bottom, then the flow

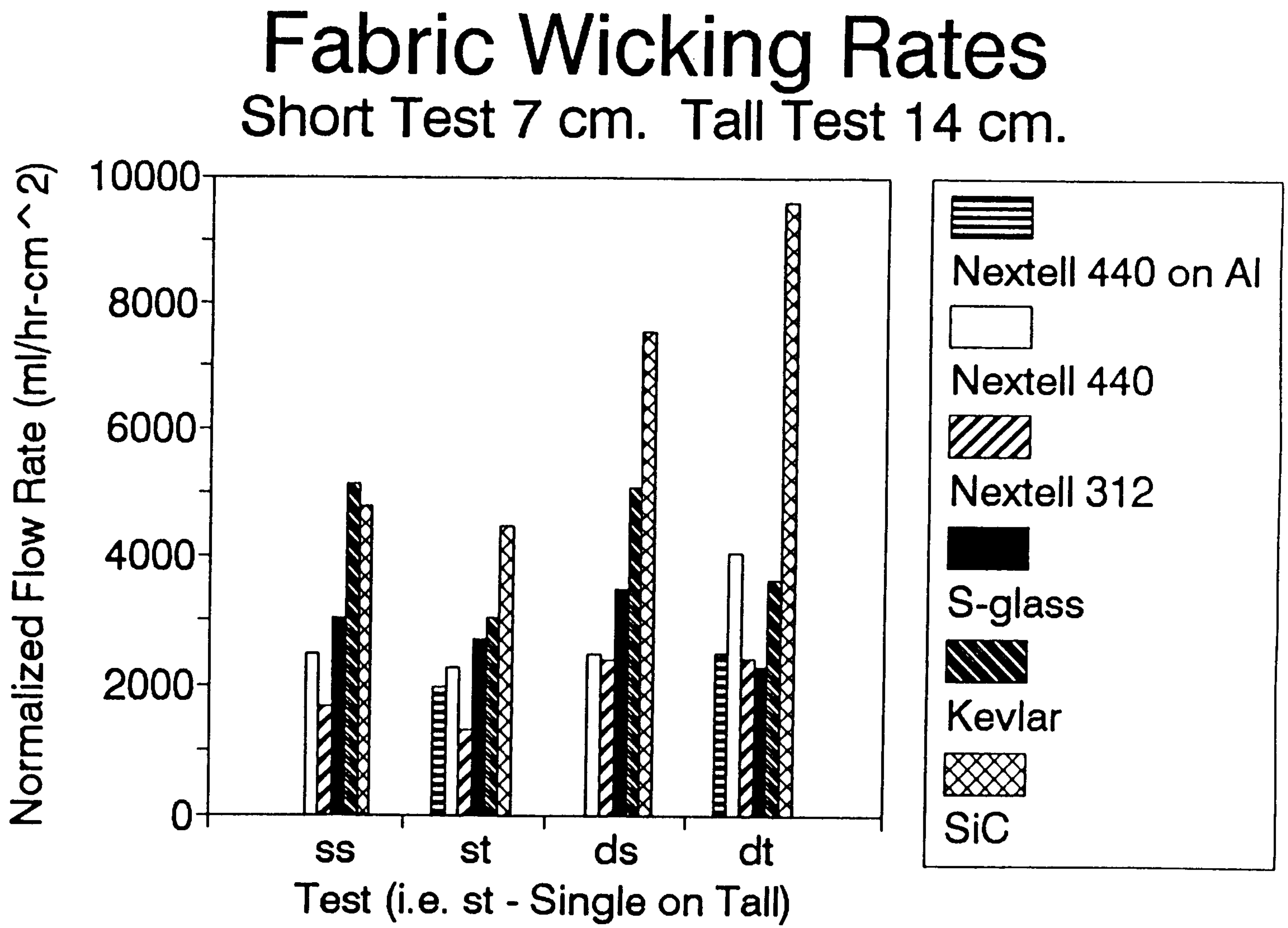


Figure 32. Normalized Flow Rates for the Five Fabrics Tested in the Four Different Set-ups.

rate would be high, if these arteries were short and narrow then the flow rate would be lower.

The addition of a second layer does not significantly change the normalized flow rate in s-glass, Nextel 312, and Kevlar in both the tall and the short set-up. It isalso true of the Nextel 440 for the tall case on aluminum and the short case on copper. If it is assumed that the amount of liquid transported within the mesh is minimal compared to the flow between the fabric and the bridge, then it is possible to say that for these four fabrics the flow between fabric layers is on the order of that between the fabric and the bridge. The data for Nextel 440 on the tall set-up and silicon carbide in both set-ups, shows an increase in flow rate by a factor of about 2. For this to be true the flow rate between fabric layers would have to be approximately 3 times the flow between the fabric and the bridge.

The data for every material shows a decrease in flow rate for the single short test to the single tall test. This implies that the added pressure head gained by the larger drop is not greater then the added resistance of the increased flow length. This is also true when two layers are used, for s-glass, Nextel 312, and Kevlar. The data shows a different behavior for silicon carbide and Nextel 440. Both of these fabrics exhibit increased flow rates when they were changed from double short to double tall. This implies that the added pressure head gained with the increased height is larger than the increased resistance gained with the extended flow length. One reason for the difference may be that both Nextel 440 and silicon carbide are much stiffer than the s-glass and Kevlar. This allows them to hold their shape better so that they do not collapse down and block the flow paths. This was evident at the end of a test when the fabric was removed from the bridge. Both Kevlar and s-glass seemed to have a small hold on the bridge and this did not appear to be the case for the Nextel 440 or the silicon carbide.

Nextel 440 was tested on both a copper and an aluminum bridge. This data showed that the flow rates on copper were larger than the flow rates on aluminum. This was the expected result and verifies assumptions made in the test design.

If the experiment were to be run again, a different procedure might lead to more consistent results. Two improvements are strongly suggested. First, the top tray, bridge, and collection tray should be permanently fastened together or constructed in such a way that they are always in the same position relative to each other when put together. The second improvement would be to set the top tray up with a continuous feeder, so that the water level stays constant throughout the test and between separate tests. In this system a container of water is filled and placed upside down in the top tray. Holes in the water container would be positioned so that they allowed air to enter and water to come out when the level dipped below these holes. These two improvements would eliminate much of the inconsistency generated by the procedure used in this investigation. By eliminating those inconsistencies generated by the procedures the investigator will be able to get a firm idea of just how much inconsistent the actual process is.

IV SUMMARY.

An Ultralite Fabric Reflux Tube has been successfully tested in the OSU Heat Pipe Test Facility under both long term steady state and transient conditions. Over 800 hours of life time testing was completed with solid performance. Longer time could have easily been accomplished. The reflux tube life test was terminated in order to visually observe the reflux tube, and not because of any degradation in performance. The only change observed, was a slight color change in the reinforcing fabric. This fabric became a dull copper. The discoloration was uniform and did not interfere with the ability to restart the reflux tube. Several start-up and shut down transients were performed to observe the transient performance of the reflux tube. Several interesting phenomena were observed during these tests. These include temperature and pressure cycling while the reflux tube was held at steady state and pressure and temperature changes following the drawing of a vacuum in the test chamber.

The Heat Pipe Test Facility provides an excellent means for testing the performance of reflux tubes. The data acquisition system provides for continuous monitoring of the reflux tube parameters during transient and steady state operations. Hence, the HPTF is suitable for testing start-up, shutdown, and transient behavior, evaluating operating limits, or performing life tests.

Wicking rate tests were performed on two PNL supplied and three OSU supplied fabrics. These tests provide data on the relative wicking effectiveness of the different fabrics, and showed that the action of wicking between a fabric and a metal support is not a consistent process. But it is also the dominant transport mechanism.

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