Kootenay Canal Flow Rate Measurement Comparison Test Using Intake Methods

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ABSTRACT

Despite the fact that Kaplan-type turbines with short, converging intakes are in widespread use, neither of the two test codes most commonly used in North America [1, 2] provide a practical method for measuring flow rate in this type of unit. Code-accepted flow rate measurement methods generally require relatively long sections of uniform penstock or a well-formed bellmouth inlet, which rarely exist with low-head Kaplan units.

This paper describes the execution and results of an ASME and CEATI-sponsored test comparing methods for flow rate measurement suitable for use in the short converging intakes which are typical of low-head hydro plants.

Three flow rate measurement technologies were evaluated – acoustic transit time, current meters, and acoustic scintillation. The former was installed in a non-uniform transition section, and the latter two in an intake gate slot. An existing code-accepted acoustic flowmeter 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 [1]. Furthermore it was conducted "blindly", meaning the flow rate data was not shared among test participants during testing.

The testing is described and the results of the comparison measurements are presented, including a statistical analysis that compares the intake method flow rate measurements with the reference meter at the 95% confidence level. A comparison is also made with the results of flow rate comparison tests sponsored by EPRI at Kootenay Canal in 1983 [3]. That test included only methodologies inside the penstock, including acoustic transit time, current meter, salt velocity, pressure time, and dye dilution. Because the same acoustic transit time flowmeter section was used for both tests, the results for all methods are directly comparable.

In addition to the intake flow rate measurement methods, a CFD model of the intake flow field was implemented, and comparison of the CFD model with the field measurements is briefly discussed.

Introduction

A cross-section view of a typical low-head Kaplan unit with a short converging intake is shown in Figure 1. Most code-accepted methods for the measurement of flow rate cannot be used in the short converging intakes typical of a Kaplan unit because there is not a sufficient length of uniform upstream water conduit to allow their use. The only method which is allowed is the current meter method, but the restrictions on its implementation to meet code requirements are so restrictive as to render its use impractical, although it is nonetheless often used in turbine tests. Recognizing the need for practical methods of flow measurement in short converging intakes, the American Society of Mechanical Engineers (ASME) Performance Test Code 18 (PTC 18) undertook to identify, demonstrate, and evaluate flow measurement technologies which would be practical to implement in this type of intake.

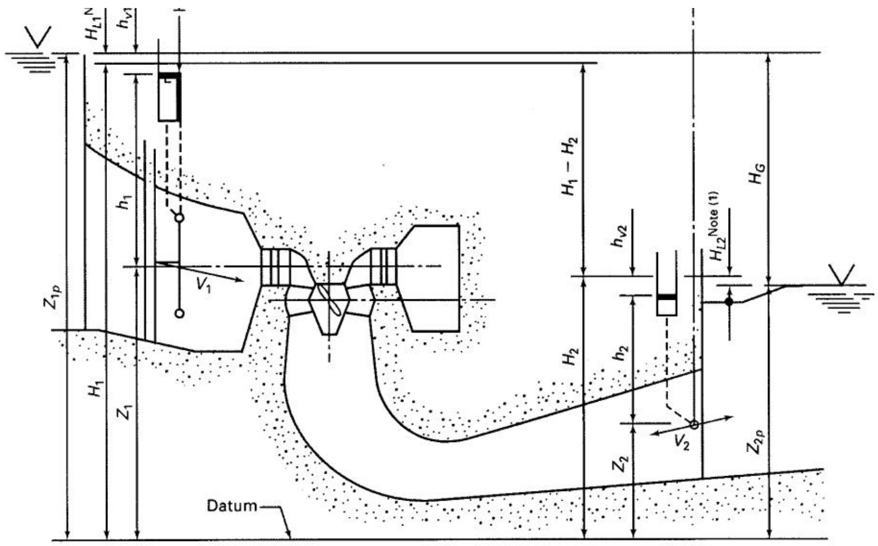


Figure 1. Typical Kaplan unit short, converging intake

Flow Rate Measurement Technologies and Supporting Investigations

Three technologies were identified by PTC 18 as being potentially accurate and practical enough for inclusion in the test codes:

- Current meters in an intake gate slot, with fewer restrictions than in the test codes.
- Acoustic transit time in the intake in a non-uniform section.
- Acoustic scintillation in an intake gate slot.

The first two methods are code-accepted for use in long, uniform penstocks, and have been applied to intakes. The third is relatively new, but has been installed in several low-head hydro plants.

Current Meters

The current meter method (CM) utilizes a row of current meters affixed to a moving frame which travels vertically in an intake gate slot. The rotational speeds of the current meters are measured at a number of fixed elevations in the flow field, and these rotational speeds are converted to velocities using calibrations for each meter. The resulting grid of point velocity measurements is numerically integrated over the flow area to yield the flow rate.

Although the normal mode of operation of the current meter frame is to position it at fixed elevations in the flow field, velocities can also be recorded continuously as the frame moves vertically, so that continuous velocity profiles can also be obtained and integrated. Both modes of operation were evaluated in the test program.

Current meter measurements were performed by Hydro-Québec of Montréal, Québec, Canada.

Acoustic Transit Time

The acoustic transit time (ATT) method employs pairs of ultrasonic transducers located diagonally on opposite boundaries of a water passage, as shown schematically in Figure 2. Each transducer can both transmit and receive an acoustic pulse. The pulse travels faster when it is travelling with the flow and slower when it is traveling against. The average velocity along the transducer path is a function of the path length, angle, and travel times for the two directions. In practice, two symmetrically installed transducer pairs are installed in a cross-path orientation, as shown in Figure 2. This arrangement, if properly oriented, can cancel out errors caused by cross (rotational) flows present downstream of bends. Transducer pairs are installed at multiple elevations in the conduit, and the flow rate is obtained by integrating the laterally-averaged velocities over the height of the conduit.

The acoustic transit time measurements were performed by Accusonic Technologies of West Wareham, Massachusetts, USA.

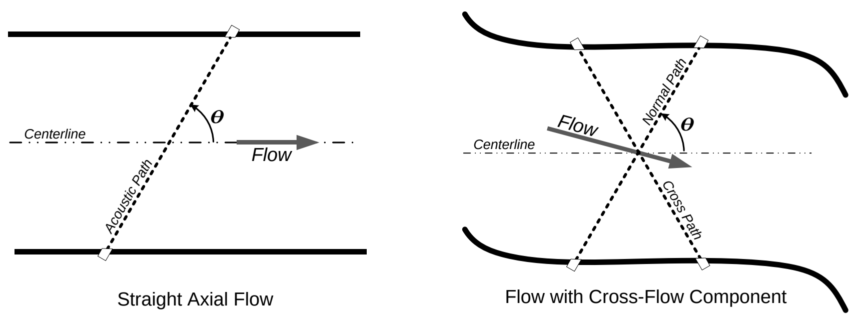


Figure 2. Acoustic Transit Time Flowmeter Principle of Operation

Acoustic Scintillation

The principle of operation of the Acoustic Scintillation (AS) method is illustrated in Figure 3. In its simplest implementation, two ultrasonic transmitters are placed on one side of the flow conduit and two receivers on the other. The transmitter-receiver pairs are separated by a known distance along the flow axis. Ultrasonic pulses are sent from the transmitter and picked up by the receiver. Turbulence in the flow causes scattering of the transmitted sound, so that the amplitude at the receiver varies randomly (referred to as "scintillation"). Because the distance between transducer pairs is small, the turbulence causing the scintillation changes very little as the flow moves between the two paths, and the amplitude variations at the downstream path are very similar to those of the upstream path, but shifted by a time difference. The time difference is determined by performing a cross-correlation analysis of the two signals. The average velocity in the plane of and perpendicular to the two paths is given dividing the path separation by the correlation time.

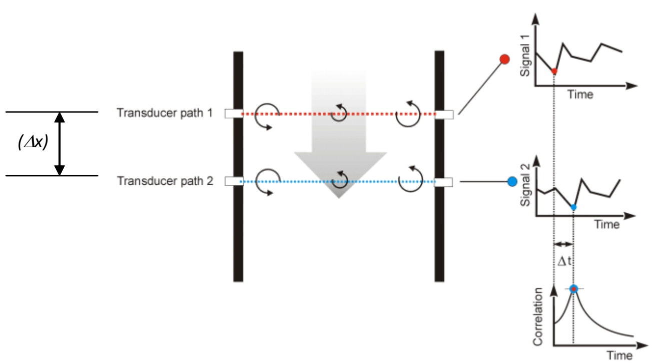


Figure 3. Acoustic Scintillation Flowmeter Principle of Operation

In practice, three paths in a triangular arrangement are used at each measurement level, allowing the longitudinal and vertical components of the velocity to be measured. The transducer sets are mounted at multiple elevations on a frame which is inserted into the intake gate slot. The flow rate is determined by vertical integration of the measured laterally-averaged velocities. The acoustic scintillation measurements were performed by AQFlow, Victoria, British Columbia, Canada.

Supporting Measurements

The BC Hydro Test Team performed other measurements that would normally be a part of a turbine efficiency test, including operation of the reference flowmeter, measurement of forebay and tailwater elevations, power output, Winter-Kennedy flowmeter differentials, and turbine inlet pressure. They also made independent measurements of the reference meter flow section geometry.

Computational Fluid Dynamics

In addition to the flowrate measurement methods, a finite-element numerical model of flow patterns in the intake was commissioned, with the objective of both assessing and improving the state of the art of computational fluid dynamics when used in intakes. The CFD modeling was performed the Lucerne University of Applied Sciences, Lucerne, Switzerland.

Selection of Test Site

Unit 1 at BC Hydro's four-unit Kootenay Canal Generating Station was identified as being nearly ideal for a comparative test program. Although the plant is not low head, the intakes, shown in Figure 4, are located in a feeder canal, and are of a low-head design with the essential features of a short, converging intake:

1. The intake is short, with no appreciable upstream length to condition the flow to a fully-developed profile
2. The intake is rectangular at the entrance
3. The intake geometry is non-uniform along the flow path
4. The intake gate slots are accessible from the head deck
5. Relatively low velocities typical of a low-head intake are achievable

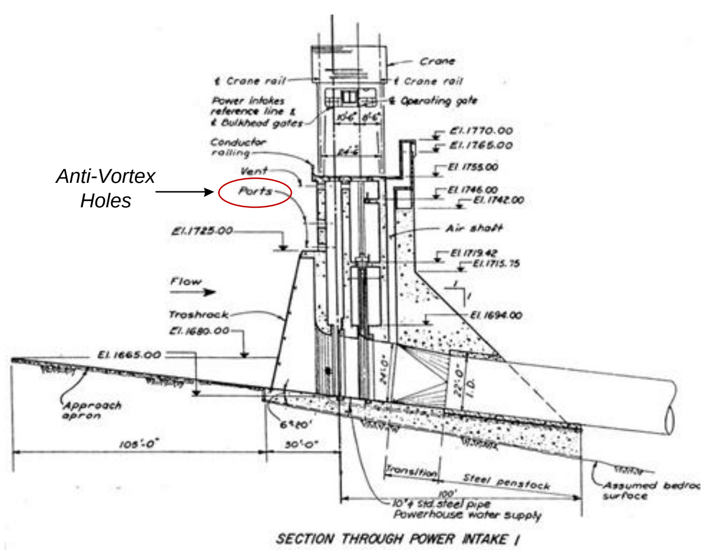


Figure 4. Unit 1 Intake at Kootenay Canal

A significant advantage of Kootenay Canal's Unit 1 is that it has a code-accepted acoustic transit time flowmeter section in its 6.7 m diameter penstock, about 22 diameters downstream of the intake. This flowmeter served as a "reference" flowmeter against which the other methods could be compared. This flowmeter section was used in another comprehensive series of comparative flow tests conducted in 1983 by the Electric Power Research Institute (EPRI), offering the further advantage of allowing comparison of those results to results from this test program. Another significant advantage was the willingness of BC Hydro and the Kootenay Canal plant manager to host these tests.

Test Program and Unit Operations

A detailed test plan was developed and, after a number of iterations, was agreed to by all organizations participating in the tests. Two groups of tests were defined:

1. Multiple tests at selected flow rates to assess accuracy and repeatability (primary program)
2. Evaluation of effect of adjacent unit operation (secondary program)

A primary consideration in developing the test program was to ensure that sufficient data was collected to allow for robust statistical analysis of the data. This consideration resulted in the design of a test program with many repeat runs at three flow rates. The three flow rates were chosen to correspond to a range of velocities typically found in low head intakes, which meant that the unit was operated below 50% gate for the entire test program.

A summary of the nominal primary test program is shown in Table 1. Tests are conducted at flow rates corresponding to axial velocities at the maintenance gate slot of approximately 1.0, 2.0, and 3.0 m/s. Twelve separate flow rate measurements, conducted in groups of four, are performed at each of the three flow rates. For each day, each of the three flow rates is measured in blocks of four consecutive tests. The order of the flow rates changes for each day. The test runs are made in blocks of four at a given condition allows for the back-to-back repeatability of each method to be assessed. With each flow rate being measured each day, the day-to-day repeatability can be assessed. Finally, for each flow rate, twelve tests are run, allowing for good statistical analysis of the data. The actual test program did not exactly follow the design sequence, due to operational and time constraints, but all tests were performed.

Table 1. Primary Test Program

	Nominal Intake Velocity (m/s)		
	1.1	2.0	3.0
	Nominal Discharge (m^3/s)		
	38.7	72.4	108.8
	Nominal Gate Opening (%)		
	21.6	35.4	49.1
Run Number	**Day 1**		
	P1	P5	P9
	P2	P6	P10
	P3	P7	P11
	P4	P8	P12
	Day 2		
	P17	P21	P13
	P18	P22	P14
	P19	P23	P15
	P20	P24	P16
	Day 3		
	P33	P25	P29
	P34	P26	P30
	P35	P27	P31
	P36	P28	P32

The secondary test program consisted of making back-to-back runs, alternating between Unit 2 being on and off, for each of the three flow rates.

Care was taken during testing to ensure constancy and repeatability of hydraulic conditions. To minimize disturbance and wave action in the canal, and to keep the gross head as constant as possible, total plant discharge was kept nearly constant by balancing the flow rate changes on Unit 1 with corresponding changes on either Unit 2 or Unit 3 (Unit 4 was out of service at the time of the tests). Unit 3 was the balancing unit for the primary test program. Units 2 and 3 alternated as balancing units for the secondary test program. Gate openings for setting the three flow rates were set by the use of machined gate blocks, so that gate openings could be precisely maintained and repeated. The Unit 1 was maintained at or near unity power factor for the duration of the tests.

Installation and Preparations

The locations of the three flow measurement methods being evaluated are shown in Figure 5. Both the current meters and acoustic scintillation methods were located in the upstream (maintenance) gate slot. The acoustic transit time method was in the transition section between the rectangular intake and the circular penstock.

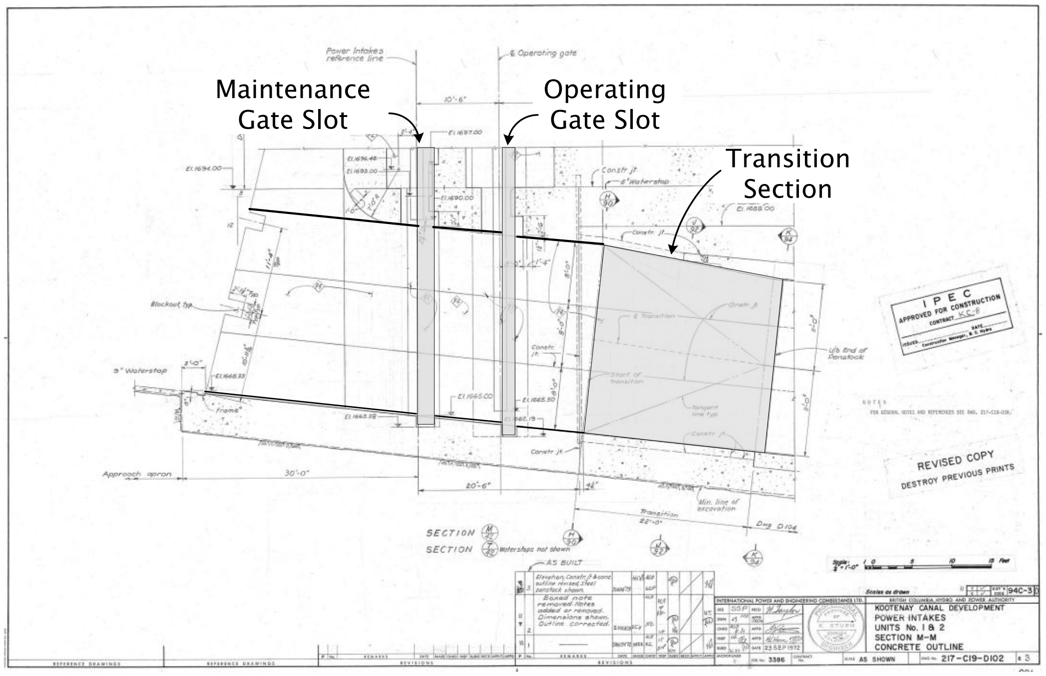


Figure 5. Flow Rate Measurement Locations

Both the current meter and scintillation methods occupy an intake gate slot, but only one intake gate slot was available for the installation of test equipment at Kootenay Canal. An innovative gate slot frame was designed to accommodate both the fixed scintillation transducers and the moving current meter frame at the same time, allowing all test flowmeters to be measured simultaneously. This had the benefits of speeding up the test program and improving the quality of the results. A photograph of this gate slot frame being installed is shown in Figure 6. The current meters are seen near the top of the frame, and one set of the scintillation transducers are seen on the inside of the far leg. The frame was designed with enough stiffness that no bottom cross-member was needed. The inside faces of the legs of the frame are flush with the intake walls. The interiors of the legs are used to convey the AS transducer cables to processing electronics in canisters on the cross members.

Figure 6. Current Meter and Acoustic Scintillation Frame

Access to the acoustic transit time flowmeter installation and the reference flowmeter installation was through a one-meter access flange in the penstock. A photograph of the acoustic transit time flowmeter during installation is shown in Figure 7.

The Chief of Test and the three flowrate measurement organizations were housed in trailers on the intake deck. The BC Hydro test team was located in the control room. During tests, the test organizations were isolated from each other, so that no organization knew any of the flowrate results, other than their own, as the testing progressed.

Figure 7. Installation of Acoustic Transit Time Flowmeter

The primary test program was conducted from October 21-23, 2009. The secondary test program was conducted on October 24. All of the nominal primary tests were conducted, although operational and time constraints dictated that some of the four-test sub-blocks be conducted in a different order than planned.

A typical test run required 20 minutes to complete. It took about an additional ten minutes to obtain the flow results from all test organizations, during which time the unit was moved to the next operating point, if needed.

Analysis Methodology

Objectives

The objectives of the analyses presented in this paper are to characterize for each flow rate measurement method:

1. The difference between the method and the reference flowmeter, determined by comparing the mean values;
2. The repeatability of the method, determined from the 95% confidence intervals of the test data; and
3. The test uncertainty associated with the method, evaluated from the 95% confidence interval of mean.

These objectives are evaluated for each aggregate flow rate (12 runs), and for the entire test program (36 runs). The statistical analyses apply to the primary test program only. The secondary test program is instead evaluated on the basis of back-to-back test runs, because not enough data is available for meaningful statistical analysis.

The analyses presented here are primarily based on normalized flow rates expressed as a percent absolute deviation from the reference flowmeter. The percent deviation of a given flow rate measurement from the reference flowmeter is computed at each test point by

$$\%\, Deviation = \frac{Q_i - Q_{Ri}}{Q_{Ri}} \times 100$$

where

Q_i is an individual flow rate measurement

Q_{Ri} is the corresponding reference flowmeter flow rate

Working with the percent deviations allows comparative analyses for a given method at each of the three flow rates and over the entire test program, encompassing all flow rates. Additionally, because flow rate ratios are evaluated, correlations from run to run due to real changes in flow rate will tend to cancel, so that the real variability in the method is evaluated.

Basis for Statistical Analyses

The statistical analysis characterizing a given flow measurement method without reference to any other method is illustrated in Figure 8, which illustrates the 95% confidence interval of the test data (sample) and the 95% confidence interval of the computed mean of the test data. The former interval is a measure of the repeatability of the method. The latter is a measure of the confidence in the averaged test result for the method. In this figure, the following quantities are defined:

$\bar{Q}$ = average flow rate

s_Q = standard deviation of the sample

$s_{\bar{Q}} = s_Q/\sqrt{n}$ = standard deviation of the mean

n = number of samples

$t_{0.025}$ = Student's t-statistic at the 2.5% level with n-1 degrees of freedom

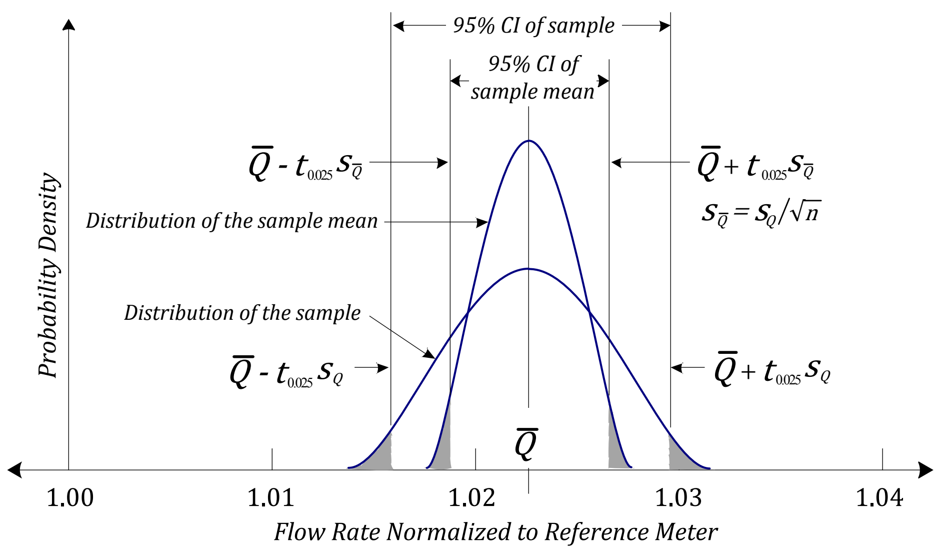


Figure 8. Definition Sketch for Statistical Analyses

The 95% confidence interval defined here is a two-sided confidence interval about the mean.

When comparing the results for a given method to a standard method (in this case, the reference flowmeter), the basis of the statistical analysis is illustrated in Figure 9. Because the test results tended show a bias towards higher flow rates than those measured by the reference meter, it is appropriate to evaluate a one-sided confidence interval as shown in the figure. In the example shown in the figure, the true mean of the flow meter being assessed is, at the 95% confidence level, within about 2.6% of the reference meter mean.

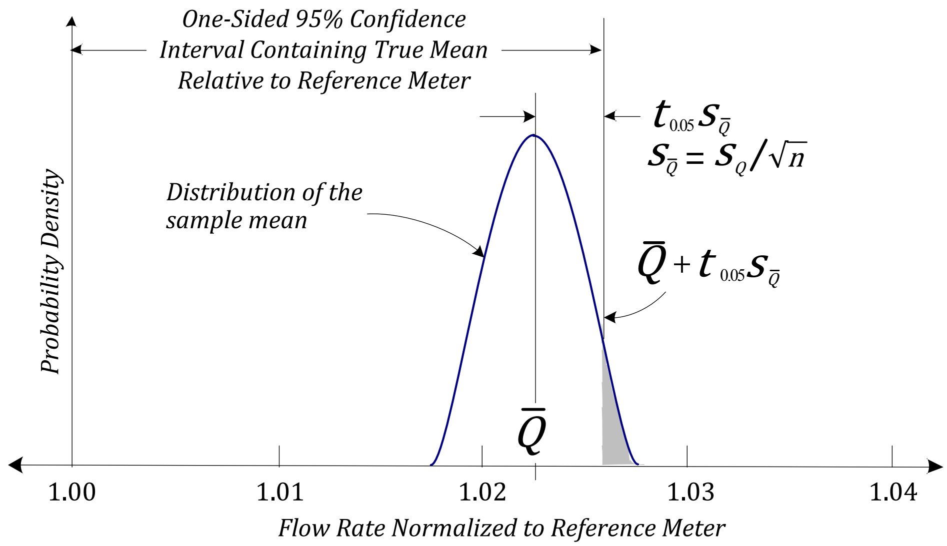


Figure 9. Evaluation of Test Uncertainty at the 95% Confidence Level

Results

Repeatability of Test Conditions

The repeatability of the test conditions for each of the three flow rates and each of the three blocks (sub-groups of four consecutive tests) for each flow rate is presented in Figure 10, which shows the percent deviation of the reference flowmeter flow rate from the average of each block, and the range of deviations from the average over all blocks.

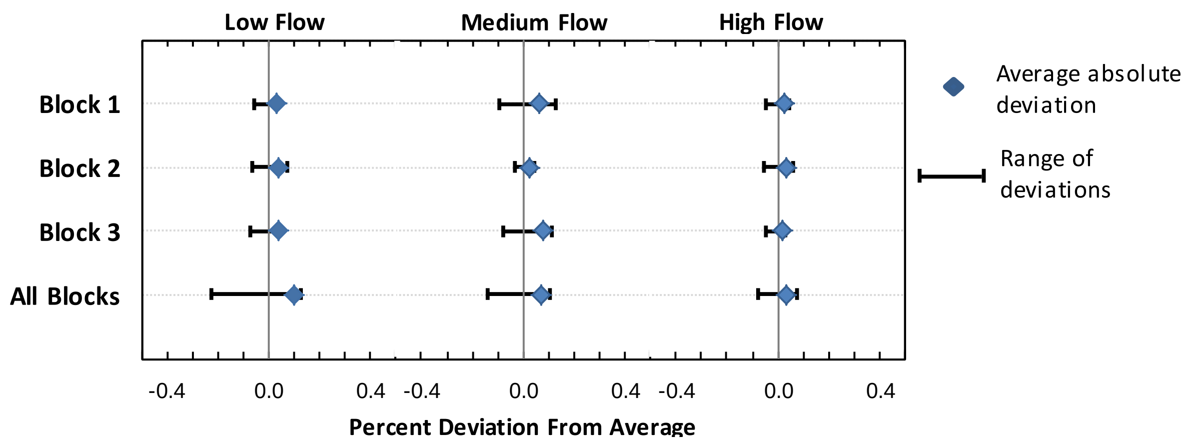


Figure 10. Repeatability of Test Conditions

The flow rate repeatability was quite good. Within flow blocks, the range of flow rates was typically within ±0.1% of the average for the block. Maximum deviations for each flow ranged from about 0.25% at the low flow to 0.1% at the high flow.

Average Deviations from Reference Meter

The average deviations of the flow rates from the reference flowmeter are shown graphically in Figure 11. This figure shows that the ATT method is the closest to the reference flowmeter, on average being higher than the reference by about 0.1%, with very little change with flow rate. The AS method average flow rate is about 0.4% higher than the reference flowmeter, and also exhibits little variability with flow rate. The two current meter methods track each other very closely, and range from about 0.8% higher than the reference flowmeter flow rate at the low flow rate, to about 1.2% higher at the high flow rate.

The Winter-Kennedy method, though not one of the intake methods under test, is shown because it a commonly-used flowmeter. It exhibits the greatest deviation from the reference flow rate, ranging from about 3.25% at the low flow rate to about 1.5% at the high flow rate. It should be noted that the W-K results are based on the 1983 flow rate calibration, which was performed entirely at flow rates higher than the highest flow rate tested here. The Winter-Kennedy results are discussed in more detail in the full report of these tests [4].

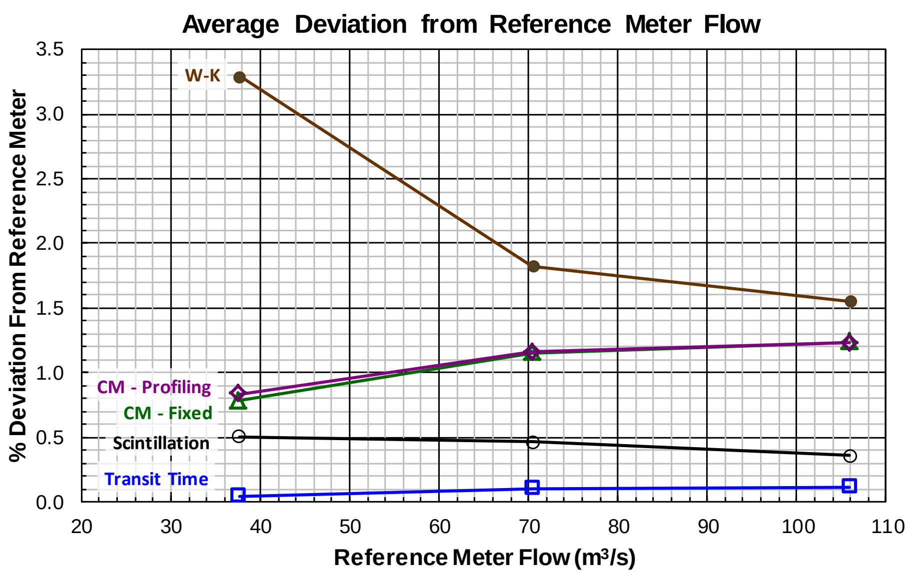


Figure 11. Average Deviation from Reference Meter Flow

95% Confidence Intervals about the Mean for Each Method

The variability of each method, expressed as the 95% two-sided confidence intervals for the measured flow rates at each reference flow rate is shown graphically in Figure 12. The ATT method shows the least variability (better repeatability) at all flow rates, with a 95% confidence interval (CI) of about ± 0.4%. The other methods have a 95% CI of about 0.6% at the low flow rate, and generally trend to smaller CI values at higher flow rates. At the highest flow rate, the AS, ATT, and WK methods exhibit 95% CIs of about 0.2%, while the CM methods are about 0.45%.

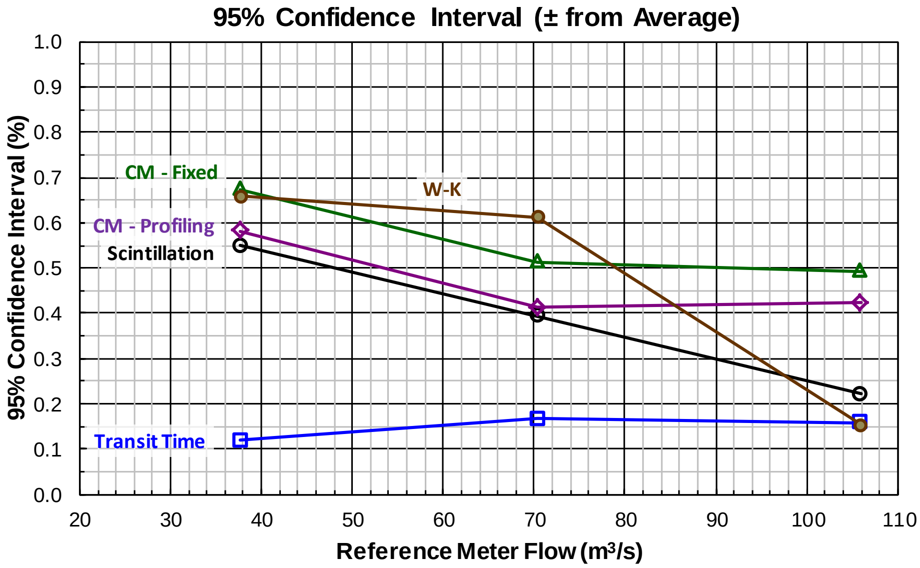


Figure 12. Variability of Test Data for Each Method

95% Confidence Intervals of the Sample Mean for Each Method

The 95% confidence intervals (CIs) of the sample means are summarized in Table 2. These confidence intervals are a measure of how well the true means of the methods have been determined. The table shows that all of the intake flow measurement methods have very tight confidence intervals of the means associated with them, with a maximum CI at any given flow rate being less than 0.2%. When the statistic is computed for all flowrates for a given method, the maximum CI is 0.11% for the intake methods. Note that the CIs for the "all flowrates" case tends to be smaller beause there are more data points, which reduces the CI of the sample mean. These results indicate that the test program resulted in sufficient sample sizes and repeatable conditions that the true means of the measured flowrates have been determined with a high degree of confidence.

Table 2. Table 95% Confidence Interval of the Sample Mean

	95% CI of Sample Mean (± from mean)				
Ref Meter Flow	AS	ATT	CM - Fixed	CM - Profile	W-K
m^3/s	%	%	%	%	%
37.7	0.16	0.03	0.19	0.17	0.19
70.4	0.11	0.05	0.15	0.12	0.22
106.0	0.06	0.05	0.14	0.12	0.05
ALL	0.06	0.02	0.11	0.09	0.33

Deviation from the Reference Flowmeter

The deviations from the reference flowmeter at the 95% confidence level as defined in Figure 9 are shown in Figure 13. The average deviation and the deviation at the 95% confidence level computed from data over all flow rates are summarized in Table 3.

The acoustic transit time method showed the best agreement with the reference meter, with a deviation at the 95% CI of about 0.1% at all flow rates. Acoustic scintillation ranged from about 0.6% at the low flow rate to about 0.5% as the high flow rate. Current meters, both in fixed and profiling modes, closely tracked each other, and were within 1% of the reference flowmeter at the low flow rate, increasing to about 1.3 % at the high flow rate.

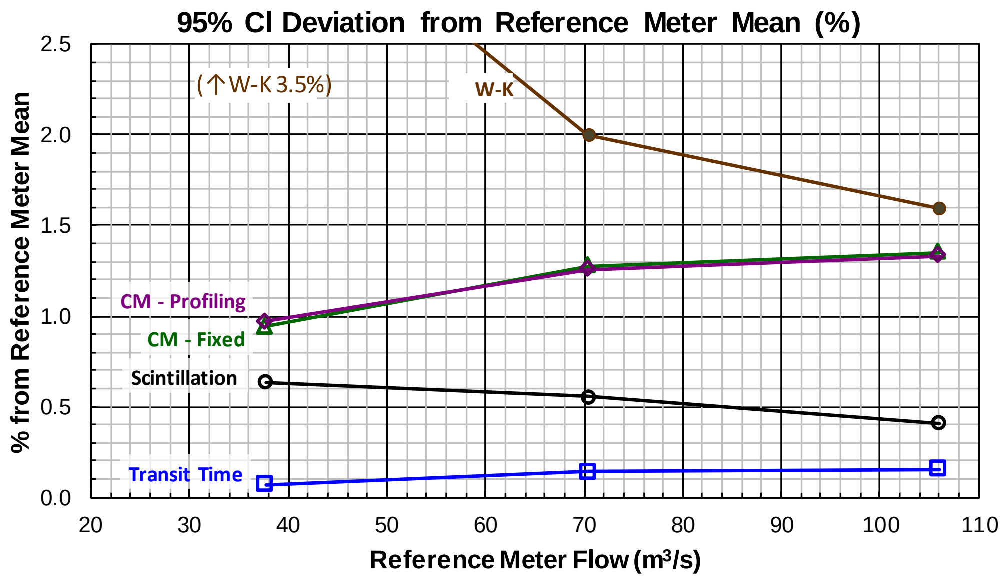


Figure 13. Deviations from the Reference Meter at 95% Confidence

When evaluated over the entire range of flow rates, all methods were within 1.15% of the reference meter at the 95% confidence level, as shown in Table 3.

Table 3. Deviations From Reference Flowmeter

Intake Flow Rate Measurement Method	Average Deviation From Reference Flow Meter	Deviation From Reference Flowmeter at 95% CI
Acoustic Scintillation	+0.44	+0.50
Acoustic Transit Time	+0.09	+0.11
Current Meters - Fixed	+1.06	+1.15
Current Meters - Profiling	+1.07	+1.15

The average deviations and the deviations from the reference flowmeter at the 95% confidence level are very close, the maximum difference between the two being less than 0.1%. This can be attributed to the fact that all methods showed very good repeatability and the testing program was designed to allow for robust statistical analysis.

Effect of Adjacent Unit Operation on Measured Flow

As discussed earlier, the objective of the secondary test program was to evaluate the effect of adjacent unit operation on the flow rate measurement methods. During the primary program, Unit 3 was always 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. The results are summarized in Figure 14. Note that the balancing flowrate is also shown on the figure. Though not shown here, the reference flowmeter was essentially unaffected by the adjacent unit operation, with a maximum change of only 0.04%.

The transit time flowmeter also showed very little sensitivity to adjacent unit operation over the range of flow rates, the maximum effect being less than 0.1%. The scintillation and two current meter methods showed greater sensitivity, ranging from about 1% at the low flow rate to less than 0.1% at the high flow rate.

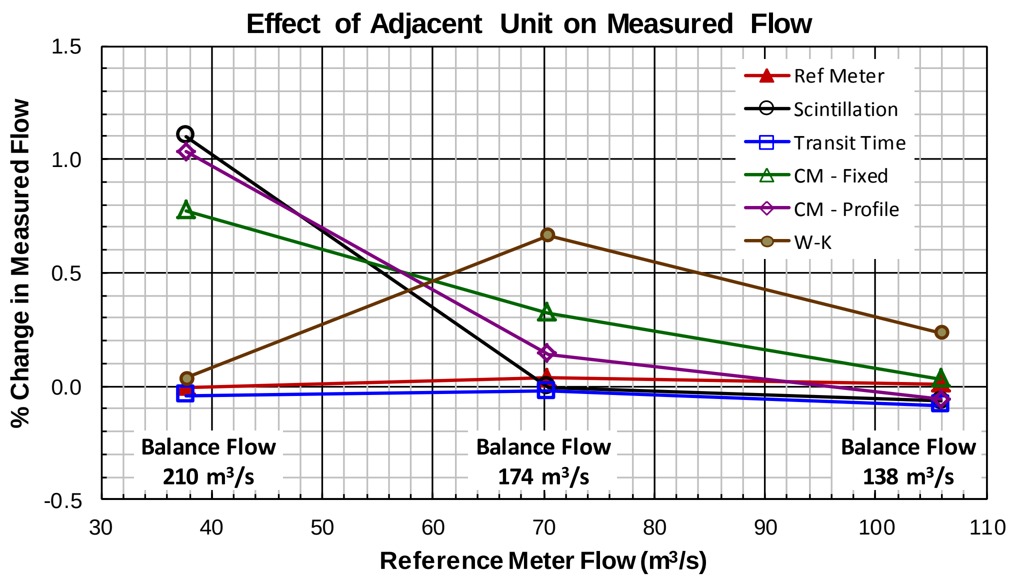


Figure 14. Effect of Adjacent Unit Operation

The greater sensitivity of the AS and CM methods to adjacent unit operation at the lower two flow rates is probably explained by the fact that at these low flow rates, the flow rate of the balancing unit was significantly greater than the unit under test. At the low flow rate, the balancing unit flow rate was 5.5 times that of Unit 1. At the medium and high flow rates, 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 rate, and less significant at the high flow rate. When the balance unit flow rate was of the same magnitude as the Unit 1 flow rate (high flow rate case), there was virtually no effect on the measured flow rate for any of the intake methods.

In typical multi-bay Kaplan intakes flow rates in adjacent bays of the same unit can vary as much as 20%. The high flow rate case, for which the adjacent unit flow rate was about 30% higher than the Unit 1 flow rate, most closely matches the flow rate differences likely to be experienced in normal operations and testing. At this flow rate, all intake methods showed very little effect from adjacent unit operation.

Comparison with the 1983 EPRI Tests

The results of this test are directly comparable to the EPRI-sponsored 1983 test [3] using the same intake and penstock. The reference flowmeter data is common to both tests. Figure 15 compares the results of the two sets of tests. For the 1983 tests, only the pressure-time and penstock current meter results are shown, because these are the only of the tested methods still in common use today (other than the acoustic penstock flowmeter, which serves as the common reference flowmeter).

The figure shows that all methods were within -0.6% to + 1.25% of the reference meter flow. It is interesting to note that the intake methods are all higher than the reference meter flow rate, while the penstock methods were lower.

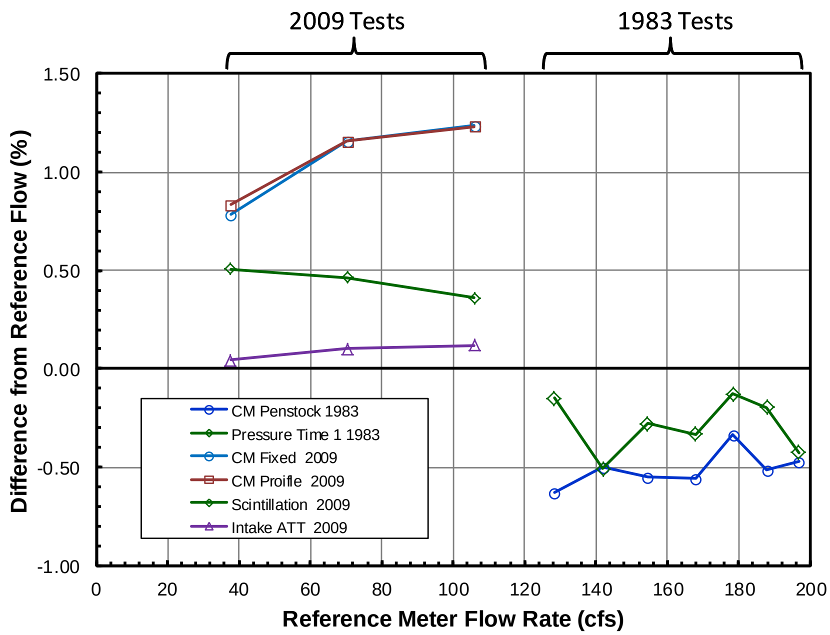


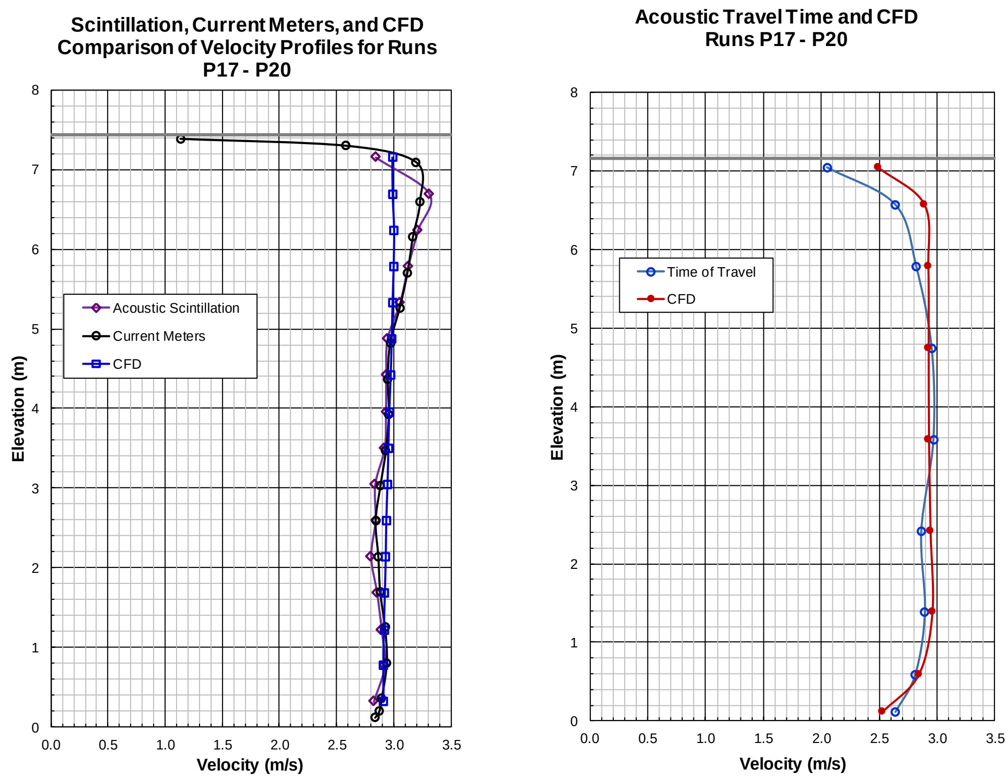
Figure 15. Comparison with EPRI 1983 Tests

Computational Fluid Dynamics Modeling

Figure 16(a) shows the comparison of the CFD velocity profiles with the intake gate slot profiles (scintillation and current meters). Figure 16(b) shows the comparison with the transit time meter installed in the intake transition section. At the intake gate slot, the agreement between the CFD and the measurements is relatively poor, with the CFD method showing very little variation in the velocity profile from top to bottom. The likely reason is that the trapezoidal intake canal was not modeled, and thus velocity variations in the channel that directly influence the flow field in the intake would not have appeared in the CFD model.

The comparison with the transit time meter installed in the transition section is more favorable. The CFD model tracks the general shape of the measured profile, showing the greatest difference near the top. The improved agreement is likely due to the fact that the CFD model did incorporate the intake geometry upstream of the transition section where the ATT flowmeter was installed, and thus the influence of the intake section on the velocity profile was modeled.

It is likely that the CFD model would have shown much better agreement had the trapezoidal intake channel been at least partially modeled, but including this free-surface flow would have come at the cost of greater computational complexity expense. The fact that reasonably good agreement was obtained in the transition section supports this conclusion. CFD shows promise for modeling the flow in short converging intakes, so long as approach conditions are properly accounted for.



(a) (b)

Figure 16. Comparisons with CFD results

Conclusions

The principal results of the testing program are as follows:

1. The constancy of the hydraulic conditions and repeatability of the flow rates 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 rate ranged from less than 0.2% for the ATT method, about 0.5% for the AS method, to 0.8 – 1.2 % for the CM method. In all cases the test methods yielded higher flow rates 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% confidence interval, the AS method ranged from ±0.6% to ±0.2 %, and the CM method ranged from about ±0.6% to ±0.4%.
4. In comparing the measured flow rates to the reference flowmeter at the 95% confidence level over the entire testing program, the ATT method was generally within about 0.1%, the AS method within 0.5%, and the CM method within about 1.2%.
5. The current meter fixed elevation and profiling methods yielded nearly identical results.

6. The secondary test program showed that changing the flow balancing unit from Unit 3 to Unit 2 had almost no effect on the reference flowmeter or the acoustic transit time meter. Current meters and acoustic scintillation show about a 1% change at the low flow rate, but showed virtually no influence of adjacent unit operation at the high flow rate. The high flow rate case, for which the balancing flow rate was about 30% higher than the Unit 1 flow rate, is the most realistic in normal operations, since short multi-bay converging intakes have variations between bays on the order of 20%, even when adjacent units are equally loaded.
7. The CFD model showed relatively poor agreement with measured velocities at the intake gate slot. This is almost certainly due to the fact that 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.
8. Using the reference flowmeter as the basis for comparison, the commonly-used methods in the 1983 EPRI tests and those considered here differ from the reference flow rate by about -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.

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