TURBINE FLOW MEASUREMENT IN INTAKES WITH THE ACOUSTIC SCINTILLATION FLOW METER

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ANNOTATION

Turbine flow measurement in low-head, short-intake hydroelectric plants has long been recognized as difficult. For several decades, the current meters were the only suitable technology. The Acoustic Scintillation Flow Meter (ASFM) now offers a major technological breakthrough, as it replaces moving mechanical equipment with solid state electronic parts and thus eliminates the need for mechanical maintenance and calibration. Furthermore, as its sensors are placed outside of the water flow, the ASFM can be used for long-term flow monitoring, previously not possible in the short-intake plants.

The paper introduces the principles of the ASFM technology and its application in turbine flow measurement during the past 20 years. Representative results from measurements in Canada, USA, France and Spain are presented, with emphasis on the 2009 tests at the BC Hydro’s Kootenay Canal plant in British Columbia. In that test, supervised by the ASME PTC-18 code committee, three intake methods (acoustic scintillation, current meters and acoustic time-of-travel) were compared against a ‘reference’, penstock-installed acoustic time-of-travel flow meter. All three intake methods showed very good agreement with the reference meter and very good repeatability, proving that accurate and repeatable flow measurements in intakes can be performed, provided that the intake has suitable characteristics. These characteristics are briefly outlined, together with the results of a number of comparative measurements in terms of accuracy and repeatability. The paper concludes with the description of the ASFM cost-effectiveness for flow measurements in the intakes of low-head plants, and its potential for the same in plants with higher heads.

KEY WORDS

Hydroelectric power plant, turbine flow measurement in intakes, acoustic scintillation

1. ASFM PRINCIPLES OF OPERATION AND HISTORICAL OVERVIEW

The ASFM uses a technique called acoustic scintillation drift (*Ref. 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 flow. 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. In its simplest form (Fig. 1), 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 vector 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 multibay intake, the discharges through each bay are summed to compute the total discharge.

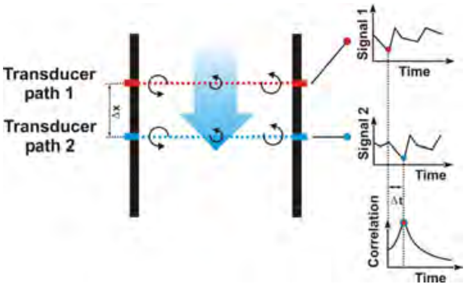


Fig. 1: Schematic representation of acoustic scintillation drift

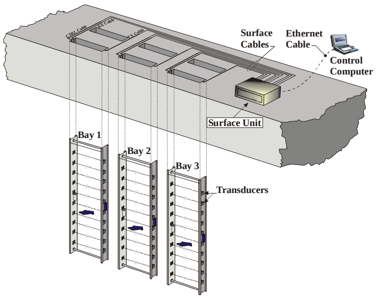


Fig. 2 – Schematics of a 3-bay, 10-paths stationary system

The ASFM has no moving parts and requires virtually no mechanical maintenance and calibration. Its acoustic paths are oriented perpendicular to the axis of the intake, making it suitable for the shortest intakes often associated with low-head turbines, such as Kaplan or bulb units. For the intakes with stoplog or other slots available, the ASFM transducers are mounted on a frame which is then inserted into the slots fully instrumented (Fig. 2). And because the transducers are mounted on the frame with their faces flush with the intake walls and the cabling is inside the frame, the ASFM does not obstruct the flow, is not vulnerable to debris impact and can be used for long term monitoring. Once in the slot, the ASFM mounting frame can remain stationary (if it spans the full height of the intake and is equipped with a full set of acoustic paths – Fig. 3), or it can travel the height of the intake (if it is smaller, with only one or two rows of acoustic paths – Fig. 4).

Fig. 3 – Stationary frame (courtesy USACE)

Fig. 4 – Moving frame (courtesy EDF)

Fully instrumented frames can be moved from intake to intake relatively quickly and easily without intake dewatering. At plants with no slots available for the ASFM frame to be inserted into, the advantage of the ASFM's portability is largely lost. Special measures are required in such circumstances. Ref. (*6*) describes in detail the ASFM measurements at several plants owned by Gas Natural Fenosa Generación, Spain. There, the ASFM was utilized in two parts: fixed parts were attached to the walls ahead of time and a fully-instrumented portable part was attached to the fixed part and then moved between intakes as required. A similar approach would be used for installations where long-term flow monitoring is required (*Ref. 7*), unless long-term use of the slots is available and preferred. The advantages of the ASFM portability are best illustrated by the measurements at Edison Sault Electric Company in Michigan, where flow measurements in 74 small units were completed in just 4 weeks (*Ref. 8*).

It should be noted that the scintillation drift method has been successfully used to measure solar wind with radio waves for almost 70 years, lower atmospheric winds with lasers for over 40 years and ocean currents with sound for 30 years (*Ref. 3,4*). Such was the success of the acoustic scintillation technology for ocean flow measurements that the U.S and Canadian Governments jointly acquired a patent on it (now expired), and ASL Environmental Sciences was granted exclusive license on this patent. ASL performed its first ocean tidal current measurements near Victoria, B.C. in 1984 (*Ref. 5*) and has since been involved in such measurements in the Arctic Ocean, Black Sea, the Mediterranean Sea

Client, Country	**Plant, Year**	**Reference**
Chelan County PUD, USA	Rocky Reach, 1992, 2000	18
USACE, USA	Lower Granite, 1995, 2004	7, 8
B.C. Hydro, Canada	Revelstoke, 1996	
TVA, USA	Fort Patrick Henry, 1997	19
Hydro Québec, Canada	Laforge-2, 1997	20
USACE	McNary, 1998, 1999	9
USACE	Bonneville, 1998, 1999, 2000	11, 12
TVA	Wheeler, 1999	11
Manitoba Hydro, Canada	Seven Sisters, 1999	
Swed Power, Vattenfall, Sweden	Mellanfallet Spillway, 1999	
Chelan County PUD	Rock Island, 2000	11
Hydro Québec	Coteau Rapids Spillway, 2000	13
Hydro Québec	Les Cèdres, 2000	13
B. C. Hydro	Stave Falls, 2000	
USACE	The Dalles, 2000, 2001	11, 12
Nova Scotia Power, Canada	Deep Brook, 2001	
USACE	John Day, 2002	30
USACE	Lower Monumental, 2002	9, 30
Hydro Québec	Outardes II, 2002	
Hydro Québec	Rapides des Quinze, 2002	13
Douglas County PUD, USA	Wells Dam, yearly 2002 - 2008	21
USACE	Little Goose, 2003	30
Hydro Québec	La Grande 1, 2003, 2009	7, 10
UAH - Hydro Kennebec, USA	Kennebec, 2003	
ESE, Sault St. Marie, USA	Edison Sault Electric Company, 2004	8
Portland General Electric, USA	TW Sullivan, 2005	
Korea Water Resources Corp., Korea	Yongdam, 2005	
Korea Water Resources Corp.	Namgang, 2006	
Hydro Québec	Rocher-de-Grand-Mère, 2006	23
Electricité de France, France	Kembs, 2006, 2010	
Electricité de France	Sisteron, 2007	
Electricité de France	Pinet, 2007	
Electricité de France	Cusset, 2007, 2010	
Electricité de France	La Rance, 2007	
Gas Natural Fenosa Generación, Spain	Velle, 2007	6, 28
Gas Natural Fenosa Generación	Frieira, 2007	6, 28
Gas Natural Fenosa Generación	Castrelo, 2007	6, 28
New York Power Authority, USA	St. Lawrence, 2007, 2008	15
Brookfield Renewable Power, USA	Dolby, 2008, 2009	
Hydro Québec	Rupert Control Structure, 2009	7
Companie Nationale du Rhône, France	Châteauneuf-du-Rhône, 2009	24
B.C. Hydro	Kootenay Canal, 2009	25, 27
USACE	Chief Joseph, 2011	

Table 1

and the Bosporus. The development of the ASFM for hydroelectric applications started at Chelan County PUD's Rocky Reach plant on the Columbia River in the early 1990s. The ASFM has since been used by ASL AQFlow in flow measurements at more than 40 plants, initially in North America, more recently in Europe and Asia (Table 1).

2. ASFM REQUIREMENTS

The experience obtained during the past 20 years of measurements with the ASFM has been described in several papers (*Ref. 9-15*). Successful applications of the ASFM, where the systematic uncertainties within ±1.0% can be expected, require the following:

1. The trash rack vertical structural supports to be less than 100 mm in width and more than 6.0 m from the measurement plane (if there are no large vertical supports, the 6.0 m distance requirement can be relaxed). The trash rack to be cleaned prior to the testing.
2. The horizontal angle between the inflow velocity vector and the axis of the intake not to exceed 15 degrees, and the operation of the neighbouring units and the spillway, if applicable, to be controlled to the degree necessary to stay within this limitation during the period required to perform the measurements.
3. Measurements with average flow velocities less than 0.5 m/s and more than 8.5 m/s to be avoided. Measurement section widths less than 1.5 m to be avoided.
4. Non-typical intake conduit shapes that may produce cross-flow to be investigated before the measurement.
5. The fish diversion structures, such as fish screens, located upstream of the measurement plane, require special considerations.
6. Excessive air bubbles and/or acoustic noise should be avoided.
7. Recirculation should be avoided.

For the intakes where the above requirements are not fulfilled, it may be possible for the systematic uncertainties of the measurement to be predicted and removed from the measurement results. In a normal ASFM installation, the acoustic beams are horizontal, and thus the vertical trash rack supports have the potential for introducing bias into the ASFM measurements (Fig. 5). The magnitude of the measurement bias is strongly dependent on the contrast between the turbulence of the intersecting vertical wakes and the turbulence within the remainder of the acoustic path, the distance between the measurement plane and the trash rack support and the width of the trash rack supports. If the wakes from the major trash rack supports, parallel to the acoustic beams, have merged before they reach the measurement plane, then it is very likely that the bias due to the wakes from the vertical support members will be reduced to a negligible amount. The distance downstream of the trash rack, X_{merge} required for the wakes from the horizontal members to merge may be estimated as

$$\frac{X_{merge}}{D} = 1.44\left(\frac{H}{D}\right)^{2.2}$$

where H is the vertical separation between the major horizontal trash rack supports, D is their width in the vertical and X is the distance between the trash rack and the measurement plane (all dimensions in meters).

If the distance to the measurement section is less than X_{merge}, an upper bound for the bias error due to wakes from the vertical members may be estimated using numerical calculations (*Ref. 16*) and comparisons with the available experimental data on similar structures (*Ref. 17*).

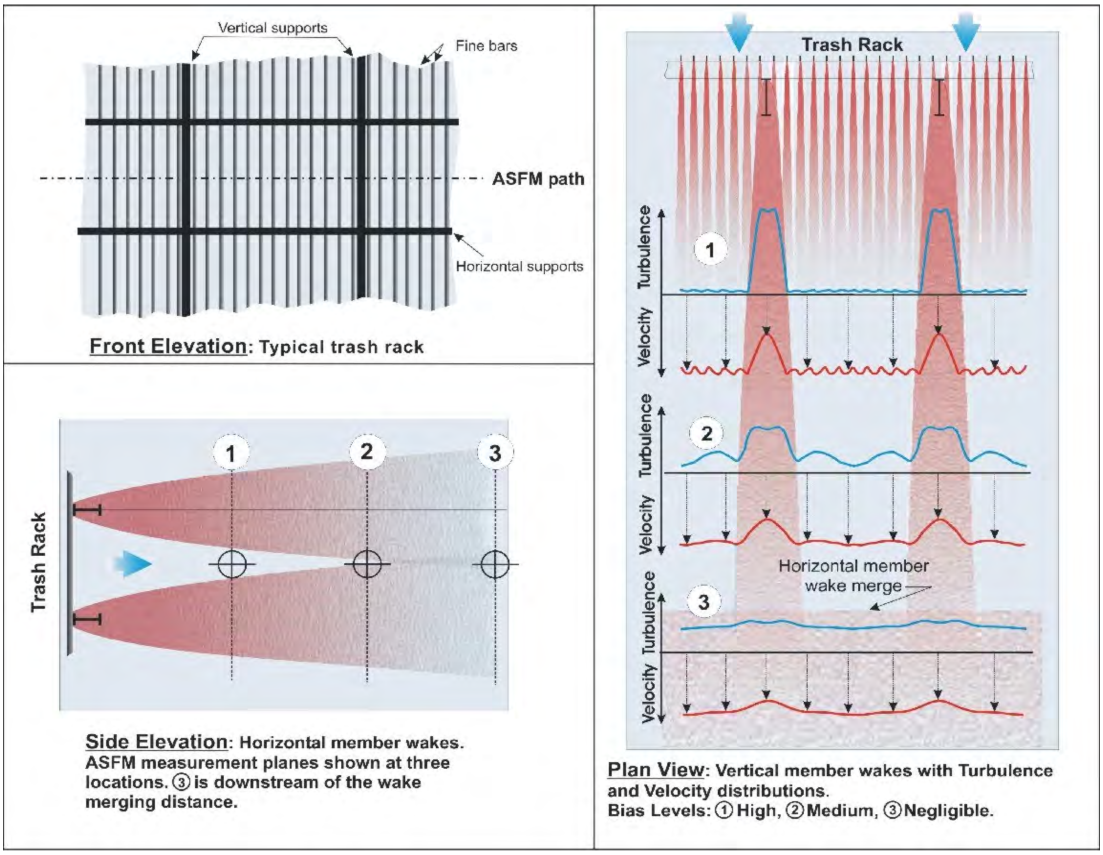


Fig. 5: Illustration of the bias produced by large vertical trashrack supports

Experience has shown that with these corrections the resulting systematic uncertainty of measurements with the ASFM can be close to ±2% for many of these difficult intakes. However, there will be some exceptionally difficult intakes where no acceptable measurement uncertainties will be achievable.

3. ASFM ACCURACY AND REPEATABILITY

The tow-tank tests performed at Ocean Engineering Center, Vancouver, in 1994 (*Ref. 18*) demonstrated that under controlled conditions the ASFM is capable of measuring the spatially-averaged velocities to within ±1%. Subsequent comparative measurements under field conditions have shown good agreement between the ASFM results and independent measurement of turbine flows at the following plants:

- 1997 TVA’s Fort Patrick Henry, against current meters (*Ref. 19*): <1%
- 1997 HQ’s Laforge-2, against current meters (*Ref. 20*): <1.5%
- 1999 HQ’s La Grande-1, against current meters (*Ref. 10*): 0%

- 2000 HQ’s Les Cèdres, against current meters (*Ref. 10*): <1.75%
- 2002 Douglas County’s Wells, against acoustic time-of-travel in intake (*Ref. 21*): acceptable
- 2004 USACE’s Lower Granite, against acoustic time-of-travel in intake (*Ref. 22*): <1.6% without fish diversion screens, <3.7% with fish diversion screens
- 2006 HQ’s Rocher-de-Grand-Mère, against current meters (*Ref. 23*): 1.1%
- 2009 CNR’s Châteauneuf-du-Rhône, against ADCP (*Ref. 24*): <3.1%
- 2009 BCH’s Kootenay Canal, against acoustic time-of-travel in penstock (*Ref. 25,26*): 0.44%

The results of the 2009 comparative measurements at the B.C. Hydro’s Kootenay Canal plant are particularly significant. The Kootenay Canal plant has a low-head type of an intake which fulfills the requirements listed above, and has a long, straight penstock equipped with a well-proven acoustic time-of-travel flow meter. Interestingly, Kootenay Canal played a major role in the process of acceptance of the acoustic time-of-travel method some 30 years earlier, as it was one of the sites used by Electric Power Research Institute *(*EPRI) in 1983, when nine flow measurement methods were evaluated as part of extensive testing of penstock measurement methods (*Ref. 27*).

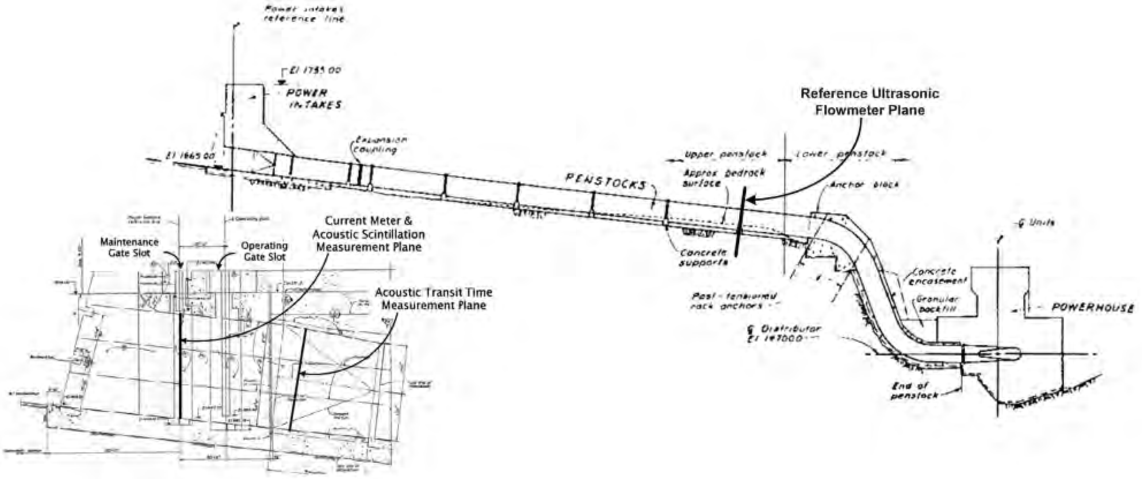


Fig. 5 – Kootenay Canal profile and intake detail (lower left, courtesy CEATI)

The 2009 measurements were sponsored by the Canadian Centre for Energy Advancement through Technological Innovation (CEATI), supervised by the American Society of Mechanical Engineers (ASME) PTC-18 test committee and run as a ‘blind’ test. The ASFM was one of the three intake measurement methods tested (the other two were the current meters and the acoustic time-of-travel), with the reference measurement provided by an acoustic time-of-travel flow meter installed in a code-approved location in the penstock. The average deviation of the ASFM results from the reference meter results was 0.44%. Equally importantly, the ASFM results exhibited little scatter, with a 95% population confidence interval of ±0.39% (*Ref. 26*). Also, the ASFM exhibited little sensitivity to the changes in the operation of the neighbouring units: less than 0.1% for changes typical during normal operation of a plant, when the units are dispatched within their normal operating range.

The fact that the results from all three intake methods were within 1.1% of the reference measurement results and showed little scatter and little sensitivity to operation of neighbouring units confirms that turbine flow measurement can be made in the intake and can be accurate and repeatable, provided the intake has favourable characteristics.

As another example, at the Gas Natural Union Fenosa plants on the River Mino in northwestern Spain, where stable operation of adjoining units and stable head conditions were maintained during the measurements, repeatability between ±0.1 and ±0.3% was achieved (*Ref. 28*). In fact, as long as the flow conditions remain reasonably unchanged throughout the measurement (head, adjoining units/spillway operation), the ASFM has consistently delivered results with random uncertainties better than ±0.5 %.

Although further comparative measurements will be required, both the IEC 600041 and ASME PTC-18 test committees are currently in the process of incorporating guidance on flow measurement in intakes into the next editions of their respective publications. This represents a major step in the development of these codes, as no such guidance has been provided for the owners of low-head plants until now (perhaps with the exception of ISO 3354). “No existing standard deals with discharge measurements in short penstocks or intakes, especially for low-head plants” according to the current edition of the IEC 600041 (*Ref. 29*).

4. ASFM COST-EFFECTIVENESS

If we accept that the ASFM, used in appropriate intakes and subject to further comparative testing, can produce accurate and repeatable measurement results, the question remains: is it cost-effective? Here the answer is a definite yes. The main contributor to the ASFM cost-effectiveness is its portability. Once a fully instrumented frame (or a set of frames for multibay intakes) is available, it can be relatively quickly and easily moved between units at the plant (or even between units at neighbouring plants, provided their intakes and stoplog slots have identical widths) without equipment dismantling and re-installing, without intake dewatering and, if required, without unit stopping.

When the slots are available, the cost advantages of the ASFM for the owner of a low-head, short-intake plant are twofold:

Firstly, the turbine performance improvements obtainable from modified cam curves derived from the measurements typically represent 1% or more, depending on the unit age and other factors (*Ref. 30*). As far back as May 2004 (*Ref. 31*), a senior USACE hydraulic engineer was quoted “…During past seven years, the Corps has conducted index testing on seven hydro plants. In every case, the testing resulted in engineers adjusting the blades and gates according to flow. On average, the Corps is obtaining 1.5 to 2 % increases in efficiency, enough to economically justify the cost of the tests.” As an example, a 1% improvement in the efficiency of a 240 MW unit at a conservative energy price of $35/MWh will be in the order of almost $500,000 per year (*Ref. 32*).

Secondly, in cases where limited storage requires water to be spilled, additional major savings will be obtained as a result of the ASFM requiring shorter unit stoppage than other technologies. As an example, the cost of lost generation for a 240 MW unit at $35/MWh will be in the order of $200,000 per day (*Ref. 32*).

As already mentioned, the portability of any intake method depends on the plant being equipped with the service gate or stoplog slots. Several decades ago, when only the current meters could benefit from such slots, the late Prof. Mosonyi pleaded for the provision of the slots (*Ref. 33*): “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.” It is disappointing to see that now, when we have the current meters and the ASFM which could both utilize such slots and make the measurement cost-effective, so many new plants are still being designed and built without the slots.

5. ASFM IN INTAKES OF HIGHER HEAD PLANTS

While low-head plants do not have code approved methods for turbine flow measurement, medium and high head plants typically have an option to measure those flows with code-approved flow meters installed in the penstocks. The installation costs, however, can be high, particularly if the penstocks are inaccessible. More frequently than not, flow meters are installed only in ‘representative’ units, and an assumption is made that other units at the plant are performing identically. As units age and lose efficiency unequally, this assumption is frequently incorrect and leads to sub-optimal plant operation.
The recently published study by BC Hydro (*Ref. 34*) attempts to deal with this situation by moving the measurement from the penstocks to the intakes. BC Hydro’s 2,730 MW G.M. Shrum underground powerplant has 10 generating units operating under 130 m of head. Units 1-5 are currently being replaced and for cost reasons (penstocks are buried), measurement with penstock installed acoustic time-of-flight flow meter 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. As this would leave differences in the individual unit performance which can produce large benefits in optimal dispatch (*Ref. 35, 36*) undetected, BC Hydro is investigating technologies which would facilitate economically justifiable measurement and monitoring of every one of these new units.
The relative costs of the intake-installed acoustic-time-of-travel (ATF), current meters (CM) and the ASFM (AS) were investigated, with the results shown in Table 2 (*Ref. 37).*

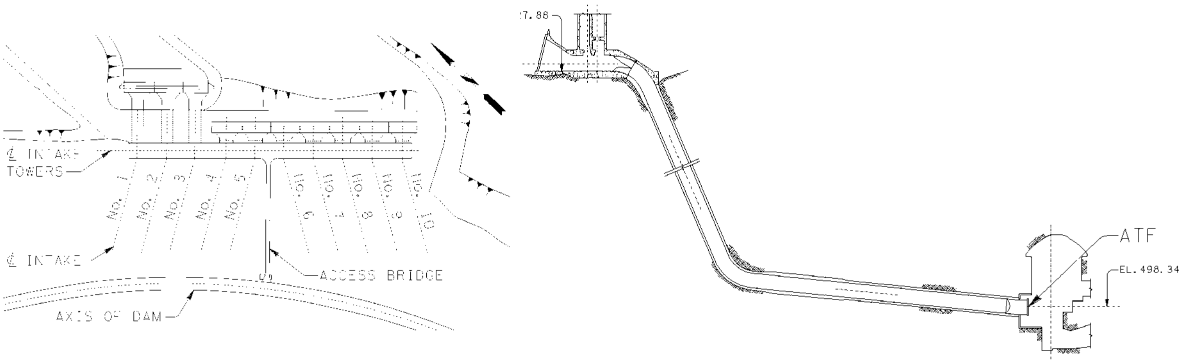
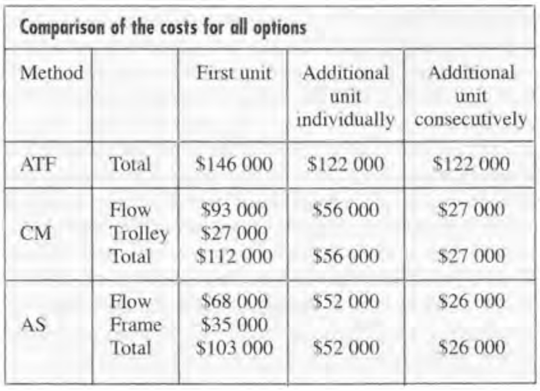


Fig. 6 – G. M. Shrum Plant plan and profile



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 Trolley Total	$93 000 $27 000 $112 000	$56 000 $56 000	$27 000 $27 000
AS	Flow Frame Total	$68 000 $35 000 $103 000	$52 000 $52 000	$26 000 $26 000

Table 2 (courtesy Aqua Media 2012)

As Table 2 shows, the cost of testing more than one unit at a single plant can be greatly reduced by using frame-mounted intake methods: if done consecutively, all five new GMS units could be tested for $207,000 (versus $268,000 for testing just two units with the ATF). And if also the remaining five old units were tested with an intake method, the total cost would be about $337,000 (versus $390,000 for testing just three units with ATF). To put these numbers into perspective: $337,000 would be repaid in 7 months with a 0.2% improvement in the overall efficiency at GMS (at a conservative $35/MWh). Much larger differences in performance of individual units at plants are being consistently identified, leading to higher improvements being achieved by owners of aging units. As another example, performance testing of ten units at the Douglas County PUD Wells project on the Columbia River revealed peak efficiency differences between units larger than 1% (*Ref. 21*).

For the upgrades at GMS there is no cost in Table 2 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 no storage and spill is therefore required, the downtime to install an ATF system in the penstock will 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 already stated, the cost of lost generation for a 240 MW unit at an energy price of $35/MWh would be $200,000 per day.

Although Table 2 shows virtually no cost difference (including the cost of unit downtime and avoided generation) between the frame-mounted current meters and the ASFM, the advantages of the solid state electronics of the ASFM over the mechanical components of the current meters remain. Furthermore, because no ASFM instrumentation is exposed to the flow and thus debris impact, if the frames can be left in the slots long-term, the ASFM can be used for long-term monitoring.

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