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CALIBRATION OF ACOUSTIC FLOW METERS WITH VOLUMETRIC FLOW MEASUREMENTS

by

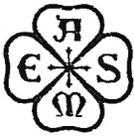
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ABSTRACT

EPRI sponsored a study to compare different methods of measuring flow in performance testing of hydroelectric and pumped storage plants. This paper presents a comparison between flow measurements made using the acoustic and volumetric methods at the Grand Coulee and Raccoon Mountain sites. The results of the comparison are used to determine uncertainty estimates for the acoustic flow meter installations at each site. The difficulties and limitations of applying the volumetric method to performance testing are also discussed.

INTRODUCTION

The Electric Power Research Institute (EPRI) sponsored a study to compare different methods of measuring flow in performance testing of hydroelectric and pumped storage plants (1). The primary objective of this study was to verify the use of acoustic flow meters under performance test conditions. As part of this study, the acoustic method was compared to volumetric flow measurements made at the U. S. Bureau of Reclamation's Grand Coulee Pumping Generating Unit P/G 9 (2) and the Tennessee Valley Authority's Raccoon Mountain Pumped Storage Unit 1. (3)

The goal of the EPRI study was to calibrate the acoustic flow meters in situ against a reference flow measurement with as small an uncertainty as possible. For piped sizes less than 4 ft. (1.2 m) in diameter, flow meter calibrations with an uncertainty of 0.5-1.0% are possible, but these smaller size flow meters can be calibrated against a weight or volumetric tank under laboratory conditions. At Grand Coulee and Raccoon Mt. the diameters of the acoustic flow meters are 12 ft (3.7m) and 10 ft (3.0m), respectively, and thus too

large for laboratory calibrations. It was hoped at the outset of this study that the volumetric measurements at the two sites would provide calibrations with uncertainties equivalent to laboratory conditions. This was possible at the Raccoon Mt. site, but at Grand Coulee the volumetric technique was subject to adverse effects.

The International Electrotechnical Commission (IEC) performance test codes (7) include the volumetric method as an accepted method of flow measurement. A secondary objective of this paper is to discuss the difficulties and limitations of applying the volumetric method to performance testing.

There were significant differences in both the acoustic meter configurations and the volumetric techniques used at each site. Therefore, each test was considered a separate calibration. The format of this paper will be to discuss the calibration theory and then discuss the test procedures and results at each site separately. Finally, general conclusions drawn from both sites are summarized at the end of the paper.

CALIBRATION METHOD

The intent of these tests was to calibrate the acoustic method with the volumetric method. The volumetric method was expected to measure the true flow rate within an interval of uncertainty. The uncertainty for both the volumetric and acoustic measurements was estimated for each test run.

In this paper the term "systematic uncertainty" (U_s) refers to uncertainties due to known inaccuracies in the technique or instruments used. This is equivalent to what Kline (4) has called "bias". The term "random uncertainty" (U_r) refers to uncertainties of unknown origins which are derived from the

statistical analysis of the measurement results. This is equivalent to Klines "precision". Unless otherwise stated, all random uncertainty values reported herein are $\pm 95\%$ confidence limits. The term "total uncertainty" (U_t) is defined as the square root of the sum of the squares of the random and systematic uncertainties:

$$U_t = (U_s^2 + U_r^2)^{1/2} \quad (1)$$

This definition of total uncertainty assumes that random error and systematic error are independent. This assumption may not always be true since some sources identified as systematic uncertainty may contribute to random uncertainty. Thus equation (1) may often provide a conservative estimate of total uncertainty.

The difference between the flow rate (or change in volume) measured with the two methods was then compared to the estimated total uncertainty for the volumetric method. This was done for each run and for the mean of all the runs at each site. If the difference was less than the volumetric uncertainty then no statement could be made about the bias in the acoustic meter. If the difference between the methods ($D_{v,a}$) was greater than the volumetric uncertainty then the acoustic meter bias E_a can be computed by:

$$E_a = \pm (D_{v,a}^2 - U_{t,v}^2)^{1/2} \quad (2)$$

where $U_{t,v}$ = the volumetric uncertainty

However, if the difference between two flow measurement methods is less than the square root of the sum of the squares of the total uncertainties of the two methods,

$$D_{v,a} \leq (U_{t,a}^2 + U_{t,v}^2)^{1/2} \quad (3)$$

then the originally estimated uncertainty for the acoustic method was sufficiently large to explain this bias.

It should be noted that this analysis is dependent on the specific site installation. However, if the a priori uncertainty analysis was sufficient to explain the bias then one can have some confidence that a similar uncertainty analysis will be correct for a similar meter configuration at another site.

GRAND COULEE TEST

Test Procedure. Two acoustic meters were installed at the Grand Coulee site by Westinghouse Electric Corp., Oceanic Division (LEF) and Ferranti, O.R.E. (ORE), respectively. Each meter was configured with four acoustic paths in each of two measurement planes. The ORE measurement section was two pipe diameters downstream of a bend in pump mode while the LEF meter was eleven diameters downstream of the same bend. In generating mode, the distances downstream from a bend were reversed.

The volumetric test at the Grand Coulee was performed in pumping mode using the feeder canal as the volumetric reservoir. The canal is approximately 100 ft (30 m) wide by 8,000 ft (2430 m) long with a surface area of 20 acres. At the start of the test the average water depth was approximately 4 ft (1.2m). The canal cross section was surveyed at 500 ft (152 m) increments to generate a table of volume versus elevation data at 0.1 ft (3 cm) increments of elevation. The water surface elevation in the canals was measured with six 0.25% accuracy pressure transducers spaced along the entire length of the canal (see Figure 1). These were recorded by a common data acquisition system at the rate of approximately once per second.

In the planning of this volumetric test, it was intended to pump a volume of 14,000,000 cubic feet (396,000 m³) to produce a 15 ft (4.6m) increase in water level in a single test run which would have lasted over 2 hours. However, after 56 minutes of pumping, the first test run was stopped due to vibrations in the salt velocity apparatus which had been installed in the penstock. Upon correction of the problem, a second run was conducted for a period of 1 hour and 15 minutes.

Results. It was intended to compute mean water levels in the canal at time intervals ranging from 5 min. to 2 hrs. during the test and then use these to compute average flow rates for each time interval to be compared to the average acoustic flow measurements for the same interval. However, during the first run the start-up surge produced a 2 ft (0.6 m) bore which traveled the length of the canal and did not significantly damp out for approximately one-half hour. A similar but smaller surge occurred at the start of the second run. At the end of each test another surge wave was generated in the canal which took several hours to damp out.

The presence of a surge wave at the start of each test was expected, however, persistence and magnitude of the reflected waves was not anticipated. Attempts were made to process the transducer recordings to eliminate the effects of the surge waves, but the elevation difference between stations was as much as 0.8 feet even after the bore had damped and the distances between stations were too large to make accurate assumptions about the surface contour between them. The significant elevation difference that existed across the wave fronts made it impossible to obtain incremental flow rate measurements.

As a result of the surge waves, it was only possible to obtain a single value for volume change for each complete test run. This was done by taking the difference between water levels prior to the start of each test and the final water level after the wave had damped out at the end of each test. Average flow rate values were computed from the volumetric results by dividing the volume differences by

TABLE 1
Grand Coulee Volumetric Test
Comparison of Flow Rates

Run No. 1 Avg. Volumetric Flow = 1673.8 cfs

Westinghouse LEF		Ferranti, ORE	
5 Min. Avg. Flow (cfs)	% Dif. LEF/Vol.	5 Min. Avg. Flow (cfs)	% Dif. ORE/Vol.
1690.4	0.99	1697.8	1.43
1687.2	0.80	1696.9	1.38
1688.8	0.89	1698.2	1.46
1690.3	0.98	1699.7	1.55
1688.0	0.85	1698.7	1.49
1688.4	0.87	1701.3	1.64
1688.7	0.89	1697.7	1.42
1686.5	0.76	1696.9	1.48
Avg.			
1688.5	0.88	1698.4	1.48
+1.2	+0.07	+1.3	+0.07

Run No. 2 Avg. Volumetric Flow = 1649.8 cfs

Westinghouse LEF		Ferranti, ORE	
5 Min. Avg. Flow (cfs)	% Dif. LEF/Vol.	5 Min. Avg. Flow (cfs)	% Dif. ORE/Vol.
1690.3	2.45	1694.3	2.70
1700.5	3.07	1695.8	2.79
1680.8	1.88	1698.3	2.94
1685.1	2.14	1695.2	2.75
1686.1	2.20	1697.8	2.91
1692.4	2.58	1695.0	2.73
1688.4	2.34	1700.9	3.10
1690.3	2.45	1695.9	2.79
1688.9	2.37	1695.4	2.77
1685.8	2.18	1695.4	2.77
1684.4	2.10	1692.0	2.56
1686.7	2.24	1695.5	2.77
1693.9	2.67	1698.9	2.97
Avg.			
1688.7	2.36	1696.2	2.81
+3.0	+0.18	+1.4	+0.09

the run times. Table 1 shows a comparison between these long-term average flow rates and short-term average values measured with the acoustic flow meters. The mean differences between the volumetric flow rates and the Westinghouse flow rates were 0.88% and 2.36% for runs no. 1 and no. 2, respectively. The mean differences between the volumetric flow rates and the O.R.E. flow rates were 1.48% and 2.81% for runs no. 1 and no. 2, respectively.

Further investigation has shown that the cause of the poor agreement in flow rates in Table 1 can be largely attributed to the uncertainty in the run times used in the volumetric method. The run time used was the difference between the time the pump motor obtained full speed to the time the pump speed began to decrease. The selection of these starting and stopping times was somewhat arbitrary in that it assumes the flow starts and stops

TABLE 2
Grand Coulee Volumetric Test
Comparison of Volume Difference

Run No.	USBR Volumetric (cu. ft.)	ORE Volume Totalizer (cu. ft.)	% Dif. ORE/USBR
1	5,679,307	5,667,156	-0.21
2	7,503,128	7,584,247	+1.08
Total	13,182,435	13,251,403	+0.52

instantaneously. However, studying the 30 sec. flow rates recorded by ORE showed that the time required to obtain full pumping rate at startup was between 60 and 90 seconds and the time required for the flow to fully stop at shutdown was between 3 and 5 minutes. Figure 1 shows a plot of the 30 second flow rates recorded by ORE as compared to the instantaneous start and stop assumed in the volumetric flow rate calculations. For performance testing, it is the steady state flow rate as measured by the acoustic meters which is required but the volumetric method flow rates shown in Table 1 include the effects of the flow acceleration during startup and flow deceleration during shutdown.

Fortunately, the ORE volume totalizer had been turned on at the beginning of each test. The volume totalizer automatically integrated the 30 sec. flow values to obtain the total volume of water which has passed through the meter during each test. Table 2 shows a comparison between volume differences measured in the canal by the total volume measured by O.R.E. flow totalizer and the volumetric method. The differences between the two methods were -0.21% and 1.08% for run 1 and 2, respectively.

It should be noted that the Westinghouse LEF acoustic flow meter also has the capabilities of obtaining 30 second flow rate averages and total flow but these capabilities were not employed during the Grand Coulee volumetric test.

Uncertainty Analysis. ORE estimated the systematic uncertainty in their acoustic meter installations at Grand Coulee to be +-0.22% (2). However, their analysis includes only electronic timing and path survey errors and does not include the hydrodynamic effects on the flow measurements. For example, it has been shown (5,6) that the asymmetry of velocity profiles downstream of an elbow do affect the results of acoustic flow meters. These hydrodynamic effects on uncertainty are site dependent and cannot yet be predicted in advance. It was intended of these calibrations to determine uncertainty due to hydrodynamic effects. It has been assumed that the systematic uncertainty due to electronics and surveying in the LEF meter is the same as for the ORE meter. The random uncertainty was observed in pumping mode at

TABLE 3
Grand Coulee Volumetric Method
Uncertainty Analysis

Run No.	% Uncertainty	
	1	2
<u>I. Systematic Uncertainty</u>		
a. Volume Survey	0.10	0.10
b. Elevation Difference	0.60	0.53
c. Time Difference	3.44	1.78
<u>II. Random Uncertainty (95% Conf.)</u>		
a. Elevation Difference	1.44	1.89
<u>III. Total Uncertainty</u>		
a. Volume Difference (Ia, Ib and IIa)	1.56	1.96
b. Volume Rate (Ia, Ib, Ic and IIa)	3.78	2.64

Grand Coulee tests was $\pm 0.22\%$ for the LEF meter and $\pm 0.59\%$ for the ORE meter(1). Thus, without considering hydrodynamic effects, total uncertainty in the LEF and ORE meters were estimated to be $\pm 0.32\%$ and $\pm 0.63\%$, respectively.

The accuracy of the volume survey was ± 0.01 ft (0.3 cm) in elevation and horizontal location, but the surface roughness of the canal was of the order of 0.1 ft (3 cm). Assuming an error due to roughness of ± 0.1 ft (3 cm) on the average canal width of 100 ft (30 m), the systematic uncertainty of the survey was estimated to be $\pm 0.10\%$. Based on the stated transducer accuracies divided by the change in elevation for each run, the systematic uncertainties in elevation measurements were determined to be $\pm 0.60\%$ and $\pm 0.53\%$ for run 1 and 2, respectively. The observed random uncertainties in elevations were $\pm 1.44\%$ and $\pm 1.89\%$, respectively. Thus the total uncertainties in the measurement of volume difference were $\pm 1.56\%$ and $\pm 1.96\%$ for run 1 and 2, respectively.

To determine the uncertainty in volumetric flow rate measurements, the time uncertainty must be combined with the volume difference uncertainty. If one half of the total

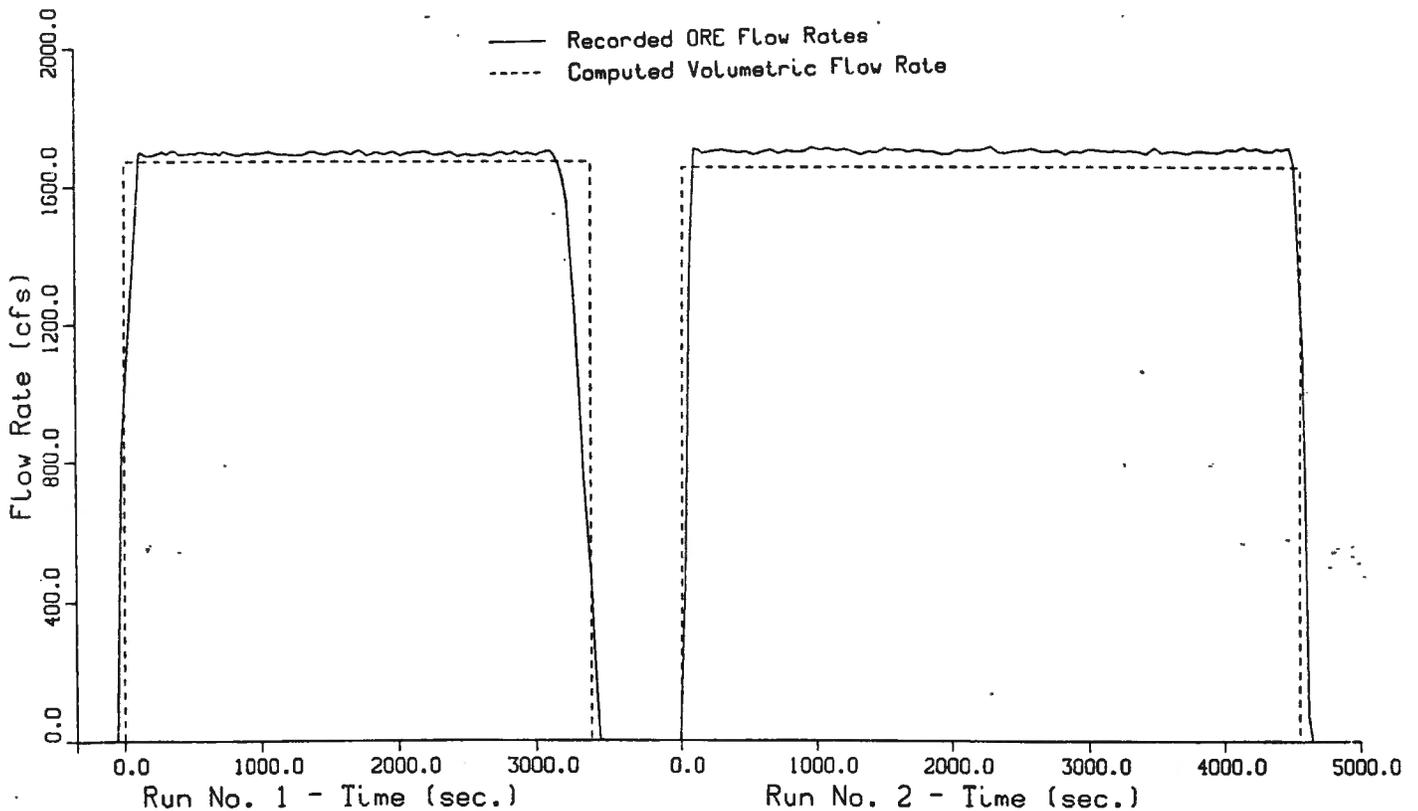


Figure 1 Comparison of Transient Acoustic Flow Rates to Computed Volumetric Flow Rates.

acceleration and deceleration time is used as an indicator of the systematic uncertainty in the time measurement, then the systematic uncertainties in time were 3.44% and 1.78% for run no. 1 and no. 2, respectively. Thus the total uncertainties of the volumetric flow measurement were +3.78% and +-2.64%.

The uncertainty in the Grand Coulee volumetric test was much greater than expected. The agreement between the volume difference measured with the acoustic and volumetric methods was significantly less than the combined uncertainty in the volumetric methods thus the results cannot be used to make any statement about the bias in the acoustic meters.

The agreement between the two methods was not as good when flow rates were compared but this poorer agreement can be explained by the uncertainty in the time measurements. Again, the volumetric results do not support a sound judgment regarding the bias in the acoustic meters.

RACCOON MT.

Test Procedure. There were some significant differences in the acoustic flow meter installation at Raccoon Mt. from those at Grand Coulee and Kootenay Canal. First, the Raccoon Mt. installation used only a single measurement plane with four chordal paths. Secondly, the location of the meter was less desirable than the acoustic meter locations at the other sites, in that, the meter was squeezed between the spherical valve and the turbine scroll case, and was less than a pipe diameter from each. Thus, in the pumping mode the meter was located in a region of highly disturbed flow.

The volumetric technique used at Raccoon Mt. was also significantly different from the volumetric method used at Grand Coulee. The upper reservoir which was used for the volumetric measurement had a surface area of approximately 500 acres which was an order of magnitude larger than the Grand Coulee Feeder Canal. The reservoir also had irregular shape and was more than 120 ft. deep at the entrance to the power tunnel. The area of the reservoir as a function of water level was surveyed using aerial photogrammetry techniques. The water surface elevation in the reservoir was measured using four float type gaging stations located in stilling basins along the south and west side of the reservoir. A microprocessor was installed at each station to record surface elevation versus time. It would have been desirable to have located some stations along the east and north side of the reservoir but due to poor access the cost of constructing gaging stations along these sides was prohibitive. To calibrate the reservoir volume elevation, aerial photogrammetry was conducted as the reservoir was being filled. The clocks at each stage gage were synchronized with the clock in the photogrammetry airplane and surface elevations were recorded during each

flyover. To avoid problems with wind waves and set up, the calibration was done on a calm day. The series of photos which were taken were analyzed using stereoscopic methods to compute a reservoir surface area from each photograph. Volume versus elevation tables were then computed by linearly interpolating area versus elevation between photos.

The volumetric testing was also conducted in a different manner than at Grand Coulee. Prior to testing, the clocks at each stage gage and at the acoustic flow meter were all synchronized. For each test run, the plant operating conditions were set and allowed to stabilize prior to the official start of the test. Then the recorders at each stage gage and at the acoustic flow meter were started and recordings were continued for the predetermined run duration while maintaining stable operating conditions. In this manner, five runs were made at different gate settings in generating mode and one run was made in pumping mode. Thus, all data was recorded under stable operations and the start-up and shutdown effects experienced at Grand Coulee were avoided. The deeper reservoir and low aspect ratio shape eliminated the problem of surge waves.

A unique method was used to compute flow rate at the Raccoon Mt. site. First, an average rate of change in surface elevation, $\partial E/\partial t$, was determined for each test from the stage gage data. Linear regression analysis was then used to determine an average volume versus elevation slope, $\partial V/\partial E$, from all the volume calibration data points over the range of elevations for each test run. Then the product of these two values was taken to compute the rate of change volume, $\partial V/\partial t$, as follows:

$$\frac{\partial V}{\partial t} = \frac{\partial V}{\partial E} \frac{\partial E}{\partial t} \quad (4)$$

Results. For runs 1 and 2 there was insufficient data at one gaging station so the results were based on just three stations.

TABLE 4
Raccoon Mt. Volumetric Test
Flow Rate Comparison

Run No.	Mode	Volumetric Flow (cfs)	ORE Flow (cfs)	% Dif. ORE/Vol.
1	Gen.	4041	3990	-1.26
2	Gen.	5043	4954	-1.76
3	Pump.	3687	3638	-1.33
5	Gen.	4640	4578	-1.34
6	Gen.	5241	5158	-1.58
			Average	-1.45
			95% Conf.	+0.26

TABLE 5
Raccoon Mt. Acoustic Flow Meter
Uncertainty Analysis

Run No.	Generating				Pumping
	1	2	5	6	3
Systematic Uncertainty (%)	0.50	0.50	0.50	0.50	1.00
Random Uncertainty (%)	0.18	0.60	0.20	0.33	0.96
Total Uncertainty (%)	0.53	0.78	0.54	0.60	1.39

TABLE 6
Raccoon Mt. Volumetric Test
Uncertainty Analysis

Run No.	Generating				Pumping
	1	2	5	6	3
Elevation Range (ft)	1.4	2.0	0.8	2.5	1.4
I. Systematic Uncertainty (%)	0.37	0.27	0.60	0.22	0.37
II. Operator Dependent Area Uncertainty (%)	0.13	0.13	0.13	0.13	0.13
III. Random Uncertainty					
a. dV/dE (%)	3.90	0.25	2.37	0.73	0.50
b. dE/dt (%)	0.12	0.48	1.25	0.12	0.41
c. dV/dt (%) (combining a and b)	3.90	0.54	2.68	0.74	0.65
IV. Total Uncertainty (combining I, II and III)	3.92	0.62	2.75	0.78	0.76

There was insufficient volume calibration data to compute flow rates for run 4. Otherwise the tests were executed without problems and the results of the volumetric method were used to compute unit efficiencies.

The comparison between the flow rates measured by the TVA volumetric method and the measurements taken by the O.R.E. acoustic meter are shown in Table 4. The mean difference between the two methods over the five runs was 1.45% with a 95% confidence interval of $\pm 0.26\%$.

Uncertainty Analysis. The uncertainty analysis for the acoustic meter at Raccoon Mt. test is given in Table 5. The systematic uncertainty for the acoustic method was estimated by ORE to be 0.5% in generating mode and +1.0% in pumping mode. These estimates were said to include the effects of the flow conditions in the meter section (8). The observed random uncertainty ranged from $\pm 0.18\%$ to $\pm 0.60\%$ in generating mode and $\pm 0.96\%$ for pumping mode (3). The larger variation in the pumping mode is probably attributable to turbulence from the pump discharge. The uncertainties were combined to obtain estimates of total uncertainty between 0.53% and 0.78% for the generating mode runs and 1.39% for the pumping mode run.

The systematic uncertainty analysis for the volumetric method showed that the uncertainty was inversely dependent on surface elevation difference over a run (3). This is because the absolute error in elevation measurements becomes relatively less significant when the measurements are made over a larger difference in elevation. As shown in Table 6, the uncertainty values ranged from 0.22% to 0.60% for individual runs. The random uncertainty between stations was much larger in runs no. 1 and no. 5 than in the other runs. Since there were only 3 or 4 stations on which the statistical analysis was performed a single "outlier" produced large confidence intervals in these two results. (The statistical uncertainties reported here are larger than those reported in reference (3) since that reference reported standard deviations.) Thus, the total uncertainty for runs 1 and 5 were 3.92% and 2.75%, respectively, while the other three runs had total uncertainty of less than 0.8%. The mean uncertainty for all five runs was $\pm 1.77\%$.

The uncertainty in the volumetric method at Raccoon Mt. was within the $\pm 0.5\%$ to $\pm 1.0\%$ goal in three out of five runs. It is believed that if it had been economically feasible to add two or three more gaging stations in the reservoir the random

uncertainty in the other two runs would have been significantly reduced.

The difference between the acoustic and volumetric flow measurements was greater than the volumetric uncertainty for the runs 2, 3 and 6 but less than the volumetric uncertainty for the runs 1 and 5. The mean difference between the methods was less than the mean volumetric uncertainty. However, since the large uncertainty of runs 1 and 5 were attributable to single outliers it was felt that it was better to base the calibration on the results of runs 2, 3 and 6 rather than the mean of all five runs.

For runs 2, 3 and 6 the bias in the acoustic method was computed with eq.(2) to be +1.65%, +1.19% and +1.10%, respectively. The average of these three is +1.31%. Per eq.(3) the computed bias was predicted by the uncertainty analysis for the acoustic method for run 3 but not for runs 2 and 6. The indication is that the systematic uncertainty was underestimated for the generating mode. It is interesting, that the computed bias for pumping mode was no greater than the bias for the generating mode in spite of being located immediately downstream of the pump discharge.

If the average random uncertainty of $\pm 0.6\%$ is combined with this observed bias the total uncertainty is estimated to be 1.5% for the acoustic meter at Raccoon Mt. In the absence of other data one might conclude that $\pm 1.5\%$ is a reasonable estimate of systematic uncertainty for a one-plane four path acoustic meter. However, this estimate may not be valid at another site due to different hydrodynamic effects. In fact, results of other tests conducted during this EPRI project indicate that the total uncertainty for acoustic meters range from 0.3% to 2.2% over seven different sets of site conditions (1). It should be noted that although this value of uncertainty is greater than that originally predicted by ORE, it is still of the equivalent to total uncertainties for the code accepted methods (7,9) which were observed to range from 0.4% to 3.2% in this EPRI project.

CONCLUSION AND RECOMMENDATION

The magnitude and persistence of surge waves in the canal at Grand Coulee made it impossible to obtain accurate flow rates during the volumetric test. Start-up and shutdown transients in the pump produced a large uncertainty in flow rates computed from the volume change over a timed run. Therefore, the ORE meter was calibrated by comparing volume change over a run to volumes recorded with the ORE volume totalizer. The two methods showed good agreement but the calibration results were inconclusive due to large uncertainty in the volumetric test.

Since the volumetric method as applied at Grand Coulee was incapable of accurately measuring steady state flow rates, it failed as a potential method to measure flow rates for performance testing. In spite of this,

the volumetric test at Grand Coulee provided a valuable lesson that the reservoir shape and pump start-up transients are important in applying this technique. This test also emphasized the flexibility of the acoustic method in measuring flow transients and integrating total volumes as well as measuring steady state flow rates for performance testing.

The volumetric test at Raccoon Mt. showed that the surge wave problems at Grand Coulee were site dependent. The volumetric method at this site provided a viable method of measuring flow rate for performance testing and showed a potential of obtaining uncertainties of less than $\pm 0.8\%$. The systematic uncertainty could have been significantly improved by increasing the elevation difference over which each run was made. It would, also, have been desirable to have a larger number of measurement stations to improve the random uncertainty in elevation measurements and thus improve the confidence in the acoustic meter calibration.

The comparison between the acoustic and volumetric method at the Raccoon Mt. site showed reasonable agreement in spite of the fact that only a one-plane acoustic meter was used in a less than optimum test section. This comparison indicated that acoustic meter installation at Raccoon Mt. had bias of +1.31% and an random uncertainty of $\pm 0.6\%$. These combine for a total uncertainty of 1.5%. This total uncertainty is consistent with the range of acoustic meter uncertainties (0.3% to 2.2%) observed in other tests conducted during this EPRI project (1). It is also within the range of uncertainties (0.4% to 3.2%) observed in this project for the code accepted flow measurement methods (7,9).

It is recommended that future efforts be made to use the volumetric method to calibrate acoustic and other methods of flow measurement. It is recommended that sites which are subject to surge waves be avoided or that a large number of gaging stations be used to allow for observation of traveling waves within small increments of distance. Even at sites where no surge waves are expected it is recommended that a minimum of six gaging stations be distributed evenly over the reservoir to statistically improve the confidence in computing the mean surface elevation.

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Tennessee Valley Authority
United States Bureau of Reclamation
Westinghouse Electric Corp., Oceanic Div.

DEDICATION

The project described in this paper was conceived and then directed by the late Professor Lawrence C. Neale up to his untimely death in October 1984. The authors feel fortunate to have had the opportunity to work with Larry on this and other projects and wish to dedicate this paper to the memory of our friend and colleague, Professor Lawrence C. Neale.

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Unit Conversions: 1 ft. = 0.305 m,
1 cu. ft. = 0.0283 m³, 1 cfs = 0.0283 m³/s
