

Turbine flow measurement in intakes: a cost-effective alternative to measurement in penstocks

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Hydro utilities require flow measurement for the settlement of turbine contracts and to support optimal operation. The high costs and inconvenience associated with traditional methods (instruments installed in penstocks) are leading some utilities to search for cost-effective alternatives. BC Hydro's investigations into flow measurement in intakes are discussed.

Typical practice for turbine flow measurement has been to install instruments in the penstock, such as current meters (CM), acoustic time-of-flight transducers (ATF) or pressure-time taps (PT). At some plants, particularly those with buried penstocks, these methods have significant disadvantages, resulting in high costs. These costs can be high enough to limit the measurement to only a selected 'representative' unit, or sometimes to dispense with the measurement altogether.

Because of their portability, intake methodologies using current meters or acoustic scintillation (AS) can be attractive alternatives to measurement in penstocks.

BC Hydro's G.M. Shrum (GMS) powerplant in northern British Columbia, Canada, represents a case in point. Five units are to be upgraded, with identical runners, within a single contract. For cost reasons, traditional practice would be to test only one of the five units with an ATF installed in the penstock. However, minor differences in individual unit performance, which could yield large benefits in optimal dispatch, would thus go undetected [Proulx and Coutier, 2011¹; Lamy and Néron, 2003²]. BC Hydro has therefore been investigating alternative flow measurement technologies, which would allow each one of the new units to be tested cost-effectively [Lampa, Lemon, Lamy and Taylor, 2007³].

It has been argued that there are no code-approved methods for measurement in converging intakes, and many people believe that accurate measurement cannot be carried out in such intakes. However, at the October 2009 comparative testing of the ATF, CM and AS technologies installed in the intake of the Kootenay Canal plant (KCL), organized by the ASME PTC-18 Committee, the ATF results were within +0.2 per cent, AS within +0.5 per cent and the CM within +0.8-1.2 per cent of the reference measurement (ATF installed in a penstock in a code-approved location) [Munro and Walsh, 2010⁴; Almquist, Taylor and Walsh, 2011⁵; Taylor, Almquist and Walsh, 2010⁶]. All three methods also showed very good repeatability. This corresponded with the results of many previous, albeit less rigorous, comparative measurements and confirmed that, provided the intakes do not have adverse characteristics, intake measurements can be accurate and repeatable. Further investigation and comparative testing are warranted, but based on the KCL testing, both IEC 60041 and ASME PTC-18 Committees are evaluating the inclusion of the intake methods in the forthcoming updates of their publications.

In this article, the costs are compared for undertaking tests using three methods: penstock-installed ATF and two intake methods, CM and AS.

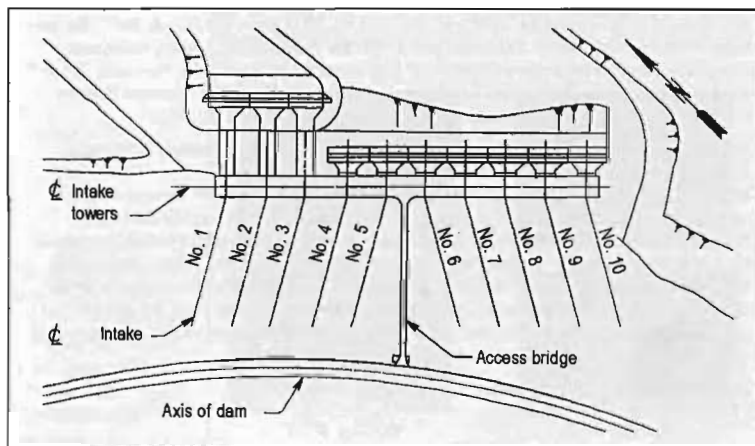
The G.M. Shrum generating station

The W.A.C. Bennett dam impounds the Peace river in northeastern British Columbia, Canada (see Fig. 1), forming the Williston reservoir. The underground GMS powerplant (see Fig. 2) houses 10 generating units of various capacities, giving a total maximum installed capacity of 2730 MW. The largest of BC Hydro's generating stations, GMS, is one of the most

Fig. 1. Location of the G.M. Shrum generating station in Canada.



Fig. 2. Layout of the GM Shrum intakes.



important components of BC Hydro's electrical system, as it supplies more than 12 per cent of all the electricity produced in British Columbia. Now more than four decades old, the station requires significant investments to renew ageing equipment

Upgrade of GMS Units 1 to 5

The turbines in Units 1 to 5, installed in the 1960s must be replaced, to ensure ongoing reliability, availability and operational flexibility. A further benefit of the upgrade project will be an improvement in turbine efficiency and capacity: an additional 177 GWh/year of energy will be generated with the same water usage.

The current maximum unit capacity of these turbines is 261 MW. The new turbines will initially be limited to the current capacity, because of other equipment constraints and existing water licence limitations. However, ultimately the generating units will be able to operate with a capacity of 310 MW. The new turbines will be delivered, installed and tested at regular intervals between October 2012 and February 2015.

Why consider measurements in intakes?

For cost reasons, measurement with a penstock-installed ATF at GMS could be economically justified at only one of the five units to be upgraded with new runners, just as in the past during the initial installation and subsequent upgrading of units 6 to 8. The differences in individual unit performance required for optimal dispatch would thus go undetected.

Fig. 3 shows penstock cross-section for Units 4 and 5 at GMS. Note the location of the ATF in the coupling chamber in the powerhouse. Figs. 4 and 5 show more detail of the two types of intake at GMS. They have different entrance elevations and upstream conduit lengths. The intakes for units 1 to 3 are 33.53 m lower than for units 4 and 5. Similarly, the upstream length is 51.8 m for units 1 to 3, compared with 23.6 m for units 4 and 5. The gate section dimensions are 3.96 m (w) by 5.94 m (h) for all units. The measurements for the AS and CM methodologies would be located in the maintenance gate slot as shown.

ATF in penstocks

The Acoustic Time of Flight method is considered to be acceptable in the two test codes (ASME and IEC) and is widely used at hydro powerplants for testing. With this method, pairs of ultrasonic transducers are located diagonally on opposite boundaries of a water passage. Each transducer can both transmit and receive an acoustic pulse. The pulse travels faster when it is travelling in the same direction as the flow, and slower when it is travelling against the flow. The average velocity along the path is a function of the difference in travel time for the two directions. In practice, two symmetrically installed transducer pairs are installed in a cross-path orientation. This arrangement cancels out errors caused by non-axial flows present downstream of intakes, bends or other geometric transitions. Transducer pairs are installed at multiple elevations in the conduit, and the flow rate is obtained by integrating the laterally averaged velocities over the area of the conduit. Historically, four pairs of paths have been used. However, the value of adding more paths to sample more of the cross-section is being recognized. The latest ASME test code suggests four or nine pairs, depending on the hydraulic conditions.

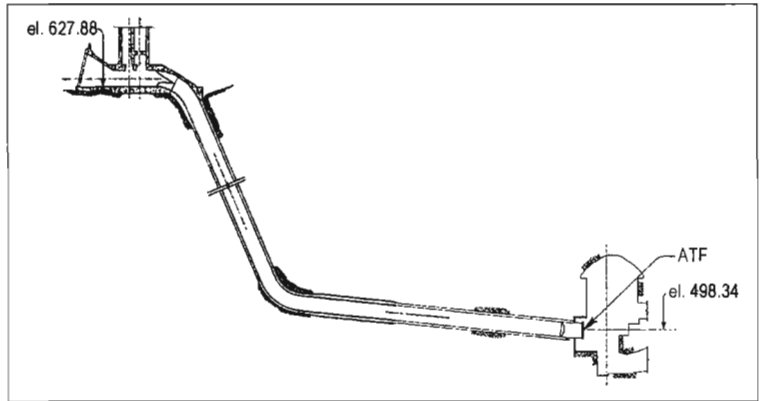


Fig. 3. Cross section of the penstock for Units 3 and 4.

If there is access to the outside of the penstock, the transducers are typically mounted in holes drilled through the penstock wall. Scaffolding is required for surveying the hole locations, drilling the holes, and measuring as-built locations after installation. When there is no access to the outside of the penstock, it is possible to mount the transducers on the inside wall without drilling. Cables from the transducers must then be run to the flowmeter outside the penstock through a penetrator. To protect the cables from the effects of penstock flow, they must be covered by half-rounds of pipe attached to the inside wall.

For a four-path ATF installation, the BC Hydro cost to purchase and install ATF transducers, to perform as-built survey and to run cables to the processor is estimated at \$146 000 (see the Table). Two days are assumed to be required for the testing. To test the addi-

Comparison of the costs for all options				
Method		First unit	Additional unit individually	Additional unit consecutively
ATF	Total	\$146 000	\$122 000	\$122 000
CM	Flow	\$93 000	\$56 000	\$27 000
	Trolley	\$27 000		
	Total	\$112 000	\$56 000	\$27 000
AS	Flow	\$68 000	\$52 000	\$26 000
	Frame	\$35 000		
	Total	\$103 000	\$52 000	\$26 000

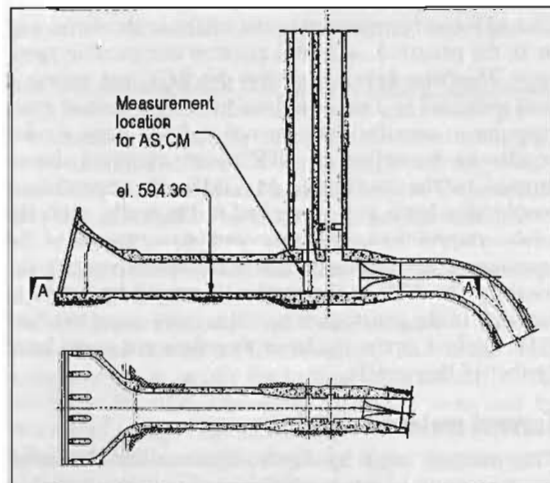
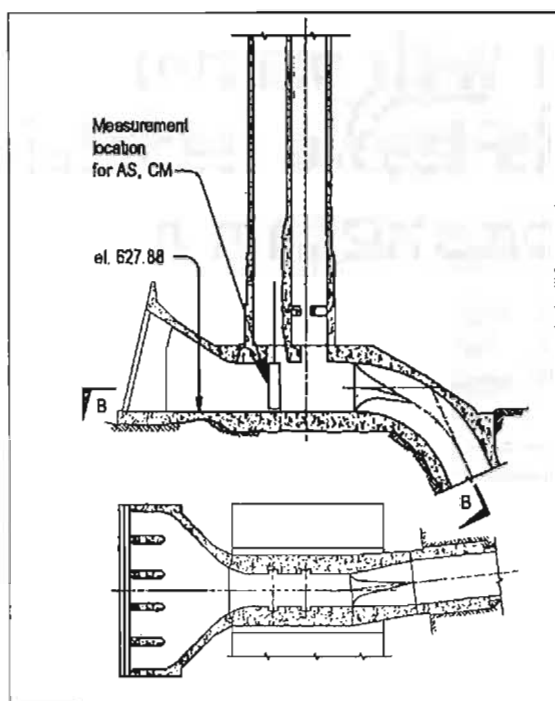


Fig. 4. Intake cross section and plan for Units 1 to 3.

Fig. 5. Intake cross-section and plan for Units 4 and 5.



tional four units it was assumed that no new flowmeter transducers would be purchased. Instead, the transducers used for the first unit would be removed and installed on the next unit. The holes on the first unit would then be filled with steel plugs. By moving the transducers from unit to unit, there is a saving of about \$24 000 per unit. It should be noted that these costs correspond to just four pairs of acoustic paths. If nine pairs of paths were to be used to sample more of the cross-section, the cost of the ATF method would increase by \$52 000 for extra transducers plus \$8000 for labour.

The costs of ancillary measurements for undertaking the efficiency tests were estimated separately, so that the total test cost could be obtained. These ancillary costs include the measurements for MW, inlet head, outlet head, stroke, water temperature, and Winter Kennedy differential. As with the measurement of flow, there is a reduction in the test costs when multiple units are tested. For clarity, the ancillary costs are not shown in the Table, as they are the same for all methods.

ATF in intakes

The ATF can be mounted in the intake in the same way as in the penstock, and will achieve comparable accuracy. This was demonstrated at the KCL test, where it was mounted in a non-uniform transition section (rectangular-to-circular) and proved to have very similar results to the reference ATF meter mounted downstream in the penstock. At GMS, the transducers would also have to be attached to the walls, with the cables routed through the air vent downstream of the operating gate. Because there is no cost advantage for locating the ATF at the intake, it would be better to install it in the penstock where it is code-accepted. The ATF method at the intake is therefore not considered further in this article.

Current meters in intakes

The method used by Hydro-Québec for discharge measurements in intake stoplog slots is to use a trolley,

on which a number of current meters are mounted [Proulx and Coutier, 2011¹; Proulx, 2010⁷].

A typical trolley is made of two horizontal profiled rods, attached to two end plates, and includes steel cables to increase the stiffness. The profiled rods have a low drag coefficient of less than 0.1, and the same profile as the one used for the calibration of the current meters. The current meters are set horizontally on the lower rod. Steel wheels help to guide the trolley in the gate slot laterally and longitudinally.

The measurements can be done while the trolley is continuously moving, or it can be set at a number of fixed elevations and the data recorded for a specific amount of time. Both methods have shown similar results [Proulx, 2010⁷].

The flow velocities in the GMS intake are rather high, with an estimated 9 m/s average velocity at the maximum discharge. Fortunately, the measurement section is located in a straight section of the intake and the straight section is preceded by a smooth convergent part, therefore the flow should be almost parallel with the axis. Measurements made in similar conditions at other plants produced smooth velocity profiles [Proulx and Coutier, 2011¹]. It is proposed to move the current meter trolley by attaching it to the lifting beam of the gantry crane (similar to the one shown in the photograph below). This would have the advantage of reducing the equipment transportation cost to GMS and making the setup of the instruments easier, especially when moving the instruments from one unit to the other. In addition, the weight of the lifting beam would counteract possible problems which could arise from uplift on the current meter trolley.

The current meter trolley for flow measurement at GMS will require a careful structural analysis, because the velocity is outside of the normal field of application that Hydro-Québec uses for intake measurement. Nevertheless, the fabrication of the trolley should be relatively simple. The total cost of the CM trolley is estimated at \$27 000. The calibration costs for the 14 current meters would be billed at the ratio of the estimated numbers of hours of usage to the maximum usage before a recalibration is required (300 hours).

For the flow measurement services required for the testing of the first turbine, rental of 14 current meters and two displacement transducers, together with one



Current meter trolley attached to a gantry crane.

Hydro-Québec engineer and one technician in the field for six days, would cost \$93 000. One day is allowed for travel and the equipment delivery to the site, three days for safety training and equipment assembly, two days for the measurement, one day for instrumentation demobilization and one day for return travel and equipment shipment. A comprehensive flow measurement data analysis and report would be included in the above price.

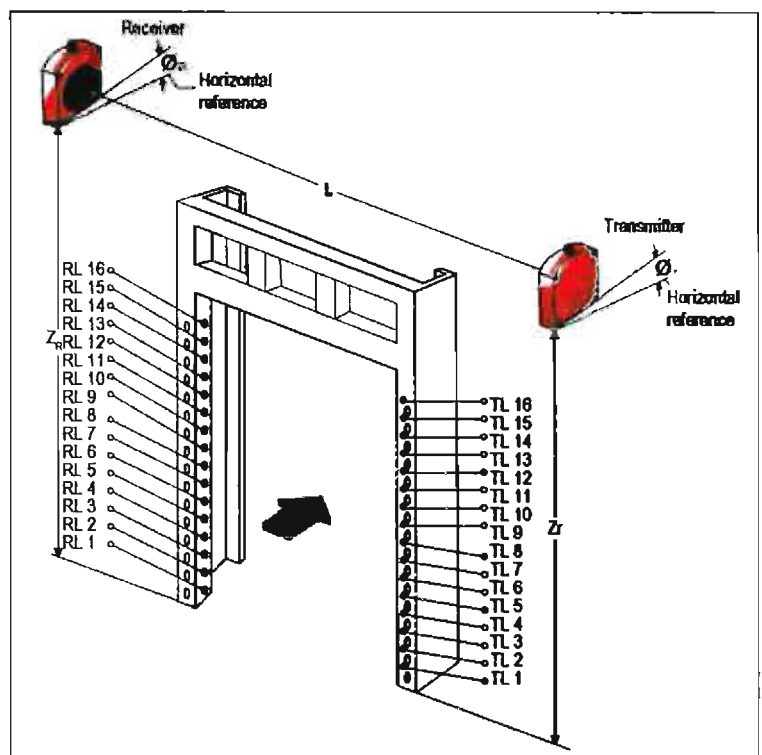
The flow measurement services required for individual testing of the second and all subsequent units would require only four days in the field and would result in a reduced flow measurement cost of \$56 000/unit (including the cost of equipment rental and data analysis and report preparation, similar to the first unit). If all four remaining units were tested consecutively, multiple mobilization and demobilization and reporting costs would be avoided, reducing the flow measurement cost further, to just \$27 000 for each of the four units.

Acoustic scintillation in intakes

The AS method uses the natural turbulence embedded in the flow to measure velocity [Lemon, Topham and Billenness, 2020⁸; Lemon, 2006⁹; Lemon and Lampa, 2004¹⁰]. With the acoustic sensors positioned directly opposite each other in an intake, the technology is suitable for short, converging intakes without straight sections of constant cross-section upstream. Whenever stoplog slots are available, AS instrumentation is installed on portable frames on the intake deck and fully instrumented frames are then inserted into the slots. As the AS instruments are flush with the walls of the intake, there is no interference with the flow or exposure to debris impact, making it suitable for long-term monitoring in real time. The required number of measurement paths is achieved by placing sensors at desired elevations on a stationary frame, as shown in Fig. 6. Alternatively, a smaller number of sensors can be mounted on a moving frame which then traverses the cross-section. The fixed frame approach is more expensive, but is faster than the moving frame option. In either case, the discharge is computed in real time by integrating the horizontal component of the laterally averaged velocity over the cross-sectional area of the intake.

Prior to measurement, BC Hydro would be procuring the AS mounting frame. AQFlow would assist with its design, particularly in terms of the elevations of the measurement paths and locations and mounting of the canisters and cables. Based on the fabrication cost of the KCL frame, the GMS frame cost is estimated at \$35 000.

For the flow measurement services required for the testing of the first turbine, AS instrumentation, consisting of 14 pairs of acoustic sensors, connecting cables, canisters, surface unit and an operating laptop, rented for a period of seven days, together with two AQFlow technicians in the field for five days, would cost \$68 000. One day is allowed for travel and the equipment delivery to the site, one day for safety training and installing the instrumentation on the frame, one day for installing the frame in the intake and conducting diagnostic tests, two days for the measurement, one day for instrumentation dismantling and one day for equipment return. With two days dedicated to flow measurement, sufficient repeats



could be made to have a high degree of confidence in the results. A comprehensive flow measurement data analysis and report would be included in the above price.

Fig. 6. An AS stationary frame.

The flow measurement services required for individual testing of the second and all subsequent units would require only four days in the field and result in a reduced flow measurement cost of \$52 000/unit (including the cost of equipment rental and data analysis and report preparation, similar to the first unit). If all four remaining units were tested consecutively, multiple mobilization and demobilization and reporting costs would be avoided, further reducing the flow measurement cost to just \$26 000 for each of the four units.

Comparison of alternatives

A comparison of the costs for the three methods is given in Table 1. For this comparison, the unit costs were assumed to be the same for all methods, so that the methods could be compared on an equal basis, regardless of which contractor would undertake the work.

It was assumed that BC Hydro, Hydro Québec and AQFlow would estimate their costs as if starting from Vancouver. The hourly rates for all three companies were assumed to be \$200 for an engineer/technologist and \$130 for electricians and mechanics. The working day was assumed to be 11 hours. If implemented, these costs would be likely to change based on the contractor chosen, but this will not alter the relative positions of the individual methods.

Costs were estimated for three scenarios. The first was for the testing of Unit 4 alone. This is the minimum testing to satisfy the turbine contract and is stipulated to be ATF. The second scenario is to cost the testing of each of the remaining turbines individually after installation, approximately eight months apart. For this, much of the equipment would remain on site,

but travel costs and extra setups would be required for each test. The third scenario is to cost the testing assuming all four remaining units would be tested consecutively, without the crews leaving the site.

As can be seen in Table 1, turbine flow measurement with frame-mounted CM or AS in intakes is an attractive alternative to measurement in penstocks. This is illustrated in the Table by the reduction in unit test costs for the four remaining units after the first one. The two intake methods have considerably reduced unit costs compared with the ATF because fully instrumented frames can be moved to the next unit at little extra cost. In contrast, for the ATF there is very little reduction in cost for the additional tests, because each penstock requires a full setup, including survey, drilling and installation.

Discussion

The figures in Table 1 show that the costs for testing more than one unit at a single plant can be greatly reduced by using frame-mounted intake methods. This may still leave the question of whether there are sufficient benefits from this to justify it, even at the reduced test cost. The following data from Hydro-Québec and BC Hydro can provide some insight into this.

The Province of Québec has an enormous potential for new hydro development, yet it has found that upgrading/refitting, together with optimization of operation of its existing plants, is cost-effective and produces a fast return on investment. For example, by operating all units at one of its 240 MW plants at best efficiency, and by operating the most efficient unit first, a gain in efficiency of 0.6 per cent could be achieved [Lamy and Néron, 2003²]. Considering the price of energy, this represented an important extra annual income per year for the same amount of water, and the cost of flow/efficiency measurement was thus repaid in approximately one year.

In the case of BC Hydro, the significantly increased capacity and the 177 GWh/year of additional energy the utility expects from the replacements of units 1 to 5 at GMS represent a great investment in green energy. The purpose of the measurements on all five units described in this paper is to confirm that the goal has been achieved. By adopting intake flow measurement methods rather than penstock methods, measuring the performance of all five units becomes more economic.

Furthermore, if the Hydro-Québec approach is adopted and the remaining units 6 to 10 are also tested, an outcome similar to that found by Hydro-Québec could be expected. Considering that GMS will have a mixture of new and old runners, it can be assumed that a gain of just 0.2 to 0.3 per cent would be achieved, representing 14 to 20 GWh/year of additional energy. At \$35 000/GWh, it would be worth \$490 000 to \$730 000 every year, and with the cost of intake measurements for all 10 units potentially (if done consecutively) as low as \$700 000 (this includes ancillary services), the payback period would be about one year.

The testing of all 10 units using intake methods is particularly appropriate for the purpose of optimal dispatch. The velocity profiles in the gate sections will be similar, so that the systematic uncertainties for all measurements will be similar (same magnitude and direction). Hydro-Québec has tested multiple units using more than one independent measurement

method and the results support the notion that the systematic uncertainty is low enough for the purpose [Proulx and Coutier, 2011¹; Lamy and Néron, 2003²].

For the upgrades at GMS, there will be no cost for taking a unit out of service, because it will already be shut down for the installation of the runner. However, for other plants where there is no extended outage before a test, and spill is required, the downtime to install an ATF system could have a significant cost in lost generation. In contrast, there is almost no downtime for the frame-mounted intake methods, as no dewatering is required and installation is much faster. As an example to appreciate the magnitude of these losses, the cost of lost generation for a 240 MW unit at an energy price of \$35/MWh would be \$200 000/day.

Measurements in stoplog slots have their own unique requirements. The stoplog slots must be available and free of debris, so that measurements can be taken as close to the sill as possible. The stoplog guides must be the same from unit to unit (within tolerances). Also the methodology can be more exposed to adverse weather conditions.

Several decades ago, when only the CM method was available, the late Professor Mosonyi pleaded for the provision of stoplog slots [Mosonyi, 1987¹¹] as follows: "Measuring facilities should be provided for at the design stage. It is advisable to choose the control section in the entrance flume, behind the trashrack and vertically to the direction of the flow. . . . The fixing grooves of the instrument frame should be provided for in the design and constructed simultaneously." It is disappointing to see how many new hydro plants have been designed and built since Prof. Mosonyi's book was published without the provision of stoplog slots.

Conclusions

The frame-mounted current meter and acoustic scintillation intake methods of flow measurement described in this paper are attractive alternatives to measurement in the penstocks, especially when more than one turbine is being tested.

The designers of powerplants which do not have stoplog slots, should provide extra slots upstream of the operating gate, so that the slots are available for flow measurement with frame-mounted intake methods in the future. 0

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