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REACTOR COOLANT FLOW MESUREMENTS AT POINT LEPREAU

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ABSTRACT

The CROSSFLOW ultrasonic flow measurement system manufactured by AMAG is fully proven as reliable and accurate when applied to large piping in defined geometries for such applications as feedwater flow measurement. Its application to direct reactor coolant flow (RCF) measurements - both individual channel flows and bulk flows such as pump suction flow - has been well established through recent work by AMAG at Point Lepreau, with application to other reactor types (eg. PWR) imminent. At Point Lepreau, Measurements have been demonstrated at full power; improvements to consistently meet ±1% accuracy are in progress. The development and recent customization of CROSSFLOW to RCF measurement at Point Lepreau are described in this paper; typical measurement results are included.

DATE: 30 April 1996

1. INTRODUCTION

1.1 Background

CROSSFLOW is an ultrasonic flowmeter using cross correlation technology that has been evolving for over 20 years from work that started at GE Canada in the 70's. Originally conceived to give accurate flow measurements needed for heavy water production, CROSSFLOW is well established for such applications as feedwater flow in nuclear generating stations. More recently, CROSSFLOW has been customized for measurement of reactor coolant flows in four feeder and two pump suction pipes at Point Lepreau G.S., under all conditions from cold to full power. This customized measurement system was installed during an outage in late 1995. During the startup of December 1995, the measurement system provided flow measurements under all temperature conditions for all designated pipes up to full power.

1.2 Overview of System Modifications

Ultrasonic flow measurement technology has been applied for many years in nuclear plant applications, and the cross correlation-based system has been extensively applied in Ontario Hydro's nuclear stations. However, most measurements, if not all, were performed in relatively low temperature applications (<250°C). There has been little reported about application in higher temperature environments (~300°C).

R.S. Flemons adapted an ultrasonic cross correlation flowmeter to measure feeder flow in a 300°C environment in Pickering N.G.S.. Currently working as a consultant for AMAG, Flemons has injected his experience into the project for the Point Lepreau G.S., especially in the transducer design. However, the Pickering technology required machining of the pipe surface, which is unsuited to the measurement of RCF in operating plants.

The greatest challenge in RCF applications has been adaptation of the transducer assembly to accommodate the temperature and reliability requirements , since they must function in areas inaccessible during operation..

The transducer assemblies developed at Point Lepreau are custom designed to meet the environmental requirements. Six assemblies - four for feeder and two for pump suction pipes - were manufactured and installed. After five months of full power operation, the capabilities of all transducer assemblies are unchanged and fully operational. This is a significant achievement in high temperature ultrasonic flow measurement.

1.3 System Components

The basic principle of the cross correlation flowmeter is to determine flow through measurement of the time taken by a disturbance to pass between two points along the direction of flow. As shown in Figure 1, the flowmeter consists of several sub-systems: the transducer assembly, the signal conditioning unit (SCU), filter, multiplexer, computer and software. The transducer assembly is attached to the pipe. It generates two ultrasound beams and receives two modulated signals. The SCU provides signals to drive the transmitter transducers and processes signals from the receiver transducers. A band pass filter is used to isolate the frequencies of interest for a specific flow. The multiplexer allows time-sharing of the SCU and computer system between different measuring locations; up to 8 are possible with each multiplexer. The computer and software perform the cross correlation calculations, determine flow rates, and provide a user interface. Each subsystem is tailored to the need in this application.

2. TRANSDUCER ASSEMBLY

2.1 Elements of the Transducer Assembly

A typical transducer assembly of the cross correlation flowmeter consists of a frame and two pairs of ultrasound transducers with a transmitter and a receiver in each pair. The frame holds the transducers onto the surface of the pipe to be measured and keeps them properly aligned. The transmitter transducers inject ultrasound beams through the pipe walls aCROSS the FLOW. The receiver transducers, identical to the transmitter transducer, are mounted on the opposite side of the pipe, receive the ultrasound beams and convert them to electrical signals.

2.2 Design Requirements

The following design requirements were identified for the transducer assembly:

- ambient temperature up to 315°C
- radiation field > 100 R/hr
- total transducer assembly and its elements must withstand vibration of feeder pipes and not loosen with time
- transducer materials must be compatible with feeder pipes
- transducer assembly must not touch neighboring feeders
- should weigh less than 15 lb.

Space restrictions, high temperature and radiation environments were the major design requirements to be overcome.

Specific transducer assembly design criteria also included requirements on signal strength, ease of installation, reliability under field conditions, and cost of fabrication.

2.3 Frame Design

The frame of the transducer assembly is required to hold the transducers onto the pipe surface, and to keep the two pairs of transducers properly aligned and separated at the designed spacing, a prime parameter in calculating flow rate.

Carbon steel is used for the frame to match the feeder pipe material. Thermal expansion must be accommodated because the transducer assemblies are installed with the system cold and operation at full power is a requirement.

To accommodate the installation reality of one-side-access-only for feeders the frame requires the installer to tighten nuts from the accessible side only; the transducers on the opposite side will align automatically. Lock nuts and lock washers are used to fasten the frame and transducers. Figure 2 shows a picture of the frame for feeders. The weight of the frame is about 4 kg. The spacing between the two transducer beams, which is defined by the frame, is 6".

For the pump suction pipes, the frame design is relatively straightforward, since both sides of the pipes are accessible. A picture of the pump suction frame is shown in Figure 3. Its weight is 15 kg, and the spacing between the two transducer beams is 10".

2.4 Transducer Design

Identical transducer design was used for both feeder and pump suction pipes. Each transducer consists of a piezoelectric crystal, a coupling medium, an electric insulator, a pressure mechanism, a mechanical interface with the frame and electrical connections. Materials were selected to avoid degrading when exposed to the feeder cabinet environment over an extended period of time. A picture of the transducer is shown in Figure 4. Its overall weight is 0.7 kg. The design or selection of the key transducer components are outlined as follows:

Crystal - a piezoelectric disk that can produce an electric field when a mechanical stress is applied and a mechanical stress when an electric field is applied.

Several crystal types were evaluated, including lead metaniobate and lithium niobate. A modified lead metaniobate piezoelectric ceramic was eventually found to be the most suitable.

Coupling Medium (Coupler) - the material between the crystal and the pipe surface which couples the ultrasound to the pipe - a key issue because this coupler directly determines the signal strength. Silicon rubber is a good coupler material and extensively used in our previous measurements, but it cannot survive the feeder cabinet temperature. The coupler selected is a square carbon steel piece with a tiny shoe - machined to match the pipe surface - on one side.. The other side of the coupler is grounded and plated. Two pieces of gold foil are used in the assembly: one between the crystal and the coupler and the other between the coupler shoe and the pipe surface. These gold foils eliminate any air gap at these critical interfaces.

Cables - The cables that connect the transducers and the CROSSFLOW SCU are specially customized for this application and can work continuously in an environment of up to 500 °C.

2.5 Laboratory Tests and Modifications

2.5.1 AMAG Laboratory Tests

A series of experimental tests were undertaken in the AMAG laboratory during the development and customization of the transducer assemblies. Feeder pipe segments of different sizes (2" and 2.5") and a section of pump suction pipe (20") were used for these tests. Various prototypes of system components were tested to assemble the best overall design.

Transducer installation procedures were also developed and practiced prior to their use in the field

2.5.2 Stern Laboratories Tests

The final version of the transducer assembly was installed at Stern Laboratories Inc. in Hamilton, Ontario. The transducer assembly was covered by thermal insulation materials after installation to simulate the needed high temperature environment. The flow temperature was raised to 300°C and maintained there for four hours. The ultrasound transmission of the transducer channels was monitored continuously, and no degradation was observed.

Beyond the reliability of transducers at high temperature, the Stern Laboratories tests also revealed that fine tuning of the ultrasonic frequency and good electronic filters are needed for measuring high flows in small pipes.

3. MULTIPLEXING HARDWARE

3.1 Background

For the Point Lepreau project, it was desirable to use one SCU to monitor the six specified flows. A multiplexer unit that could switch, under computer control, among the six transducer assemblies was therefore developed. The switching requirement for the multiplexer was one set of four signals from the CROSSFLOW SCU to six sets of four signals from each transducer. A commercial multiplexer is not available to meet this need. Accordingly, the multiplexer was designed as an eight channel unit.

3.2 Laboratory Test

The resulting multiplexer was tested in the AMAG laboratory for levels of crosstalk between inputs in each bank and for appropriate response to controlling signals. The crosstalk was found to be less than 0.5 mV maximum for loads similar to that expected for the Point Lepreau transducers. This is deemed to be acceptable performance.

3.3 Installation and Performance

The multiplexer was installed at Point Lepreau Nuclear Generating Station and the controlling circuitry was found to operate as designed. The measured flow signals with and without the multiplexer were compared with no discernible difference.

4. SOFTWARE

4.1 Background and Requirements

Prior to the Point Lepreau feeder flow measurement project, AMAG had developed a commercial software package. This software version is limited to a single measurement and uses American units. Major software changes and improvements were required to accommodate the feeder flow measurement project, including multi-channel system configuration, signal multiplexer interface, data communication gateway, and conversion to metric units. A stand-alone frequency scanning program was also needed to assist the operator in setting the SCU operating frequencies.

4.2 Interfacing with Hardware

As described in section 3, the AMAG signal multiplexer was built to allow the signals from different transducers to be multiplexed into a single signal conditioning unit. To control and automate the multiplexer, a dedicated software module was designed to interface with the National Instruments PC-DIO24 digital I/O card, which is used to control the multiplexer digitally. The multiplexer control module is started by the customized software to route the desired signal to the SCU.

4.3 Software Customization

With the customized software, the user may configure the measurement parameters of each channel individually to calculate the mass flow. The user can set the hardware configuration of the SCU for each channel so that when the system is switched to a specific channel, the applicable hardware configuration is loaded automatically. Another area of improvement in system configuration is its flexibility and ease of use. The user may configure the system to measure up to eight channels in any combination, or copy the configuration of one channel to that of another as needed. The last configured channel measurement parameters and hardware configuration used will be retained in memory for the flow measurement. The user may save the system configuration into a file which can be reused as needed.

When the user starts a measurement, the channel control module will process the system configuration from memory and initiate the flow measurement. While this module cycles the measuring channels, the results are processed and stored in their respective data files.

The customized CROSSFLOW software for the Point Lepreau feeder flow project can send the flow measurement data through a gateway computer serially to the central database system. The data format was modified so that the Point Lepreau conversion software can analyze the flow measurement data and convert them to the database format.

4.4 Frequency Scanning Program

. While the high temperature transducers were specially designed to withstand high temperature and high radiation, the ultrasonic signal transmissions delivered by these transducers are weaker than that of the regular (silicon rubber coupler) transducers. This results in difficult tuning. A stand-alone frequency scanning program was therefore developed to scan the transmitting frequencies of the SCU over the specified range. This program calculates the cross-correlation of each frequency step and plots the results in a three dimension intensity graph. From this graph, the user can determine optimal operating frequencies.

5. CALIBRATION MEASUREMENTS

5.1 Background

The transit time of the turbulence signature in a given pipe depends on the Reynolds number, the proximity of pumps, valves or other discontinuities, the distance and sharpness of the bend of an upstream elbow, and pipe wall roughness. The CROSSFLOW system measures this transit time which is then converted to flow using the applicable *Flow Profile* Correction (FPC) factor, fluid density and pipe cross-sectional area.

Currently, the FPC factor is determined empirically by measuring the true flow using a calibration facility for a given pipe configuration.

The profile correction factor C is defined as the ratio of the average pipe velocity Va to the measured velocity Vm:

$$C = Va/Vm$$

The magnitude of C depends on Reynolds number, pipe configuration and pipe wall roughness. For large pipes and high Reynolds numbers, extensive data have been determined from Ontario Hydro facilities. It showed that, 15 diameters downstream from the nearest elbow, the FPC factor is constant.

AMAG has recently developed a method of calculating C for straight pipes and high Re number beyond Ontario Hydro experience, because FPC factors for feeder pipe conditions and flows were not available . The results of this calculation methodology have been verified by measurements in large diameter pipes.

5.2 Feeder Flow Calibration

To obtain the proper FPC factor, experiments were carried out at the National Research Council Hydraulic Laboratory in Ottawa and at the Stern Laboratories in Hamilton.

The Reynolds number for cold flow at Pt Lepreau NGS ($0.8*10^6$) can be achieved at the NRC laboratory only when a booster pump is used. Unfortunately there is a high scatter in the NRC measurements as a result of pipe vibration due to pump operation. For this reason, the FPC factor was obtained using interpolating the experimental points for higher and lower Re numbers.

At Re numbers for high temperature flow ($Re = 4*10^6$) the value of C was obtained by averaging over 6 points from the Stern Laboratory test. This yielded a value in agreement with that from calculation. Therefore, the calculated factor was used for high temperature feeder flows.

5.3 Calibration For Pump Suction Flow

The flow in the pipe on the boiler outlet (Pump Suction Flow) is not fully developed turbulent flow. To determine the FPC factor for this flow, a scale model of the bottom portion of the boiler and outlet pipe was built and tested at the NRC laboratory. The model was simplified by assuming that small scale turbulence induced by the boiler tubes had decayed when it reaches the outlet pipe. A picture of the boiler model is shown in Fig 5.

Since the turbulent fluctuations of the flow in the model are concentrated in the boundary layer on the pipe wall, the measured velocity is smaller than the true average velocity across the pipe. The FPC factor derived from the scaled model was 1.2. However, it became clear later that the value of C = 1.2, a value that was later shown to be incorrect, because the assumed turbulence distribution pattern did not match actual conditions. Turbulence was more uniformly distributed over the pipe cross-section than had been assumed, theoretical calculation of C using well known approximations (H. Schlichting, Boundary Layer Theory) gave values of C= 0.986 and C = 0.989 for low and high temperature flows, respectively. These values were ultimately used to calculate the pump suction flow rates.

6.0 INSTALLATION OF THE SYSTEM

By September 28, 1995, six transducer assemblies had been successfully installed on inlet feeders B10, G11, Q04 and Q10 and pump suction pipes P2 and P4. All transducer assemblies fitted into their allowed space, and the auto-alignment procedure that had been lab-tested was successfully used.. A picture of a transducer assembly installed on a feeder pipe is shown in Fig 6.

Tight clearances transducer assembly installation difficult, specially for the feeder Q10, for which the measurement location is severely constrained by an overhead catwalk. Pre-assembly of transducer assemblies reduced field installation time spent in the feeder cabinet. Point Lepreau staff assistance was invaluable in minimizing installation time.

The on-site ultrasound transmission tests of the transducers confirmed reasonable transmission on B10, G11 and Q04. However, it was difficult to test transmission for the transducers on Q10, P2 and P4 because the power supply in the feeder cabinet contained significant noise.

After connecting the 125 foot cables, a superimposed interference was noticed on the signals received from the measurement station. Three possible sources of the interference were identified: electro-magnetic interference (EMI), grounding and high temperature cable. Tests at the site and in the AMAG laboratory indicated that the interference mainly arose from EMI. The high temperature cable was compared with normal RG59/U co-axial cable, and no difference was observed.

Tests at the AMAG laboratory also confirmed that the EMI interference would not affect the measurement results because it is not modulated by flow turbulence. However, it complicates meter tuning and necessitated development of the auto-tuning program described in Section 4.4.

7.0 FLOW MEASUREMENT

7.1 Background

Flow measurements were performed at Pt Lepreau NGS from December 13 to December 28, 1995 during start up and were repeated on February 7 - 9, 1996 at 100% power. On April 18 and 19, 1996 selected measurements were repeated during a flow verification transient from 100% to 77% power.

7.2 Results

Feeder Flow measurement during cold operation and start up

Table 1 summarizes the flows measured in the four designated inlet feeders (B10, G11, Q4 and Q10) for various power levels.
Figure 7 shows several flow measurements in B10 versus time during cold operation. The standard deviation is 1.25% which is indicative of the repeatability of the measured data.

Pump Suction Flows during cold operation and start up
The pump suction flows are also given in Table 1 for various power levels and repeated in Figure 8 in graphical form.

Feeder and pump suction flow measurement after continuing operation under high temperature and high radiation
Feeder flow and pump suction measurements were repeated on February 7-9, 1996 during operation at full power and on April 18-19, 1996 during a flow verification transient. Results are presented in Table 2 and Figure 9.

7.3 Discussion

Noise Problem
The spectrum of the turbulence signal produced in a pipe is expected to be in a frequency range of 20 to 500Hz. However, a periodic high amplitude interference frequency of approximately 150Hz was observed during cold operation and start up on all high temperature transducers. This interference limited the frequency range of the demodulated signal that could be analyzed. By filtering the interference, measurements were obtained in the narrow frequency range of 25 Hz to 75 Hz. The result was that a fine tuning of the carrier frequency was required to get a stable signal. Furthermore, small fluctuations in the carrier signal had a significant effect on the demodulated signals. Consequently it was not possible to operate in the automatic acquisition mode.

During the measurements on February 7-9, 1996, it was observed that the high amplitude periodical component was not present on some channels for extended periods of time. During these periods, measurements were performed over a wider range of frequencies; then readings were very stable and less sensitive to carrier frequency drift. An extended measurement was carried out on channel G11 for 3.5 hours without tuning. This demonstrated the feasibility of operation in automatic mode when the interferences are eliminated.

Flow Profile Correction Factor
Flow meter calibration is complicated for pump suction measurements because reproduction of real conditions in a laboratory environment is difficult. In this case, Crossflow calibration would include:

a) development of a mathematical model;
b) validation of the model in a laboratory at low Reynolds numbers;
c) correction of the model;
d) application of the improved model to plant conditions.

An alternative to Step b is "on site calibration". Feeder flow measurements by RPC (Research Productivity Council), who claim 1% accuracy, and shut down cooling flows measurements can verify the CROSSFLOW pump suction measurements during cold operation. The theoretical model which was used to calculate the FPC factor for CROSSFLOW can be validated with these measurements.

Uncertainty Analysis
The observed low repeatability of the measurements, combined with higher uncertainty obtained in the laboratory calibrations, reduces the preliminary estimate of the feeder flow accuracy to ±3% (95% confidence) with the components shown in the following table.

UNCERTAINTY SOURCES (%)

Flow Profile Correction Factor	±1.5
Repeatability of Measurement	±2.5
Cross-sectional Area of Pipe	±1.5
Transducers Separation	±0.3
Total (95% confidence)	±3.3

The work described in the following section is expected to improve the accuracy to the target level of ≤1%.

7. CONCLUSIONS AND FUTURE WORK

7.1 Current Status

As of the end of April 1996, all installed RCF transducers at Point Lepreau are operational. The ultrasonic signals remain very strong thus indicating after four months of operation in a high temperature and radiation environment no effect on the performance of the transducer assemblies.

All associated electronics, the multiplexer, the SCU and the computer also remain operational. The periodic noise that has limited the bandwidth of the analyzable signals has been observed as a transient from time to time. It appears to be a random process so that any single channel (feeder pipe) can be affected without notice. When the interference is absent, a wider bandwidth of the demodulated signals results in much stronger, steady signals and reliable read-outs..

It has been observed that the stability of the cross-correlation and the scatter in the measured flow data (time delay) is partly affected by the stability of the signal generator frequency. A stable prototype signal generator was tested in April at Point Lepreau that enabled the meter to track a power transient without manual retuning.

7.2 Future work

Agreement has been reached with Pt Lepreau NGS to continue development of the system so that it will provide stable, accurate and reliable data to system engineers. The following are required to achieve this goal.

- Replace the signal generators in the SCU.
- Install a notch filter into the current software to cancel the observed 150 Hz interference signal: this will enable us to analyze the total frequency spectrum of the signals.
- Develop the software needed to tune the system automatically to yield the best signal-to-noise ratio and ensure reliable, stable signals.
- To achieve a consistent accuracy of ±1%, a more accurate FPC factor is needed. For the feeder pipes, this appears feasible by performing more accurate measurements at the STERN Laboratory after verifying that their on-line instrumentation meets the required accuracy. For the pump suction pipes, a more accurate FPC factor may also be obtained through measurements at alternative calibration facilities (eg. Russia or Japan) an expensive proposition. An alternative is to derive the factor using three-dimensional turbulent flow computer codes such as Phoenics.
- Complete commissioning of the interface between the CROSSFLOW system and Pt Lepreau's gateway system. It is expected that with a more stable signal frequency generator and auto-tuning software, a reliable signal can be continuously transferred from the CROSSFLOW system to their station performance monitoring system.

7.3 Conclusions

Sustained reliable operation with consistent measurement data over a period of four months establishes the current design as suitable for full power operation, a key achievement of this project.

Initiatives underway will achieve improvements that should enable a consistent accuracy of better than ±1% and stabilize the signals needed for automatic monitoring.

8.0 ACKNOWLEDGMENTS

The authors wish to acknowledge many contribution to the work reported in this paper. The most essential ones are the financial support by the Candu Owners Group for the initial preparatory work to develop and test the transducer design; the support of Point Lepreau's management and staff, in particular S. Groom, T. Hitchcock and G. Plume; the dedication of all AMAG staff that participated in the measurements, in particular M. Daly and J. Vuong.

Table 1. Flow Measurements during Power Run-up

Power %	B10 kg/s	G11 kg/s	Q4 kg/s	Q10 kg/s	PS2 kg/s	PS4 kg/s
0	20.0	31.6	26.5	31.1	2760	2700
2	18.0	26.9	23.0	27.0	2250	2320
8	17.9	28.3	20.8	-	2110	2220
30	19.1	27.2	23.1	25.7	2190	2170
50	19.0	27.9	21.0	27.8	2190	2160
70	19.0	27.8	-	-	-	2230
75	17.2	28.2	20.6	27.2	2150	2180
77	18.6	26.9	22.3	27.2	2190	2170
82	19.0	27.0	22.3	27.4	2190	2190
87	18.3	26.4	24.7	27.7	2150	2210
91	17.3	27.5	24.7	27.6	2150	2210
96	17.8	25.4	24.6	27.4	2140	2210
100	17.0	25.3	24.2	27.9	2150	2190

Table 2. Flow Measurements at Full Power

Date	B10 kg/s	G11 kg/s	Q4 kg/s	Q10 kg/s	PS2 kg/s	PS4 kg/s
27-28 Dec	17.0	25.5	24.4	27.7	2146	2206
7-9 Feb	19.2	26.0	23.7	25.9	2160	2115
15 Mar	18.2	26.3	24.2	-	-	-
18-19 Apr	17.3	-	23.1	-	2171	-

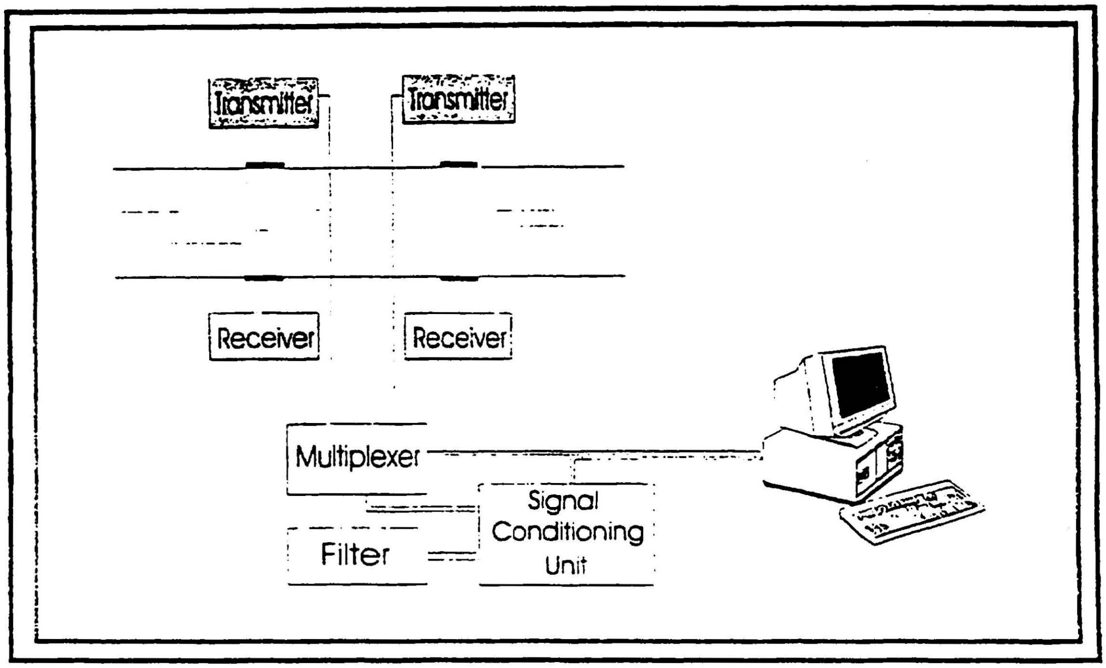


Figure 1: Schematic diagram of the CROSSFLOW system.

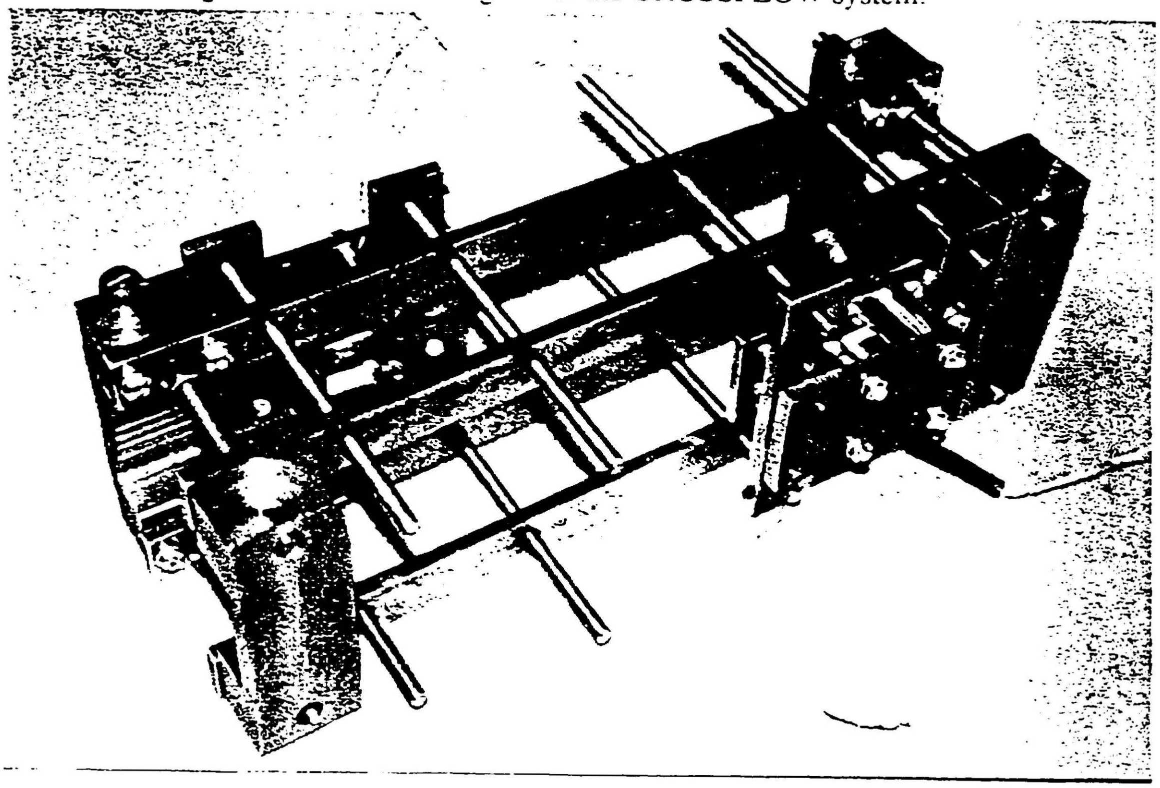


Figure 2: Transducer assembly for feeders.

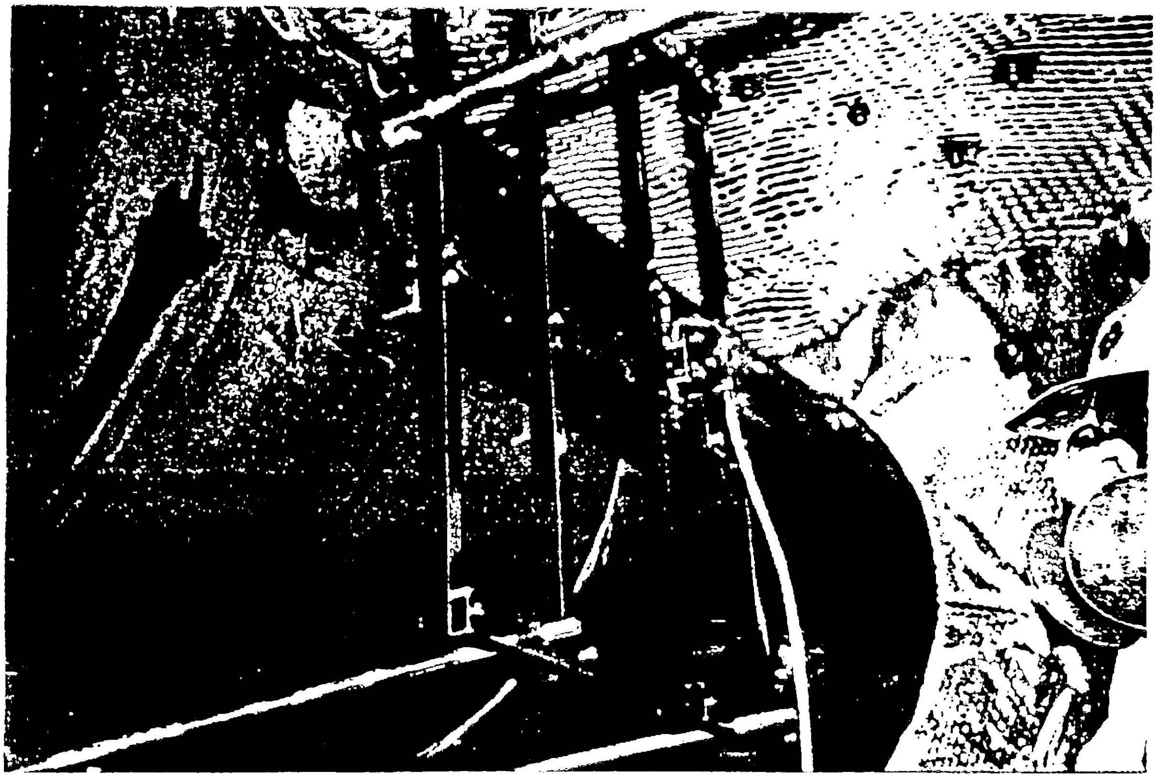


Figure 3: Transducer assembly for pump suction pipes.

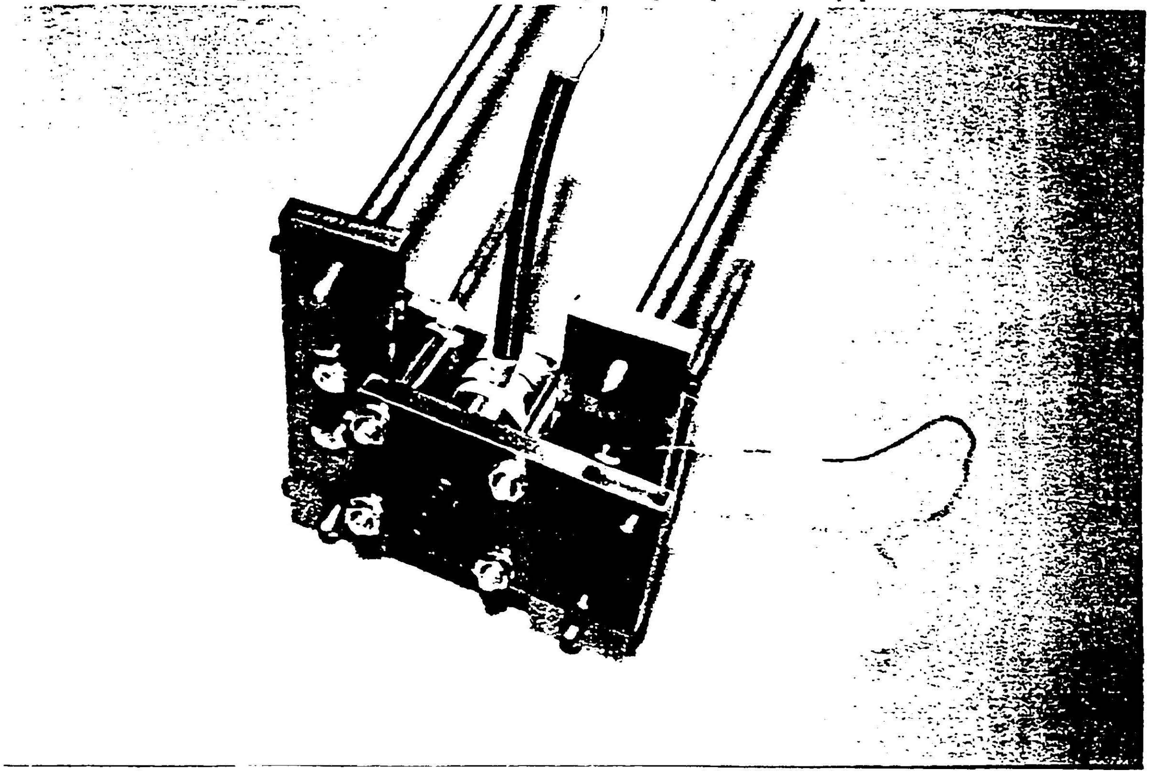


Figure 4: Transducer.

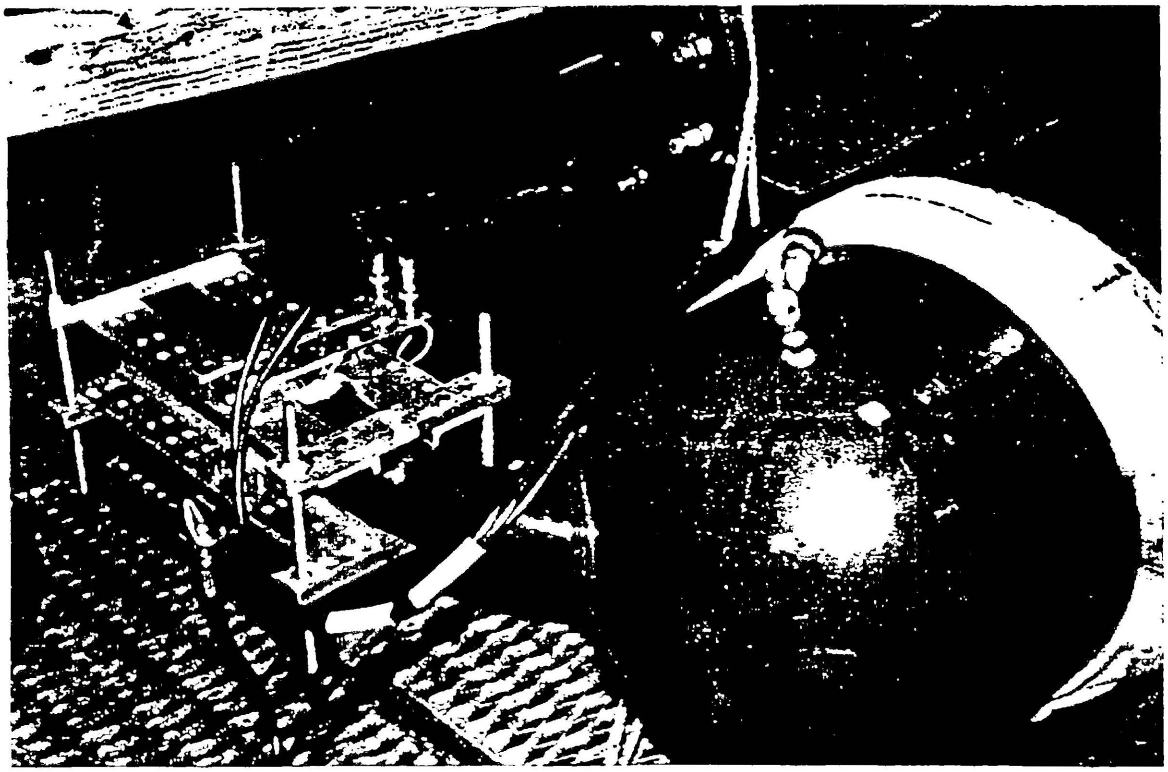


Figure 5 Boiler and pump suction model at NRC calibration facility

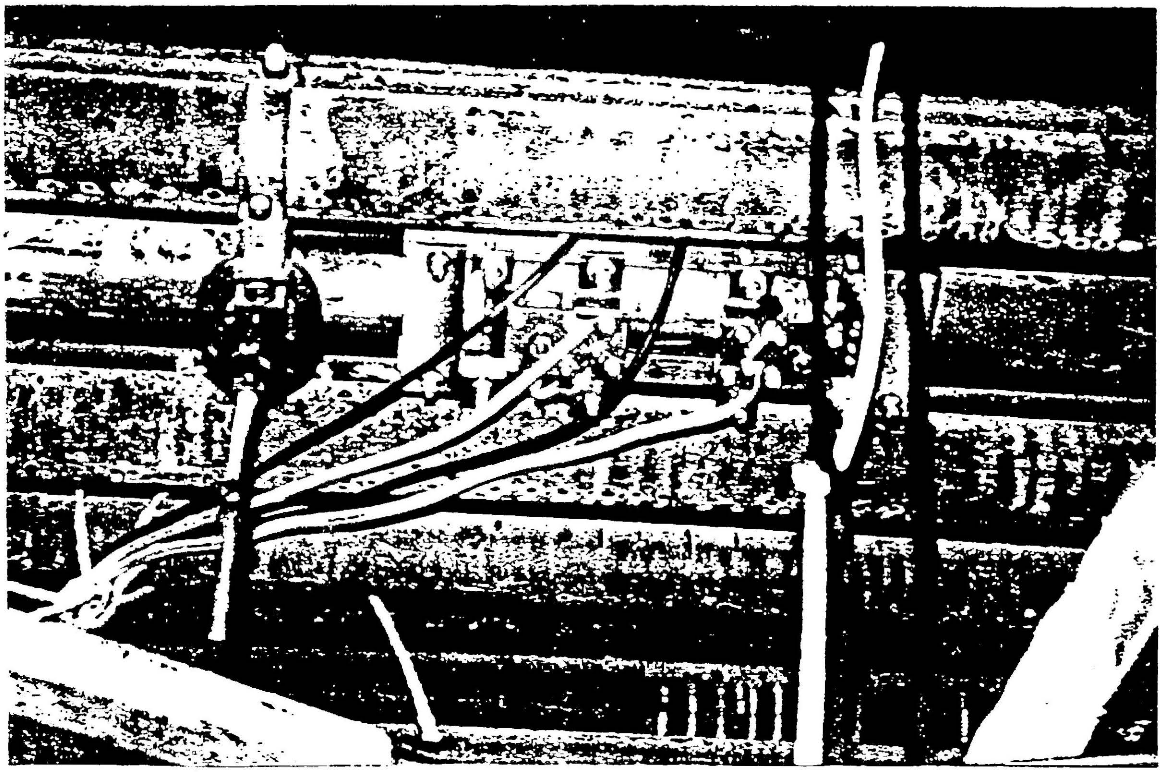
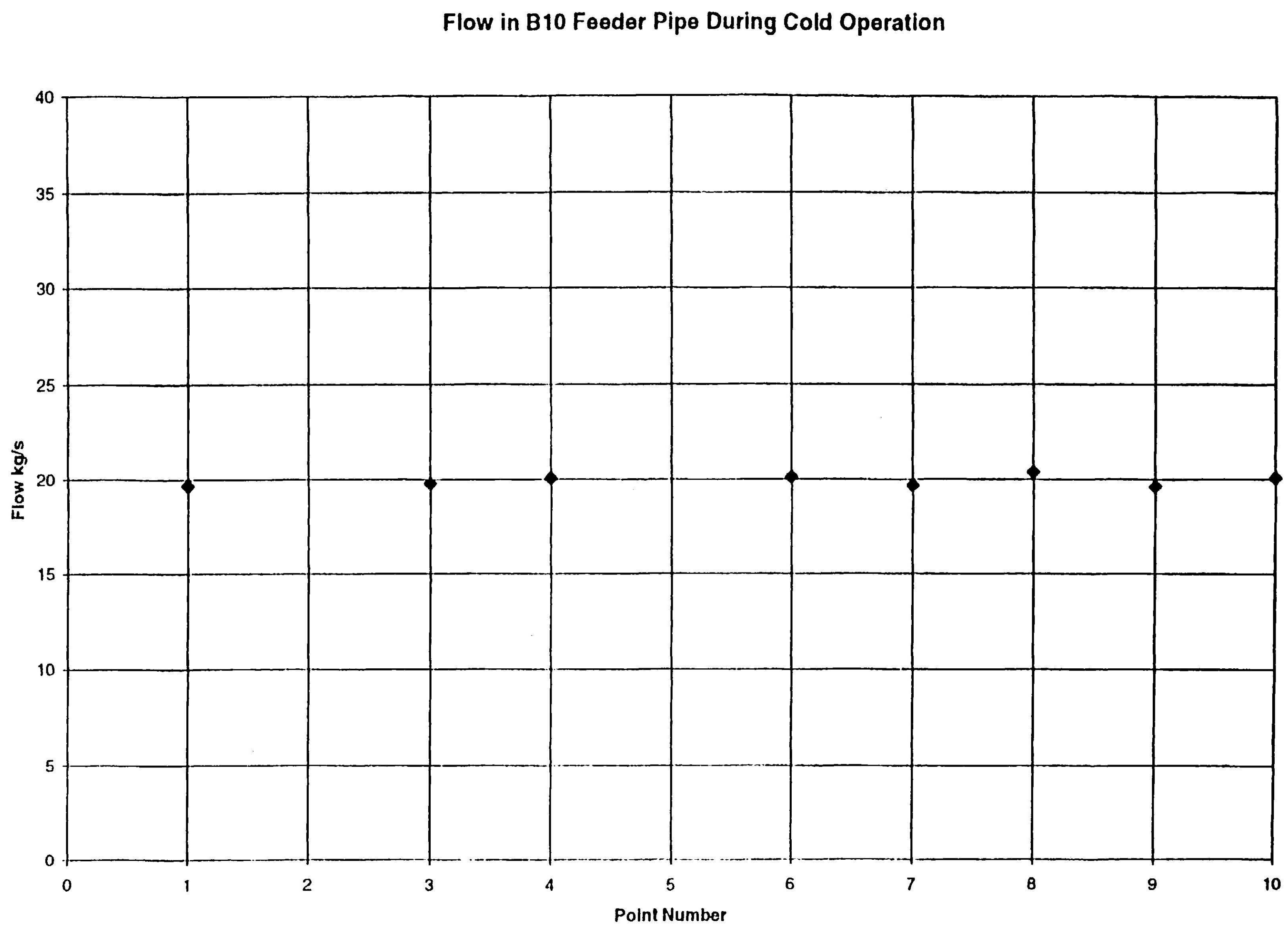


Figure 6 A transducer assembly installed on a feeder pipe.



Flow in B10 Feeder Pipe During Cold Operation
40
35
30
25
20
15
10
5
0
Flow kg/s
0
1
2
3
4
5
6
7
8
9
10
Point Number

Figure 7

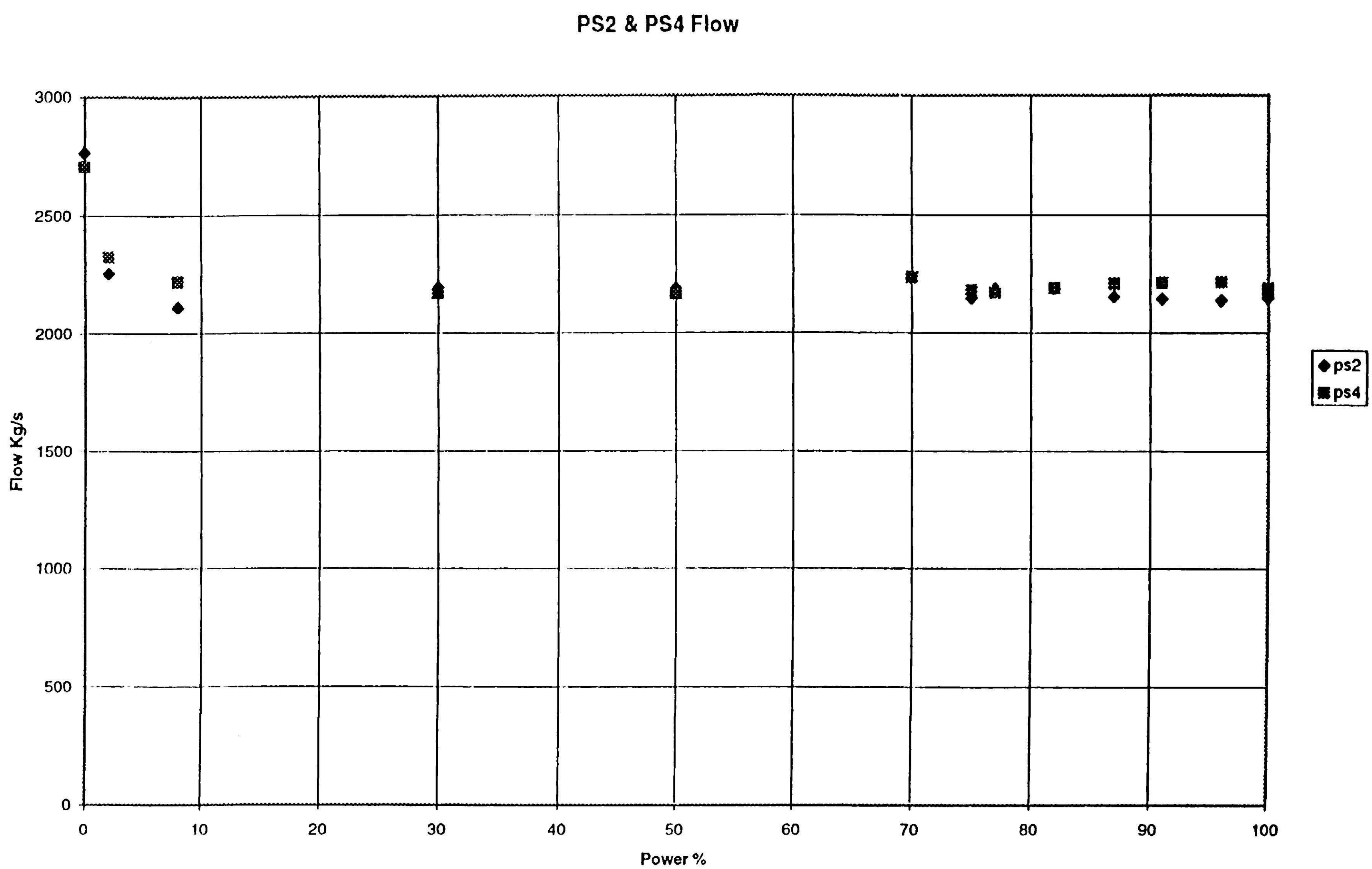

PS2 & PS4 Flow
3000
2500
2000
1500
1000
500
0
Flow Kg/s
0
10
20
30
40
50
60
70
80
90
100
Power %
ps2
ps4

Figure 8

Reactor Coolant Feeder Flow Q04. April 19,96

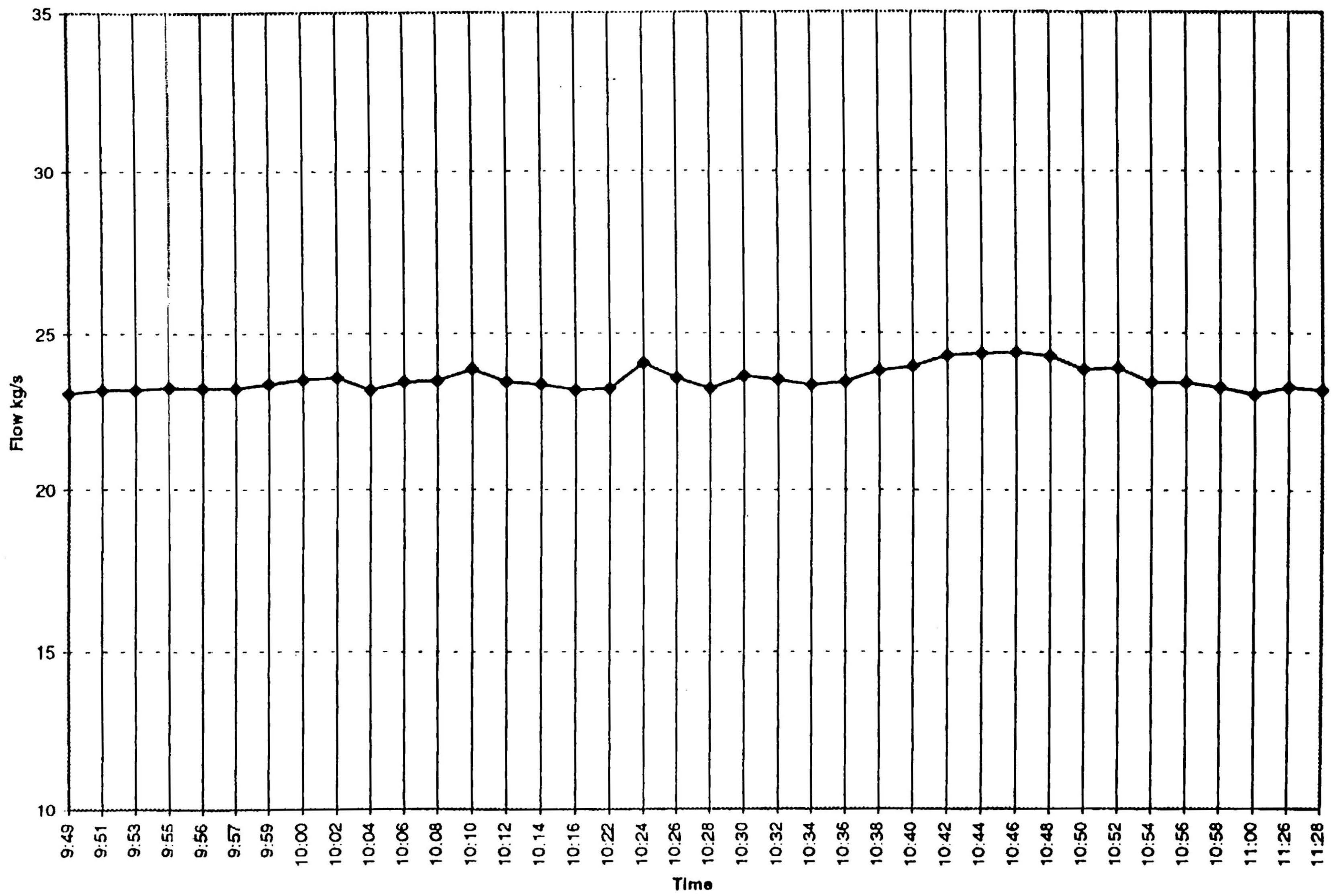


Figure 9