Reactor Core Flow Measurements during Plant Start-Up using Non-Intrusive Flow Meter CROSSFLOW

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Abstract

For the first time, direct measurements of the total reactor coolant flow and the flow distribution between the inner reactor zone and the outer zone were conducted using the non-intrusive clamp on ultrasonic cross-correlation flow meter, CROSSFLOW, developed and manufactured by Advanced Measurement & Analysis Group Inc. (AMAG). The measurements were performed at Bruce Power A Unit 1 on the Pump Discharge piping of the Primary Heat Transport (PHT) system during start-up. This paper describes installation processes, hydraulic testing, uncertainty analysis and traceability of the measurements to certified standards.

1. Introduction

Bruce A Unit 1 is a CANDU design with 8 separate steam generators. Its PHT system consists of 4 main pumps. Bruce Unit 1 went under a major refurbishment project and as part of the commissioning activities, AMAG was contracted to provide accurate total Pump Discharge flow measurements in the Primary Heat Transport (PHT) system and flow distribution between the Outer Zone Loop (OZL) and the Inner Zone Loop (IZL) during the Phase C Commissioning tests at steady state, Hot Zero Power (HZP) conditions.

AMAG's non-intrusive cross-correlation flow measurement technology was used to measure total Pump Discharge flow and flow distribution between OZL and IZL for the purpose of providing an input to the safety analysis that is performed for Unit 1; in the past, the plant relied upon estimating the total flow based on simulations and measurements of finch channel feeder flows.

The CROSSFLOW system, apart from being non-intrusive, is a permanent system which is an added benefit to the plant as it can measure flow continuously at any power level or as required by the plant.

2. Background

CROSSFLOW is a *non-intrusive* clamp-on ultrasonic flow meter which uses a cross-correlation principle to provide accurate flow measurement. It is primarily designed to measure single-phase flow. Illustration of the CROSSFLOW principle of operation is shown in Figure 1 and detailed discussions of the principles and operation of the cross-correlation flow meters, and specifically CROSSFLOW can be found in reference [1] through [6]. Nevertheless, in simple terms, the system sends two ultrasonic beams at upstream (A) and downstream (B) locations, as shown in Figure 1, which are affected by the same turbulent eddies as they move in the direction of flow from locations A to B. CROSSFLOW then registers similar signatures produced by the travelling flow eddies at upstream (A) and downstream (B) locations separated by a known distance L (given) and delayed by duration τ (measured). Time delay τ is then used to calculate axial flow velocity V_m given by the equation (1) and the flow rate by equation (2):

$$Axial\ Flow\ Velocity \Rightarrow V_m = \frac{L}{\tau} \tag{1}$$

$$FLOW = \rho A V_m C_f \tag{2}$$

where:

$\rho =$ Heavy water density (input parameter based on inlet temperature and pressure)

$A =$ Pipe cross-section area (based on the measured pipe OD and wall thickness)

$V_m =$ Average measured flow velocity (calculated using τ)

$L =$ Separation between ultrasonic beams or transducer spacing (determined by frame design)

$\tau =$ Time delay (measured by CROSSFLOW)

$C_f =$ Hydraulic Factor (to account for flow conditions inside the pipe)

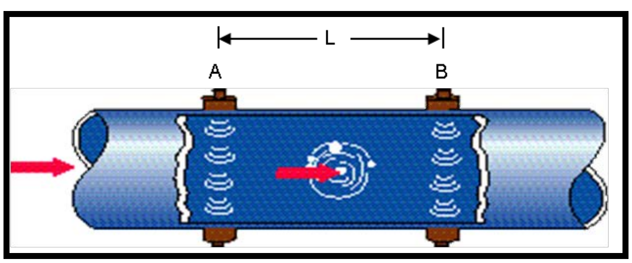


Figure 1 An illustration of ultrasonic CROSSFLOW meter

CROSSFLOW employs specialized high temperature/high radiation ultrasonic transducers (sensors), fabricated by AMAG, that are mounted on the pipe using a rigid carbon steel frame. The signals are transmitted from the transducers using custom high temperature/high radiation coaxial cables to the Signal Conditioning Unit (SCU). The Signal Processing Unit (SPU), which uses the

CROSSFLOW software, is then used to interpret and analyze the signals from the SCU to determine time delay τ which is then used to calculate flow.

3. Installation Activities

3.1 Pipe Selection and Installation Location

Based on analysis of the plant drawings and on the site walk down conducted by AMAG and Bruce Power engineers, installation locations for the CROSSFLOW meter on Pump 2 and Pump 4 discharge piping were identified as shown in Figure 2 and Figure 3, respectively. To provide traceability of the flow measurement to accepted standards, the locations of the installations should be selected such that field flow conditions can be reproduced in a laboratory test, where CROSSFLOW readings are compared with accurate independent (reference) flow measurements, traceable to NIST. The installation locations were selected based on this condition and on accessibility to the location.

The meter on the Common Header piping downstream of the pump was used to measure the total flow and the meter on the OZL downstream of the Y-section was used to measure flow in the OZL. By monitoring the total flow and the OZL flow, flow in the IZL was deduced.

It was acknowledged that the flow conditions at the Common Header piping downstream of the main pump would be significantly affected by the pump. Therefore, a laboratory test was designed to derive a Hydraulic Factor to account for disturbances in the flow due to the pump.

For the OZL flow meter, a lab test was designed to quantify the effect of the Y-section on flow conditions at the meter location, and to obtain sensitivity of the Hydraulic Factor to flow distribution between the legs of the Y-section.

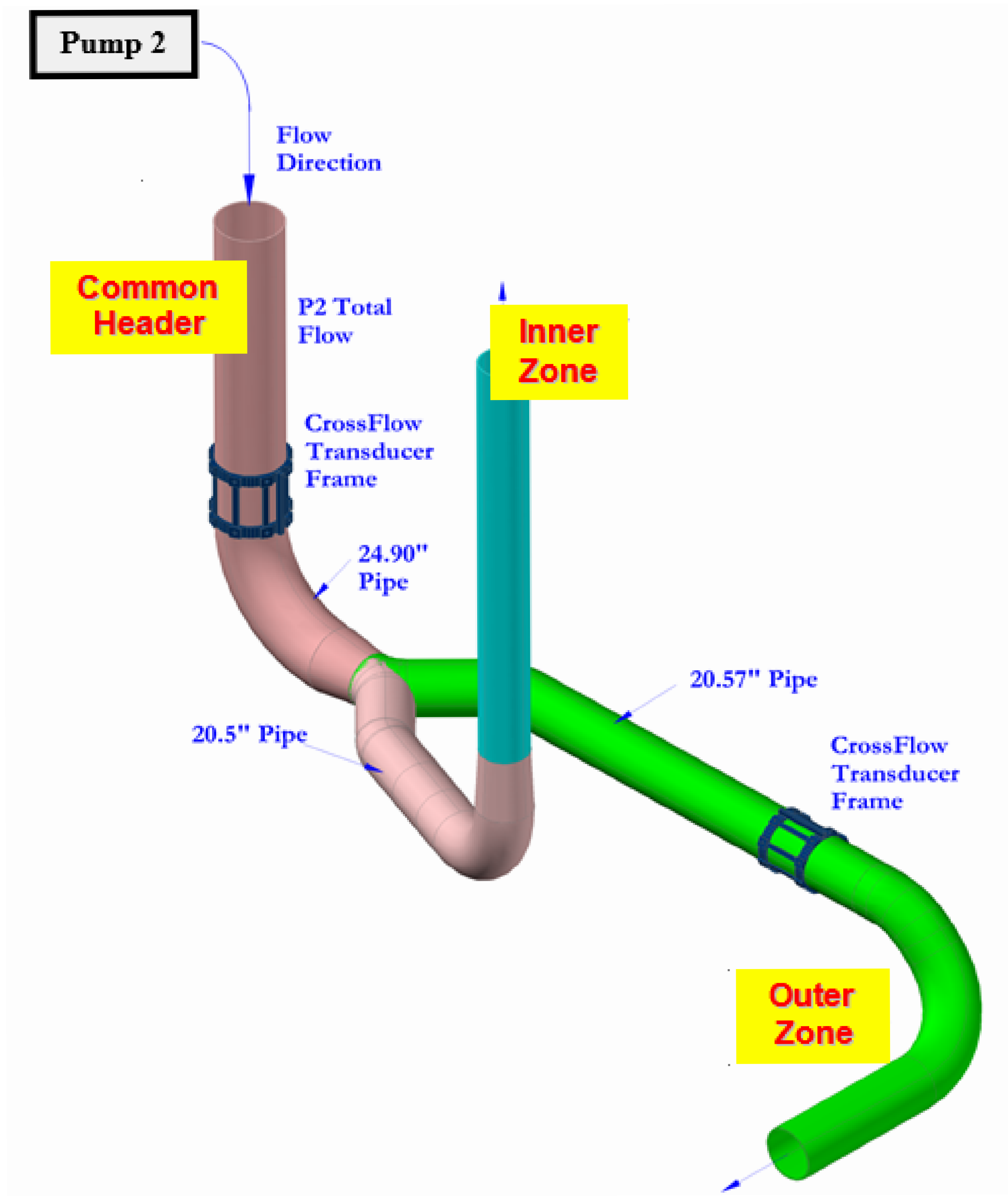


Figure 2 Bruce A Unit 1 Discharge Pump #2 piping configuration and installation locations

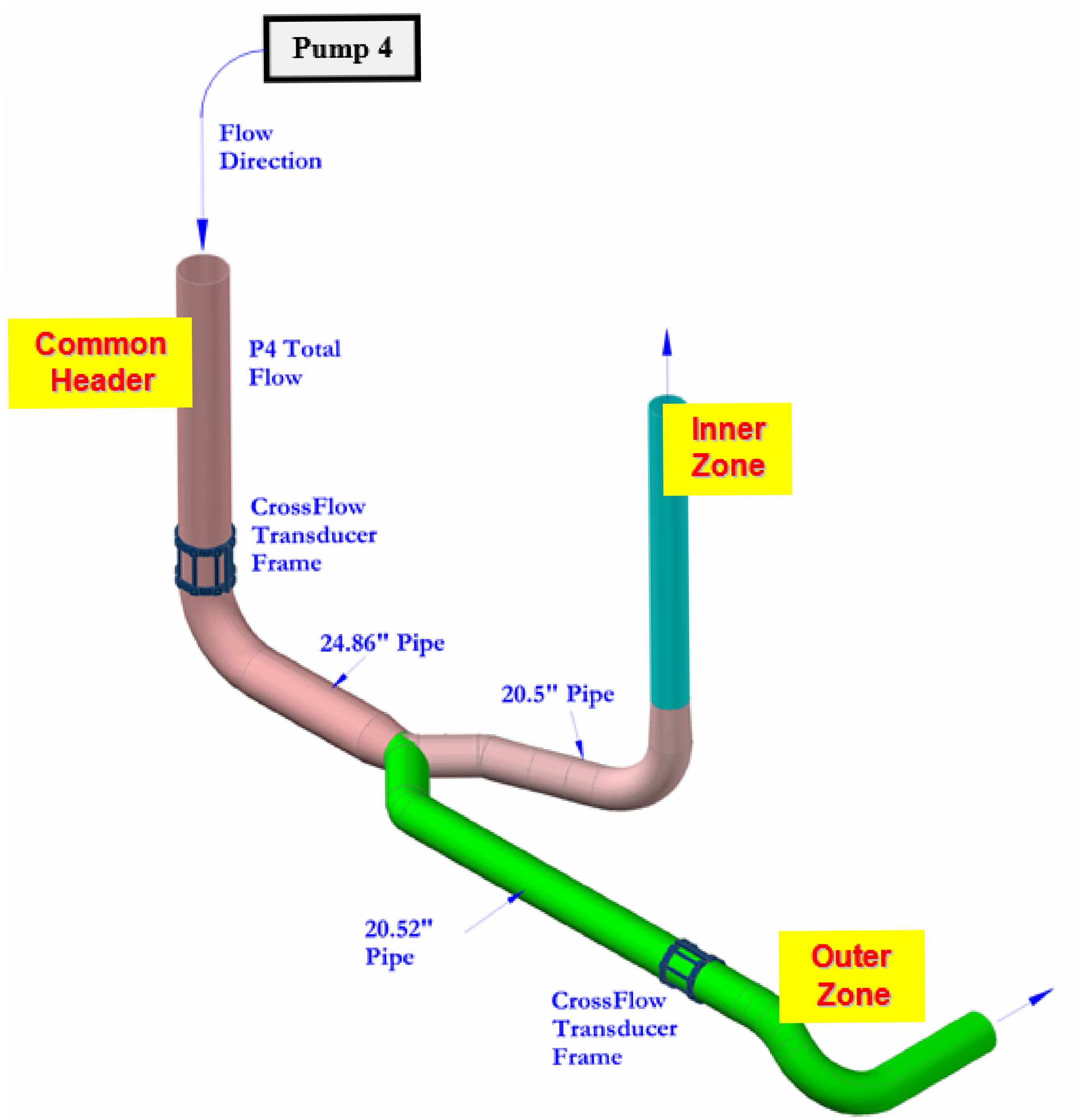


Figure 3 Bruce A Unit 1 Discharge Pump #4 piping configuration and installation locations

3.2 Permanent Transducer Assembly

The permanent transducer assembly as shown in Figure 4, consisting of the frame and ultrasonic transducers and manufactured by AMAG, was installed on each selected location of the PHT pump discharge piping. This particular transducer assembly or the Multi-Beam frame is designed to hold sixteen transducers. The Multi-Beam frame along with the multi-channel SCU allow to conduct and monitor four flow measurement readings, *simultaneously*, per location which are averaged to yield an average cross-sectional axial flow velocity.

The ultrasonic transducers are supplied with high radiation/high temperature cable. This cable can withstand temperatures up to 400 °C. Figure 4 shows a typical transducer with a 3 meter sample of cable.

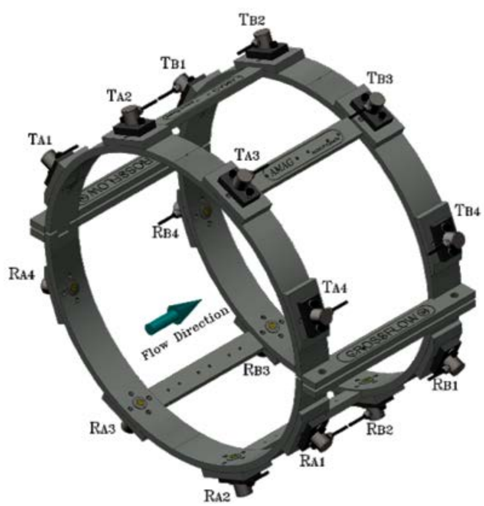


Figure 4 Multi-beam frame mount for the ultrasonic transducers (left) and ultrasonic transducer (right)

3.3 Transducer Installation

The installations were performed by AMAG personnel with support from Bruce Power staff. An outline of the most important tasks is given in this section to provide an overview of the installation activities.

i. Verification of the installation location identified during an initial plant walk-down, using plant drawings.

ii. Using a pre-cut template, marking of locations on the pipe where the transducer will make contact with the pipe.

iii. Pipe surface preparation

- Minimal pipe surface preparation was required for the CROSSFLOW meter. Each transducer location was sanded at the marked locations to ensure a suitable contact surface between the transducer and the pipe surface.

iv. Pipe surface temperature measurements using a calibrated thermocouple

v. Pipe outer diameter (OD) measurement using a calibrated digital micrometer

- There were a total of 36 OD measurements performed per location (see Figure 5)

vi. Pipe wall thickness measurement using calibrated ultrasonic thickness meter

- There were a total of 72 thickness measurements performed per location (see Figure 5)

vii. Installation of frame and ultrasonic transducers assembly (see Figure 6)

- This includes transducer electrical checks before and after the installation of transducers to verify transducer integrity.

viii. Measuring and recording of the as-installed location

ix. Routing of the cables to the temporary electronics location

- This task was performed by Bruce Power staff. Although the transducers and cables were permanent, the electronics were provisioned to be placed in the vault temporarily. Routing of the cables, permanently through the vault penetrations, is to be scheduled during the next shutdown. Routing the cables outside of the vault would mean that a permanent system can be present outside of the vault to monitor flows continuously at any power level or as needed by the plant.

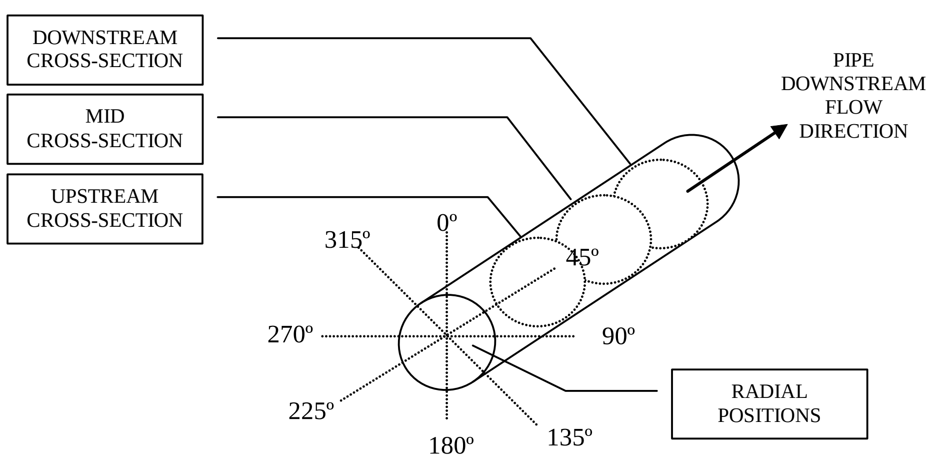


Figure 5 OD and thickness measurement scheme

The overall achieved pipe cross-section area uncertainty ranged from 0.025% to 0.100%. Therefore, it was not a critical component of the final uncertainty.

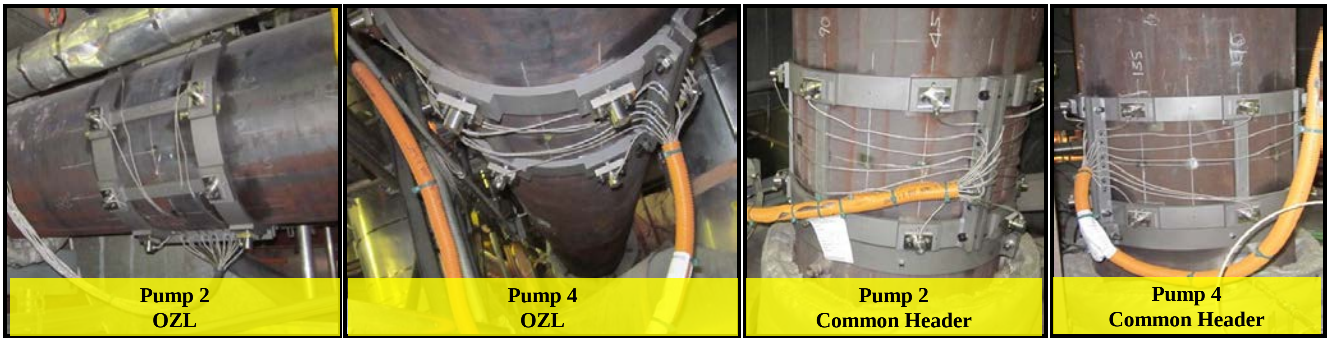


Figure 6 Installation on Pump 2 and Pump 4 OZL and Common Header pipes

3.4 Installation Verification

Subsequent to installation, verification of installation was performed by AMAG staff to ensure functionality of the system. This included visual verification to ensure proper contact of the transducers with the pipe, correct angular position of the frame, and correct record of transducer serial numbers corresponding to their respective angular position. Moreover, the torque used to tighten the transducers was verified using a calibrated torque wrench. Electrical checks were performed to ensure there were no shorts, and to verify the integrity of the as-installed transducers. Finally, the ultrasonic transmission of signals through the pipe was verified and the acoustical response and strength of the received signals were examined over a required frequency range.

3.5 Electronics Installation - CROSSFLOW System

As mentioned earlier, the CROSSFLOW system consists of transducer assembly, cables, and electronics which include SCU and SPU. The electronics were temporarily placed and setup inside the reactor vault. Two systems were setup, with each system capable of monitoring 8 flow channels simultaneously, to monitor 16 flow measurement channels – 4 flow measurement channels per frame. A Local Area Network (LAN) connection was setup through the vault penetration and two laptops were setup to remotely access the flow measurement systems inside the vault. This ensured that AMAG personnel were able to configure and setup the two flow measurement systems without having to enter the vault and get radiation and Tritium exposure. A diagram of system interconnection is shown in Figure 7.

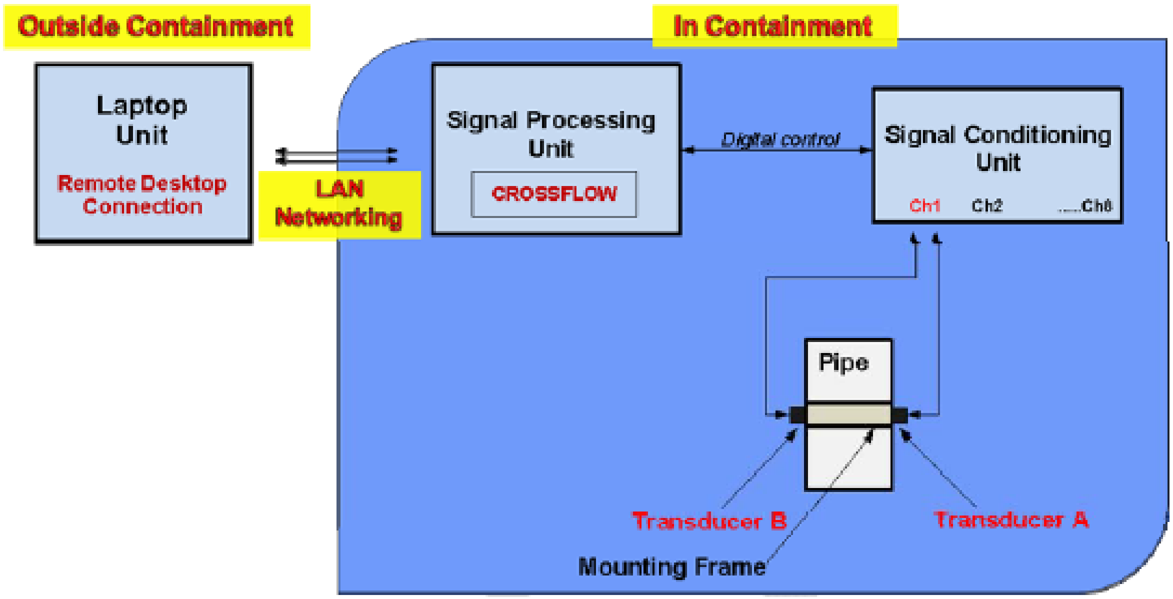


Figure 7 System interconnection setup

4. Flow Calculation

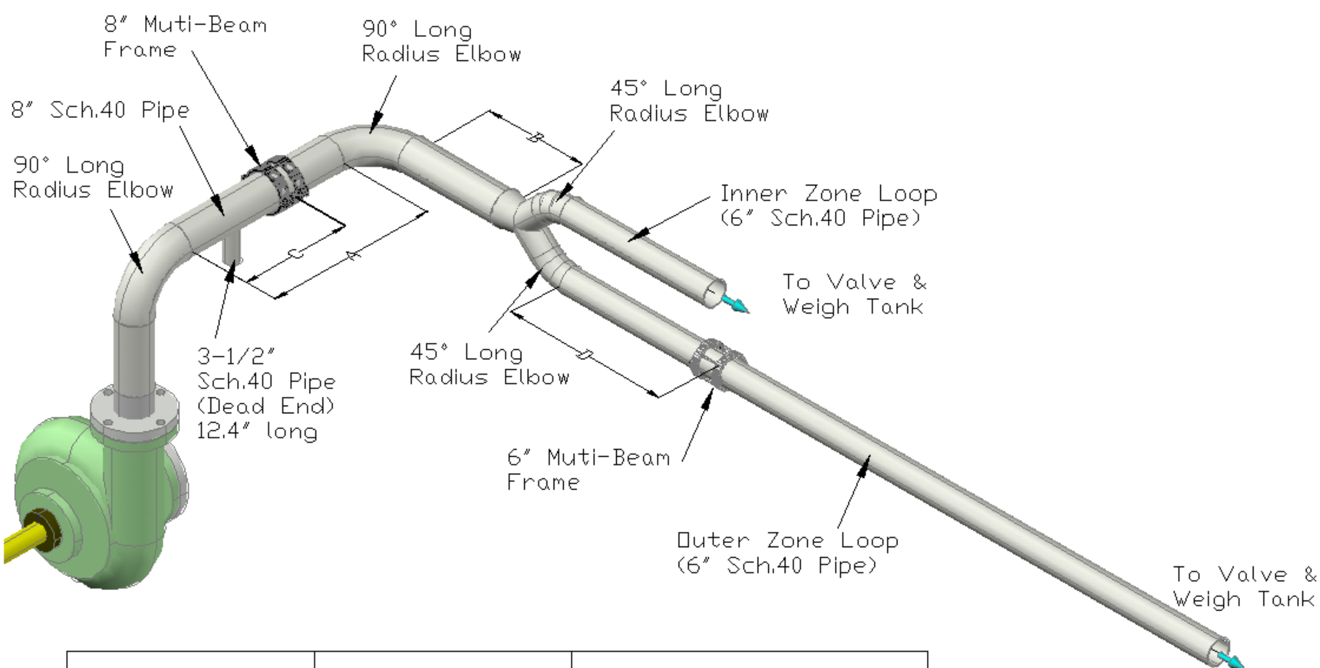
As mentioned earlier, the CROSSFLOW ultrasonic cross-correlation flow measurement system calculates the flow rate by equation (2). The input parameters to the flow rate equation were calculated for the average plant pressure and temperature, from the PI system, at HZP conditions. These parameters included pipe inside diameter **(ID)**, transducer spacing **(L)**, heavy water density **(ρ)**, and Hydraulic Factor **(C_f)**.

4.1 Hydraulic Factor

The Hydraulic Factor is necessary to account for the difference between the measured flow velocity and the bulk flow velocity. The difference in the measured flow velocity and the bulk velocity is caused by the flow conditions at the measurement location. In the case of PHT pump discharge flow measurements, the flow conditions are determined by the pump while at the OZL piping, the flow conditions are largely determined by the Y-section. To determine appropriate Hydraulic Factor and validate the CROSSFLOW meter for the locations specific to the Pump Discharge piping shown in Figure 2 and Figure 3, a laboratory test was performed at the Utah Water Research Laboratory, a NIST traceable facility with accurate flow meter calibration services.

4.2 Laboratory Modelling

The in-plant flow conditions and piping configuration represent something which is difficult, if not impossible, to reproduce exactly in a laboratory setting. Therefore, it was necessary to scale down the laboratory model to make testing possible. The complete piping section from the pump discharge to the location of the ultrasonic meter on the OZL was reproduced in the hydraulic model. The elements of the plant configuration that were represented included the pump, the first 90-degree elbow at the pump discharge, straight vertical run with internal diameter (ID) of 22 inches, second 90-degree elbow, horizontal run with ID of 22 inches, 22 x 18 splitting Y, 45-degree elbow downstream of the Y on the OZL and the long horizontal straight pipe run of the OZL with ID of 18 inches. A 1:3 scaling factor, approximately, was used for the laboratory model. A picture of the laboratory piping configuration and dimensions is shown in Figure 8.



Piping Configuration	Pipe Length		Frame Location (From Elbow)	
	A	B	C	D
1 (P2)	43.6″	8.7″	29.7″	44.5″
2 (P4)	43.6″	30.2″	28.3″	42.1″

Figure 8 Laboratory piping configuration

4.3 Hydraulic Factor Results

One of the scaling factors, that has to be maintained similar to the plant, is the ratio of the frequency of disturbance introduced by the pump rotation, F_P, and the typical frequency of the turbulence spectrum in the flow, F_F. Therefore, to represent possible plant flow conditions in the laboratory, the tests were conducted with different flow velocities. Calculation of the Hydraulic Factor for the plant was based on interpolation of the laboratory data to the plant flow velocity and pump rotation.

4.4 Hydraulic Factor Uncertainty

The total Hydraulic Factor uncertainty is calculated by including uncertainty components of all input parameters. All of the uncertainties are based on a 95% confidence interval. Here is a list of the individual uncertainties:

εA_T (%) - uncertainty in the pipe cross-section area due to the statistical uncertainty of dimensional measurements and the uncertainty of the measurement equipment.

εW_T (%) - uncertainty of the NIST traceable weigh tank as provided by Utah Water Research Facility. This was obtained during the laboratory testing.

εL_T (%) - uncertainty in the ultrasonic beam spacing due to manufacturing tolerances, and spacing measurements.

$\varepsilon\tau$ (%) - statistical uncertainty of the measured flow time delay due to data scatter, electronic and data processing uncertainty and any uncertainty due to noise removal.

εINT (%) - uncertainty due to the interpolation of the correction factor based on the ratio of F_F/F_P.

Ultimately, the final C_f uncertainty was 0.71% for the Common Header location and 0.83% for the OZL location.

4.5 Flow Measurement Uncertainty

The total flow uncertainty is calculated by including uncertainty components of all input parameters in Equation 2. Here is a list of the individual uncertainties:

εA_T (%) = uncertainty in the pipe cross-section area due to uncertainty of cold dimensional measurements and uncertainty in the thermal expansion.

εC_f (%) = uncertainty in the hydraulic correction factor obtained at Utah Water Research laboratory where the CROSSFLOW flow meter was calibrated.

$\varepsilon\rho$ (%) = uncertainty associated with the density was not included in the total flow rate uncertainty calculation because input density is calculated based on pressure and temperature provided by the plant and its uncertainty depends on the plant instrumentation. Therefore, total uncertainty was calculated for volumetric flow rate.

εL_T (%) = uncertainty in the ultrasonic beam spacing due to manufacturing tolerances and uncertainty of the thermal expansion.

$\varepsilon\tau$ (%) = statistical uncertainty of the measured flow time delay due to data scatter, electronic and data processing uncertainty and any uncertainty due to noise removal.

4.6 Flow Measurement Results

The flow measurements were performed for Unit 1 at steady state HZP conditions. The time averaged volumetric flow was calculated based on the time delay data from the CROSSFLOW system. The flow rates were provided to Bruce Power with uncertainties that were less than 1%. Bruce Power Safety department were satisfied with the results.

5. Discussion

As with any challenging project, there were many difficulties that arose from the inception of the project to the completion. This section summarizes the key difficulties/issues faced during the project and lessons learned.

It was found during the installation stage that the pipe dimensions given on the drawing referred to the inside diameter as opposed to the outside diameter which is the convention for pipes of that size. It resulted in a re-design of the frame to fit the pipe which was of a non-standard size. The installation crew, nonetheless, prepared the pipe for installation and took dimensional measurements.

During verification of transmission of ultrasonic signals through the pipe, it was observed that although there was water in the pipe, the signals on the Common Header of the pipe on pump 2 could not pass through the pipe. It appeared as if there was no water in the pipe. It was noted that the pumps were not running, however, confirmed with operations that there was water. AMAG staff re-grouped and various theories were discussed. It was ruled out that the transducers or cables were defective as electrical testing passed. It was suggested that a large air pocket or air bubble is present at the installation location which is inhibiting the transfer of ultrasonic signals through the pipe to the receiver transducers. This suggestion was confirmed when the signal transmission tests were repeated after pumps were started to re-circulate the water in the PHT system.

During setup of remote access and CROSSFLOW system, there were times when power to the systems would be shut off. These were tests performed by the plant to test the emergency backup power. Although, the systems were connected via an APC (backup battery), the power would be shut off for several hours (sometimes ~12 hours) which would cause the battery to drain and result in system shutdown. This resulted in unexpected delays to setup the systems. It is recommended, to power plants, to relay such testing schedules to the vendors.

6. Conclusion

The total reactor coolant flow and flow distribution between the IZL and OZL piping at Bruce Power were measured using AMAG's non-intrusive cross-correlation flow measurement system, during the Phase C Commissioning tests at steady state, HZP conditions. The laboratory tests were performed to establish traceability of the field measurements to the NIST standards, by accounting for the effect of flow conditions at the measurement locations onto the meter output. Measurement uncertainty of 1%

with 95% confidence interval was achieved. This project demonstrates that it is possible to implement a permanent installation of the CROSSFLOW, non-intrusive flow measurement system, to enable on-line monitoring of the total reactor coolant flow, and flow distribution between inner and outer reactor zones.

7. Acknowledgement

This project would not have been successfully completed without the efforts and cooperation of many colleagues from AMAG, Bruce Power, and AMEC NSS. First of all, the authors would like to thank Marc Kwee and Jun Xue of Bruce Power for initiating the project. Secondly, the cooperation and assistance of this project's managers, Michael Haaksma, Dominik Majda, and Kenneth Rhyno of Bruce Power is appreciated. A special thanks to Randy Long, Tom Hogan, Barbara Boddy, Brian Fosty, and Dan Foster of Bruce Power and Gregg Stewart, George Chin, Sundaram Iyer, Adele Mitchinson, Craig Glen, and David Zobin of AMEC NSS for providing their support throughout the project. Last but not least, the contribution of Sri Selvaratnarajah, Kenneth Viloria, and Derrick Madriaga of AMAG in the installation activities is much appreciated. Once again, without the efforts and hard work of many, this project would not have been possible.

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