Proving Liquid Ultrasonic Flow Meters

Class 2430

Don Augenstein, Vice President Engineering,
Caldon Inc. 1070 Banksville Ave. Pittsburgh, PA 15216

INTRODUCTION

Ultrasonic transit-time flow meter (UFM) technology is now well over 50 years old. UFM improvements in transducer design, signal processing and more importantly, the understanding of the factors that influence the performance of these meters have greatly improved these meters' performance. Current UFMs achieve accuracy and reliability comparable to or better than older mechanical technologies (i.e., turbine and positive displacement meters) and are now beginning to displace these traditional flow meters in hydrocarbon measurement applications.

This transition is being driven by a number of UFM attributes including:

- High accuracy and high turndown ratio
- Availability of large size meters
- Non-intrusiveness
- Low maintenance costs
- Providing information on flow characteristics and fluid properties
- Excellent on-line diagnostics

But unlike many mechanical meters, UFMs have had more difficulty in proving according to API Chapter 4.8.

The difference in proving performance is understood when the physical differences between mechanical meters and UFMs are considered. With mechanical meters, the flow through the device is controlled by either turbine blades or by other positive displacement mechanisms. However, with the UFM, the flow is only "measured" as it passes through the meter; in most cases without any interference from the meter itself. Since the UFM does not control the fluid motion, there will be flow variability that the UFM must "average" out. As a result, UFMs will have more difficulty in proving according to API Chapter 4.8.

Given the above, this paper's objective is to:

- Provide UFM users with relevant information necessary to understand how UFMs operate particularly with respect to measurement variability and its effect upon proving.
- Investigate potential factors that influence UFM statistics and repeatability[1].
- Illustrate the relationship between the UFM repeatability and the test volume.

DISCUSSION

This paper discusses the operation and characteristics of the UFM, as it pertains to proving, and presents these characteristics with data collected during proving.

This paper considers only the multi-path UFM and, in particular, the Caldon 240C. The multi-path UFM typically has a meter body with multiple transducer wells (see Figure 1 below).

Transducers are arranged in pairs or sets that form acoustic paths. There are normally two or more acoustic paths in a multi-path UFM.

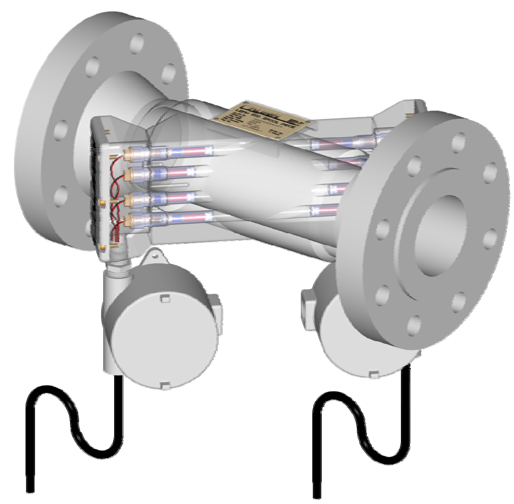

Figure 1 - Caldon 240C Chordal UFM

Each acoustic path measures a velocity along its chord. The results from all the paths are then combined or numerically integrated in order to determine the meter's average velocity and flow rate. The paths are spaced and weighted in ways to improve the numerical integration.

[1] Repeatability, in this report, refers to proving repeatability, defined as the spread in observed meter factor (K-factor) when tested under "stable" conditions with a fixed test volume. The term spread and repeatability are used interchangeably. The spread/repeatability is defined as the percent difference between maximum and minimum values of Meter Factor over 5 runs at a constant flow rate.

Measurement Scatter: The velocity measurements made by a UFM are constantly varying – even under "stable conditions". That is, from one measurement to the next, the path's velocity will vary within a band or range of values, as illustrated in Figure 2.

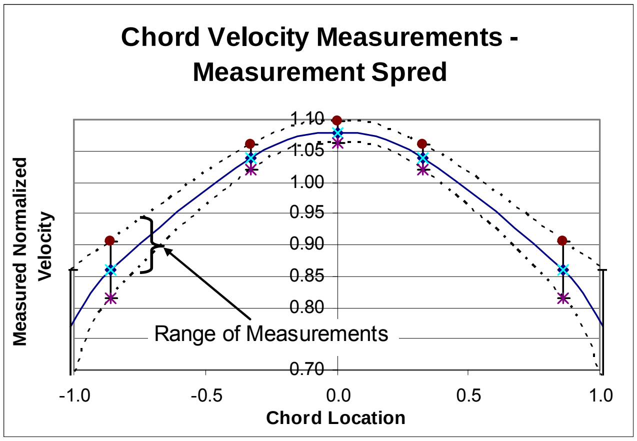

Figure 2: Velocity Variability vs. Chord Position

This variability is due primarily to the turbulence in the flow[2]. As seen in Figure 2, the data scatter increases as you go towards the pipe wall. At stable conditions, each chord's average velocity is constant and the variability has a zero mean error. However, any given set of measurements will fall within the band illustrated above. Clearly, averaging is required to get to the average velocity and flow rate.

What factors influence the magnitude of the velocity variability? The variability is largely due to turbulence and hydraulics, including factors like:

- Swirl and elbows
- Flow stability
- Flow conditioners
- Pipe fit up

The above conditions all introduce "turbulence" into the fluid.

Turbulent Frequency/Spectrum: The velocity variability has a spectrum or range of frequencies. The frequencies are influenced by the fluid velocity (e.g., a higher flow rate has a higher frequency) and by the hydraulics.

Much of the turbulent energy is at high frequencies (e.g., there are rapid changes in measured velocity). Pipe fit up (edges of flanges) and flow conditioners (plates etc.) all produce high frequency turbulence. To a lesser extent there is also low frequency energy (e.g., leisurely changes in measured velocity). Piping arrangements, like non-planar elbows produce low frequency turbulence.

According to data collected, at high frequencies the velocity variability is uncorrelated between the different chords (even when paths are crossing each other). At low frequencies, the velocity variability is somewhat correlated between the different chords.

Characteristic Statistics: For pulse output meters, the number of pulses required to obtain repeatability commonly used in prover calibrations, 0.05% from five runs, is dependant upon the pulse-to-pulse regularity[3]. The worse the regularity, the more pulses are required to obtain a given repeatability. Consider the different meters (turbine, vortex and UFM) shown below.

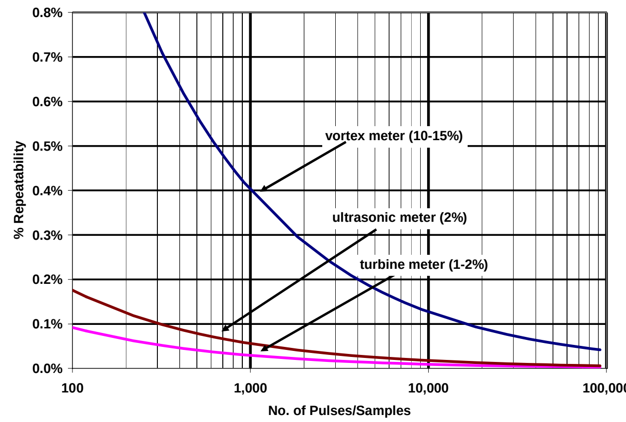

Figure 3: Predicted Repeatability vs. Number of Pulses/Samples for Varying Standard Deviations

A good turbine meter has a pulse-to-pulse standard deviation of better than 1-2%. The turbine meter meets the repeatability requirements with a relatively small number of pulses. Even with a compact prover, pulse interpolation is a valid concept because of its predictive nature (e.g., good regularity of pulse output).

A vortex meter at the other extreme has a somewhat indeterminate regularity, but from experience has a pulse-to-pulse regularity standard deviation between 10-15%. It can be seen that many more pulses are required to obtain good repeatability. The UFM falls between these extremes, but closer to that of a turbine.

Statistical Model for Proving Spread: With regard to proving a UFM, what does this mean? Since there is always going to be a band of data scatter, which is generally at high frequencies and largely uncorrelated, the UFM uncertainty during a proving test is controlled by the inherent data scatter as follows:

[2] Aside from real flow variations.

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

$$Spread_n \sim \frac{D_{(n)}\sigma_{reference}}{\sqrt{\frac{V}{V_{reference}}}} \qquad \text{Equation (1)}$$

Where:

$Spread_n$ = Average spread observed in "n" proves for a given volume, V

N = Number of proves = 5

$\sigma_{reference}$ = Standard deviation observed for a reference volume

$D_{(n)}$ = Conversion between spread and standard deviation = 2.326[4]

$V_{reference}$ = Reference volume at which the standard deviation is determined

V = Prove test volume

Equation 1 says that the proving uncertainty and spread will go down inversely by the square root of the proving volume.

The following present data that illustrate the above principle as well as field effects (such as flow stability) on proving.

PROVING DATA VS TEST VOLUME

A series of tests were performed to illustrate Equation 1. The test used an SVP (small volume prover) and a turbine meter (master meter) as repeatability standards. For smaller volumes, the SVP was used (by varying the number of strokes) and for larger volumes, a turbine meter was used.

The results for a 4 inch meter are shown below (other sizes behave similarly).

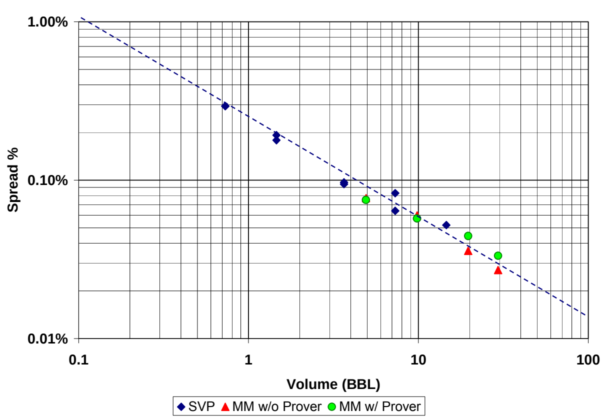

Figure 4: Repeatability vs. Proving Volume – 4 Inch Meter

Note: MM = Master Meter

From the above graph, the following are illustrated:

- Repeatability improves as volume increases, consistent with ~1/sqrt(V).
- Repeatability obtained with an SVP and that obtained with a turbine meter agree well (e.g., with regard to data scatter, there is no fundamental difference between the methodologies)

Predicted Repeatability for the Caldon LEFM 240C

Since Equation (1) can be validated by test, it can also be used to estimate the prover volume required to get 0.05% spread in 5 runs.

The standard deviation of a referenced volume was estimated (based on multiple meters) to be ~ 1% for a reference volume[5].

Using Equation (1), then the prover volume required for each size meter is predicted in the following graph.

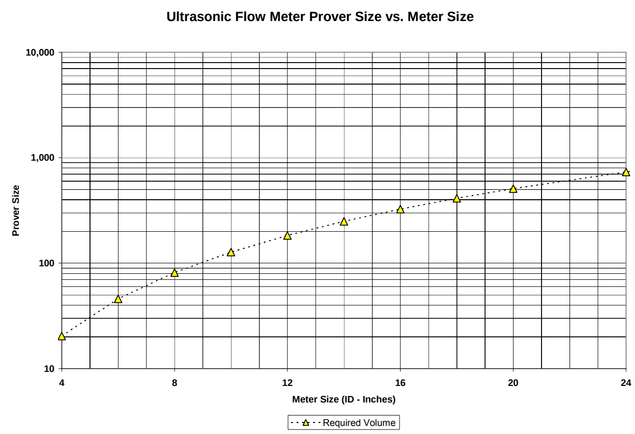

Figure 5: Statistical Tool Estimate of 5 Prove Test Spread

How well does Figure 5 match experience? Figure 6 overlays the above curve on laboratory data collected at Alden (Holden, MA), Trapil (Paris, France), NEL (Glasgow, UK) and SPSE (Fos-sur-mer, France) and field data[6].

---

[4] $D_{(n)}$ = 2.326 for 5 samples and 3.078 for 10 samples. John Mandel, *The Statistical Analysis of Experimental Data*, Dover

[5] Reference volume computed as: Vreference = Max Velocity (40 fps) x Area x Sample Period (0.02 sec)

[6] Data is presented as a predicted required prover volume by using the following equation:

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

Here the factor $D_{(n)}$ relates the range (the maximum minus the minimum) of a limited sample taken from a large population to the standard deviation σ_{test} of that population.

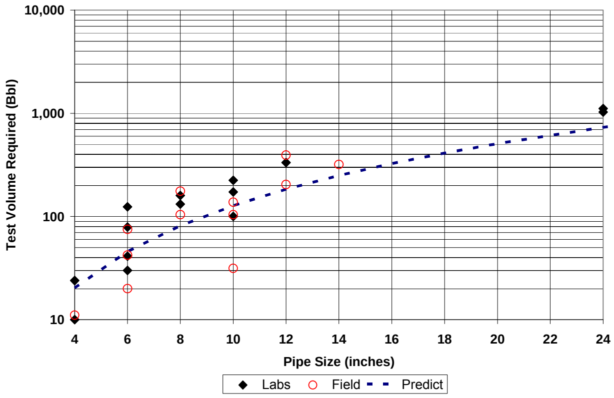

Figure 6: Statistical Model and Proving Results

Figure 6 shows that the proving results (both field and laboratory) agree fairly well with the simplified statistical model.

The following summarize the observations:

- There is plenty of scatter in the laboratory and field data. The cause for the data scatter may be flow stability and installation effects.
- Field data (e.g., pipeline data) seem to have lower spreads, likely due to more stable flows (they are much bigger systems).

The Figure 6 gives insight into what a customer might expect from performance, allowing for the fact that a simple curve does not capture the range of possible conditions. Depending on site factors, the results may be better or worse.

Proving – More the 5 Runs?

What about applications where the existing prover does not meet the size required for a UFM? The curves in the following figure show two proving criteria, that is, prover volume required to achieve a calibration uncertainty of ± 0.027% in either 5 proves or 10 proves.

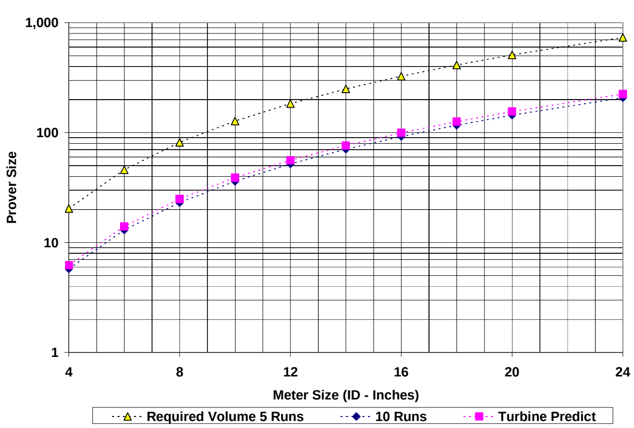

Figure 7: Prover Volume - 5 Run and 10 Run API Required Repeatability

Figure 7 clearly demonstrates the volume requirement reduction when the repeatability spread is increased by using more runs. Going from 0.05% in 5 runs to 0.12% in 10 runs reduces the required volume by a factor of 3.

The Figure 7 also shows a plot of the prover volumes one could compute for turbine meters[7]. The typical turbine prover size line falls just above the line of the 0.12% repeatability in 10 runs.

FACTORS THAT DEGRADE REPEATABILITY

Flow Instability: Now let's go back to the data shown in Figure 4, but consider flow instability. In Figure 8, we can see what happens to repeatability when large flow transients are introduced.

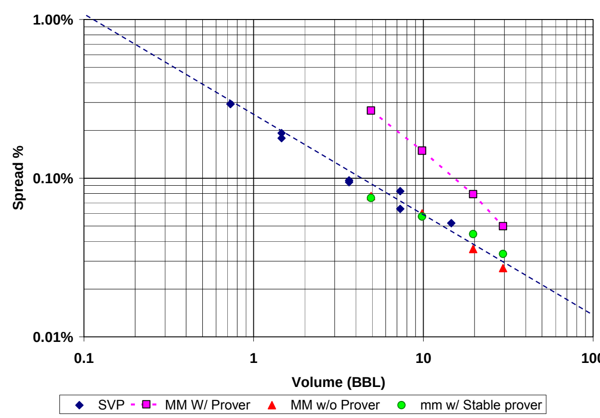

Figure 8: Flow Instability and Repeatability vs. Proving Volume – 4 Inch Meter

Note: MM = Master Meter. Stable Prover refers to when the SVP produces no flow transient

The top line of the graph is the repeatability observed when flow transients were introduced. Repeatability clearly degraded when the flow rate was unstable. The flow "instability" was artificially introduced by an unbalanced SVP. In this case, "unbalanced" means that the SVP plenum pressure was set too high for the existing flow rate and line pressure. At 150 m^3/hr, the unbalanced SVP[8] gave ~ +18% flow rate steps in the flow.

---

[7] Here the prover size was computed for a prover to achieve 10,000 pulses from a typical turbine meter.

[8] The Brooks SVP can be "adjusted" by changing the plenum pressure and for the other test cases, the SVP was adjusted such that the induced flow transients where confirmed to be less than 1%.

The SVP induced flow transient was captured with the UFM (and turbine meter) outputs and is shown in Figure 9.

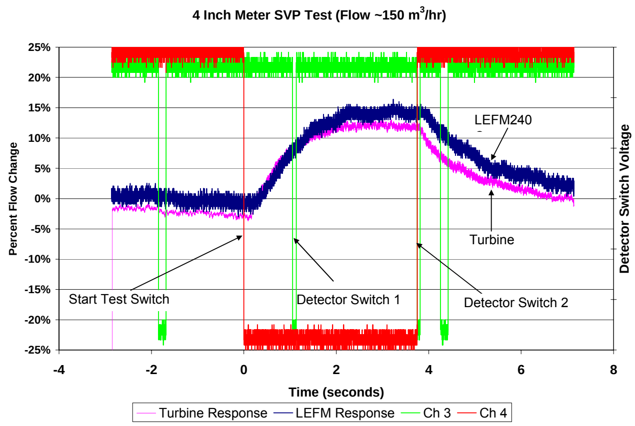

Figure 9: Flow Rate Changes During Proving-Velocity 20fps

Clearly, flow transients degrade performance, but how does the user determine if there are flow transients. Without a fast response output that is captured by an oscilloscope as in Figure 9, flow transients are only detectable via the meter's own measurements (and possibly other site indicators). But it is the capacity to provide more information than just flow is an important feature of the UFM.

In the case of the above flow transient, the UFM's flow measurement variations were compared between the times that the unbalanced SVP was operating and the times that it was not. The difference in the flow sample variations (as seen in each path) can be seen in the two samples in Figure 10[9]:

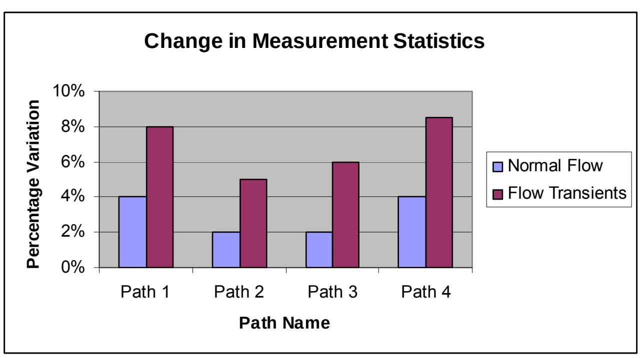

Figure 10: Meter Reported Flow Statistics during Proves with Unbalanced SVP

[9] Using parameters available via ModBus or Caldon's LEFMLink software program, the variation in flow rate is observed during each SVP test. As discussed, there was, during each run, a substantial change in flow rate. The true magnitude and the point at which the flow transient occurs cannot be determined from the ModBus data.

Therefore, the device's output statistics can be used to help identify difficult proving conditions.

FLOW TRANSIENTS AND PROVING ERRORS DUE TO "SAMPLED" PULSES

In addition to degrading repeatability, flow transients that are systematic with proving (like the transient shown in Figure 9), can introduce proving errors. Since UFMs use electronic means to produce pulses that represent volume throughput, the UFM output has a delay between the time that the throughput is sensed and the time that the pulses are formed. Additionally, some UFMs may have a damping filter to smooth turbulent variations in the sensed flow rate. Output damping further adds to the delay.

The delay between the sensed throughput and the pulse output is harmless provided the flow rate remains constant during the proving run. However, if the flow rate at the beginning of the proving run is different than the flow rate at the end of the proving run, the pulses counted during the proving run will not properly represent the volume that was displaced by the prover. This may lead to an incorrect meter factor.

The magnitude of error is related to four (4) factors:

1. Flow Rate Update Period (PD)
2. Damping Filter Time Constant (DT)
3. Proving Run Time (PT)
4. Flow Rate Change in percentage (RC) during the Prove Run.

Mathematically, these factors are related as follows:

$$Error(\%) \leq RC \frac{(PD + DT)}{PT}$$

This error is shown in Figure 11.

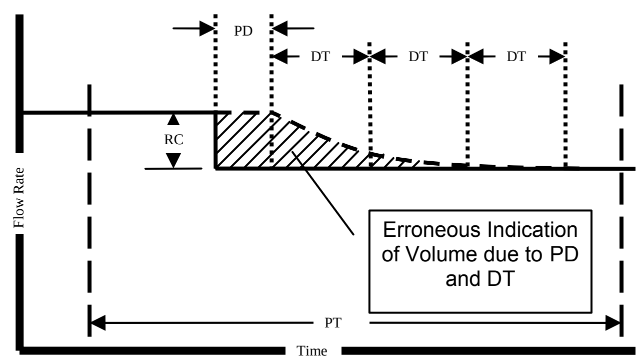

Figure 11: Potential Measurement Errors Due to Time Response of Meters

PT is either given directly from the proving report or can be determined from the average flow rate. The magnitude of the flow rate change is not readily determined from the meter being proved (because of its processing delays), but can be estimated from other instrumentation (e.g., the change in a downstream pressure indication during a prove). In any case, it is clear that the error is minimized when PD and DT are small and when PT is large.

Example (Caldon LEFM 240C):

Flow Update Period (PD) = 0.020 sec. (50 Hz)
Damping Time (DT) = 0.020 sec.

Assuming the rate change (RC) during the proving run to be less than 2%. What is the minimum run time (PT) to ensure a meter factor error of less than 0.02%?

$$PT = \frac{RC(PD + DT)}{Error\%} =$$

$$\frac{0.02 \cdot (0.02 + 0.02)}{0.0002} = 4\,\text{sec}.$$

HYDRAULIC EFFECTS AND REPEATABILITY

Hydraulics alone can degrade repeatability. There have been field examples of installations with degraded repeatability due to:

- “Witch’s Hat” strainers upstream of meters
- Lack of flow conditioning with swirling profiles or prover inlets upstream of the meter.
- Flow conditioners in close proximity to the meter or flow conditioners with debris caught on them.
- Improperly aligned flow meters (flanges not aligned)

All these conditions could not possibly be discussed within this paper. But in order to give a quantitative example, Caldon did experiments with swirl and no swirl at a flow laboratory[10]. The results are as follows:

- Swirl/Distortion (Inlet 8.5 L/D upstream) – 0.15% Repeatability
- Same hydraulics but with a Mitsubishi FS installed 5 L/D upstream – 0.05% Repeatability

The above illustrates that providing reasonable flow conditions has a good influence on repeatability[11].

CONCLUDING THOUGHTS

- The UFM meter does not prove as well as a turbine meter, but it does prove. Even when using an undersized prover, the UFM can prove by using more runs.
- The objective in proving a UFM is different than that of a turbine or PD. For a UFM, the objective is to verify/determine the meter’s calibration alone and not to also determine the meter’s operating condition and health, as with the turbine meter.
- Given that the UFM does not have the mechanical issues of a turbine or PD, it is not necessary to prove as frequently. Therefore, the additional number of proves required (at stable conditions) to satisfy API Chapter 4.8 is justifiable.
- Many users are considering laboratory calibrations in lieu of field calibrations. Given that perspective, meter factor stability and ability to detect problem conditions become important (features at which UFMs are strong).
- Repeatability and standard deviation performance follow closely the predicted curve against increased volume.
- Repeatability improves when the flow rate is more stable. When the flow rate is unstable, the repeatability degrades. Therefore, all other installation conditions being equal, one test site might have better (or worse) repeatability simply because the flow rate is more (or less) stable.
- A statistical model (e.g., Equation 1) can be used to predict the spread and statistics for a given site.
- Testing with an SVP showed that the SVP can be used to cause considerable flow transients if the plenum pressure is not set well[12]. This flow transient could introduce a bias into the recorded meter factor depending on its magnitude (as percentage) and the flow meter’s flow update rate.

[10] Test conditions had a non-planar header 8.5 L/D upstream of the meter.

[11] A separate topic is the good and bad effects of flow conditioners themselves in proximity of the UFM.

[12] In most field applications, it is difficult for the SVP to produce substantial flow transients.