An ASFM Application for Penstock Rupture Detection

Faheem Sadeque[1], Jan Buermans[2],
Dave Billenness[2], David Lemon[2]

[1]BC Hydro, 6911 Southpoint Dr., A02-126, Burnaby, BC V3N 4X8, Canada
[2]ASL Environmental Sciences Inc. 1-6703 Rajpur Place, Victoria, B.C., V8M 1Z5, Canada
E-mail (corresponding author): jbuermans@aslenv.com

Abstract

A reliable over-velocity detection system (OVDS) was required for a BC Hydro project with a long conduit system. The intake tunnel is 25 m below the floor elevation of the intake structure. The access to a tunnel flow section is limited either through the maintenance gate slot or the air-shaft downstream of the intake operating gate. The operation and maintenance team opposed the installation of commonly available flowmeters to avoid the risk of damage to the turbomachinery by damaged flowmeter components and to avoid the hazards associated with frequent tunnel dewatering and diving for repair and maintenance of the flowmeter.

BC Hydro had prior experience of satisfactory flow measurement with ASFM (Acoustic Scintillation Flow Meters) for turbine efficiency testing. It was known for accurate flow measurement at the intake section. ASFM flow sensors were mounted on a metal horse-shoe frame with sensors and cables inside the frame and away from the flow. The installation and recovery were conveniently managed from the intake floor without the help of a diver or draining the intake flow section. These attributes made ASFM a single viable alternative for the project. The novel application for over-velocity or rupture detection required long term, unattended, continuous flow monitoring posing some challenges.

Two independent 4-path ASFM systems were installed on an aluminum frame inside the maintenance gate slot for redundancy. These systems were deployed to collect samples in sequential mode to avoid interference. Each measured flow has been reliably reported to a PLC (Programmable Logic Controller) via Modbus communication link with some data quality parameters to avoid outliers to cause false detection of over-velocity during generating unit start-up and load ramping conditions. Three consecutive over-velocity readings with good quality parameters from an ASFM system has been considered to cause an OVDS alarm and gate tripping.

---

1. Introduction

British Columbia Hydropower Authority (BC Hydro) was looking for a reliable and accurate flow monitoring system for penstock rupture detection at Wahleach Generating Station (WAH). The WAH project is located approximately 125 km east of Vancouver, BC. A 4.3 km long tunnel conveys water from an intake at Jones Lake (JLK) through Four Brothers Mountain. Then the water passes through a 515 m long surface steel penstock to the powerhouse. Figure 1 shows a general layout of the project.

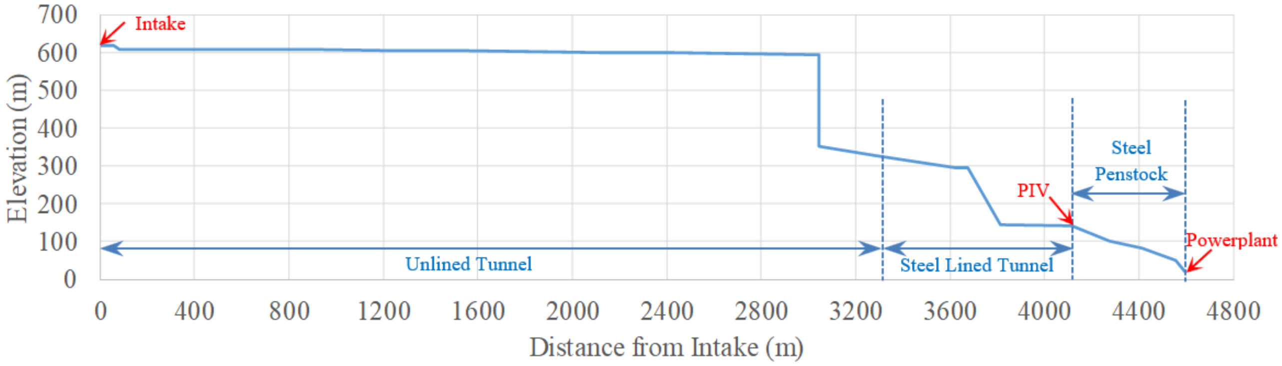

Figure 1: Wahleach project layout.

The project was originally constructed in 1950-52 with a mechanical over-velocity detection system (OVDS) at the Jones Lake (JLK) intake. A second OVDS was installed later at the valve house upstream of Penstock Inlet Valve (PIV). These systems used to operate independently of each other and were designed to trip the intake operating gate (INOG) or close the PIV upon detection of a rupture in the power conduit. There was no communication linkage to or from the OVDS located at JLK. The mechanical OVDS at JLK caused multiple false trips and caused rapid tunnel dewatering in recent years. There are no documented ways to confirm the calibration of the existing mechanical OVDS. The PIV OVDS, which detects over-velocity on the basis of pressure differential at a tapered penstock section, has been performing well. Therefore, BC Hydro station operations wanted to replace the mechanical OVDS at the JLK intake building with a reliable alternative. In general, the key requirements for the new OVDS were to be simple, reliable (good quality, no false trips, and no frequent repair/maintenance), easy to maintain, and relatively inexpensive.

The primary user requirement for this project was to sense uncontrolled flow due to tunnel rupture and initiate mediation. Intake gate (INOG) closure is essential to prevent draining of the reservoir. PIV closure is also important, as the conduit has sufficient water and head to run the unit (un-noticed in existing communication set-up) for about 30 minutes after full INOG closure. This may cause fast dewatering of the tunnel, which creates a significant geotechnical risk. In the case of a penstock rupture, PIV closure will prevent uncontrolled release of water. However, it was considered prudent that the INOG and PIV should both be closed in the event of a detection of over-velocity at either location. This required a communication linkage between the two OVDS located at the JLK intake building and the PIV house so that a unified OVDS signal can be transmitted to the powerhouse operator.

BC Hydro station operations had some additional requirements. They preferred an OVDS system which will neither require underwater inspection, nor dewatering of the tunnel for installation, maintenance, or repair, i.e., all operation and maintenance work to be done from the intake floor. They also wanted the new flow monitoring system to avoid flow obstruction and the possibility of loose objects in the water (to avoid damage to turbomachinery at the powerhouse).

BC Hydro Hydrotechnical Engineering investigated project constraints and flow monitoring alternatives available in the market to satisfy the above user requirements. This paper provides background information for the selection of the ASFM (Acoustic Scintillation Flow Meter) and technical details of its design, installation, and commissioning for tunnel and penstock rupture detection at WAH project.

2. Project constraints

The JLK intake is located on the reservoir side of a tall mountain. It is a two-story concrete structure, approximately 600 m above the powerhouse, immediately next to a steep rocky slope with tall trees towering over the roof. A narrow unpaved forest service road is used to access JLK. It has steep slopes and sharp turns on the way to JLK. The road access is often unavailable in winter.

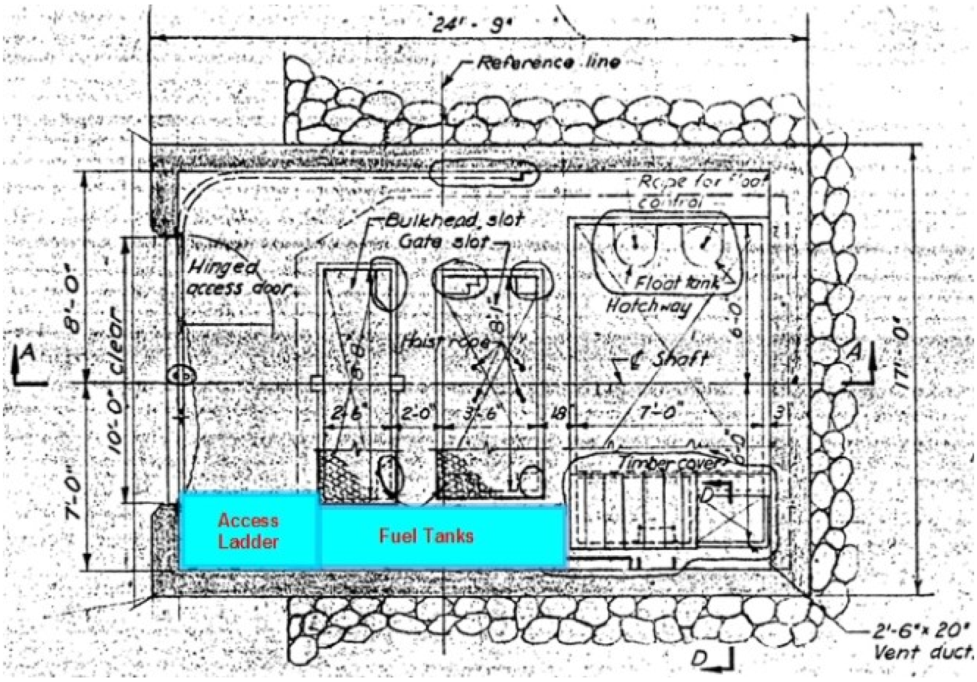

Figure 2: JLK main floor plan.

The floor spaces (6.78 m x 4.57 m) were pre-occupied with gate control system, batteries, water level monitoring system, fuel tanks, electric panels, steel ladder and landing. Moreover, the intake tunnel is 25 m below the intake floor. The access to measure flow at intake is limited. There are only three slots from the main floor to access water (see Figure 2).

a) The bulkhead or maintenance gate (INMG) slot (2.64 m x 0.76 m opening) with its gate in dogged position below the floor,

b) The intake operating gate (INOG) slot (2.46 m x 1.07 m opening), which is always occupied by an active gate, and

c) The debris removal shaft (also called air-shaft, 3.66 m x 2.13 m opening), which is used for access to the tunnel for inspection and maintenance, and ventilation purpose to assist penstock filling and draining procedure.

There is no power line to JLK. The small electrical load used to be managed by a 12 Vdc battery bank and a back-up diesel generator. An old-fashioned VHF radio based RTU communication system was used to transfer gate position and lake level data to the operator via multiple relays. As a result, the OVDS project at WAH had to consider power supply and telecommunication upgrades and an innovative design of the flow monitoring system to overcome project constraints. BC Hydro considered various flowmeters available in the market that can be deployed in the intake tunnel using a frame inside the available vertical slots.

3. ASFM principles of operation

The ASFM uses a technique called acoustic scintillation drift [1, 2] to measure the flow velocity perpendicular to a number of acoustic paths established across the intake to the turbine. Short (16 µsec) pulses of high-frequency sound (307 kHz) are sent from transmitting arrays on one side to receiving arrays on the other, at a rate of approximately 250 pings /second. Fluctuations in the amplitude of those acoustic pulses result from turbulence in the water carried along by the current. The ASFM measures those fluctuations (known as scintillations) and from them computes the lateral average (i.e., along the acoustic path) of the velocity perpendicular to each path. The ASFM utilizes the natural turbulence embedded in the flow, as shown in Figure 3. In its simplest form, two transmitters are placed on one side of the measurement section, two receivers at the other. The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and the flow. If the two paths are sufficiently close (Δx), the turbulence remains embedded in the flow, and the pattern of these amplitude variations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, Δt. This time delay corresponds to the peak in the time-lagged cross-correlation function calculated for Signal 1 and Signal 2. The mean velocity perpendicular to the acoustic paths is then Δx/Δt. Using three transmitters and three receivers at each measurement level allows both the magnitude and inclination of the velocity to be measured. The ASFM computes the discharge through each bay of the intake by integrating the horizontal component of the velocity over the cross-sectional area of the intake. In a multi-bay intake, the discharges through each bay are summed to compute the total discharge.

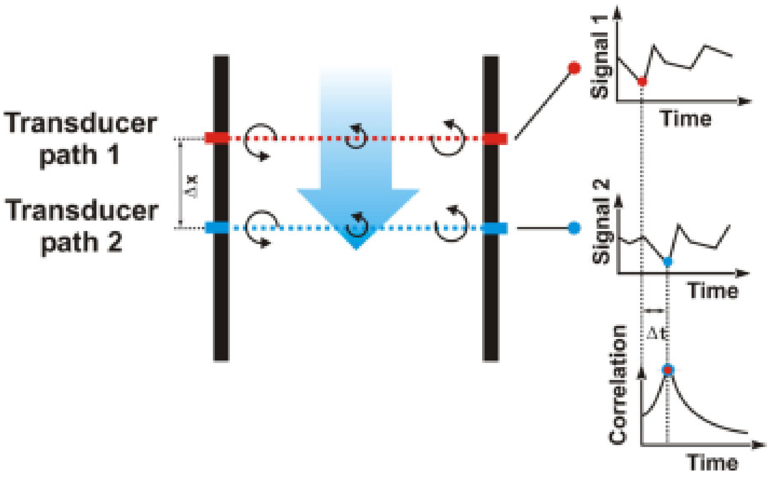

Figure 3: Schematic representation of acoustic scintillation drift.

4. Previous BCH experience

As well as the literature reports on the use of acoustic scintillation for measuring flows in hydroelectric plants, BC Hydro had two previous experiences using the method at its own sites.

In October 2009, a comparative test of three intake flow measurement methods (acoustic scintillation, current meters and acoustic travel time) was carried out at BC Hydro's Kootenay Canal power plant, in Unit #1. Reference flow data was provided by a code-accepted acoustic travel time instrument installed in the penstock. The test was sponsored by CEATI (the Centre for Energy Advancement through Technological Innovation) and supervised by the PTC-18 Committee of the ASME. The comparison was run as a blind test; none of the test participants had knowledge of the reference or any other test discharges until after the completion of the measurements.

Each unit at Kootenay Canal has a single intake, 7.44 m high and 4.88 m wide. Both current meters and acoustic scintillation sensors had to be deployed in the maintenance gate slot, the only one available for installing instruments. Measurements were conducted at three discharges (low, medium, and high). In the primary measurement program, the flow in all other units was held constant; it was followed by a shorter, secondary program in which the flow in neighbouring units was allowed to vary.

Agreement with the reference flow was very good in both the primary and secondary test programs as shown in Figure 4. In the primary test program, the average deviation of the ASFM flow from the reference flow was 0.44%, with a standard deviation of 0.19%. The difference showed no significant trend with discharge.

In October 2015, BC Hydro and ASL AQFlow carried out another comparison flow measurement test in Unit #4 of the GM Shrum power plant between an acoustic scintillation system mounted in the intake and an acoustic travel time instrument installed in the penstock. The comparisons were conducted as a blind test for the acoustic scintillation method. The flow comparisons were carried out in conjunction with other engineering tests being performed on the turbine. Repeat measurements were done at three different flows, with nominal power outputs of 185, 230 and 275 MW. Measurements were also made at other flows, when the engineering test program presented opportunities to do so; however repeat measurements for these tests could not usually be accommodated.

The agreement between the two methods was again good: the difference between the average discharges at each repeat setting was nearly constant at -0.7% for the two lower settings but increased to -1.1% at the highest flow condition. The scatter in the difference was greatest at the lowest flow, as shown in Figure 5.

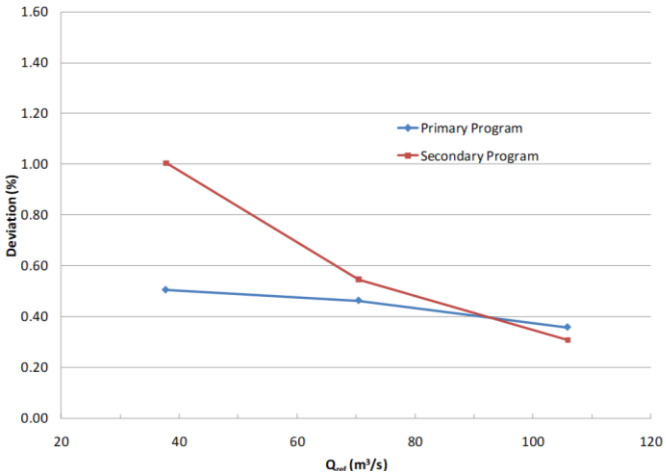

Figure 4: Difference between the ASFM and reference discharge at Kootenay Canal test.

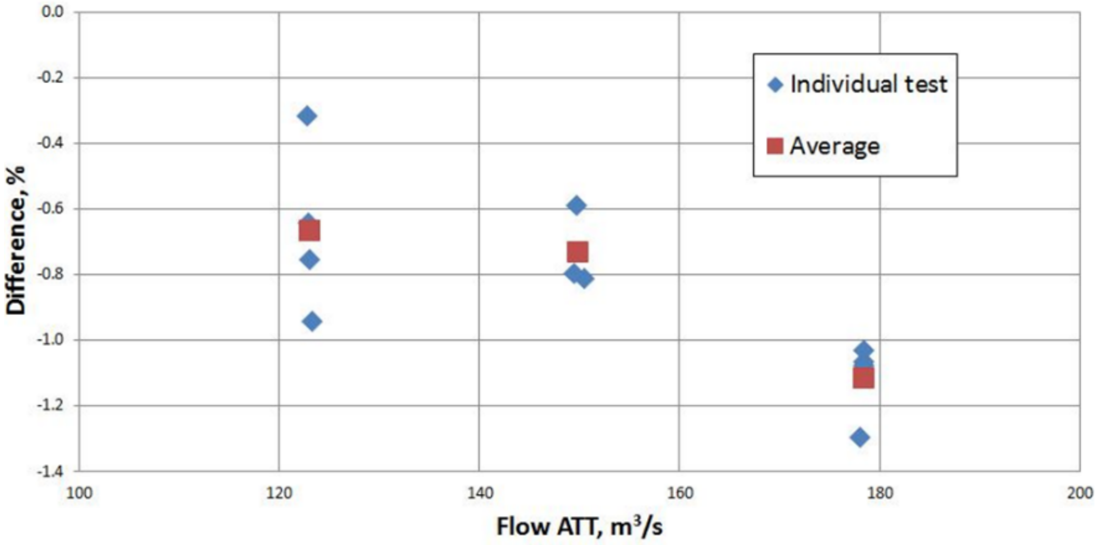

Figure 5: Average and individual differences between AS and ATT flows at each repeat setting at GM Shrum.

The estimated uncertainty of the ATT method is ±1% when installed and operated in accordance with the requirements of the ASME PTC-18 Code (ASME, 2011). The difference between the AS and ATT flows ranged from -0.3% to -1.1%, with an average value of -0.9%. The conclusion may, therefore, be drawn that the flows measured with AS in the intake are not significantly different than those measured by the ATT in the penstock and have an uncertainty of no more than ±1%.

The results of these two direct experiences, as well as the body of literature on the use of acoustic scintillation, allowed BC Hydro to conclude that the ASFM is a good alternative for accurate flow monitoring. Due to the availability of information on local constraints, user requirements and prior experience with various flow meters, the project team was able to review and evaluate the advantages and disadvantages of the available alternatives in needs phase and make a recommendation to select the ASFM as the single viable alternative.

5. Custom design requirements for long-term application

The ASFM is conventionally used for turbine efficiency testing, especially for projects with short penstocks. Test set-ups can have an ad hoc arrangement for cable management, power supply and data collection. The ASFM test set-up can be conveniently laid at the top of the dam and recovered once data collection is completed. However, a robust, durable and reliable set-up was required for OVDS application where ASFM will be used for long-term continuous flow monitoring. Therefore, BC Hydro provided the following requirements for a custom design of the ASFM system.

- The ASFM transducers are required to fit in the available space inside the proposed mounting frame which will be lowered into the maintenance gate slot.
- Two independent ASFM systems are required to work in parallel from the same mounting frame.
- The transducers are required to be capable of path substitution for any failed flow transducer without disruption to the flow measurement.
- The signal cables are required to support the gravity load (tension due to the attached counter-weight) expected for the proposed cable management system.
- The signal cables are required to have easy disconnect from the surface units.
- The ASFM units are required to have remote bi-directional Ethernet communications with the PLC (programmable logic controller) system.
- The ASFM data output are required in Mod BUS format to ensure PLC system reliability standard.
- The ASFM output are required to produce timestamp, calculated flow, single path velocity, and internal diagnostics.
- The ASFM data output are required to refresh in less than 3 minutes.
- Accuracy and repeatability of flow measurement are required to be within 2-5%.
- The ASFM units are required to store data for at least 30 days.
- The ASFM systems are required to operate using 24 Vdc power.
- The ASFM systems are required to have resistance to electrical surges.
- The ASFM systems are required to be free from EMF (electro-magnetic field) interference with other electronics in the intake building.

In addition, a set of spare parts including a pair of transducers with necessary cables, a pair of transmitting and receiving canisters and a surface unit were purchased and stored at site so that station operations crew can quickly replace a component in case of failure.

6. Design and installation at Wahleach intake

6.1 ASFM design details

This project included two independent 4-path ASFM instruments mounted on the same frame, with one serving as a master (ASFM-A) and one as a slave (ASFM-B), using alternating transducers on an 8-pair array (see Figure 6). The slave runs simultaneously or sequentially with the master. For quality assurance purposes and to evaluate if there are faults, flows between the two instruments can be compared in real time. Each instrument can also be compared to itself through the computation of the standard deviation of sequential measurements.

Each ASFM system was equipped with four acoustic paths. Figure 6 show a schematic diagram of the components of the two ASFM systems as installed in the plant. Each ASFM system consists of four major components: transmitting (Tx) and receiving (Rx) transducers and underwater cabling, switching canisters, surface connection cables and a data acquisition Surface Unit.

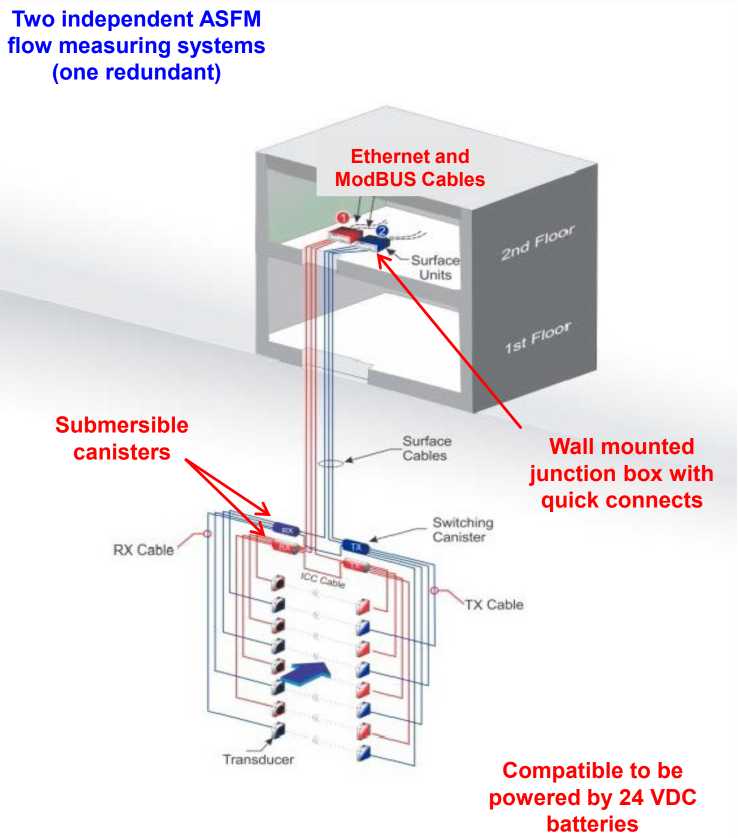

Figure 6: Two independent ASFM systems designed for WAH OVDS project.

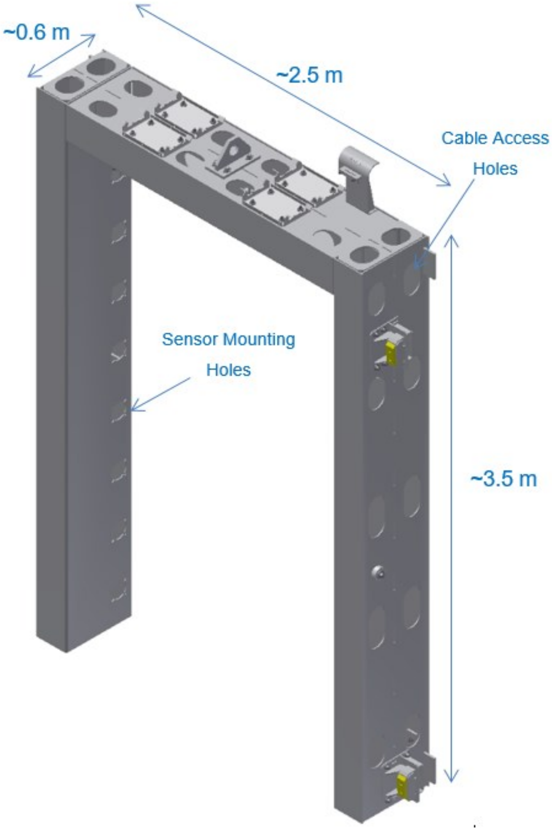

Figure 7: OVDS frame to mount the ASFM sensors in the maintenance gate slot.

6.2 Other design details

Other design details included:

- A horse-shoe frame was designed by BC Hydro Mechanical Engineering team to mount ASFM transducers in the maintenance gate slot (see Figure 7). The frame was made of Aluminum to increase durability and reduce dead weight. It has void spaces and brackets to securely hold the ASFM cables and submersible canisters without causing flow obstruction or damage during liftingBC Hydro Mechanical Engineering also designed a cable management system without a winch to simplify the requirement of spooling ASFM cables at the working surface. There are multiple sheaves and a counterweight to guide six cables into the slot so that twisting and tangling of cables does not occur, as the OVDS frame is raised and lowered.
- Two electric chain hoists were designed for lifting the INMG and the OVDS frame.
- A monorail beam with transverse supports were designed for the hoists and cable management system.
- Steel brackets were designed to store the INMG and the OVDS frame when not in use.
- Power supply at JLK was upgraded with 24 Vdc Nickel-Cadmium batteries. Multiple large solar panels with higher capacity battery chargers and voltage regulators were installed for efficient charging of the batteries and to minimize the use of back-up diesel generator.
- A C-band satellite linkage was designed to establish a LAN communication system at JLK for quick and reliable data transfer for improved operating capability.
- The existing PLC system for the unit operation was also upgraded for improved protection and control along with the new OVDS.

The ASFM systems were installed after all other associated upgrades were completed at JLK.

7. Commissioning of the ASFM and data monitoring

7.1 Performance tests

Performance tests were conducted for both steady and unsteady flow conditions. Steady flow measurements obtained from the ASFM were compared with turbine efficiency test data (see Figure 8) for the full range of turbine operating load. The agreement of the ASFM measured discharges were quite good. They were found reliable and repeatable with a systematic uncertainty of 2.0 to 2.5% for higher discharges at turbine loads ⩾40 MW. Relatively lower accuracies of the ASFM for low flows are due to inadequate turbulence scintillation caused by the trashracks located approximately 50 m upstream of the flow measurement section. However, this inaccuracy at low flows does not affect the ASFM capability to detect over-velocity under rupture conditions because the detector is intended to work only at high flows.

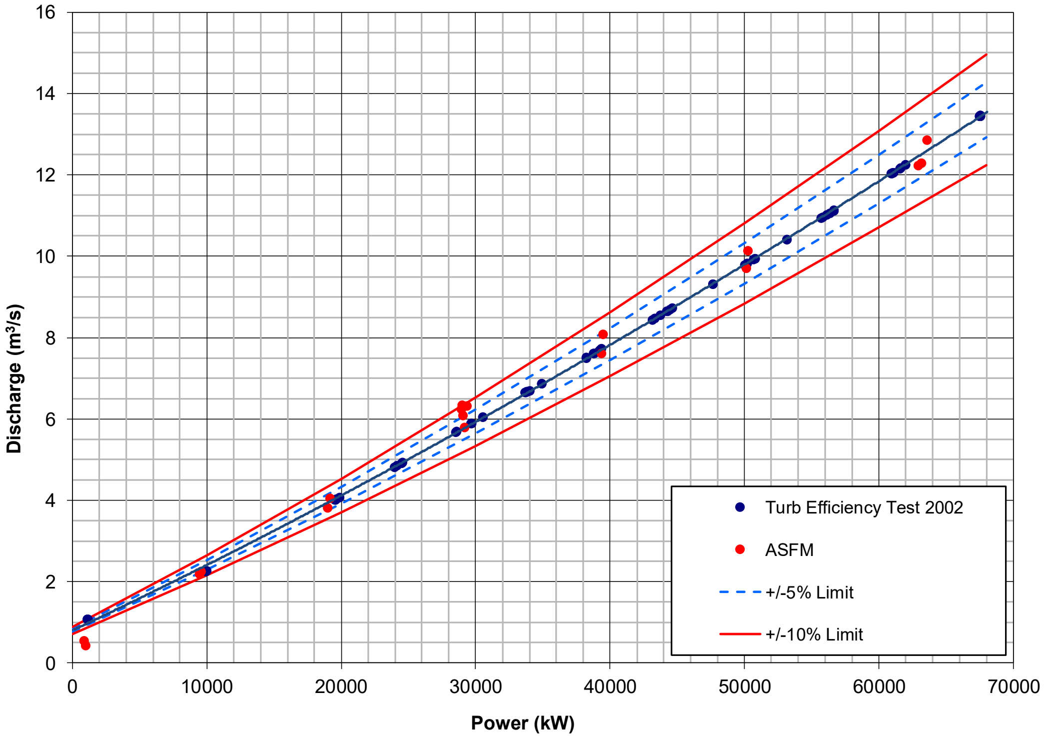

Figure 8: The ASFM measured flows compared with previous turbine efficiency test data.

The ASFM measured flows were observed during unit load ramping conditions. Each ASFM system outputs a data stream with Qe, Qc, Qr and Qi discharge values. Qc is calculated from the last velocities collected on each of the 4 paths. When a new velocity is collected, the old velocity from the same level is discarded and the new one is used in its place. Qe is an estimated flow and is based on the last flow (Qc) computed and the ratio of the old and new velocity measurement of the level just completed. Qr is calculated from the last three Qc values representing an average of the last 6 velocity measurements. Qi is calculated from the last three fully independent Qc values from data representing an average of the last 12 velocity measurements.

It was found that out of the four discharge estimates (Qe, Qc, Qr and Qi based on different averaging algorithm), Qc and Qr are more reliable as they do not create noise and consistently provide output within ±1 m^3/s of the estimated flow based on head-discharge-power relationship for the generating unit. Therefore, Qc and Qr were considered to compare with alarm and gate tripping set-points for over-velocity detection purpose. A comparison of the discharge estimates between the two ASFM systems is shown in Figure 9.

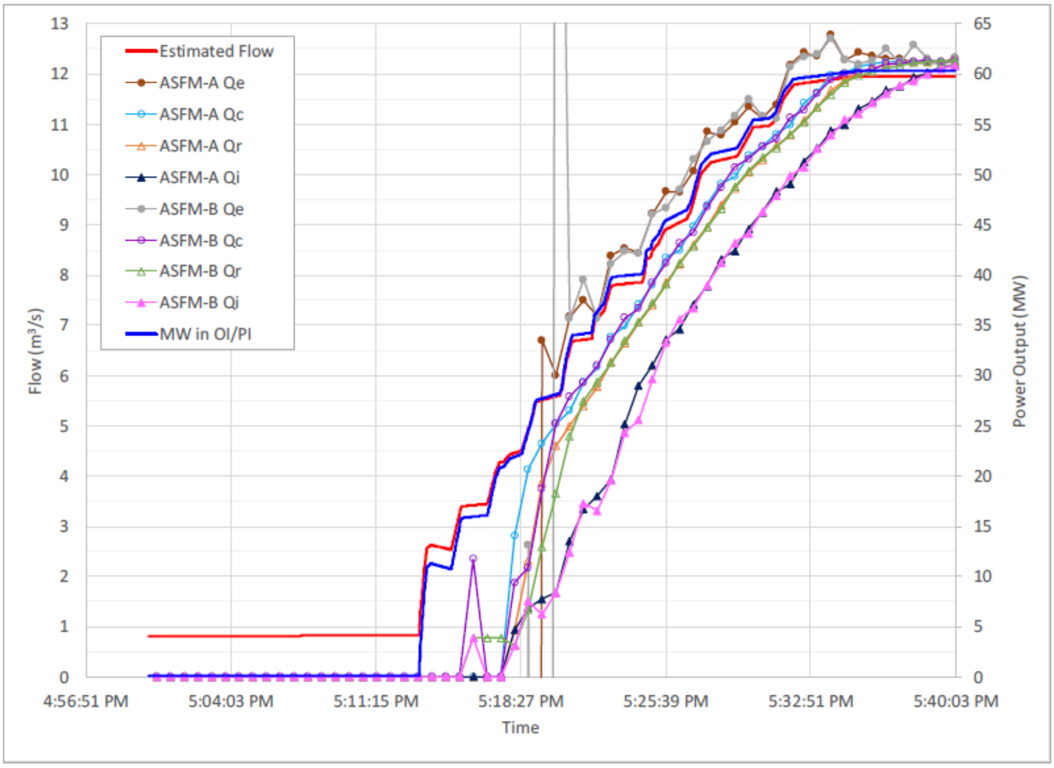

Figure 9: The multiple flow estimates provided by the two ASFM systems compared with power output.

7.2 Technical issues addressed during data monitoring period

There were several technical issues encountered with the ASFM during the data monitoring period, including external noise in the ASFM signal, signal interference between the two ASFM instruments when operating simultaneously, poor data quality during low and zero-flow conditions and problems detecting zero-flow conditions.

The ASFM cannot measure in zero-flow since the measured amplitude signals are essentially flat-lined and there is no signal to correlate. The ASFM uses the Scintillation Index (SI) to estimate zero-flow conditions. The scintillation index is a measure of the level of turbulence intensity sensed by the acoustic signal (the normalized variance of the intensity).

During commissioning, data collected with zero-flow showed larger than normal fluctuating amplitude levels and SI up to ten times higher than normal. Possible causes were outside noise being injected into the system from the supplied 24Vdc power, noise from the 24Vdc power supplies inside the surface units (which were new additions and a requirement by BC Hydro) or from the RS-232 serial port connection. After fixing several ground faults from outside sources, noise filtering was added to the input power connectors on the analog signal conditioning board on the Surface Units, the 12Vdc power to the timing board, and the 24Vdc power to the timing board. This brought the scintillation index down well below the minimum specified for calculation of zero velocity (< 1e-5).

Once the system noise had been reduced from the 24Vdc power supplies, it was evident that noise was still present when the two ASFMs were operating simultaneously. The noise appeared to be caused by signal interference from the two paths sampling at the same time. The data collection was changed to alternate sampling between each level of each unit to avoid signal interference.

There were occasional issues that remained with low flow conditions and the detection of zero-flow, as seen in Figure 10. There were very low turbulence levels at low flows caused by the trashracks being located approximately 50 m upstream of the flow measurement section. The scintillation index was used to detect zero flow (< 1e-5), however, occasionally there were bad velocities measured for single levels. The discharge was set to zero if more than two levels out of the four are set to zero by the SI threshold. This prevents a single bad value from giving large/bad discharges. The improvements to the zero-flow detection are shown in Figure 11.

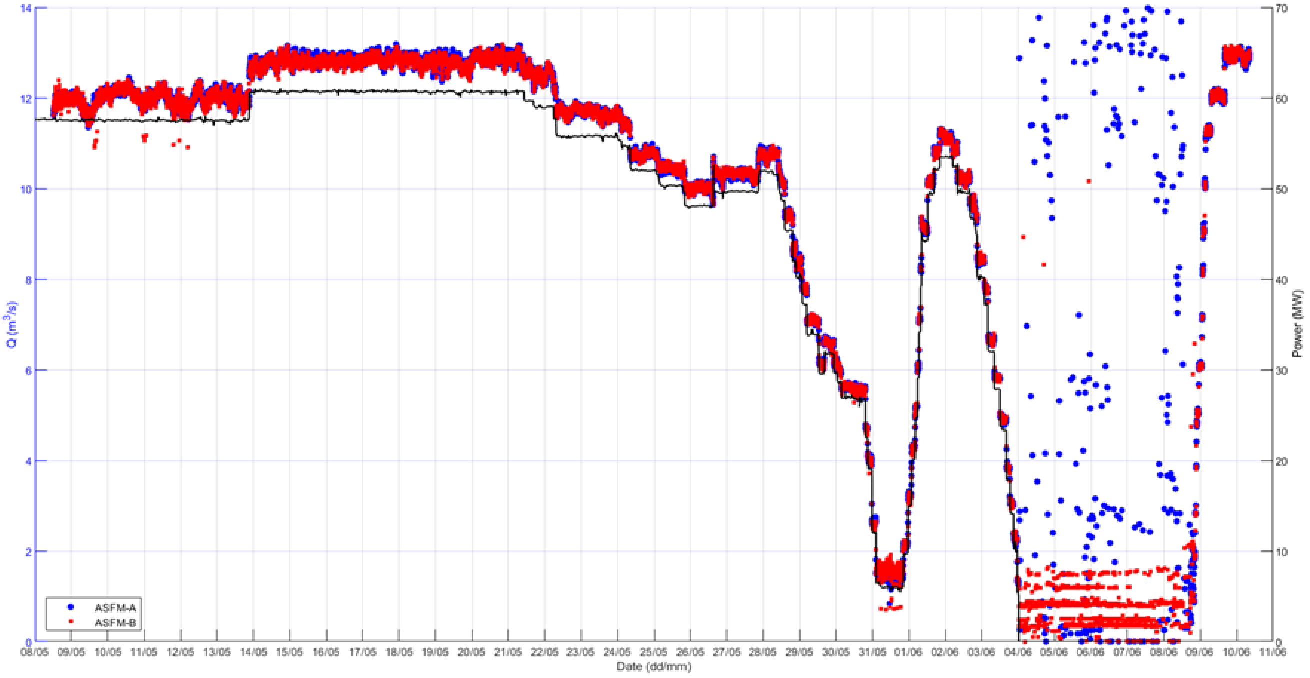

Figure 10: Discharge measured by the two ASFMs: ASFM-A (blue) and ASFM-B (red). The unit power (MW) is shown in black. Errors in the zero-flow detection are shown.

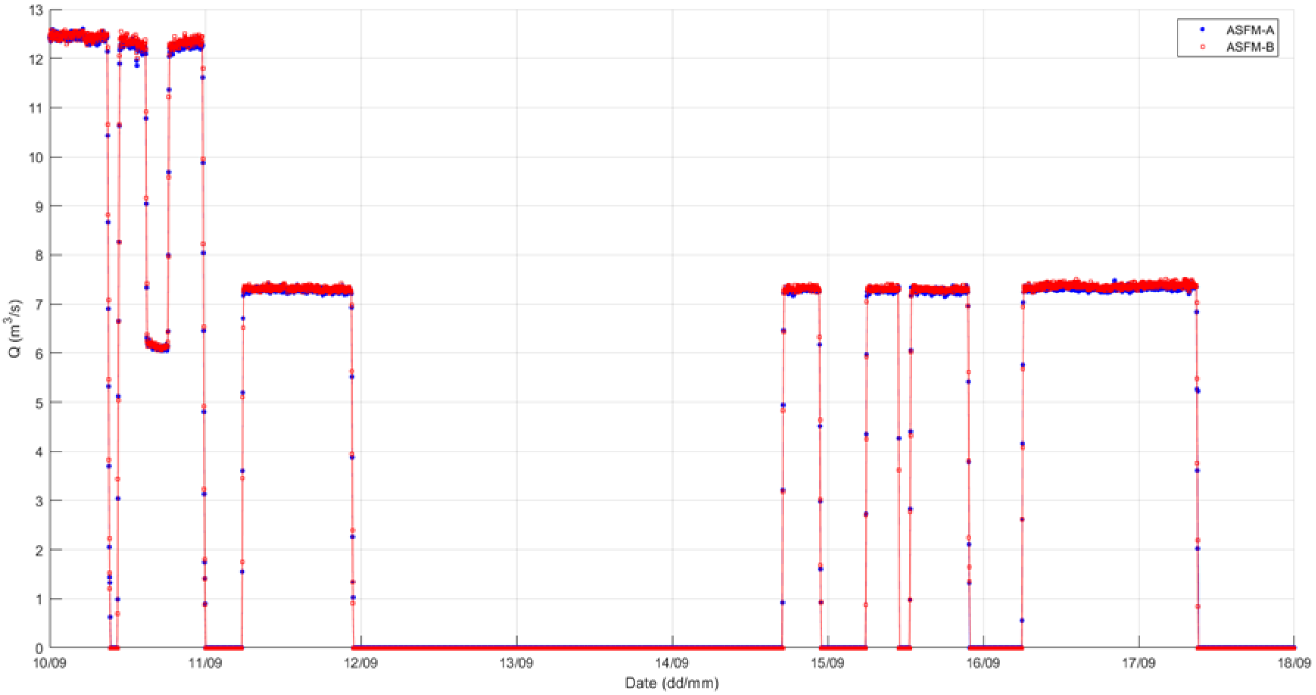

Figure 11: Discharge measured by the two ASFMs: ASFM-A (blue) and ASFM-B (red), showing improvements to the zero-flow detection.

7.3 Final settings

After an 18-month data monitoring period, all technical issues were addressed and the ASFM systems were adjusted for the best possible output. The alarm and gate trip set-points has been programmed in the PLC system as 14.3 m^3/s and 15 m^3/s, respectively. These are 5% and 10% above the maximum turbine discharge of 13.6 m^3/s. Three consecutive readings of discharge above the set-points were considered to execute an alarm or trip command. This will take approximately 3x80=240 second lag time after an actual event of penstock rupture. This lag time has been considered acceptable considering the INOG and PIV closure time of ~15 min and ~200 sec, respectively. In order to avoid spurious detection of over-velocity, the PLC system has been programmed to take additional ASFM output (e.g., data quality parameter, instrument status and "Zero Flow" comments) into consideration. A soft unit shutdown has been considered along with OVDS tripping. Moreover, the OVDS will stop the unit in case of loss of communication for a long period.

8. Lessons learned

Here is a list of lessons learned during the project:

- The project was initially believed to be intensive on Hydrotechnical aspects, but Telecom, and Protection & Control complexities appeared to be far more important than initially anticipated.
- The ASFM was rather simple to install to measure flow. However, an innovative design for submersible canister and gravity-driven cable management system were integral to the project's success.
- The ASFM systems are found easy to operate and maintain from the intake floor. It provided great convenience for the station operation crews at the site.
- The ASFM measured flows were very accurate, especially for higher flows.
- Distance and configuration of the trashracks have found to affect ASFM signal amplitudes as it depends on the turbulence in water. This caused relatively poor accuracy for low flows. However, this inaccuracy at low flows does not affect the ASFM capability at WAH to detect over-velocity under rupture conditions because the detector is intended to work only at high flows.
- Electronic signal interference can be caused by other devices (e.g., grounding, battery controller) and results in noise in ASFM data.
- Overall, the ASFM based OVDS has performed well since October 2019. No repair or replacement was required to date.
- The conventional serial communication output does not satisfy Protection & Control standards. ModBUS communication has been adopted for future designs.
- The detection of zero-flow is being accomplished using the scintillation index.
- Direct Current (dc) voltage convertors can cause electrical noise which can interfere with the ASFM signals.

References

[1] Clifford, S. F. and D. M. Farmer, Ocean flow measurements using acoustic scintillation. J. Acoust. Soc. Amer., 74 (6), 1826-1832, 1983.

[2] Farmer, D. M. and S. F. Clifford, Space-time acoustic scintillation analysis: a new technique for probing ocean flows. IEEE J. Ocean Eng. OE-11 (1), 42-50, 1986.