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

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Introduction

Flow measurement is routinely undertaken by hydro utilities for settlement of turbine contracts and to support optimal operation. Typical practice has been to install instruments in the penstock for this, such as current meters (CM), acoustic time-of-flight transducers (ATF) or pressure-time taps (PT). At some plants, these methods have significant disadvantages. Installation and removal can be onerous, especially for CM systems. Difficult access can also be an issue, sometimes forcing the instruments to be in locations with poor hydraulics. Furthermore, outage durations can be problematic. For these reasons, intake methodology can be an attractive alternative to measurement in penstocks. BC Hydro's G.M.Shrum (GMS) powerplant in Northern British Columbia, Canada, represents a case in point. Five units will 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 a penstock-installed ATF. However, minor differences in individual unit performance, which could yield large benefits in optimal dispatch, will thus go undetected. BC Hydro has therefore been investigating alternative flow measurement technologies which would allow every one of the new units to be tested cost-effectively. This initiative is based on recent developments in technologies measuring the flows in the intakes of hydroelectric plants, particularly the October 2009 comparative testing of the ATF, CM and acoustic scintillation (AS) technologies installed in the intake of its Kootenay Canal plant (KCL).

It has been argued that there are no code-approved methods for measurement in converging intakes, and many people believe that accurate measurement in such intakes cannot be performed. However, at KCL the three intake technologies were within 1% of the reference measurement (penstock-installed ATF). This agreed with the results of many previous, albeit less rigorous, comparative measurements and confirmed that, provided the intake does not have adverse characteristics, intake measurements can be accurate and repeatable. Both IEC 60041 and ASME PTC-18 code committees are now evaluating how to respond to these discoveries in the forthcoming updates of their publications.

In this paper, the costs are compared for undertaking tests using three methods: penstock-installed ATF and two intake methods, CM and AS. The comparative costs for using the PT method were not included in this analysis because most of the penstock lengths at GMS are inaccessible and PT taps were therefore not included in the original design.

1. G.M. Shrum Generating Station – description and history

The W.A.C. Bennett Dam impounds the Peace River in north-eastern British Columbia (Fig. 1), forming the Williston Reservoir. The underground GMS powerplant (Fig. 2) houses 10 generating units of various capacities giving a combined maximum output of 2,730 MW. The biggest of BC Hydro's generating stations, GMS is one of the most important components of BC Hydro's electrical system. This station alone supplies more than 12 per cent of all of the electricity produced in B.C. each year. Now more than four decades old, the station requires significant investments to renew ageing equipment.

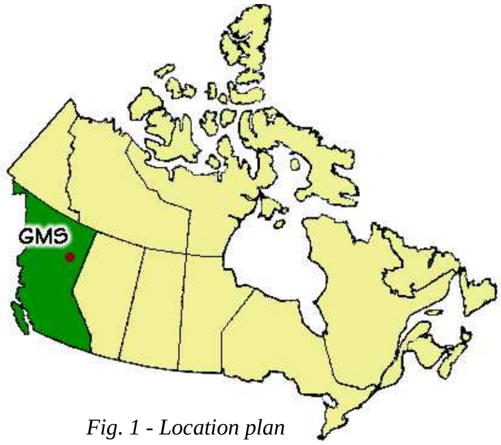

Fig. 1 - Location plan

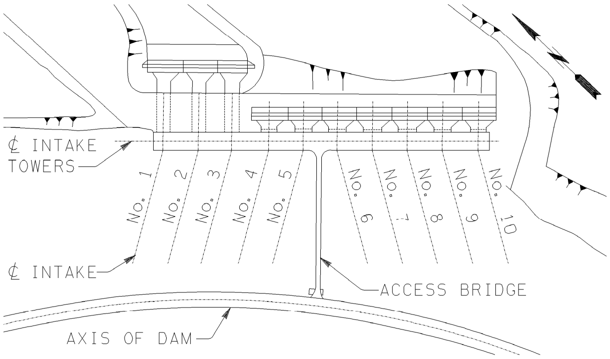

Fig. 2 – Layout of GMS intakes

2. Upgrade of Units 1 – 5

2.1. Background

The 1960s era turbines in Units 1 to 5 must be replaced to ensure ongoing reliability, availability and operational flexibility of these units. Another benefit of the project will be an improvement in turbine efficiency and capacity. Modern turbine design will provide an additional 177 GWh of energy annually with the same water usage.

The current maximum capacity of these turbines is 261 MW each. The new turbines will be initially limited to the current capacity, because of other equipment constraints and existing water license limitations. However, it will ultimately allow the generating units to operate at a capacity of 310 MW. The new turbines will be delivered, installed and tested as shown in Table 1.

Date	**Item**	**Remarks** ***Alternatives under consideration (in italics)***
October 2012	G4 installation complete	Do contractual test on G4 (ATF in penstock) *Simultaneously do comparison test on G4 (ATF in penstock vs. intake methods)*
May 2013	G1 installation complete	*Do efficiency test on G1 (intake method)*
December 2013	G2 installation complete	*Do efficiency test on G2 (intake method)*
July 2014	G5 installation complete	*Do efficiency test on G5 (intake method)*
February 2015	G3 installation complete	*Do efficiency test on G3 (intake method)*

Table 1 – Installation and testing sequence

2.2. Why consider measurements in intakes?

Absolute flow measurement is required for settlement of turbine contracts and to support optimal operation. Several techniques are approved by the existing IEC 60041and ASME PTC-18 codes for this, such as CM, PT and ATF methods. These all require closed conduits with adequate straight lengths upstream. Typical practice has therefore been to install instruments in the penstock for this. However, at plants with buried penstocks, these methods have significant disadvantages. Installation and removal can be onerous. Difficult access can also be an issue, sometimes forcing the instruments to be in locations with poor hydraulics. Furthermore, outage durations can be problematic and tests on multiple units of the same type can be costly - costly enough to limit the measurement to only a selected 'representative' unit, or sometimes to dispense with the measurement altogether.

At GMS, five units are being upgraded with identical runners. For cost reasons, measurement with a penstock-installed ATF could be economically justified at only one of the five units, just like it was in the past during the initial installation and subsequent upgrading of units 6-8 in the plant. Minor differences in individual unit performance, which can yield large benefits in optimal dispatch (Ref. 1,2), would thus go undetected. BC Hydro is therefore investigating alternative flow measurement technologies which would allow every one of the new units to be measured/monitored cost-effectively.

BC Hydro is basing this initiative on recent developments in technologies measuring the flows in the intakes of hydroelectric plants (Ref. 3) and recent activities of IEC and ASME code committees. The October 2009 comparative testing of the ATF, CM and AS technologies installed in the intake of KCL (Ref. 4,5,6) has been particularly valuable, as it was organized and run by the ASME committee. KCL is a medium head plant with single bay intakes and adequately long straight penstocks. The tested unit has an ATF system installed in a code-approved location that provided reference flows for rigorous comparisons with each of the three intake methods.

The measurement results at KCL were encouraging. All three intake technologies were within 1% of the reference measurement (+0.09% for the ATF, +0.44% for AS and +1.06% for CM). All three also showed very good repeatability. These results agreed with the results of many previous comparative measurements and confirmed that, provided the intake does 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 and ASME code committees are now evaluating how to respond to these developments in the forthcoming updates of their publications.

Figure 3 shows penstock cross-section for G4-G5 at GMS. Note the location of the ATF in the coupling chamber in the powerhouse.

Figures 4 and 5 show more detail of the two intake types at GMS. They have different entrance elevations and upstream conduit lengths. The intakes for G1-G3 are 33.53m lower than for G4-G5. Similarly, the upstream length is 51.8 m for G1-G3 compared to 23.6 m for G4-G5. 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.

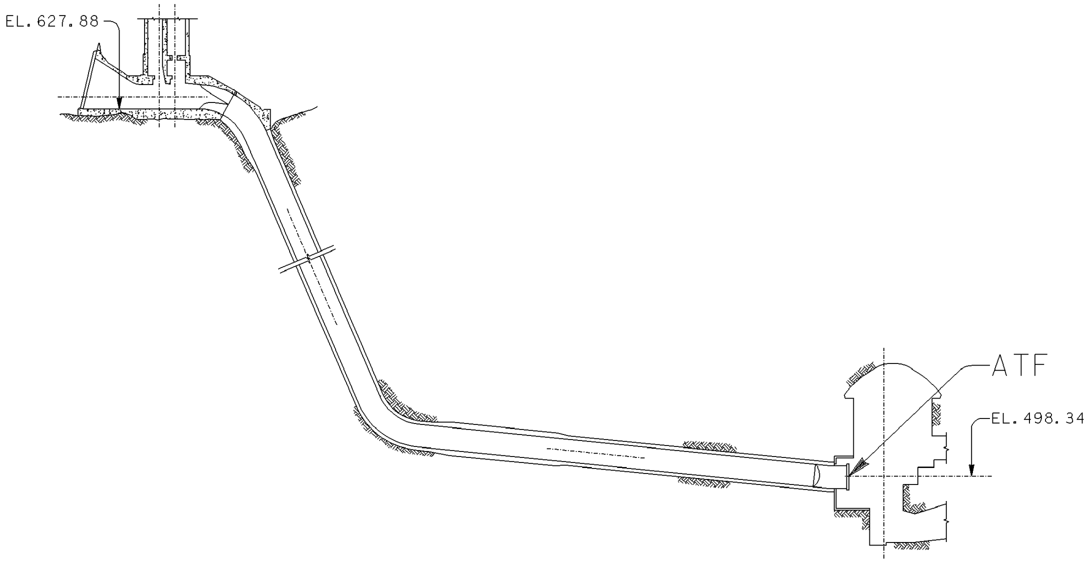

Figure 3 – Penstock cross-section for G4-G5

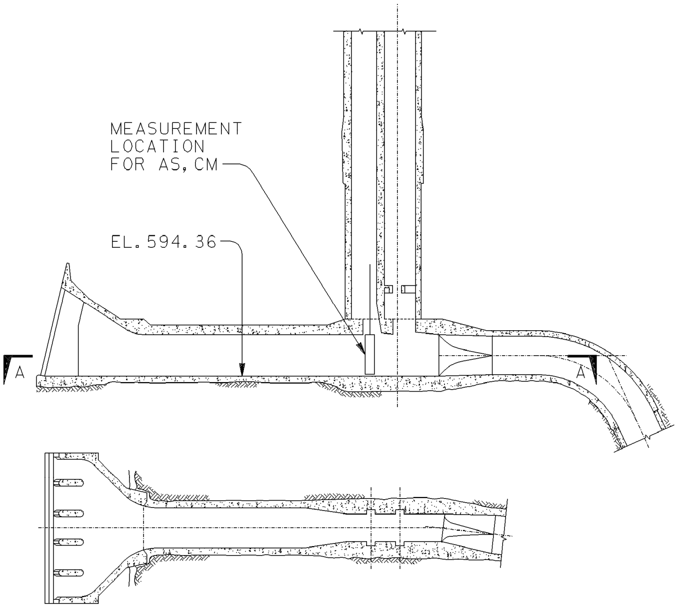

Fig. 4 – Intake cross-section and plan for G1-G3

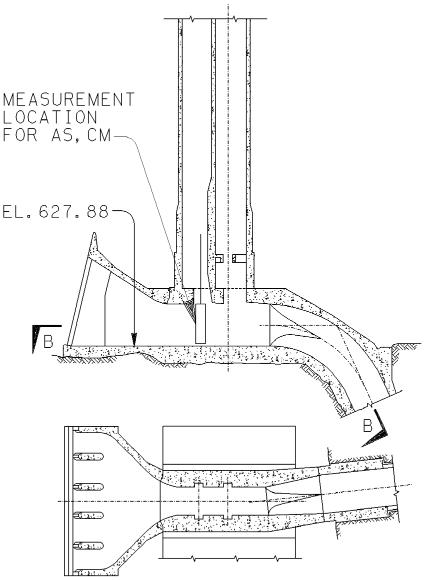

Fig. 5 – Intake cross-section and plan for G4-G5

2.3. Acoustic Time of Flight in penstocks

Description

The ATF method is considered to be acceptable in the two test codes (ASME and IEC) and is widely used in hydro powerplants for testing. With this method, pairs of ultrasonic transducers are located diagonally on opposite boundaries of a water passage, as shown schematically in Figure 6. 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 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, as also shown in Figure 6. 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 are 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.

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 located 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.

Costs

For ATF installation (4 paths), the BC Hydro cost to purchase and install ATF transducers, to perform as-built survey and to run cables to the processor is estimated to be $146,000. The cost of ancillary measurements for undertaking the efficiency test on G4 is $99,000, bringing the total test cost for this method to $245,000. Two days are assumed to be required for the testing. For testing the additional four units it was assumed that no new flowmeter transducers would be purchased. Instead, the transducers used for G4 would be removed and installed on the next unit. The holes on G4 would be filled with steel plugs. By moving the transducers from unit to unit there is a saving of about $40,000 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 $8,000 for labour.

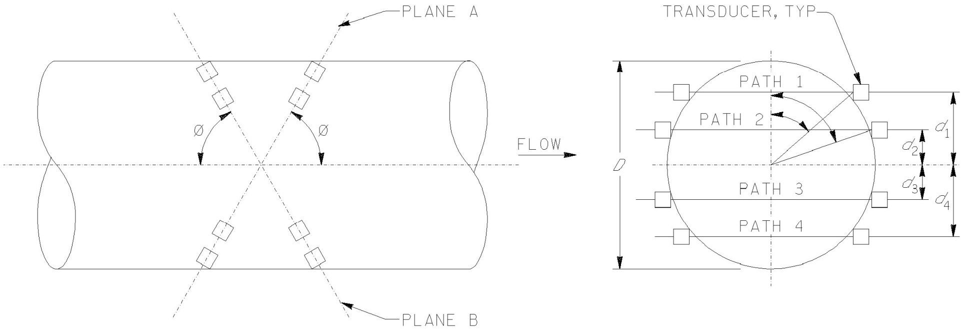

Fig. 6 – ATF principle of operation

The costs of ancillary measurements for undertaking the efficiency tests were estimated separately, so that the total test cost could be estimated for the three methods. 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. All costs are given in Table 2.

2.4. Acoustic Time of Flight in intakes – description and costs

The ATF can be mounted in the intake in the same manner as in the penstock and achieve comparable accuracy. This was demonstrated at 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. If there were no slots available at GMS for frame-mounted CM and AS equipment and wall mounting were to be necessary, the costs for all three methods might be somewhat comparable. 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 will not be considered further in this paper.

2.5. Current Meters in intakes

Description

The method used by Hydro-Québec for performing the discharge measurement in intake service gate slot is to use a trolley on which a number of current meters are mounted (Ref. 1,7).

A typical trolley is made of two horizontal profiled rods, attached to two end plates, and includes steel cables for increasing the stiffness. The profiled rods have a low drag coefficient of less than 0.1 and have 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 guiding 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 (Ref. 7).

The flow velocities in the GMS intake are rather different from a typical low head power plant intake, with an estimated 9 m/s average velocity at the maximum discharge. However, the measurement section is located in a straight section of the intake and the straight section is preceded by a smooth convergent part, and therefore the flow should be close to parallel with the axis. Measurements made under similar conditions at other plants produced a smooth velocity profile (Ref. 1). Given these characteristics, 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 Figure 7). This would have the advantage of reducing the equipment transportation cost to GMS (Hydro-Québec normally uses chain hoists and variable speed power drive to move the trolley) 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 that may arise from uplift on the current meter trolley.

Fig. 7 – Current meter trolley attached to a gantry lifting beam

Costs

The current meter trolley for flow measurement at GMS would 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 fourteen 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 HQ engineer and one technician in the field for 6 days, would cost $120,000. 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 4 days in the field and 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 $108,000 for all 4 units.

2.6. Acoustic Scintillation in intakes

Description

AS method utilizes the natural turbulence embedded in the flow (Ref. 8,9,10). 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 or service gate slots are available, AS instrumentation is installed on portable frames in the yard 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 each desired elevation on a stationary frame, as shown in Fig. 8. Alternately a smaller number of sensors can be mounted on a moving the frame which then traverses the cross-section. The fixed frame approach is more expensive but faster than the moving-frame alternative. 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.

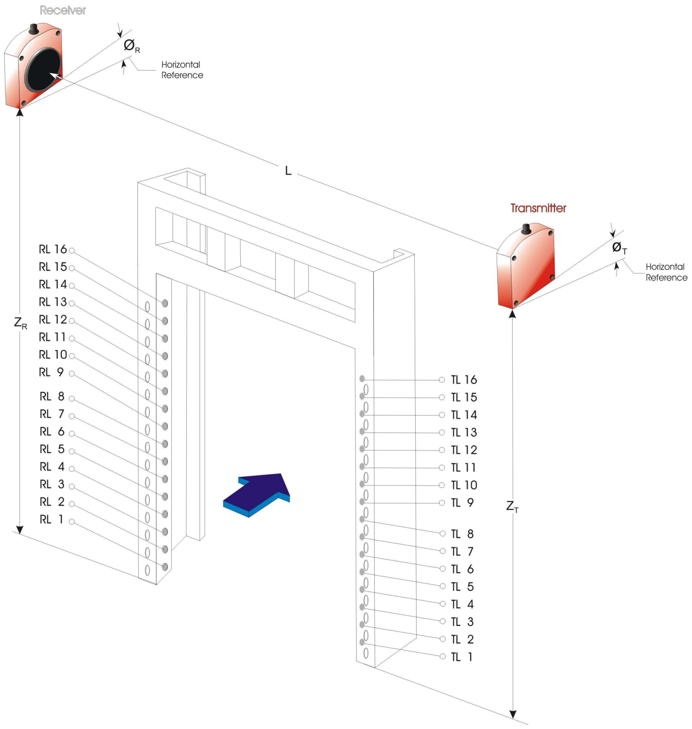

Fig. 8 – AS stationary frame

Costs

Prior to measurement, BC Hydro would be procuring the AS mounting frame. It would be similar to the frame designed by and built for BC Hydro for the measurement at KCL in 2009, only slightly smaller and without the internal provisions for the current meter trolley. 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 7 days, together with two AQFlow technicians in the field for 5 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. Training of the BC Hydro's staff would be provided on an as-required basis. With two days dedicated to flow measurement, sufficient repeats of the measurements 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.

The flow measurement services required for individual testing of the second and all subsequent units would require only 4 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, reducing the flow measurement cost further, to just $104,000 for all 4 units.

2.7. Comparison of alternatives

A comparison of the costs for the three methods is given in Table 2 below.

In order to ensure that the costs between different organizations were comparable, common assumptions were adopted. It was assumed that BC Hydro, Hydro Quebec 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 work day was assumed to be 11 hours.

Method	**Services**	**G4**	**G1,G2,G5,G3 individually**	**G1,G2,G5,G3 consecutively**
ATF	Flow measurement	$146,000	$122,000 each	$489,000 all 4
	Ancillary measurements	$99,000	$73,000.00	$231,000 all 4
	Total	**$245,000**	**$195,000 each**	**$720,000 all 4** **($180,000 each)**
CM	Flow measurement	$93,000	$56,000 each	$108,000 all 4
	Trolley	$27,000		
	Ancillary measurements	$99,000.00	$73,000 each	$231,000 all 4
	Total	**$219,000**	**$129,000 each**	**$339,000 all 4** **($85,000 each)**
AS	Flow measurement	$68,000	$52,000 each	$104,000 all 4
	Frame	$35,000		
	Ancillary measurements	$99,000	$73,000 each	$231,000 all 4
	Total	**$202,000**	**$125,000 each**	**$335,000 all 4** **($84,000 each)**

Table 2 – Comparison of costs for all alternatives

Costs were estimated for three scenarios. The first scenario was for testing of G4 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 8 months apart. For this, much of the equipment would remain at site, but travel costs and extra setups would be required for each test. The third scenario is to cost the testing as if all four remaining units were tested consecutively without leaving the site. This would have the lowest unit cost because the equipment can easily be moved from unit to unit with little additional adjustment.

As can be seen in Table 2, 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 G4. The two intake methods have considerably reduced unit costs compared to 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.

2.8. Discussion

The data in Table 2 shows that the costs for testing more than one unit at a single plant can be greatly reduced by using frame-mounted intake methods. This still leaves the question of whether there are sufficient benefits from this to justify it, even at the reduced test cost. Data from Hydro Quebec and BC Hydro can provide some insight into this.

The Canadian Province of Quebec 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% was achieved (Ref. 2). This represented an extra $300,000/year from the same amount of water, and the $300,000 cost of flow/efficiency measurement was thus repaid in 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 1-5 at GMS represent a great investment in green energy. The purpose of the measurements on all 5 units described in this paper is to confirm that the goal has been achieved. By employing intake flow measurement methods rather than penstock methods, it will be easier to justify measuring the performance of all 5 units, not just the one initially anticipated in the contract.

Furthermore, if the Hydro Quebec approach is adopted and the remaining units 6 – 10 are also tested, an outcome similar to that found by Hydro Quebec could be expected. Considering that GMS will have a mixture of new and old runners, let’s assume that a gain of only 0.2 to 0.3 % would be achieved, or 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, 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 Quebec 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 (Ref. 1,2).

For the upgrades at GMS there is no cost for taking a unit out of service because it is already out of service 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 can 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. The cost of lost generation for a 240 MW unit at an energy price of $35/MWh would be $200,000 per day.

Measurements in gate slots can have their own unique problems. The intake gates slots must be available and free of debris so that measurements can be taken as close to the gate sill as possible. The gate guides must be the same from unit to unit (within tolerances). This methodology can be more exposed to weather, such as with winter conditions.

The two frame-mounted intake flow measurement methods in this paper can only be used when a service gate or stoplog slots have been provided. Several decades ago, when only one of the methods was available, the late Professor Mosonyi pleaded for their provision (Ref. 11) 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 trash rack 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.” Now there are two intake flow measurement methods with which to make accurate, repeatable and cost-effective turbine flow measurements.

3. Conclusions

The frame-mounted CM and AS 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 that do not have intake maintenance gates 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.

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