Proving of Multi-Path Liquid Ultrasonic Flowmeters

By

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Abstract

For Fiscal and Custody transfer operation, statutory requirements and good practice have led to the in-situ proving of liquid flowmeters. Proving has been used not only to remove the installation effects, but also to demonstrate the continuing performance of the meter. The characteristics of positive displacement meters and turbine meters have made in-situ volume proving both necessary and cost effective.

Newer technology meters, such as Coriolis and Ultrasonic meters, have demonstrated greater short-term variability in their outputs, making them more difficult to prove by commonly used procedures. This characteristic makes it essential to look closely at the factors affecting this variability, and its implications for the proving process.

This paper identifies the factors affecting the provability of multi-path chordal ultrasonic meters. It also presents proving data for such meters, for a range of meter sizes, at several independent certified hydraulic laboratories around the world, as well as data from meters at various field installations. These data show that repeatability is predictable and generally is controlled by hydraulic/turbulence statistics. The statistics are zero biased and subject to the flow conditions at the site. The understanding of the proving characteristics gained by this analysis leads to proving procedures whereby a specified calibration accuracy, such as the ±0.027% of the API Standards, can be achieved. The paper describes this process and demonstrates its application using field data.

1.0 INTRODUCTION

The development of ultrasonic transit-time flow meters began over 50 years ago. Early versions of these meters were at times disappointing in accuracy and reliability. While the basic principle remains unchanged today, the technology has evolved substantially. The major improvements have been in the areas of transducer design, signal processing and, even more importantly, in understanding the factors that influence the performance of these meters. Recent designs of multi-path transit-time ultrasonic flowmeters now routinely achieve an accuracy and reliability comparable to or better than older mechanical technologies (i.e., turbine and positive displacement meters).

Unlike older mechanical technology meters, ultrasonic flowmeters can provide information about flow characteristics within the pipe and the properties of the liquid (or gas). It is this information along with the intrinsic possibilities of low uncertainty, low maintenance and large flow-range, as well as extensive diagnostics that make these meters attractive. These features have pointed to the use of these meters for Fiscal / Custody Transfer applications. As these applications have traditionally required on-line calibration of the meters using Meter Provers, the proving characteristics of ultrasonic meters are receiving increased scrutiny.

Proving of Fiscal / Custody Transfer Meters

Before discussing the use of provers with Ultrasonic Flowmeters, it is worth considering the reasons for proving meters.

- Proving can remove the effect of pipe fittings and installation hydraulics (reducers, planar and non-planar elbows, flow conditioner specifics) that may cause profile asymmetry, swirl, pulsations and high levels of turbulence, all effects that influence the majority of meters, often in an unpredictable way.

- In its simplest form, proving ensures that a meter, be it Positive Displacement, Turbine, Coriolis, or Ultrasonic, is yielding a calibration uncertainty meeting the expectations of both parties to the custody transfer.

- Proving on site can eliminate effects from variations in fluid properties such as viscosity.

- When trended over long periods of time, proving results can give an indication when meters require maintenance.

- Proving not only validates the meter, but also validates the equipment used to prove the meter (detector switches, valves etc.)

- Finally, minimization of measurement uncertainty is becoming more important than ever as the economic value of liquid hydrocarbons increases. Proving has become mandatory with some National Standards organisations. It is also likely to be desired by the users of ultrasonic flow meters as well.

We must therefore conclude that it would be beneficial for any meter used for Fiscal /Custody Transfer purposes to be capable of being proved in-situ.

Proving Ultrasonic Meters; Issues and Perceptions

For any meter, the validity and quality of the proving process is affected by several meter attributes:

- Its repeatability --Because the objective of the proving process is to establish a calibration factor with acceptable precision in a small number of proving runs, the short term variablity of the meter output—its repeatability is a key element in achieving acceptable proving performance.

- Its rangeability—Depending on the application, proves may be required over a range of flow rates. To trend meter performance, and to ensure acceptable accuracy if flow rate varies during a transfer, it is clearly desirable that the calibration of the meter be insensitive to flow rate.

- Its stability—Trending of a meter's proving performance over the long term provides valuable information about its health. Additionally, because ultrasonic meters do not degrade mechanically, a stable performance base effectively enhances the precision of subsequent proves.

- Its sensitivity to product properties—If the calibration performance of a meter is insensitive to a product's density and viscosity, then proves for a range of products effectively enhance one another.

This paper will focus on the repeatability and stability of ultrasonic meters. Additional papers on the rangeability and product sensitivity of Ultrasonic flow meters are contemplated.

As with any new meter, and ultrasonic meters are new to this application, perceptions about their performance are beginning to develop, not all of which will prove to be valid. This state of affairs will persist until sufficient experience and data are accumulated upon which guidelines and rules of thumb can be developed. One of these perceptions is that the short-term repeatability of the meter will not meet the API standards for Turbine meters, a yardstick for this type of measurement. This perception appears to be true, and it will be seen the repeatability of ultrasonic meters is a function of many features, prover size, installation conditions, prover type and, different to other meters, turbulence levels in the fluid. As there is an element of design influence on meter repeatability, as such, the data presented here relate only to the design of the Caldon LEFM Ultrasonic meter (LEFM 240C).

2.0 FACTORS AFFECTING THE REPEATABILITY OF ULTRASONIC FLOWMETERS

Most Ultrasonic flow meters proposed for use in custody transfer applications measure fluid velocities along multiple acoustic paths. [1] For example, the acoustic paths of a Caldon LEFM 240C are arranged in the single plane forming four parallel chords as shown in Figure 1. This plane is oriented at an angle (the path angle) with respect to the centreline of the pipe. A photograph of an LEFM 240C installed at a crude oil batching facility is shown in Figure 2.

[1] The principles of operation of transit time ultrasonic flowmeters have been describe in detail in the technical literature and will therefore not be covered in this paper. The reader desiring more information is directed to the Caldon Website.

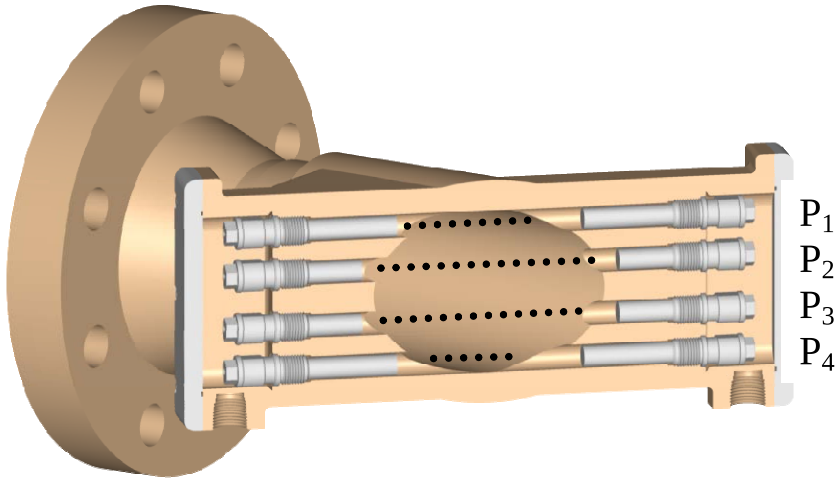

Figure 1: Cut-Away of a 4-Path Chordal LEFM – 240C

Figure 2: Installed 4-Path Chordal LEFM – 240C

All Ultrasonic flow meters currently used in custody transfer applications determine fluid velocity along an acoustic path by measuring the transit times of pulses of ultrasonic energy travelling along the path in each direction. Ultrasonic flow meters are sampled data systems. That is, the transit time measured for a single pulse travelling in one direction along an acoustic path samples the fluid velocity and sound velocity along that path. These variables, and particularly the fluid velocity vary in time because of turbulence, flow control operations and other factors. Hence a single sample does not establish the mean velocity. In Caldon systems, the individual chordal velocities, determined from a pair of transit time measurements (one with and one against the flow) are combined numerically by quadrature integration to form a single flow sample. This result too is affected by the statistics of the turbulence, though its effect is smaller than it is on a single path measurement. Thus, for a four-chord system like that in Figure 1 a set of eight-transit time measurement produces a measure of the flow. Multiple samples are necessary to refine the precision of the measurement. It will be noted that the sampling characteristic of Ultrasonic flow measurements is fundamentally different than the characteristics of turbines and positive displacement meters, which integrate the flow field mechanically and tend to smooth time-wise flow variations by their rotational inertia.

It is now appropriate to tabulate the factors affecting the repeatability of Ultrasonic flow meters:

- As noted above, the intensity of the turbulence encountered by a pulse as it makes its way along an acoustic path [2]. Typically, the root mean square value for local turbulence will lie in the range of 3 to 7% of the mean axial velocity [3]. The magnitude is sensitive to upstream hydraulics as will be discussed later. A mean velocity measurement along a single path will be below the 3 to 7% figure because of averaging during the transit (typically ranging 2 to 4%).

- The sample rate of the Ultrasonic flow meter. A proving run takes place over a finite time period—for a ball prover, 10 to 20 seconds is typical. It would appear that the more frequently an Ultrasonic flow meter samples the flow during the run period, the more precise the measurement of the calibration coefficient. This is true to a degree, but the precision is also affected by the turbulence spectrum as

[2] The focus of this paper is on the proving of ultrasonic meters with flow in the turbulent regime, that is, for Reynolds numbers greater than 10,000. Proving in the laminar or transition regions presents a different set of problems and will be discussed in a separate paper.
[3] Reference “Boundary Layer Theory”, Schlichting

described below. As a benchmark, Caldon meters typically sample and update the flowrate at a rate of about 60 Hz.

- The variations in fluid velocity due to turbulence are random and multidirectional and can be characterized by a frequency spectrum that varies inversely with pipe interior diameter and directly with fluid velocity. The low end of the spectrum presents the greatest proving challenge—higher frequency disturbances tending to average out during a prove.

It should also be pointed out that prover quality and type (compact or line prover) affect the repeatability of the meter being proved. Assuming, however, that the prover is perfect (or has a negligible contribution to uncertainty and repeatability), then, from the discussion above the repeatability will be a function of certain meter and application characteristics. In particular, it will depend on 1) the meter path configuration, 2) the sample rate, 3) the prover volume, 4) the turbulence, 5) the fluid velocity, and 6) the pipe diameter.

Characteristic Statistics

It has been shown that for pulse output meters, the number of pulses required to obtain repeatability, as for example defined in the repeatability commonly used in prover calibrations, 0.05% from five runs, is dependant upon the pulse-to-pulse regularity (pulse to pulse regularity for ultrasonic meter determined by the factors described in the preceding section). The worse the regularity the more pulses are required to obtain a given repeatability. Also, there is a finite limit to the achievable repeatability, which is a function of the numbers of pulses and pulse-to-pulse regularity. The methodology of Mr. R. Paton [4] has been used to construct a typical set of curves for a normally distributed pulse output is shown in Figure 3.

[4] *The Predictions of Calibration Repeatability Using Compact Provers and Pulse Interpolation*, R. Paton

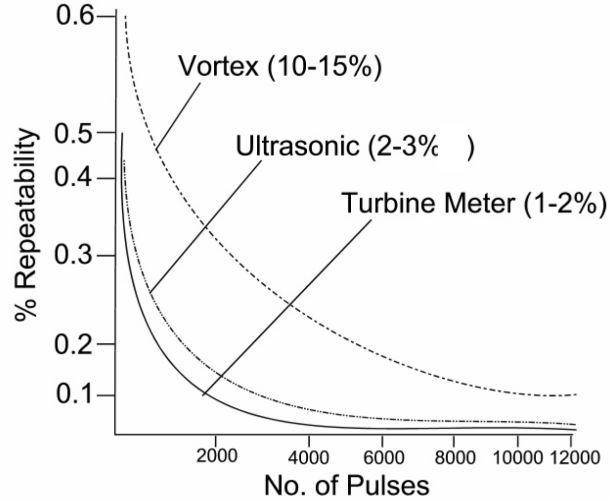

Figure 3 – Predicted Repeatability vs. Number of Pulses for Varying Standard Deviations

The data on the figure represent the authors' experience for the various meters shown.

A good turbine meter will have a pulse-to-pulse standard deviation of better than 1-2%, although there is more complex variation due to inter-rotational irregularity. As can be seen the turbine meter has a natural ability to get to the repeatability requirements with a relatively small number of pulses. Further with a compact prover, pulses interpolation is a valid concept because of its predictive nature, requiring a good regularity of pulse output. A Vortex meter at the other extreme has a somewhat indeterminate regularity, but from the authors' experience has a pulse-to-pulse regularity standard deviation of between 10-15%. Referring to the curves it can be seen that many more pulses are required to obtain good repeatability and that for all practical purposes they never reach the theoretical 0.05% repeatability. In fact, our experience showed that 0.1% was the best repeatability of a conventional Vortex meter.

Included on this curve is the “statistical” performance typifying a Caldon 4 path LEFM. The 2-3% figure shown on the figure represents the standard deviation of a single flow measurement sample from the mean—implicitly, one pulse per measurement, no pulse interpolation. The pulse output from an ultrasonic meter is derived from the converting the sampled velocity measurements into pulses. The “jitter” or standard deviation is due to turbulence and hydraulic variability that in turn produce variability in the pulse output. As discussed above, increasing the sample rate to pulse output rate will improve resolution, but not necessarily provability.

Note that Figure 3 can be interpreted in terms of a prover volume requirement. To achieve a desired repeatability in a set of calibration runs for a specific meter type, the prover is sized such that at the system flow rate, the meter produces the number of pulses required for the desired repeatability.

To achieve the repeatability typically required for a 5 prove set, Figure 3 implies significant increases in the prover volumes, with consequent cost and size penalty, or alternatively, to use a larger number of runs. Experience shows that proving of ultrasonic meters by both in-line and compact provers can yield repeatability comparable with turbine meters, but at other times, without an obvious external reason, the repeatability is inferior. It is probably safe to assume that this is due in most cases to the statistical nature of the process and/or to variations in turbulence levels.

Alternatively, the use the API MPMS Chapter 4.8 Table A1 provides a method for obtaining a the desired calibration factor uncertainty--±0.027% (two standard deviations) without requiring large provers or an inordinate number of runs. This results in the following table: The approach is substantially similar to that proposed by Folkestad.[5]

[5] "Testing a 12" Krohne 5-Path AltoSonic V Ultrasonic Liquid Flow Meter on Oseberg Crude Oil and on Heavy Crude Oil", Folkestad, 19th North Sea Flow Measurement Workshop 2001

Runs	**Repeatability (max-min)/min %**
5	**0.05%**
6	**0.06%**
7	**0.08%**
8	**0.09%**
9	**0.10%**
10	**0.12%**
12	**0.14%**
13	**0.15%**
14	**0.16%**
15	**0.17%**

Table 1: Summary of API MPMS Chapter 4.8 Table A1

As will be shown from the results, Caldon LEFM Ultrasonic meters achieve acceptable and reproducible results by taking more runs. However, this approach does not have, in our experience, wide acceptance as a method for line provers, where 0.05% from 5 straight runs is the norm. For compact provers, however, the situation appears to be different, where the volume can be increased by taking a number of passes to make an individual run.

In-Line Proving of Ultrasonic Flowmeters – Performance Summary

The following results presented are for a number of sites, including field installations (when data was made available) as well as at three independent laboratories. It is noted that the data is more heavily weighted with lab data, which interestingly, is typically worse than field data (possibly due to control loop stability). The meter sizes are from 4” to 12” diameter and oil viscosities varying from 0.7 to 100 CS. Data is presented as a predicted required prover volume by using the following equation:

$$\frac{\text{repeatability}}{D_{(n)}\sigma_{\text{test}}} = \sqrt{\frac{\text{Volume}_{\text{test}}}{\text{Volume}_{\text{required}}}}$$

Where $D_{(n)}$ = 2.33 for 5 points and 3.078 for 10 points.

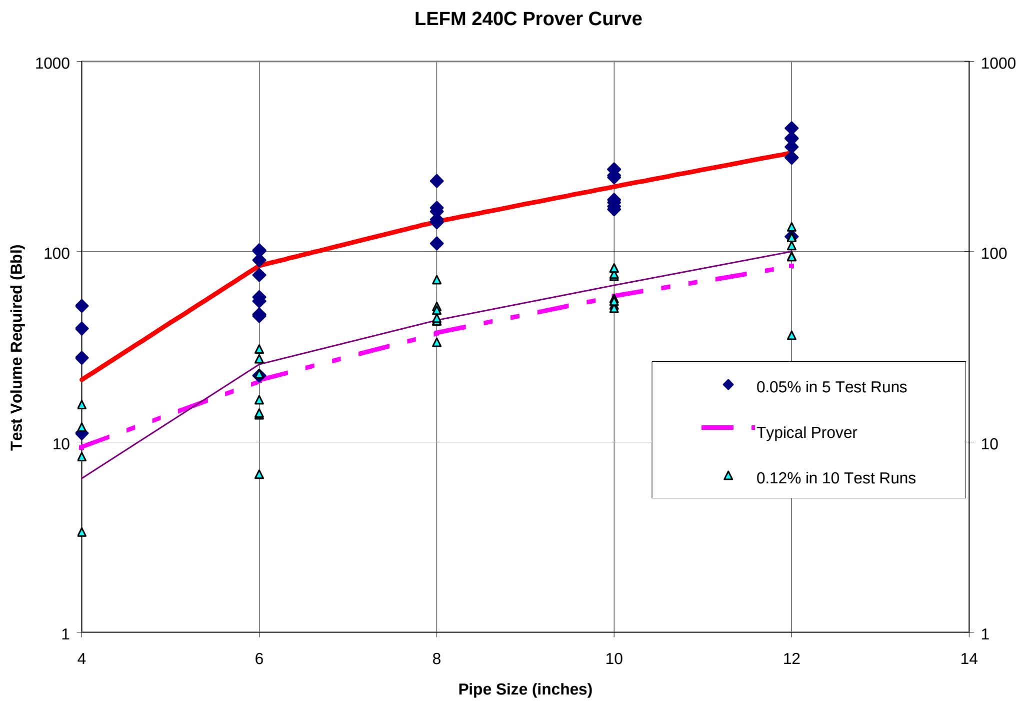

Figure 4: Prover Volume for 5 Run and 10 Run API Required Repeatability vs. Meter Size

The results based on the data collected are shown in Figure 4. Plotted on top are the curve fits for the two criteria, that is, the prover volume required for 5 proves and 10 proves.

The graph clearly demonstrates the improvement in repeatability by taking more repeat points. Going from 0.05 in 5 runs to 0.12 in 10 runs reduces the required volume by a factor of 3. The curves show a plot of the typical volumes used for turbine meters (Note: Typical prover size computed for a prover receiving 15,000 pulses from a typical turbine meter). The typical prover size line falls almost on top of the curve fit line of the 0.12% repeatability in 10 runs. However, the prover volume for the 0.05% repeatability in 5 runs requires a much larger prover than for equivalent size turbine meter. The Table 2 shows the expected repeatability against the API Specification. The darker shading indicates the values that are within the required API specification. (It is noted, that there is always a probability that the meter will meet the API specification a percentage of the time even for the number of runs that are not shaded).

		"Expected Caldon" Meter Repeatability				
Runs	Acceptable Repeatability	4	6	8	10	12
5	0.05%	0.08%	0.08%	0.10%	0.09%	0.10%
6	0.06%	0.09%	0.09%	0.11%	0.10%	0.11%
7	0.08%	0.09%	0.10%	0.12%	0.11%	0.11%
8	0.09%	0.10%	0.10%	0.13%	0.12%	0.12%
9	0.10%	0.10%	0.11%	0.13%	0.12%	0.13%
10	0.12%	0.10%	0.11%	0.14%	0.13%	0.13%
11	0.13%	0.11%	0.11%	0.14%	0.13%	0.13%
12	0.14%	0.11%	0.12%	0.14%	0.13%	0.14%
13	0.15%	0.11%	0.12%	0.15%	0.14%	0.14%
14	0.16%	0.12%	0.12%	0.15%	0.14%	0.14%
15	0.17%	0.12%	0.13%	0.15%	0.14%	0.15%

Table 2: Summary of API MPMS Chapter 4.8 Table A1 and Typical Data Scatter for Various Pipe Sizes

Proving Ultrasonic Flowmeters with a Compact Prover

We are only just beginning to collect and organize data of calibration using Compact Provers, the results of which are encouraging with good success on several meters. Figure 5 shows a photograph of a compact prover used to calibrate an LEFM 240C. The method of calibration used includes taking groups of pulses, calculating the mean value of the group and taking that as one run.

Figure 5: Compact Prover Test Configuration

Figure 6 shows data collected at a particular installation that had difficulty proving when using a Compact prover. The graph shows the effect of taking groups of passes to make up an individual run on two 6” meters, by plotting the data against effective proving volume, that is, the total volume produced by the passes for each run. The passes varied from one pass per run upwards. Repeatability was taken as maximum to minimum deviation in 5 runs.

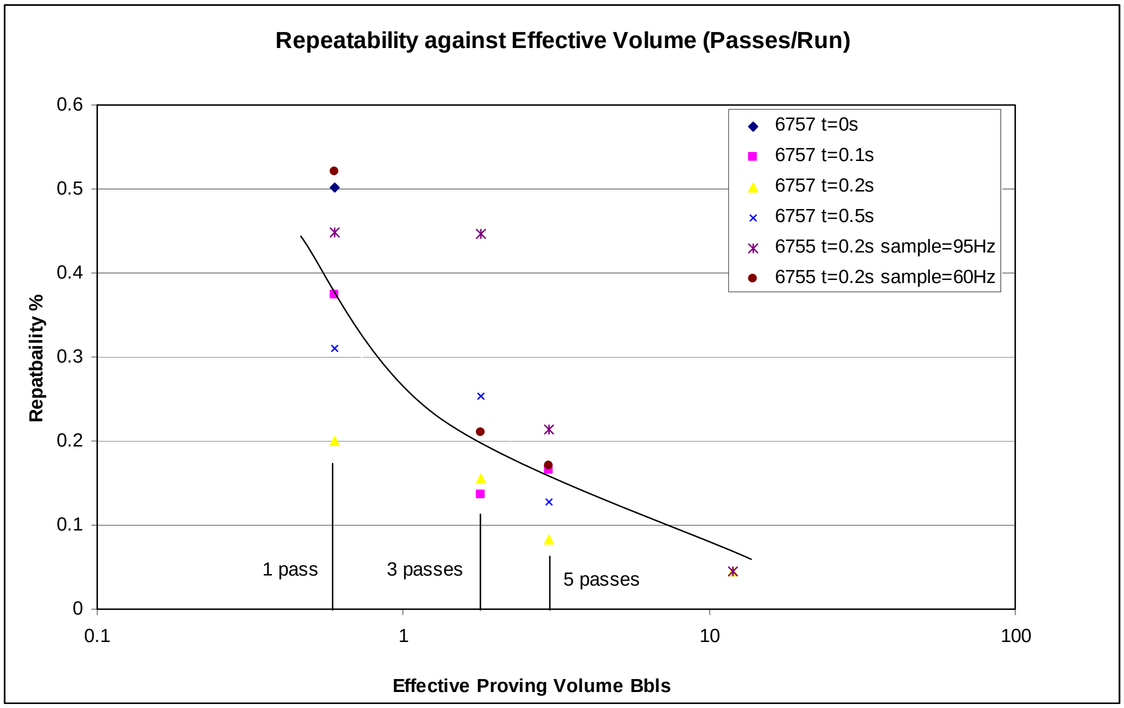

Figure 6: Example of Repeatability (6 inch) Using a Compact Prover Configuration – Difficult Hydraulics

To achieve the better performance numbers in Figure 6, the upstream hydraulics for meter 6757 were modified such that an upstream strainer was removed. After the hydraulic change out, a clear decrease in turbulent intensity was observed and the meter proved using groups of 3 passes in 5 runs. Also, after evaluation, it was determined that tests for meter 6755 had the compact prover configuration upstream of the meter. When the prover was installed downstream, the repeatability improved by a factor of 2 to 3.

The graph also contains data for the effect of a varying time constant and the sampling rate. The time constants for smoothing the data from the ultrasonic paths between 0.1 and 0.2 seconds appear to be good choices for a steady output as well as negating the influence of flow changes as the piston starts its run, even with a high plenum pressure.

While the success of several meters and the understanding of some installation effects are not conclusive and the number of results small, the indications are that a compact prover may be another solution for proving ultrasonic flowmeters other than just the line prover.

Upstream Hydraulic Effects on Proving Ultrasonic Flowmeters

While it is clear that upstream hydraulics and turbulence can influence the repeatability of ultrasonic flowmeters, quantifying the sensitivity to hydraulics and establishing exhaustive ground rules is a major task. Likewise, the effectiveness of various types of flow conditioners should also be considered. Limited parametric tests have been performed in order to gauge the sensitivities of ultrasonic meters to varying upstream hydraulics.

Non-Planar Elbows

The first item evaluated was the sensitivity to swirl producing hydraulics. For this evaluation, an installation known to be a swirl producer was used, see Figure 7.

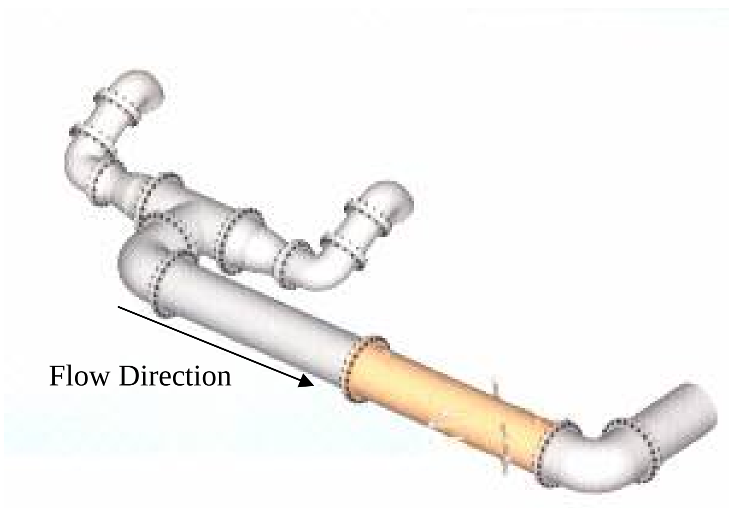

Figure 7: Swirl Producing Installation Used to Evaluate Repeatability

This installation used a 26 inch meter with two measurement planes each with four paths (i.e., an eight-path meter). The profile measured showed an asymmetry in opposite directions with the two four path meters, due to cross flow, and profile distortion.

We performed special repeatability tests using a gravimetric standard for comparison. Two tests were performed with and without swirl eliminating flow straighteners upstream. The results for repeatability are shown in Table 3.

Conditions	4 Path (1)	4 Path (2)	8 Path
Straightener (5D Upstream)	0.05%	0.04%	0.03%
No Straightener	0.22%	0.14%	0.05%

Table 3: Summary of Repeatability of Swirling Hydraulics and Downstream Flow Straighteners

The swirl was found by experiment to be ~33rpm at 17 ft/s (5 m/s). It is clear that the cross-flow degraded the four paths systems repeatability. It is also clear that even without a straightener the repeatability of the eight-path, with its natural cancellation of cross flows, remained within the required tolerance.

Reducing Tees

The next item evaluated was the repeatability's sensitivity to the elimination of flow conditioning when installing downstream of planar elbows and tees. For this evaluation, the repeatability of a 12 inch meter installation installed per API guidelines (10 L/D with a tube bundle) was compared to the repeatability of the same meter at the same site, but installed downstream of a reducing tee. The products tested were crude oils that were proved at regular intervals (each batch). The flowrate range was 2:1, the viscosity range was ~2 to ~60 cS.

	Installed per API Guidelines	Installed Immediately Downstream Reducing Planar Tee
Repeatability (5 runs)	0.10%	0.15%
Min Meter Factor	0.9952	0.9933
Max Meter Factor	0.9992	0.9970
Std Dev Meter Factor	0.08%	0.09%

Table 4: Repeatability Comparison – Installed per API Guidelines as well as without any Flow Conditioning

Table 4 shows that the repeatability degrades by 50% without flow conditioning. Table 4 also shows that the linearity of the meter is not degraded by the upstream hydraulics, and that the calibration has a 0.2% shift, due to hydraulic effects.

Flow Conditioning

The last item evaluated was the repeatability's sensitivity to flow conditioning. These tests were performed with an 8-inch meter at Alden Research Laboratories using water as the test liquid. The repeatability reference standard was an independent turbine meter, un-influenced by hydraulic parametric tests. Table 5 documents configurations evaluated and the results.

Flow Conditioning - Description	Repeatability
Straight Pipe – 20 L/D	**0.11%**
Mitsubishi Plate Flow Straightener – Upstream 0 L/D	**0.10%**
Vortab Flow Straightener – Upstream 3 L/D	**0.14%**
V-Cone – Upstream 3 L/D	**0.35%**

Table 5: Repeatability Summary for Various Flow Conditioning

Again, from the data shown, flow conditioners and obstructions (i.e., V-cone) near to the meter, that produce large-scale turbulence (shedding vortices) degrade repeatability. Likewise, plate flow conditioners close to the meter may slightly improve repeatability.

Stability--Long Term Repeatability of Ultrasonic Flowmeters

The short-term repeatability of meters is important but ultimately the long-term repeatability, stability of the mean meter calibration is more important. Most turbine meters for example drift with time due to a combination of mechanical changes and tolerances and varying flow conditions. The ultrasonic flowmeters appear to have a more stable calibration with time. This is demonstrated in the tests shown below. A standard turbine meter, a helical turbine meter and Caldon LEFM Ultrasonic meter were used in series for batch measurement of

Crude Oil over a period of nearly 1.5 months. They were proved at regular intervals. The flowrate changed by 2:1, the viscosity changed from 1.8 to 66.5 cS and the density changed from 0.79 to 0.90. As can be seen in Figure 8, the variation of the LEFM ultrasonic flow meter mean calibration over this time is more stable under all flow conditions than for either of the other two meters.

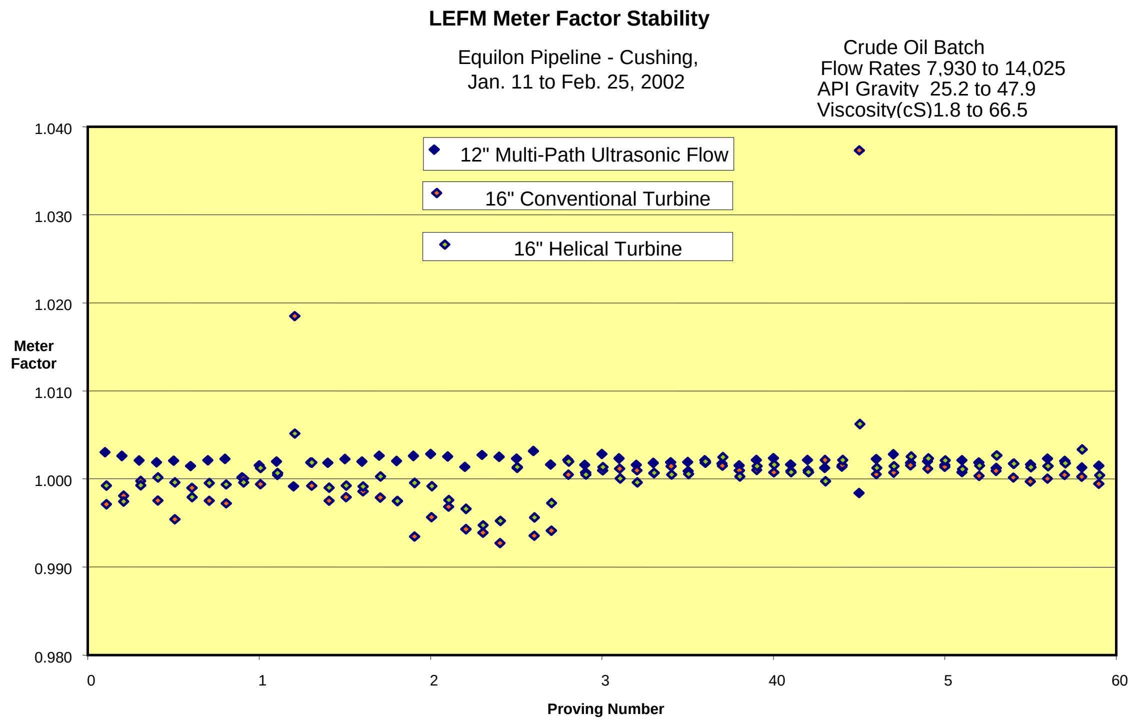

Figure 8: Long Term Repeatability – Ultrasonic, Helical and Standard Turbine

Other Methods of Proving Ultrasonic Flowmeters

The most obvious solution to the problem of repeatable proving results is to use a master meter. This would allow proving over any length of time, using for example a prover calibrated Turbine meter as a transfer standard. The Turbine meter would be packaged with the prover and calibrated on the process fluid, before proving the meter. Pulses from the Turbine would then be used to gate the Ultrasonic meter output, choosing the appropriate number of pulses to give adequate repeatability. Caldon has results for this method, and in principle it should work in the same way that the method is used for Coriolis meters (we do not have data from Coriolis meters for comparisons). While the master meter approach will reduce the size of the prover, the downside is obviously addressing the uncertainty of measurement, due to the use of an intervening meter.

Proving Ultrasonic Flowmeters – Future Work

The next steps Caldon is in the process of taking include the following:

- The impact of flow conditioning on meter performance (with respect to linearity and repeatability) – Tube Bundles and pipe reducers have already been extensively studied
- The compact prover and small volume prover evaluations teaming with an SVP manufacturer
- Adoption of some nuclear industry meter techniques (8-path meters and their natural turbulence reduction properties).

4.0 CONCLUSIONS

This paper looks at the proving of Caldon LEFM240C Ultrasonic Flowmeters. As the meter is relatively new to fiscal / custody transfer operation, data is only just beginning to come through. The points that are becoming self evident are:

1. The operation with provers is dependant on the design, type and manufacture.
2. Much of the output irregularity is due to turbulence in the flow. The higher the turbulence, the more irregular the signal output.
3. The irregularity can be alleviated by proper installation, such as 20 diameters of upstream straight meter run.
4. The results with in-line provers indicate that the Caldon meter needs to either use a large volume prover than the conventional or to use more runs to achieve a standard deviation of 0.027% for repeatability.
5. The initial results with compact provers indicate good repeatability. The method that appears to work is to take groups of 10 to 14 passes to obtain a mean calibration value. There appeared to be no problem experienced with the change in flow at piston startup.