Results of Kootenay canal flow comparison test using intake methods

John W. Taylor
BC Hydro
6911 Southpoint Drive
Burnaby, BC V3N 4X8
Canada

Charles W. Almquist
Principia Research Corporation
P.O. Box 1693
Nashville, Tennessee 37212
USA

James T. Walsh
Rennasonic, Inc.
372 Hayway Road
East Falmouth, Massachusetts 02536
USA

Introduction

This paper describes the execution and results of a test comparing methods for measuring flow suitable for use in short converging intakes, which are typical of low head hydro plants. At present, there are no practical code accepted methods for measuring flow in this type of hydro plant. The background leading up to the test is given in a companion paper in this conference [1].

The American Society of Mechanical Engineers' (ASME) Performance Test Code Committee 18 for hydroturbine efficiency testing initiated this project. A subset of members of this committee acted as a Steering Committee to guide the test. Dr. Charles Almquist of Principia Research Corporation acted as the Chief of Test, taking responsibility for technical aspects. Funding was provided by The Centre for Energy Advancement through Technological Innovation (CEATI) with additional contributions from the ASME.

Three flow measurement technologies suitable for intakes were evaluated – acoustic travel time (ATT), current meters (CM), and acoustic scintillation (AS). An existing code-accepted acoustic flowmeter mounted in the penstock served as a "reference" measurement. The test was executed at the level of accuracy required for turbine acceptance testing, generally in accordance with ASME PTC-18. Furthermore, it was conducted "blindly", meaning the flow data was not shared among test participants until months after the test.

The layout of the Kootenay Canal Plant is shown in Figure 1. A power canal delivers about 850 m^3/s to a gravity structure consisting of 4 intakes. Each intake leads to a penstock and 140 MW generating unit. The tests were undertaken on Unit 1 which is on the right hand side looking downstream. Although this is not a low head plant, the intakes are similar to those typically found in low head plants.

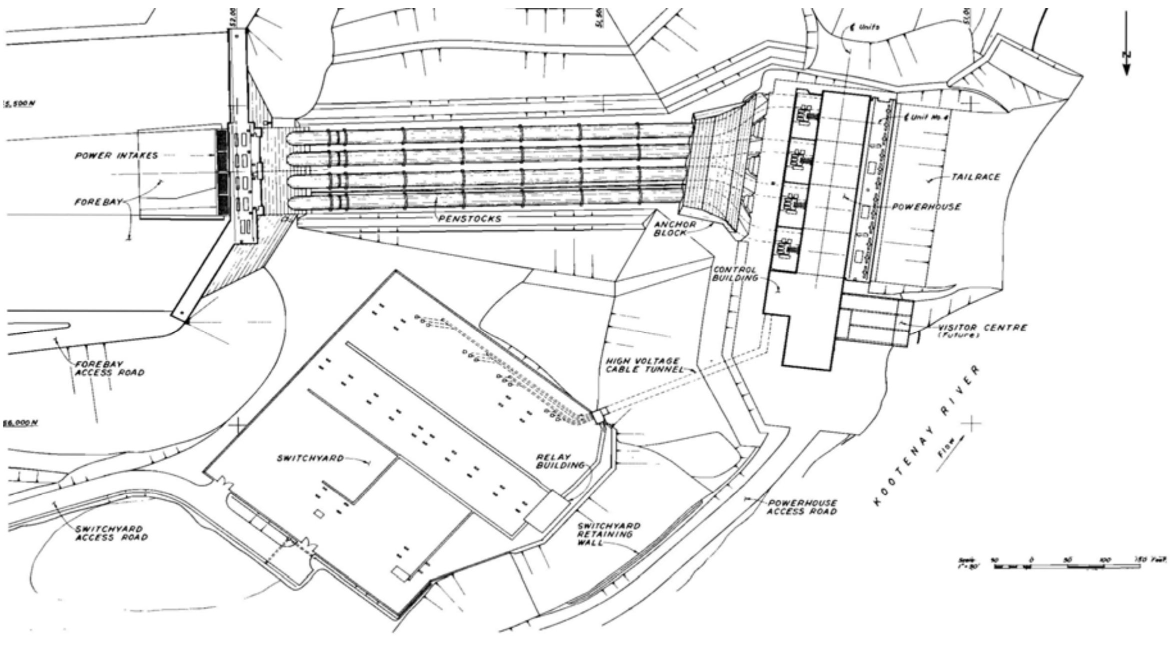


Figure 1 Plan View of Kootenay Canal Generating Station

1. Description of the Methods

Three candidate technologies were implemented at the Kootenay Canal test. Detailed description of the methods is given in companion papers at this conference and in other references, and so will not be repeated here. These methods were:

1.1. Current Meters (CM fixed and CM profile)

Fourteen current meters were mounted horizontally on a carriage which travelled vertically along the guides of a fixed frame mounted in the maintenance gate slot as shown in Figure 2. During testing the carriage was set at the desired elevation, then the current meters were sampled. The carriage was then moved to the next elevation. The measured velocities were integrated horizontally and vertically to calculate the flow. The velocities near the wall were estimated using a power law. Two sets of data were taken using this instrumentation. One set sampled with the carriage stationary at fixed vertical positions (called “CM fixed”). The other sampled the entire vertical section without stopping (called “CM profile”). This instrumentation was installed and operated by Hydro Quebec, Montreal, Canada.

1.2. Acoustic Scintillation (AS)

Sixteen pairs of equally-spaced transducer assemblies were mounted on the fixed frame located in the maintenance gate slot, making 16 horizontal paths. Each transducer assembly contained 3 transducers so that both vertical and horizontal velocities could be resolved. The transducer assemblies were sampled sequentially to provide 16 average velocities, one for each elevation. These velocities were then integrated vertically to calculate flow. The velocities near the wall were estimated using a power law. This instrumentation was installed and operated by ASL AQFlow Inc., Sidney, B.C., Canada.

1.3. Acoustic Transit Time in a non-uniform section (ATT)

Transducers were mounted on the concrete walls of a non-uniform transition section (rectangular to circular), located immediately downstream of the operating gate. See Figure 2. Eighteen paths (9 paths in each of two crossed planes) were installed using a total of 36 transducers. The spacing was Gauss-Legendre. Although this method is generally accepted for turbine tests in circular penstocks, it is unusual and difficult to use this technology in a non-uniform section. This instrumentation was installed and operated by Accusonic Technologies, Inc., Wareham, Massachusetts, USA.

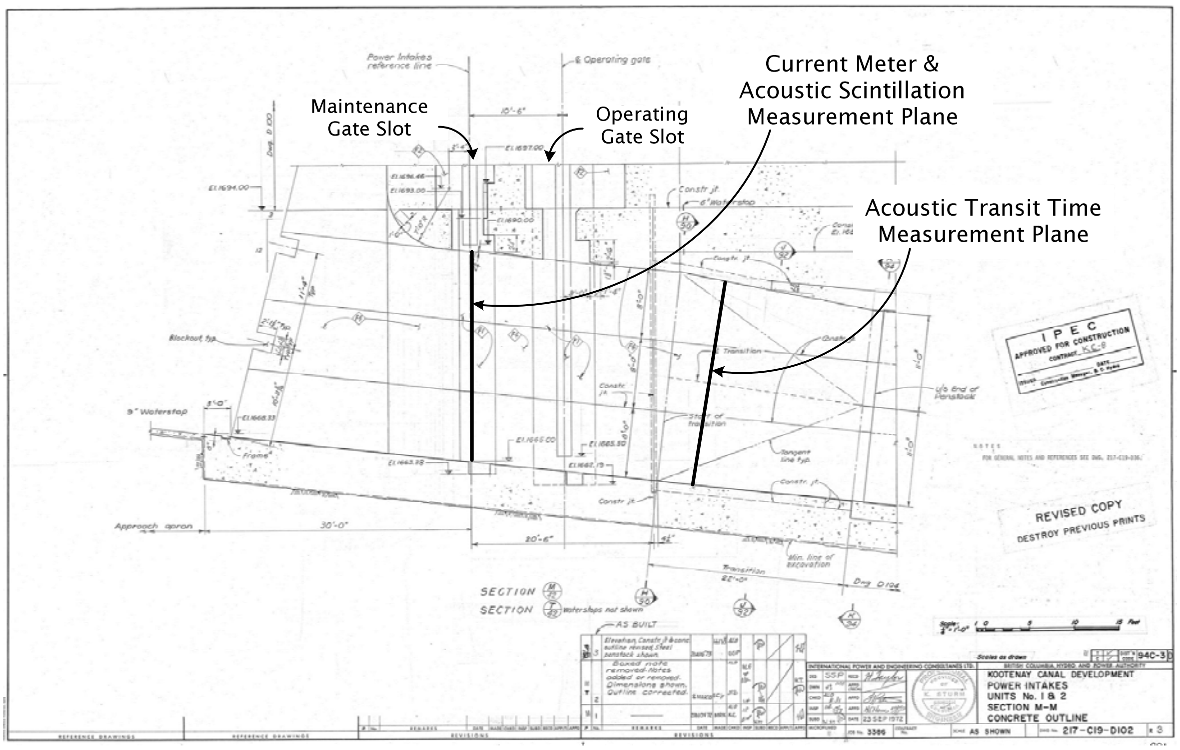


Figure 2 Location of Intake Flow Measurements

1.4. Reference Flowmeter (RM)

The reference flow meter for these tests was an acoustic transit time flowmeter installed in the lower penstock at the location shown in Figure 3, at a distance of 23 diameters downstream of the intake. This is the location of the Westinghouse flowmeter used in the previous EPRI tests in 1983 [2], with the transducers in the same mounting holes. This section forms an eight-path meter (4 paths in each of two crossed planes). The paths are oriented vertically, which is somewhat unusual in an installation of this type, and are spaced according to the Gauss-Legendre method as specified in PTC18 [3]. The principle of operation is the same as that of the ATT meter installed in the intake, although the installation and calculations are different.

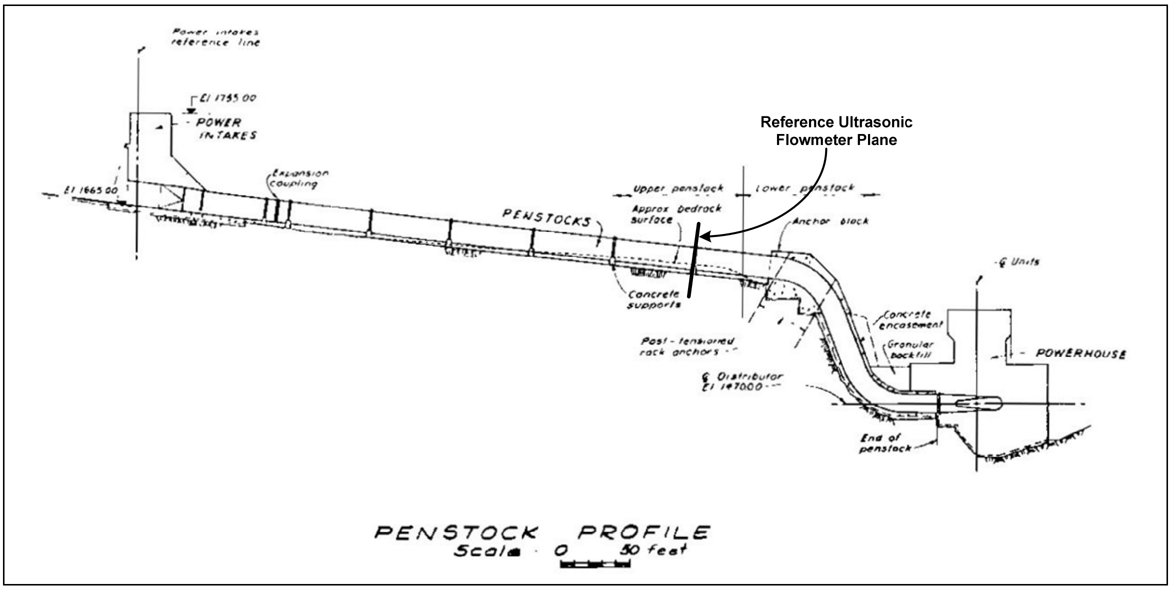


Figure 3 Location of Reference Flowmeter

1.5. CFD

In addition, a computational fluid dynamics (CFD) model of the selected intake was deemed to be a high priority, both to help in interpreting test data, and to help advance CFD modeling by providing high quality field data for comparison to model predictions. However, the comparison between CFD and measured velocities at the intake gate slot was inconsistent. Further downstream in the transition region the comparison of CFD to the ATT was improved. It is likely that this is because the trapezoidal intake canal (shown in Figure 4) was not modeled, and that velocity variations in the real channel would not have been exhibited in the CFD model. In this paper the CFD results will not be presented.

Figure 4 Picture of the intake after de-watering showing trapezoidal channel.

1.6. Auxiliary Measurements for Test Analyses and Quality Control

Additional measurements taken by the BC Hydro test crew for analyses and quality control of the comparison tests are summarised in Table 1.

Table 1 Auxiliary Measurements

Measurement	Instrument
Winter-Kennedy differential	Differential pressure cell
Wicket gate opening	Linear motion transducer
Forebay elevation	Plant gage
Tailwater elevation 1	Ultrasonic downlooker
Tailwater elevation 2	Ultrasonic downlooker
Tailwater elevation 3	Ultrasonic downlooker
Water temperature	Reference flowmeter
Generator power	Digital watthour meter
Generator VARs	Digital watthour meter
Turbine inlet pressure	Gage pressure transducer
Turbine inlet pressure calibration	Deadweight tester

2. Test Program

Testing was conducted on four days, October 21 – 24, 2009 and consisted of a primary program and a secondary program. The purpose of the primary test program was to compare the flows measured at the intake to the reference flowmeter in the penstock. The purpose of the secondary test program was to determine whether the measurements at the intake were sensitive to the operation of the adjacent unit. The test program is summarized in Table 2.

Table 2 Summary of Actual Testing Schedule

Primary Test Program

Oct 21 - 23, 2009

	Intake Velocity (m/s)		
	1.04	1.94	2.92
	Discharge (m^3/s)		
	37.68	70.42	105.95
	Gate Opening (%)		
	20.5	34.4	48.0
	Day 2	**Day 1**	
Block	P9	P1	P5
	P10	P2	P6
	P11	P3	P7
	P12	P4	P8
	Day 3	**Day 2**	
Block	P25	P13	P17
	P26	P14	P18
	P27	P15	P19
	P28	P16	P20
Block	P33	P29	P21
	P34	P30	P22
	P35	P31	P23
	P36	P32	P24

Secondary Test Program

Oct 24, 2009

Intake Velocity (m/s)		
1.04	1.94	2.92
Discharge (m^3/s)		
37.72	70.42	105.92
Gate Opening (%)		
20.5	34.4	48.0
S1 (U3)		S9a (U3)
S2 (U2)		S10 (U2)
	S6 (U3)	
	S8 (U2)	

All tests planned for the primary program were achieved. It was intended to test each block of flows all on one day in order to keep conditions as constant as possible. However, this was not possible because of time constraints, which required both setup and testing to occur on the first day, so there was no time to do a complete test block of common flows. Therefore the medium flow tests were spread in blocks of four over all three days.

3. Constancy of Test Conditions

An objective of the test program was to keep the discharges and gross heads as constant as possible, through the use of servo blocks to ensure repeatability of the gate openings and by using a balancing unit to maintain plant discharge as constant as possible, resulting in stable headwater and tailwater elevations.

Table 3 shows the variation in gross head and flow rate measured by the reference meter for all runs in the primary test program. Results are presented for uncorrected flows and flows corrected to 81 m gross head.

It is seen from the table that heads and flows were stable and repeatable over the entire primary test program. The range of heads was only about ± 1/2 % of the average value, well within the ± 2% range specified by the test codes for affinity law corrections. This range of heads indicates that the uncorrected flow rates, which would be expected to vary as the square root of the head, should have a range of about 0.5%. In fact, the uncorrected flows deviate from the average ranging from 0.81% for the low flows to 0.22% for the high flows.

When corrected to a common gross head of 81 m, the range of flow deviations from the average is nearly constant at about 0.15 m^3/s, corresponding to ranges from 0.35% at the low flows to 0.15% at the high flows. This result indicates that the flow rate was quite steady and repeatable throughout the primary test program since test blocks were used on the wicket gate servo-motor piston.

Table 3 Constancy of Head and Flow During Primary Program

	Head	Uncorrected Flow (m^3/s)			Corrected Flow (m^3/s)		
	(m)	Low	Med	High	Low	Med	High
Average	80.94	37.67	70.39	105.80	37.68	70.42	105.95
Max	81.44	37.80	70.51	105.92	37.73	70.50	106.03
Min	80.57	37.50	70.23	105.69	37.60	70.32	105.87
Range	0.87	0.30	0.28	0.23	0.13	0.17	0.16
% Range	1.07	0.81	0.40	0.22	0.35	0.25	0.15

The headwater elevations, tailwater elevations, and gross heads measured during the entire testing program are shown in Figure 5. It is seen in the figure that the headwater elevations were quite stable, that the tailwater rose slightly as each test day progressed, and the gross head fell slightly during each test day. Note that the gross head is shown at a greatly expanded scale.

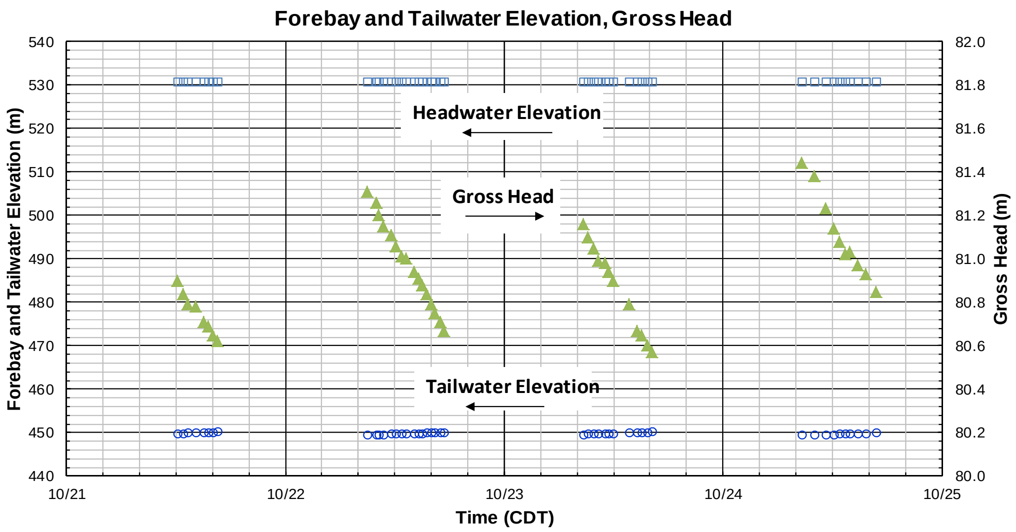


Figure 5 Variation in Head During the Test Program

All flow data was corrected to a gross head of 81 m. These corrections were made using the affinity law:

$$Q_C = \left(\frac{H_N}{H_T}\right)^{\frac{1}{2}} Q_T$$

where

Q_C = corrected discharge (m^3/s)
H_N = average test gross head during reference run (m)
H_T = gross head measured during test (m)
Q_T = flow measured during test (m^3/s)

4. Primary Program Results

Table 4 presents the corrected flows as a percent deviation from the reference flow, with the test runs grouped by nominal flow rate (low, medium, and high).

Table 4 Primary Program Test Results

		Flows - % Deviation from Reference Meter				
Run	Q	RM	ASL	AST	HQ Fixed	HQ Profile
		%	%	%	%	%
P9	L	0.00	0.47	0.10	1.13	1.18
P10	L	0.00	0.57	0.09	0.38	0.61
P11	L	0.00	0.44	0.10	1.18	1.31
P12	L	0.00	0.90	0.03	0.25	0.69
P25	L	0.00	0.22	-0.01	1.11	0.88
P26	L	0.00	0.46	0.05	0.40	0.40
P27	L	0.00	0.14	-0.02	0.81	0.56
P28	L	0.00	0.32	0.14	0.75	0.91
P33	L	0.00	0.65	0.02	0.96	0.81
P34	L	0.00	0.87	0.06	0.86	0.71
P35	L	0.00	0.28	0.00	0.71	0.88
P36	L	0.00	0.75	-0.02	0.86	1.07
P1	M	0.00	0.42	0.01	1.62	1.39
P2	M	0.00	0.39	0.14	1.34	1.53
P3	M	0.00	0.60	0.26	1.27	1.23
P4	M	0.00	0.65	0.15	0.94	0.95
P13	M	0.00	0.44	0.05	1.13	1.08
P14	M	0.00	0.57	0.07	0.68	1.01
P15	M	0.00	0.44	0.08	1.28	1.01
P16	M	0.00	0.52	0.07	0.97	1.00
P29	M	0.00	0.16	0.05	1.27	0.98
P30	M	0.00	0.75	0.21	1.13	1.33
P31	M	0.00	0.14	0.02	1.14	1.14
P32	M	0.00	0.47	0.12	1.10	1.25
P5	H	0.00	0.29	0.19	1.58	1.46
P6	H	0.00	0.49	0.10	1.20	1.28
P7	H	0.00	0.29	0.24	1.31	1.11
P8	H	0.00	0.53	0.07	1.53	1.68
P17	H	0.00	0.33	0.10	1.20	1.20
P18	H	0.00	0.37	0.02	1.18	1.20
P19	H	0.00	0.28	0.12	1.10	1.16
P20	H	0.00	0.44	0.13	1.27	1.18
P21	H	0.00	0.17	0.19	1.31	1.27
P22	H	0.00	0.44	0.10	1.04	1.18
P23	H	0.00	0.37	0.17	1.38	1.17
P24	H	0.00	0.31	0.00	0.74	0.88
S1	L	0.00	0.32	0.08	0.59	0.37
S2a	L	0.00	1.43	0.04	1.37	1.41
S2b	L	0.00	1.25	0.13	1.01	1.19
S5a	M	0.00	0.61	-0.04	1.46	1.45
S5b	M	0.00	0.58	0.09	0.17	0.33
S6	M	0.00	0.52	0.05	0.61	0.70
S8	M	0.00	0.48	-0.01	0.90	0.80
S9a	H	0.00	0.31	0.05	0.98	1.01
S9b	H	0.00	0.27	-0.01	0.94	0.94
S10	H	0.00	0.34	0.09	0.92	1.01

Note: Shaded runs are secondary test program pairs used in the analyses

Table 5 presents statistics from the primary program normalized flow data. The normalized results are presented as percent deviations from the reference flowmeter. For each method, the table shows the average deviation of the test runs from the reference meter, the standard deviation of the runs, and the 95% population confidence interval, which is determined by multiplying the sample standard deviation by Student's t statistic for the degrees of freedom at each flow rate. The value of the t-statistic used is t = 2.201 for all cases (12 runs, 11 degrees of freedom).

Table 5 Statistics for Normalized Flows (Percent Deviation)

	Low Flow			Medium Flow			High Flow			All Flows		
Method	**Avg**	**Std Dev**	**95% Interval**	**Avg**	**Std Dev**	**95% Interval**	**Avg**	**Std Dev**	**95% Interval**	**Avg**	**Std Dev**	**95% Interval**
	%	%	%	%	%	%	%	%	%	%	%	%
CM - Fixed	0.78	0.31	0.67	1.16	0.23	0.51	1.24	0.22	0.49	1.06	0.32	0.65
CM - Profile	0.83	0.26	0.58	1.16	0.19	0.41	1.23	0.19	0.42	1.07	0.27	0.56
Scintillation	0.51	0.25	0.55	0.46	0.18	0.39	0.36	0.10	0.22	0.44	0.19	0.39
Transit Time	0.04	0.05	0.12	0.10	0.08	0.17	0.12	0.07	0.16	0.09	0.07	0.15

Table 5 shows that the acoustic transit time method is the closest to the reference meter (0.09% average for all flows), and exhibits the least scatter, with a 95% population confidence interval of ± 0.15% when computed for all flows.

The test data is presented graphically in Figure 6(a)- 6(d). From this figure it is seen that the all flow measurement methods yield higher flow rates than the reference meter, with the acoustic transit time being the closest to the reference flow, followed by acoustic scintillation, the current meter methods.

The trend with flow rate for the average deviation from the reference meter is shown in Figure 7. It shows that differences from the reference meter vary from 0% to 1.2%. It also shows that there is an insignificant difference between CM fixed and CM profile measurements.

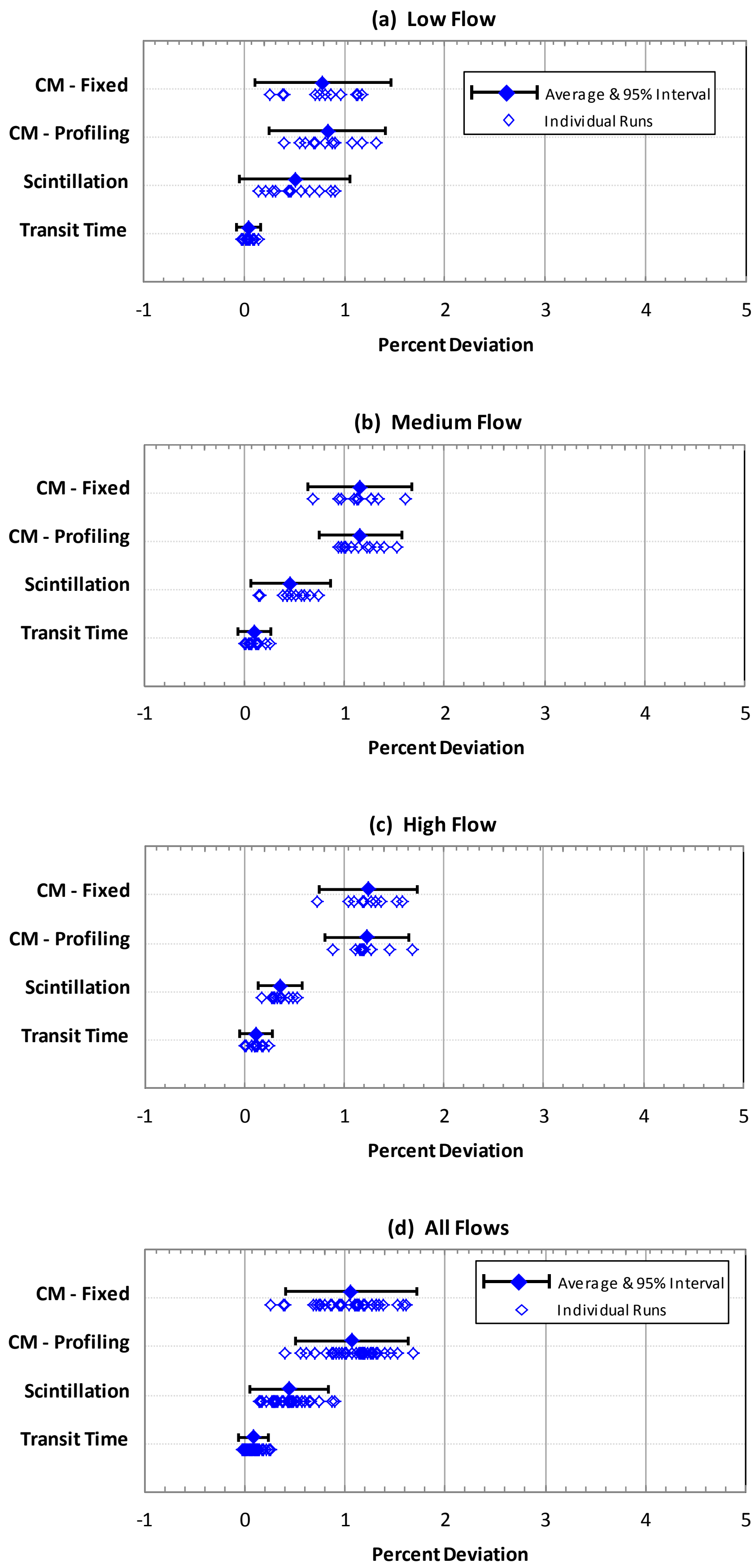
5. Secondary Program Results – Effect of Adjacent Unit Operation

As discussed previously, the objective of the secondary test program was to evaluate the effect of adjacent unit operation on the flow measurement methods. During the primary program, Unit 3 was always used as the flow balancing unit. During the secondary program, a test run was made with either Unit 2 or Unit 3 as the flow balancing unit, followed by a test run with the balancing flow shifted to the other unit. Originally, two changes of the balancing unit were planned for each flow rate, but difficulty in shifting the load quickly between Units 2 and 3 limited the testing to one change for each flow.

Table 6 and Figure 8 show the effect of adjacent unit operation, defined as the percent change in flow from Unit 3 operation to Unit 2 operation. Positive values indicate that the flow with Unit 2 operating was higher than with Unit 3 operating.

The reference meter flow was essentially unaffected by the adjacent unit operation, with a maximum change (at the medium flow) of only 0.04%. Because it is located a relatively long distance from the intake, it is reasonable that it is affected the least. The transit time flowmeter (ATT) also showed very little sensitivity to adjacent unit operation over the range of flows, the maximum effect being less than 0.1%. The scintillation and two current meter methods showed greater sensitivity, ranging from nearly 1% at the low flow to less than 0.1% at the high flow.

The greater sensitivity of the AS and CM methods to adjacent unit operation at the lower two flows is probably explained by the fact that at these low flows, the flow rate of the balancing unit was significantly greater than the unit under test, as shown in Table 6. At the low flow, the balancing unit flow was 5.5 times that of Unit 1. At the medium and high flows, the corresponding ratios were 2.5 and 1.3. Thus, the relative disturbance to the flow at the Unit 1 intake would be expected to be quite significant at the low flow, and less significant at the high flow. When the balance unit flow was of the same magnitude as the Unit 1 flow (high flow case), there was virtually no effect on the measured flow rate.



Figures 6(a) – 6(d) Plot of results relative to reference flowmeter

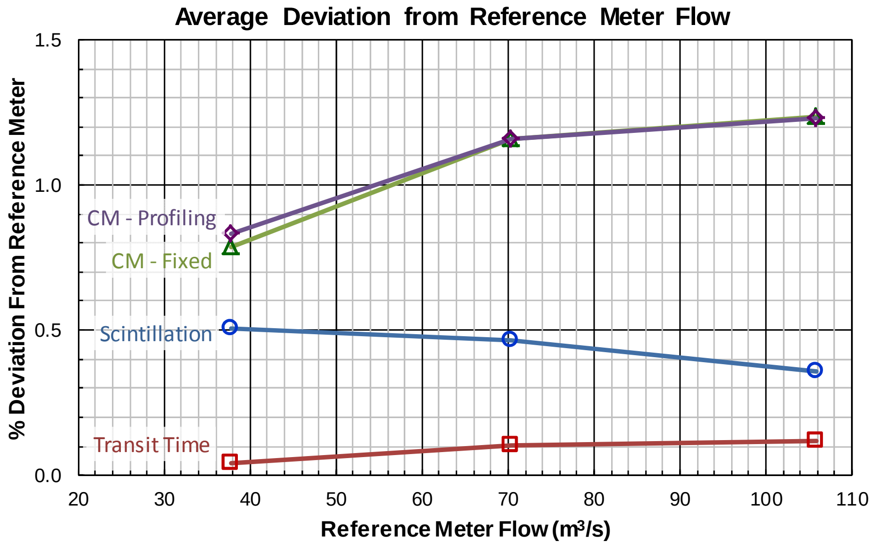


Figure 7 Average Deviation from Reference Meter Flowrate

Table 6 Effect of Adjacent Unit Operation

			(a) Measured Flows				
Test Run	**Balance Unit**	**Balance Flow (Approx)**	**Ref Meter**	**AS**	**ATT**	**CM - Fixed**	**CM - Profile**
		m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s
S1	U3	210	37.72	37.84	37.75	37.94	37.86
S2a	U2	210	37.72	38.26	37.73	38.23	38.25
S6	U3	174	70.41	70.77	70.44	70.84	70.90
S8	U2	174	70.43	70.77	70.43	71.07	71.00
S9b	U2	138	105.93	106.21	105.92	106.93	106.93
S10	U3	138	105.92	106.28	106.01	106.89	106.99

		(b) Change in Measured Flows				
Run Pair	**Ref Meter Flow**	**Ref Meter**	**AS**	**ATT**	**CM - Fixed**	**CM - Profile**
	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s
S2a - S1	37.72	0.00	0.42	-0.02	0.29	0.39
S8 - S6	70.42	0.02	0.00	-0.02	0.23	0.10
S9b - S10	105.92	0.01	-0.07	-0.09	0.04	-0.06

		(c) Percent Change in Measured Flows				
Run Pair	**Ref Meter Flow**	**Ref Meter**	**AS**	**ATT**	**CM - Fixed**	**CM - Profile**
	m^3/s	%	%	%	%	%
S2a - S1	37.72	0.00	1.10	-0.04	0.77	1.03
S8 - S6	70.42	0.04	0.00	-0.02	0.32	0.14
S9b - S10	105.92	0.01	-0.07	-0.08	0.03	-0.06

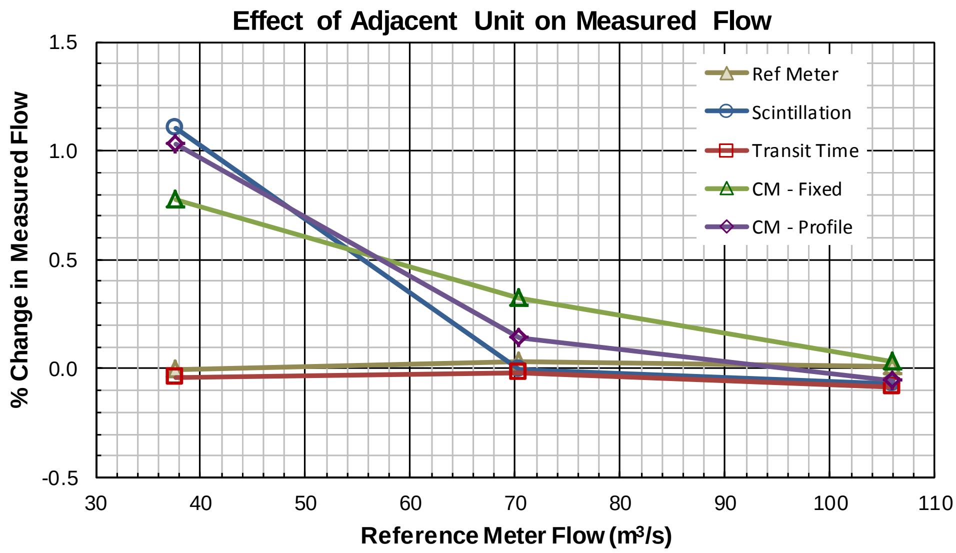


Figure 8 Effect of Adjacent Unit Operation

The range of flow rate ratios experienced during these tests is probably uncommon during normal operation of a plant, in which all units would be dispatched within their normal operating range. However, it does provide a measure of the sensitivity of the intake flow methods for multibay low head Kaplan units. In these units, flow rates in adjacent bays of the same unit can vary as much as 20%.

6. Comparison to the 1983 Tests

The results of this test are directly comparable to the data taken in 1983 using the same intake and penstock. The reference flowmeter data is common to both tests. Table 7 compares the data.

Table 7 Comparison to 1983 Test:
Average Difference from Reference Meter

1983 penstock methods	
Current meters mounted in penstock	-0.52%
Salt velocity	0.32%
Pressure time with transducer	-0.32%
Pressure time with Gibson Apparatus	-1.80%
Dilution - batch sample	-2.06%
Dilution - indirect flow through	-0.70%
Dilution - direct flow through	-1.59%
2009 intake methods	
Current meter fixed positions – CM fixed	1.06%
Current meter profiling – CM profile	1.07%
Scintillation – AS	0.44%
Acoustic time of travel in transition - ATT	0.09%

This data is plotted as a percent difference from reference flow in Figure 9. In Figure 10 a subset of this data is presented of only the more common methods used today. This plot shows that all the commonly-used methods differ from the reference flow by amounts in the range -0.6% to +1.25%. It is interesting that all the intake methods compared higher than the reference flowmeter, while the penstock methods were generally lower, except for Salt Velocity.

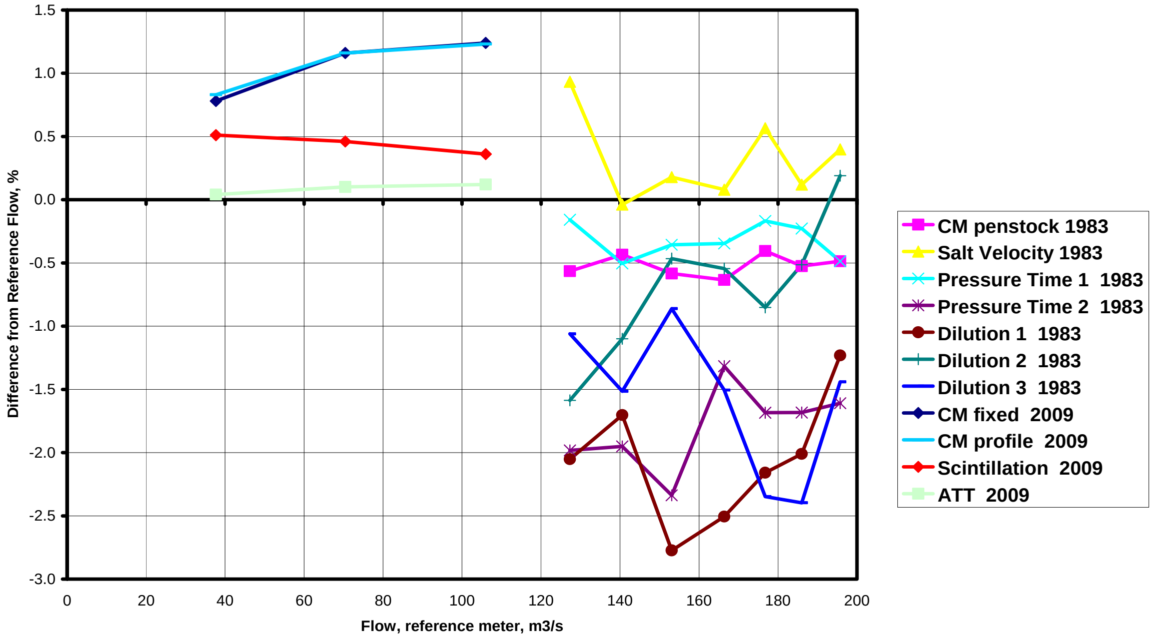


Figure 9 – Comparison of all data between 2009 and 1983

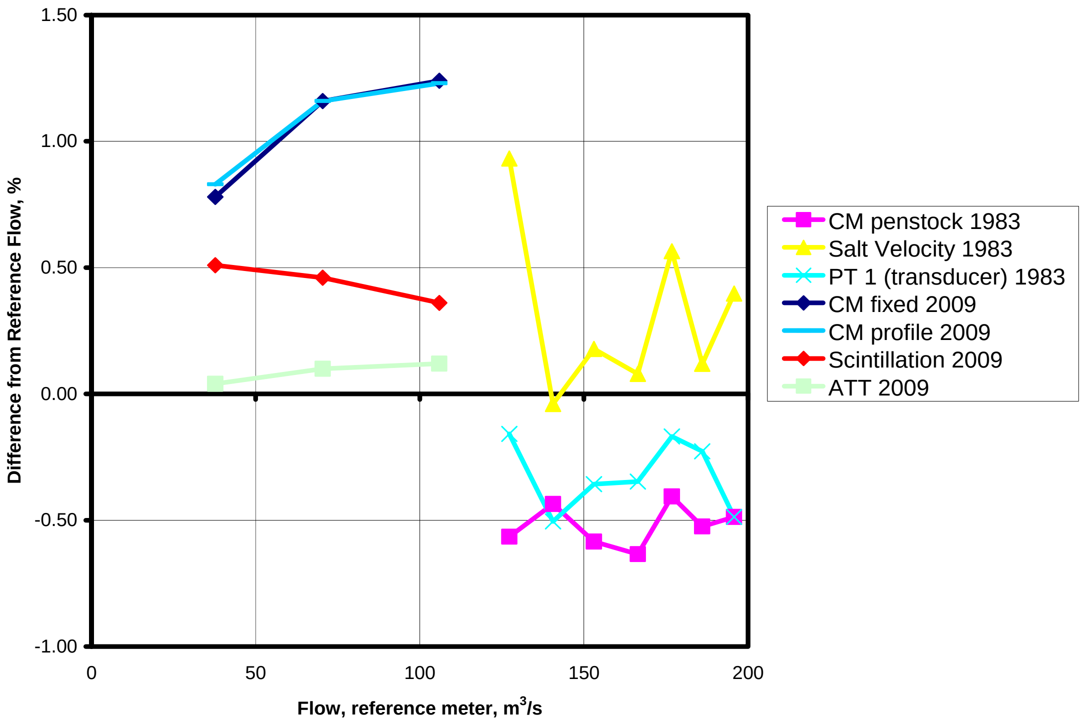


Figure 10 Comparison of commonly-used methods only

7. Conclusions

The principal results of the testing program are as follows:

1. The constancy of the hydraulic conditions over the course of four days of testing was excellent.

2. All three methods showed good agreement with the reference flowmeter. The average deviations from the reference flow ranged from less than 0.2% for the ATT method, about 0.5% for the AS method, and 0.8 – 1.2 % for the CM methods. In all cases the test methods yielded higher flowrates than the reference flowmeter.

3. All methods showed very good repeatability. At the 95% confidence level for the sample population, the ATT method showed less than 0.2% spread, the AS method ranged from 0.2 to 0.6 %, and the CM method ranged from about 0.4 to 0.6%.

4. The current meter fixed elevation and profiling methods yielded nearly identical results.

5. The secondary test program showed that changing the flow balancing unit from Unit 3 to Unit 2 (the adjacent units) had almost no effect on the reference meter or the acoustic transit time meter. Current meters and acoustic scintillation show about a 1% variance at the low flow, but showed virtually no influence of adjacent unit operation at the high flow.

6. The CFD model showed less than ideal agreement with measured velocities at the intake gate slot. This is almost certainly due to the fact the intake canal was not modeled. At the location of the ATT method, the agreement was much better, indicating that CFD modeling is likely capable of achieving realistic results so long as the upstream flow conditions are modeled in sufficient detail.

7. Comparison of the present results to 1983 data, using the same reference flowmeter, shows that all commonly-used methods differ from the reference flow by amounts in the range -0.6% to +1.25. All of the intake methods showed flows higher than the reference meter, while most of the penstock methods came out lower.

8. Based on the results of this comparative testing program, all three flow measurement techniques evaluated are worthy of further consideration for incorporation into the codes for hydroturbine efficiency testing. But further investigation is warranted.

8. References

1. **Munro, R.I. and Walsh, J.T.**, "Kootenay Canal Flow Comparison Test Using Intake Methods – Background and Goals", *Proceedings Hydro 2010*, Lisbon, Portugal 2010.

2. **British Columbia Hydro & Power Authority**, "Comparison of Acoustic and Other Flow Measurement Systems: Kootenay Canal Tests", Electric Power Research Institute, Palo Alto, California, USA, 1986.

3. **Performance Test Code 18**, "Hydraulic Turbines and Pump-Turbines", American Society of Mechanical Engineers, New York, 2002.

The Authors

John W. Taylor, P. Eng., graduated in Civil Engineering from the University of British Columbia, Vancouver, in 1973. He has worked for over 30 years at British Columbia Hydro in various capacities including 25 years as BC Hydro's Chief of Test for turbine field tests.

Charles W. Almquist, P.E., Ph.D., graduated in Engineering Science from the California Institute of Technology in 1973, received his Master's degree from the Massachusetts Institute of Technology, and a Ph.D. from the University of Texas at Austin. He was a Senior Technical Specialist at the Tennessee Valley Authority before founding Principia Research Corporation in 1992.

James T. Walsh, P.E., graduated with an electronics and computer engineering degree from University of Massachusetts, Massachusetts in 1979. He has worked for ORE, and Accusonic Technologies in various capacities including director..Recently he has started his own consulting firm, Rennasonic, that deals with the application of transit time meters, turbine performance testing and optimal dispatch of units at multiunit hydroelectric projects.