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Revenue Recovery Through Meter Replacement

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REVENUE RECOVERY THROUGH METER REPLACEMENT

by

Devan J. Shields

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Steven L. Barfuss Major Professor	Michael C. Johnson Committee Member
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UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Revenue Recovery through Meter Replacement

by

Devan J. Shields, Master of Science

Utah State University, 2011

Major Professor: Steven L. Barfuss
Department: Civil and Environmental Engineering

Previous studies have identified water meter inaccuracy at low flow rates as a significant source of non-revenue flow for water systems; however a lack of available data makes it difficult to include low flow accuracy degradation in meter replacement plans. This thesis examines results from an extensive accuracy test program carried out at the Utah Water Research Laboratory on small water meters over a wide range of flow rates and at various levels of throughput. The study compares expected apparent losses of different types of water meters based on a flow profile and expected daily use for the State of California. By including an average composite charging rate, use of the method developed in this study can determine the meter replacement payback period for different meter types. The analysis contained in this document is intended as a guide to assist utility managers when developing meter replacement plans.

(36 pages)

PUBLIC ABSTRACT

An important water conservation measure that has been taken at nearly all utilities in the United States is the metering of potable water. Charging water users in proportion to how much they use decreases the volume of water used, and provides funding necessary for utilities to continue to provide clean water to the communities they serve. Water supply systems are not perfect, so there is always more water that is treated and put into the system than the sum of the meter readings account for. One way to reduce this difference and improve the efficiency of a water system is to improve the accuracy of water meters used in the system. This study examines water meter accuracy and develops a method by which utility managers can use meter accuracy test results to determine when it is most cost-effective to replace water meters based on how much water is passing through the meter undetected compared with the cost of replacing the meter. Through the use of this method, utility managers can improve the efficiency of water systems and provide better service at a lower cost to water users.

ACKNOWLEDGMENTS

Utah State University gratefully acknowledges that the Water Research Foundation, formerly known as the American Water Works Association Research Foundation, is the joint owner of the technical information upon which this thesis is based. Utah State University thanks the Water Research Foundation and Environmental Protection Agency for their financial, technical, and administrative assistance in funding and managing the project through which this information was discovered.

I would like to thank my major professor, Steven Barfuss, for his contributions to this analysis, which include but are not limited to: directing the Water Research Foundation project the analysis is based on, guiding my research and analysis of the test results, encouraging me to expand my ideas for development of the project, and suggesting revisions all along the way. I would also like to thank Dr. Michael Johnson for his insight and guidance through the process, as well as Dr. Joseph Caliendo for consistently keeping my ego in check and being a friend throughout my educational experience at Utah State University.

I also need to thank my family, friends, and Utah Water Research Laboratory associates for their patience and support throughout the project.

Devan J. Shields

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LITERATURE REVIEW

Previous studies have identified key components of water meter performance that have influenced the analysis performed in this study. Work done in this study (Lund, 1988) utilized optimization theory discussed in (Noss et al., 1987) to compare economic benefits of different meter replacement plans based on individual water meter accuracy. This paper investigates development of meter replacement plans based on meter type and total registry, and is based on average accuracy test results of different meter types at different levels of total throughput. A key assumption for the research is that water meter accuracy degrades with increasing throughput, particularly at low flow rates. This has been concluded in these studies (Bowen et al., 1991; Noss et al., 1987; Tao, 1982), and has been further explained in (Arregui et al., 2005).

In this work as well as (Lund, 1988) loss of revenue due to inaccuracy of water meters is used to be compared with the cost of meter replacement. Significant revenue losses can be caused by water meters that are stuck, or fail to register throughput at any flow rate, but these meters are easily identified by meter readings (Lund, 1988). Gradual accuracy degradation is more difficult to detect through meter readings, so a meter replacement plan that is based on correlation of significant accuracy degradation and meter type and throughput or service time would be a useful tool for water utility managers to minimize revenue losses due to meter inaccuracy. This paper illustrates the development of a simple method using average meter accuracy test results to estimate revenue losses based on meter type and throughput.

INTRODUCTION

Meter repair and replacement decisions must be made by every water supplying utility. Although planned meter replacement programs which specify that meters should be in service for a certain time period before replacement are the simplest to implement, previous studies have reported that replacement methods involving meter malfunction detection and repair or replacement are more economical (Lund, 1988). This paper examines basing meter replacement plans on meter type and total registry, a method that would be easily implemented but still involve meter performance data. Meter accuracy test data is used to approximate the volume of water that is expected to pass through a meter without being recorded, or non-revenue flow. A basic method for applying meter accuracy test results in determining decreases in non-revenue flow is developed as a guide for similar analyses performed by utilities. Though it is simple to detect meter stoppage based on monthly readings, gradual accuracy degradation at low flow rates is not as readily determined based only on monthly readings (Lund, 1988). Analyses like that presented here, when performed using data specific to a utility, provide the utility with data that identifies meters in a system that are likely to have poor low flow accuracy based on meter type, total registry, or service time.

Different meter types use differing methods for measuring the water volumes passed through them, and as a result, their performance is likely to vary at various flow rates and levels of throughput, or total meter registry. An understanding of the capabilities of different meter types to record low flow rates can be helpful for utilities to increase efficiency and reduce apparent losses (Richards et al., 2010). Since meter accuracy varies most at low flow rates for the various meter designs there is also the most potential for changes in accuracy with increasing flow throughput at these flow rates (Arregui et al., 2005).

The results from accuracy tests that were performed during an extensive Water Research Foundation project (Barfuss et al., 2011) on several meter types used in water systems today are presented in this paper. The results provide a low flow accuracy comparison between meter types both out-of-the-box and at various levels of throughput. The effects of accuracy degradation are also examined in this study.

TEST PROCEDURE

Six types of meters were tested at different flow rates and levels of throughput at the Utah Water Research Laboratory (UWRL) in Logan, Utah. Tested meter types included displacement piston (DP), single-jet (SJ), multi-jet (MJ), nutating disc (ND), fluidic oscillator (FO), and turbine (TU) meters. Figures 7-12 in the Appendix show the mechanisms used by each meter type to measure flow. New meters were purchased through local distributors for the project as shown in Table 1.

Laboratory accuracy tests were conducted using a gravimetric test bench using weight tanks traceable to the National Institute of Standards and Technology (NIST). Each target flow rate was set using calibrated magnetic flow meters and double-checked by timing each flow entering the weight tank. Flow rates for the tests were based on the American Water Works Association (AWWA) maximum, minimum, and intermediate flow rates for each meter size. Low flow tests were conducted at the AWWA minimum flow rate, as well as at 1/2, 1/4, and 1/8 of the AWWA minimum flow rate for each meter size, as shown in Tables 2 and 3. Flows were passed through the test meters and into a weight tank, with beginning and ending

Table 1. Sample sizes by type

	Size (in.)	
Type	5/8 x 3/4	3/4
Displacement Piston (DP)	48	30
Multi-jet (MJ)	42	30
Nutating Disc (ND)	30	18
Single-jet (SJ)	24	12
Fluidic Oscillator (FO)	6	6
Turbine (TU)	0	6

weights recorded to provide the net weight of water which passed through the meters during each test run. Water temperature was also recorded and used to calculate the volume from the measured water weight. This volume was then compared to the volume recorded by each meter to give the percentage of total volume registered by each meter.

To reduce errors associated with testing, it was necessary to use test volumes that minimized uncertainty caused by weight tank precision. This was done by using two different weight tanks, a smaller tank that measured to within 0.6% of a gallon for low and intermediate flow rates, and a larger tank that measured to within 6% of a gallon for the high flow rates. A minimum volume of 10 gallons was used for the low and intermediate flow rate tests, which further reduced measurement error to 0.06%. A minimum test volume of 100 gallons was used in the high flow rate tests, which also reduced measurement error to 0.06%.

After the new meters accuracy tests were completed, throughput was increased by circulating water through the meters. Testing setup is illustrated in Figure 13 in the Appendix. While meter throughput was increasing, the flow rate passing through each meter was periodically changed to prevent uneven wear from a constant flow rate. The different flow rates passing through the meters and the length of time the flow was passing through the meters were controlled using programmable timers and solenoid valves. In addition to accuracy testing the meters in their new condition, they were also accuracy tested at four different levels of throughput, through the estimated "full life" of the meter. For the 5/8 x 3/4-inch meters, full life was estimated as the throughput of a meter for a household that uses 400 gallons per day and is in service for 15 years, rounded to a total of 2 million gallons. For the 3/4-inch meters, the full life estimate was increased based on the increase in AWWA maximum flow and similar testing period to 3 million gallons. Testing on the meters was done over a period of about 2 years, with each throughput level taking about 2 months to reach.

LABORATORY TEST RESULTS

Accuracy test results are reported in this paper as averages for each meter type and size. Individual meter accuracy test results are shown the full Water Research Foundation report. The accuracy test results for each meter type differed most significantly at the smallest flow rates tested. Tables 2 and 3 show the relative performances of each meter type at the smallest tested flow rates in the new condition. The different meter types are ranked according to their average accuracy at each flow rate. The average percentage of flow registered at each flow rate is shown in parentheses.

As indicated in the tables, the new nutating disc meters generally registered more flow at lower flow rates than the other meter types. The new 3/4-inch single-jet meters also received high rankings. Table 3 shows that the 3/4-inch turbine meters were the least effective in registering flow at low flow rates.

Though specific manufacturers are not identified here, it is important to note that meters of the same type and size made by different manufacturers did not always produce consistent accuracy results. In some cases, one or two meter manufacturers pulled down the overall meter type average accuracy results. For example, Table 4 shows the

Table 2. Comparative performance of new 5/8 x 3/4-inch meters

	Flow rate			
Type	1/32 gpm	1/16 gpm	1/8 gpm	1/4 gpm
DP	*2 (2.7%)	2 (39%)	4 (84%)	4 (95%)
FO	5 (0%)	5 (10%)	1 (96%)	3 (97%)
MJ	4 (0.1%)	3 (28%)	5 (83%)	5 (93%)
ND	1 (44%)	1 (87%)	2 (96%)	2 (99%)
SJ	3 (0.9%)	4 (24%)	3 (87%)	1 (100%)

*Type rank (average registry)

Table 3. Comparative performance of new 3/4-inch meters

	Flow rate			
Type	1/16 gpm	1/8 gpm	1/4 gpm	1/2 gpm
DP	*2 (30%)	4 (63%)	3 (95%)	3 (99%)
FO	5 (0%)	5 (25%)	5 (72%)	5 (86%)
MJ	4 (7.9%)	3 (72%)	4 (94%)	4 (96%)
ND	1 (72%)	1 (94%)	2 (98%)	1 (100%)
SJ	3 (20%)	2 (86%)	1 (99%)	2 (99%)
TU	6 (0%)	6 (2.9%)	6 (27%)	6 (81%)

*Type rank (average registry)

percentage of the meters (including both sizes) from each of the 14 manufacturers represented in this study that passed the AWWA low flow standard when tested in the new condition. Only 6 of the 14 manufacturers were able to meet the low flow AWWA accuracy standard more than 85% of the time. Only meters from manufacturers that specified on their website or in marketing literature that their meters met AWWA standards were used in the study.

Proper meter placement and replacement can result in substantial reduction of apparent losses for utilities, increased revenue, and more equitable billing for customers. Whether it makes more fiscal sense for entities to implement a gradual replacement plan or replace meters all at once will largely depend on the anticipated revenue recovery. To determine whether it is advantageous to replace different types of meters based only on throughput levels, the results for the laboratory meter endurance testing were analyzed. By averaging decreases in accuracy at different levels of throughput, revenue losses from these inaccuracies can be estimated and compared with the cost of replacement.

Table 4. Percent of new meters passing AWWA low standard by manufacturer

Manufacturer	Passing AWWA low standard
1	100%
2	100%
3	100%
4	94%
5	92%
6	92%
7	83%
8	78%
9	71%
10	67%
11	67%
12	61%
13	50%
14	33%

Comparing these costs for each type of meter within a system can help utilities develop an optimal replacement plan.

Figure 1 shows the endurance testing results for the 5/8 x 3/4-inch meters at half of the AWWA low standard. The single-jet and multi-jet meters showed the greatest decrease in average accuracy with increasing throughput. With the multi-jets as well as the single-jets there appeared to be significant drop between 1.5 and 2 million gallons of throughput. The displacement piston and nutating disc meters also showed some decrease in accuracy with throughput at low flow, but not as much as meters pulled from service with similar levels of throughput as shown in the Water Research Foundation report. The 5/8 x 3/4-inch fluidic oscillators actually showed slight improvement at 1/8 gpm, and they were certainly the most consistent meter type at flow rates where their initial performance was good.

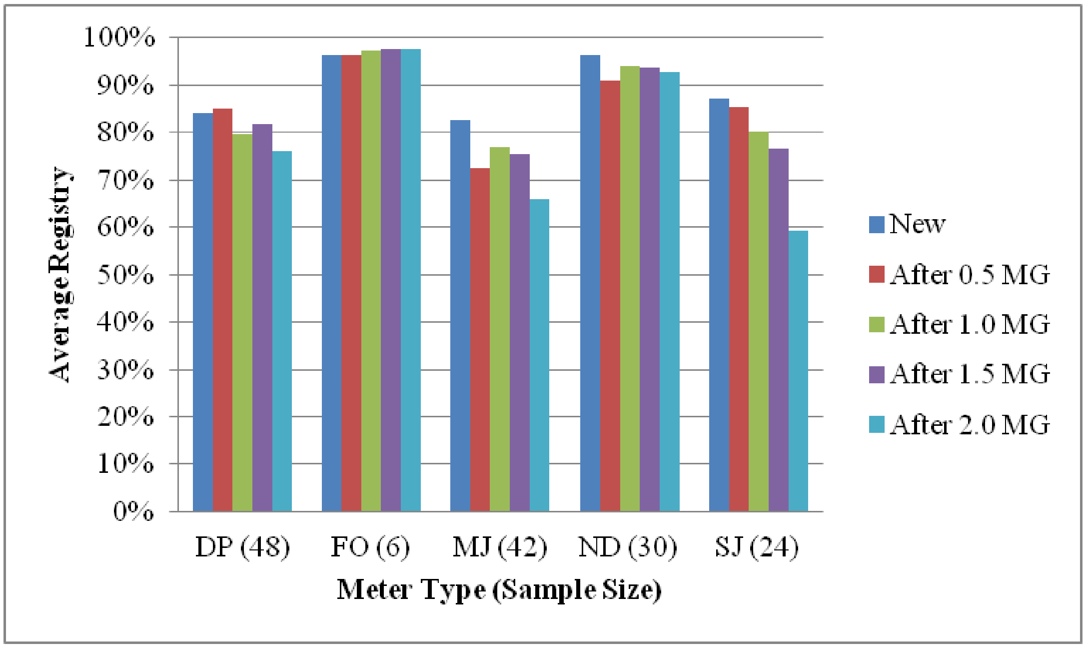

Figure 1. Endurance results for 5/8 x 3/4-inch meters at 1/8 gpm after various levels of throughput

Results for the 3/4-inch meters (Figure 2) showed similar trends, with the exception of the multi-jet meters which maintained a higher degree of accuracy than the single-jets. Turbine meters are not designed to perform well at low flows, but showed very little change with increasing throughput at flows within their operable range. The 3/4-inch fluidic oscillators were slightly less accurate than their 5/8 x 3/4-inch counterparts, but again showed no net decrease in accuracy with increasing throughput.

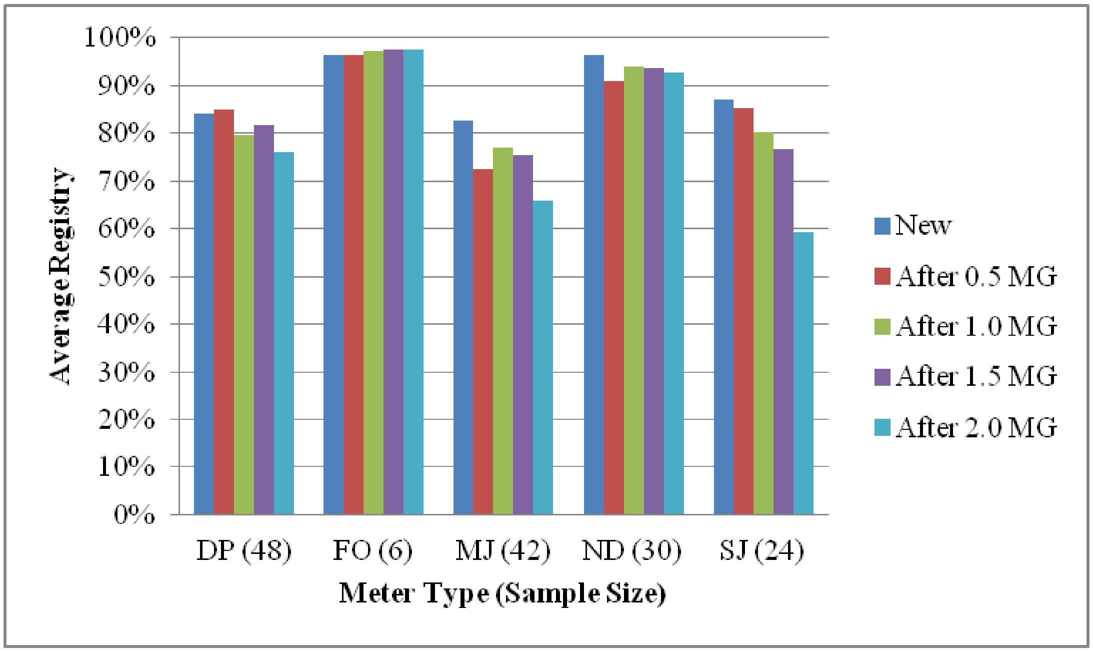

Figure 2. Endurance results for 3/4-inch meters after various levels of throughput

DATA ANALYSIS

Endurance data for the entire range of tested flow rates can be used together with a typical user flow profile to generate an estimation of apparent losses due to meter inaccuracy. Using these estimates along with a charging rate can produce estimates of revenue recovered by replacing meters after different levels of throughput. For this analysis a flow profile adapted from a 2009 study (DeOreo et al., 2009) was used to approximate losses. The profile is shown in Table 5. Since the flow profile data was obtained using meters that had been in service prior to the flow profile data acquisition, it is likely that the actual low flow volume is greater than is shown in Table 5 because of water meter inaccuracy at the lower flow rates. Though this impacts the total revenue recovery for each meter type and throughput level, the relative recovery for different throughput levels is not affected by the possible error in low flow volume.

Table 5. Water use profile from 750 single-family homes in California

Flow Rate Range (gpm)	Timed Flow Through Meters %	Measured Volume Through Meters %
0-1/4	77.9	5.0
1/4-1/2	4.2	2.0
1/2 to 1	3.1	3.1
1 to 2	5.7	11.8
2 to 4	4.9	18.9
4 to 6	1.7	11.4
6 to 10	1.3	13.8
>10	1.2	34.0

Adapted from DeOreo et al, 2009

To generate estimates of apparent losses due to meter inaccuracy for each meter type and level of throughput, the data within each flow range shown in Table 5 were averaged. For example, low flow accuracy test data were available for the 5/8 x 3/4-inch meters at 1/32, 1/16, 1/8, and 1/4 gpm, so the average accuracy in the flow rate range 0-0.25 gpm was calculated as the average of the accuracy test results at each of the low flow rates. Losses in each flow range were then calculated as shown in Equation 1:

$$L = (1 - A) * V \tag{1}$$

in which L is the loss per day per connection in gallons for each flow range, A is the average accuracy of the meter type in that flow range expressed as a decimal, and V is the expected volume (in gallons) in that flow range each day. The expected daily volume in each flow range was calculated by multiplying the percentage of volume in each range shown in Table 5 by the total expected daily volume for each connection. The total expected daily volume for each connection was calculated by multiplying California's domestic per capita use of 124 gal/day (Kenny et al., 2009) by the state's average household size of 2.96 persons (U.S. Census Bureau, 2009) to get 367 gallons per connection per day. Table 6 shows an example of the daily loss calculations for 5/8 x 3/4-inch nutating disc and single-jet meters after two million gallons of throughput.

The apparent losses in some flow rate ranges are shown as negative due to the average meter accuracy in that range exceeding 100%, which would mean that most of the meters registered more flow than had actually passed through the meters in those flow ranges. As expected, the flow ranges that were consistently responsible for the greatest volumes of losses were those between 0 and 0.25 gpm, where the meters were most

Table 6. Daily apparent loss calculation sample for 5/8 x 3/4-inch ND and SJ meters

Flow rate range (gpm)	Fraction of total flow in range (%)	Total volume in range (gal)	ND (new)		SJ (new)	
			Accuracy in range	Apparent loss (gal)	Accuracy in range	Apparent loss (gal)
0-0.25	5	17.61	65.83%	6.27	42.48%	10.56
0.25-0.5	2	7.04	100.05%	0.00	99.71%	0.02
0.5-1	3.1	10.92	100.88%	-0.10	99.35%	0.07
1-2	11.8	41.56	100.87%	-0.38	99.80%	0.09
2-4	18.9	66.57	100.67%	-0.47	100.08%	-0.06
4-6	11.4	40.16	100.46%	-0.19	100.10%	-0.04
6-10	13.8	48.61	100.15%	-0.07	100.13%	-0.07
>10	34	119.76	99.35%	0.82	100.16%	-0.21
			Total Loss:	5.87	Total Loss:	10.37

Flow rate range (gpm)	Fraction of total flow in range (%)	Total volume in range (gal)	ND (after 2 MG throughput)		SJ (after 2 MG throughput)	
			Accuracy in range	Apparent loss (gal)	Accuracy in range	Apparent loss (gal)
0-0.25	5	17.61	57.69%	7.76	31.85%	12.51
0.25-0.5	2	7.04	98.86%	0.08	90.56%	0.69
0.5-1	3.1	10.92	100.35%	-0.04	93.74%	0.71
1-2	11.8	41.56	100.48%	-0.21	96.23%	1.63
2-4	18.9	66.57	100.11%	-0.08	97.07%	2.03
4-6	11.4	40.16	99.90%	0.04	95.18%	2.02
6-10	13.8	48.61	99.59%	0.21	92.34%	3.88
>10	34	119.76	98.85%	1.44	84.81%	18.96
			Total Loss:	9.21	Total Loss:	42.43

inaccurate, and greater than 10 gpm, where the total volume consumed each day was the greatest.

The difference in total daily loss per connection for each type of meter can then be combined with an average composite charging rate to find the amount of revenue recovered by replacing meters. This is shown in Equation 2:

$$R = (L_1 - L_2) * 365 \text{ days/year} * r/1000 \text{ gal} \tag{2}$$

in which R is the yearly revenue recovered per connection by replacing the meter in dollars, L_1 is the estimated daily loss per connection for the old meter in gallons, L_2 is the estimated daily loss per connection for the new meter, and r is the composite rate charged for every 1000 gallons in dollars. For this study, an average rate for California of $2.76

per 1000 gallons (PPIC, 2008) was used. Meter repair or rehabilitation is often an effective alternative to replacement but was not considered in this analysis because accuracy data for repaired meters of each type and size was not available.

Table 7 shows the yearly revenue recovered by replacing 5/8 x 3/4-inch meters after 2 million gallons of throughput with different types of new meters. Although most meter replacement possibilities result in relatively small recoveries in yearly revenue per connection, these recoveries add up in systems with many connections. The most extreme case shown involves replacing a displacement piston with a new nutating disc meter after 2 million gallons of throughput, in which $9.28 would be recovered per connection in a year by making the replacement (based on 367 gallons per connection per day and a charging rate of $2.76/1000 gallons). The results shown in Table 7 exclude 4 of the single-jet meters that failed to register any flow after moderate levels of throughput. These meters are more easily identified in water systems than meters whose accuracy is gradually degraded at some flow rates and were excluded from the analysis.

Table 7. 5/8 x 3/4-inch replacement annual revenue recovery per connection

		Old meter type (after 2 MG throughput)				
		DP	FO	MJ	ND	SJ
New meter type	DP	$4.49	$3.64	$ 0.82	$ (1.40)	$ 4.28
	FO	$1.80	$0.95	$ (1.87)	$ (4.09)	$ 1.59
	MJ	$4.59	$3.74	$ 0.92	$ (1.30)	$ 4.38
	ND	$9.25	$8.40	$ 5.58	$ 3.36	$ 9.04
	SJ	$4.44	$3.59	$ 0.77	$ (1.45)	$ 4.23

*Parentheses indicate a negative value

Table 8 shows the yearly revenue recovered by replacing 3/4-inch meters with different types of new meters after 3 million gallons of throughput. The results are similar to those shown for the 5/8 x 3/4-inch meters, but greater decreases in accuracy produced larger amounts of yearly revenue recovered at each connection by replacing the meters. The greatest recovery of revenue per connection came from the replacement of a fluidic oscillator meter with a new nutating disc meter, which resulted in an annual recovery of $15.32 per connection based on the same consumption and charging rate used for the smaller meter estimates. As with the smaller meters, larger annual recovery amounts were calculated for the set of single-jet meters, but because the results were most influenced by 5 failed meters in the set the failed meters were excluded..

Since the losses due to meter inaccuracy were smallest in both cases with the nutating disc meters, revenue recovered by replacing different types of water meters at different levels of throughput with new nutating disc meters was calculated. The results of these calculations are shown in Figures 3 and 4.

Figures 5 and 6 illustrate the impact of the failed single-jet meters on the group averages. The first set in each figure includes the entire set of meters tested while the

Table 8. 3/4-inch replacement annual revenue recovery per connection

		Old meter type (after 3 MG throughput)				
		DP	FO	MJ	ND	SJ
New meter type	DP	$ 4.14	$ 8.42	$ 4.57	$ (6.25)	$ 1.54
	FO	$ (5.92)	$ (1.64)	$ (5.49)	$(16.31)	$ (8.52)
	MJ	$ 2.27	$ 6.54	$ 2.70	$ (8.13)	$ (0.33)
	ND	$ 11.05	$ 15.32	$11.48	$ 0.65	$ 8.45
	SJ	$ 5.93	$ 10.21	$ 6.36	$ (4.46)	$ 3.34

*Parentheses indicate a negative value

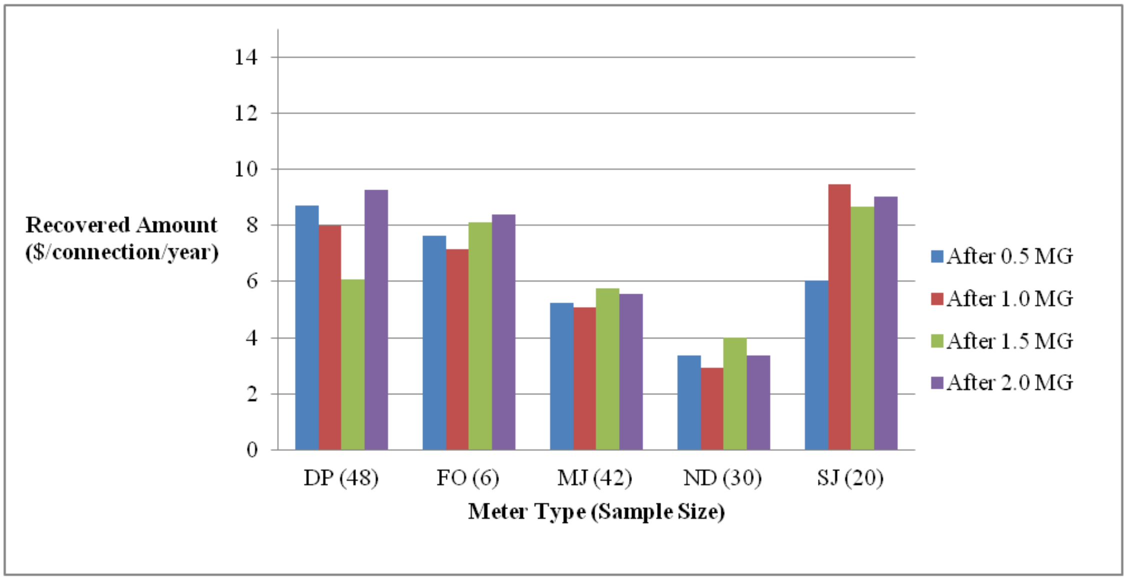

Figure 3. Revenue recovered by replacing 5/8 x 3/4-inch meters with nutating disc meters

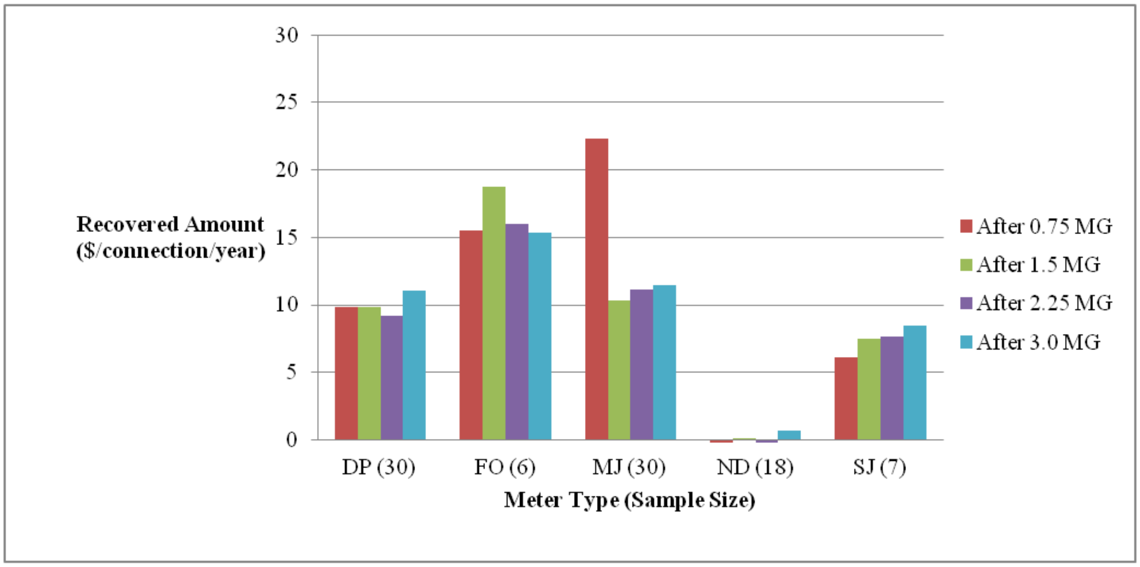

Figure 4. Revenue recovered by replacing 3/4-inch meters with new nutating disc meters

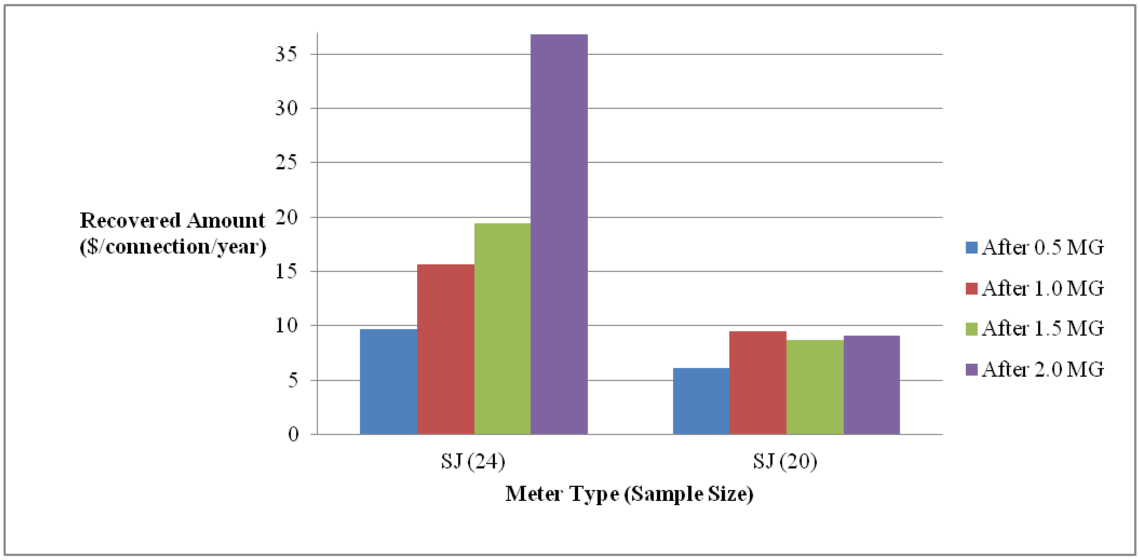

Figure 5. Comparison of revenue recovered by replacing 5/8 x 3/4-inch single-jet meters including and excluding meters that failed during the tests

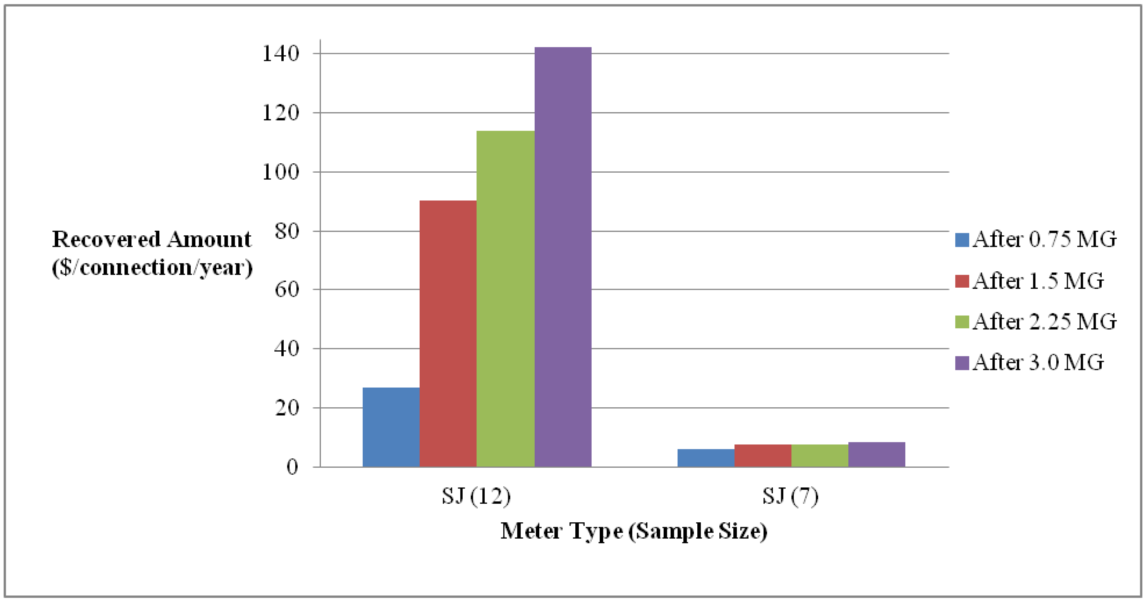

Figure 6. Comparison of revenue recovered by replacing 3/4-inch single-jet meters including and excluding meters that failed during the tests

second group excludes the meters that failed during the tests, as shown with the different sample sizes. The values shown in the reduced sets are consistent with the other types of meters, and show very little increase in revenue recovered by replacement with increasing throughput. This would suggest that basing a meter replacement plan only on meter type and total throughput up to the levels tested in this study is not an effective alternative to using of specific utility testing data. Without the effects of water quality and time, the accuracy of the working meters did not decrease significantly during the tests.

There are some limitations that must be considered in the interpretation of these results. Since the tested flow rates did not match exactly with the flow profile data used in the analysis, meter accuracy was assumed to vary linearly between the known values. In addition, accuracies for each range in the flow profile were calculated by averaging all the test data within each range. Also, for flow profile ranges in which no test data was available, an average value was produced by interpolation between the nearest values for which data was available. As always, the analysis was based on average values for each meter type and size. Some of the meters failed or registered little volume in any range after moderate levels of throughput, and these meters had a significant effect on the average for the meter group. The extreme case in both 5/8 x 3/4-inch and 3/4-inch meters involved average endurance of single-jet meters, as shown in Figures 5 and 6. Test results also showed a significant difference between manufacturers. For the 3/4-inch single-jet meters, the average unmetered volume per connection per day after 3 million gallons of throughput for meters from one manufacturer was 278 gallons, compared to 11.5 gallons for the same type of meters from another manufacturer. Since meters that register little or no flow are usually easy to identify (Lund, 1988), repairing or replacing these meters within a system would recover much of the loss attributed to the average accuracy of each meter group.

CONCLUSIONS

The different types of meters tested in this study varied in accuracy performance at the lower flow rates examined. From these results it is expected that placing meter types that are most accurate at the expected low flow rates can substantially reduce apparent losses due to metering inaccuracy. Although the revenue recovered at each connection by replacing working meters based only on meter type and throughput would not normally justify replacement, the reduction in non-revenue flow can be significant on a system-wide basis. Using billing rates and daily volumes applicable to specific areas, utilities can calculate the payback period associated with each meter replacement.

Another item of interest in meter replacement discussed in the report is the difference in accuracy of meters from different manufacturers. Meters from 14 manufacturers were included in the study, but meters from only 6 of the 14 met the AWWA low flow standard more than 85% of the time. Accuracy testing can help utilities ensure that the selected new meters meet or exceed AWWA standards before purchasing and installing the meters throughout the system.

As expected, accuracy at lower flow rates decreased slightly with increasing throughput for most of the meter types. Low flow inaccuracy was responsible for most of the increase in non-revenue flow for all the meter types except the single-jet meters. Decreases in low flow (below 0.5 gpm) accuracy in the 3/4-inch meters for all types except the single-jets accounted for an average of 61% of the increase in revenue loss after 3 million gallons of throughput. In the single-jet meters of the same size and stage the accuracy decrease at low flows accounted for less than 3% of the total increase in non-revenue flow, which illustrates the large impact of meter failure compared with low flow accuracy degradation.

Since much more of the volume consumed at single-family residential connections is at higher flow rates, meters whose accuracy decreased at higher flow rates had a greater impact in increasing revenue loss due to meter inaccuracy. Due to the number of single-jet meters that failed during the tests compared with the small sample size, significant revenue recovery through replacement was calculated based on the average for the meter type and size, as shown in Figures 5 and 6. It must be noted again that these values are based on the average of all the meters of a particular type and size, and meters from different manufacturers varied significantly. Neglecting the single-jet meters that failed and for the other types of meters tested, revenue recoveries from replacing meters were much lower, between $5 and $10 per connection for the 5/8 x 3/4-inch meters and between $10 and $20 for 3/4-inch meters each year. Since there was not a significant increase in revenue recovery through meter replacement due to low flow accuracy degradation with increasing throughput, basing meter replacement decisions based only on meter type and the throughput levels tested here is not a viable alternative to individual utility testing. Since specific water quality, flow profile, and effects of time were not factors in the UWRL tests, utility test results would yield different results. Performing similar analyses at utilities based on local conditions and test results from meters pulled from service is likely to provide useful data for identifying meters for which significant low flow accuracy degradation is probable.

REFERENCES

Arregui, F.; Cabrera, E.; Cobacho, R.; & Garci-Serra, J., 2005. Key Factors Affecting Water Meter Accuracy. Proc. Leakage 2005, waterloss2007.com/Leakage2005.com/unterseiten/final_program.htm (accessed Feb. 12, 2009).

Barfuss, S.L.; Johnson, M.C.; & Nielsen, M.A., 2011. Accuracy of In-Service Water Meters at Low and High Flow Rates. Water Research Foundation. Project No. 4028.

Bowen, P.T. et al.,1991. Evaluating Residential Water Meter Performance. AwwaRF and AWWA, Denver.

DeOreo, W.B.; Mayer, P.W.; & Hayden, M., 2009. California Single-Family Residential End Use Study. Aquacraft Inc., Boulder, Colo.

Kenny, J.F. et al., 2009. Estimated Use of Water in the United States in 2005: U.S. Geological Survey Circular 1344, p. 20.

Lund, J.R., 1988. Metering Utility Services: Evaluation and Maintenance. *Water Resources Research*. 24:6:802.

Noss, R.R.; Newman, G.J.; & Male, J.W., 1987. Optimal Testing Frequency for Domestic Water Meters. *Jour. Water Resources Planning & Management Div.—ASCE*. 113:1:1.

PPIC (Public Policy Institute of California), 2008. Water Supply and Quality, September 2008. San Francisco, <www.ppic.org/content/pubs/jtf/JTF_WaterJTF.pdf>, (accessed Jan. 21, 2011).

Richards, G. L.; Johnson, M.C.; & Barfuss, S. L. 2010. Apparent Losses Caused by Water Meter Inaccuracies at Ultra Low Flows. *Jour. AWWA*. 102:5:123.

Tao, P., 1982. Statistiscal Sampling Technique for Controlling the Accuracy of Small Meters. *Jour. AWWA,* 74:6:296.

U.S. Census Bureau, 2009. 2009 American Community Survey, GCT1105. Average Household Size, American FactFinder, <factfinder.census.gov>, (accessed Jan. 18, 2011).

APPENDIX

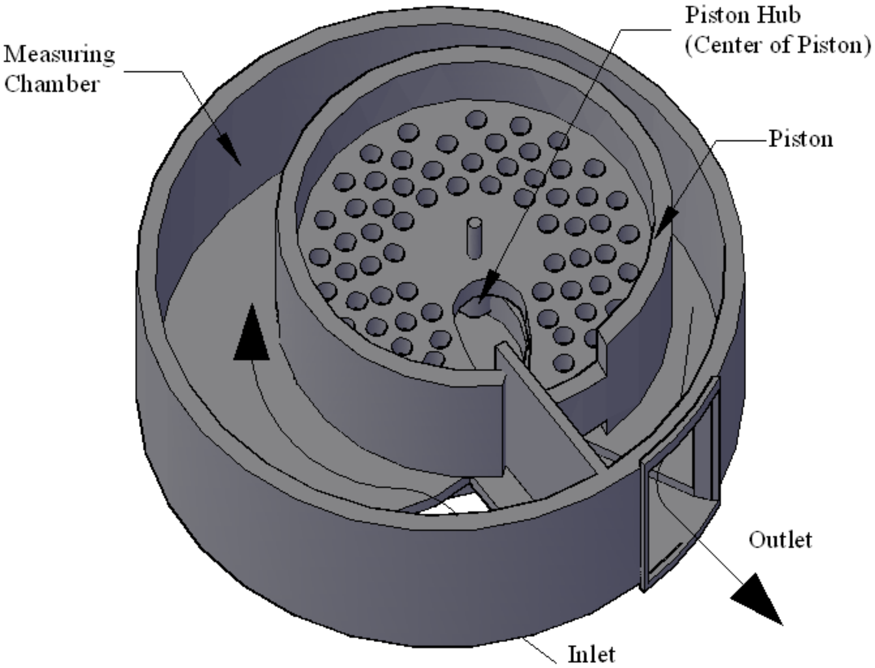

Figure 7. Displacement piston meter components

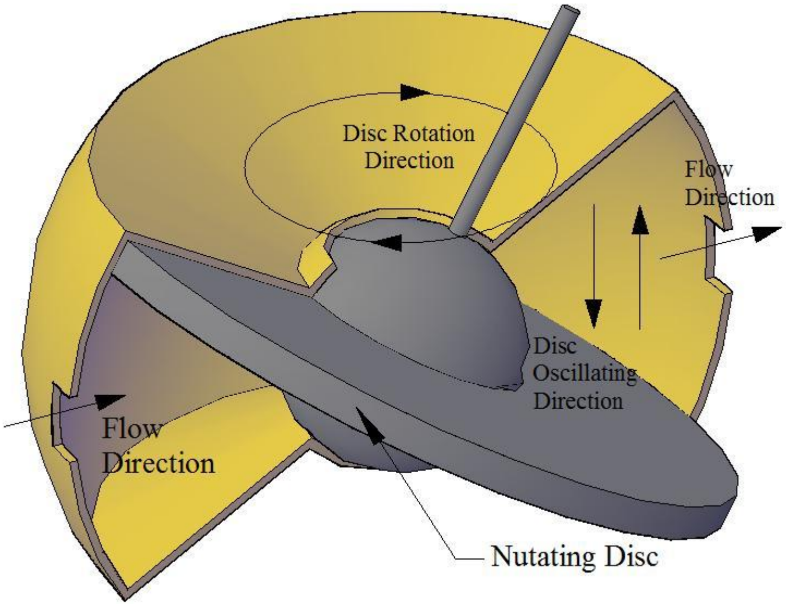

Figure 8. Nutating disc meter components

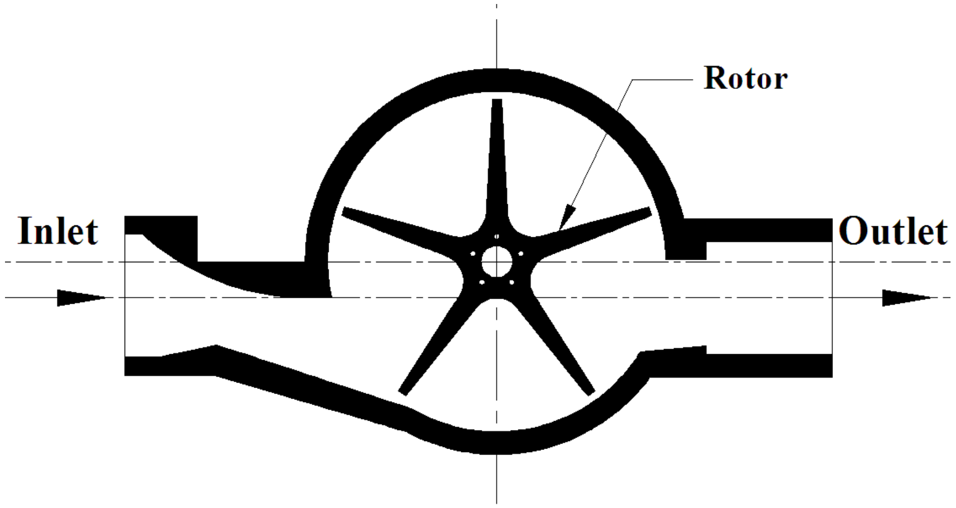

Figure 9. Single-jet meter components

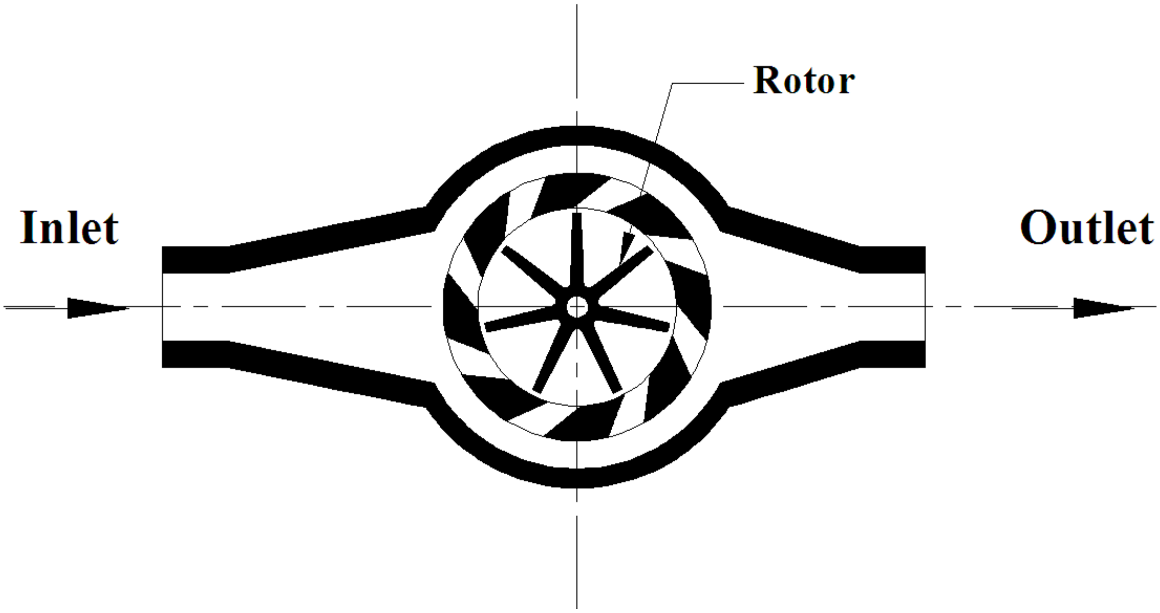

Figure 10. Multi-jet meter components

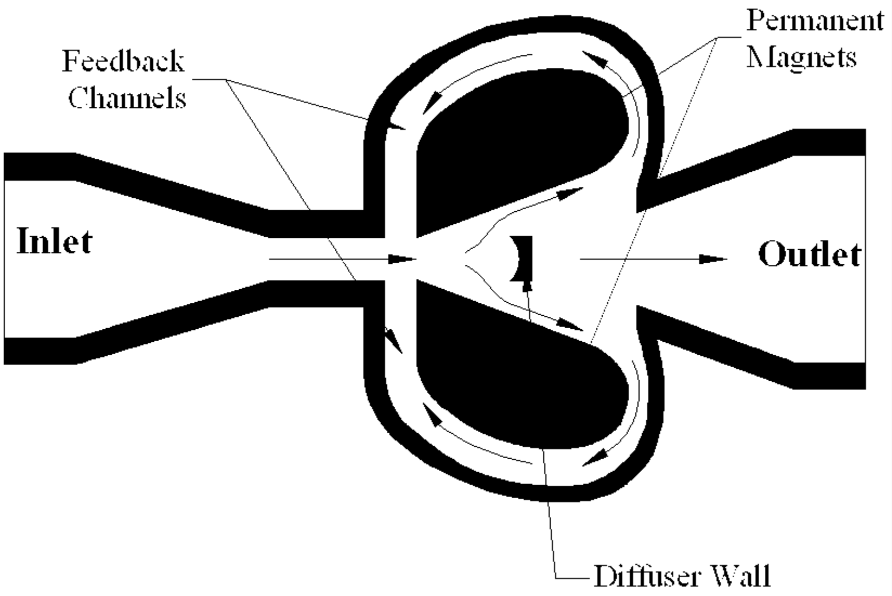

Figure 11. Fluidic oscillator meter components

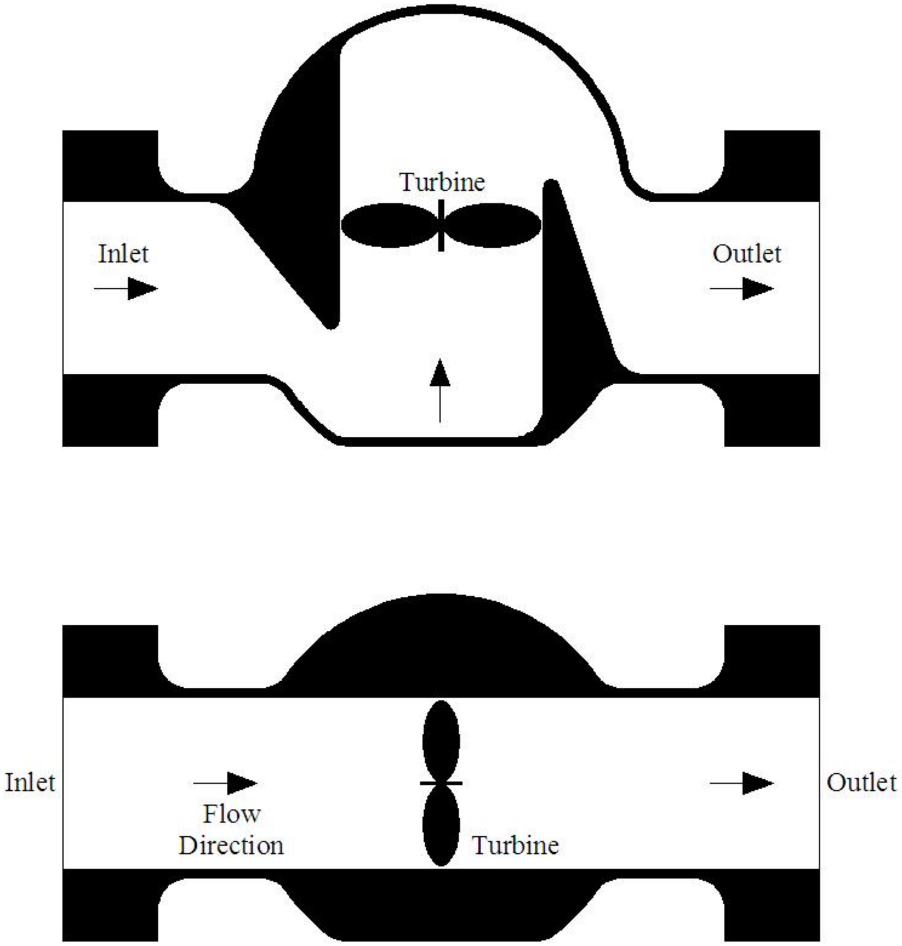

Figure 12. Turbine meter components

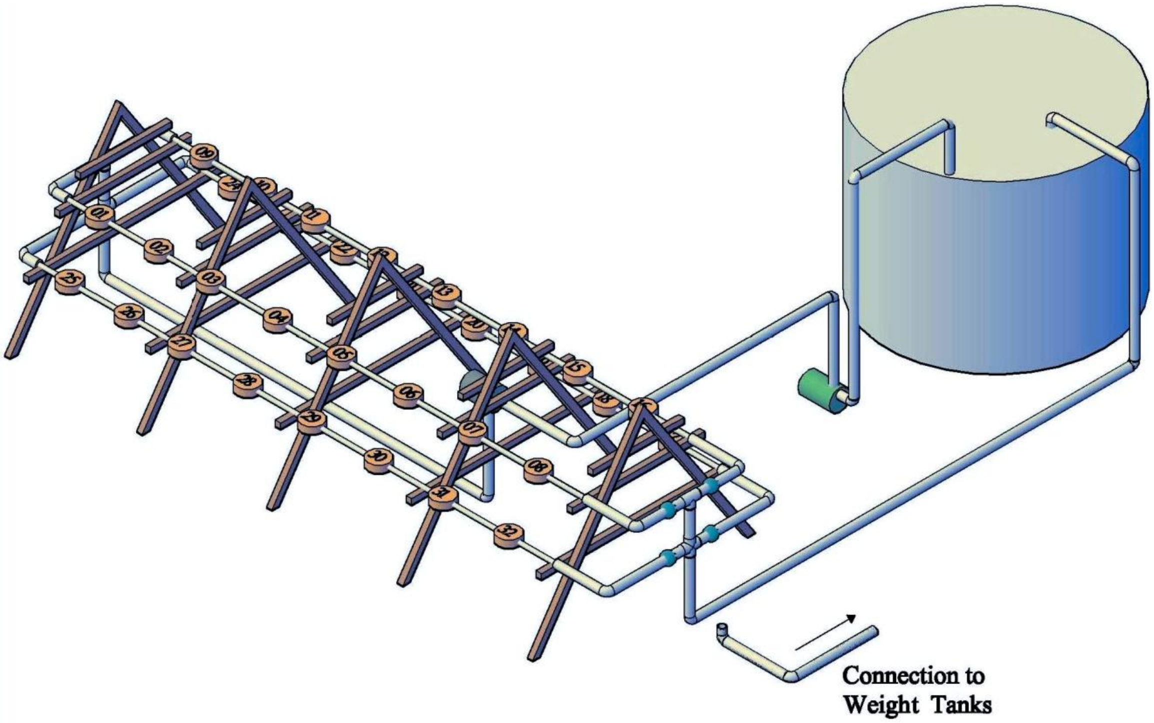

Figure 13. Endurance testing configuration