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Technical Paper

Proving Coriolis Meters with Small Volume Provers

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1 INTRODUCTION

Coriolis meters have many advantages for mass flow and volumetric measurement in a wide variety of applications. Inherent reliability, linearity and stable meter factor (MF) on a wide variety of products make them an ideal choice for pipeline transfer. With the recent introduction of high flow rate meters, Coriolis technology can now be used in line sizes up to 16". Custody transfer of products is very common in these large pipelines; in many applications contractual requirements dictate that meters be proved in situ periodically to ensure accurate measurement over time and/or product changes.

Traditionally, large stationary pipe provers have been employed at metering stations. These provers are large, expensive and take up valuable real estate. Maintenance costs of the complex four-way valve can also be a concern. Small volume "ballistic" or "piston-type" provers are becoming more common because they have a much smaller foot-print and reduced maintenance costs. Even the largest small volume provers are small compared to pipe provers; a large small volume prover has a measuring volume that is as much as 10 times smaller than an equivalent pipe prover. Additionally, small volume provers disturb the flow slightly when the piston launches. Because the measuring volume is small, the rate change created by the prover becomes an integral part of the proving cycle and is measured by the metering device.

Coriolis meters are "manufactured pulse" devices. Sophisticated signal processing resolves the vibrating characteristics of the meter, namely phase and frequency, to calculate mass or volume flow rate. The pulse output is generated from the calculated flow rate within the transmitter. The signal processing to calculate the flow measurement, then translate that measurement into a pulse output, takes a finite amount of time. The delay associated with the signal processing must be fast enough such that it properly measures the change in flow created by the small volume prover. The signal processing must also filter the signal noise properly to achieve adequate repeatability (typical API requirement is five consecutive runs within 0.05%).

Data will be presented that illustrates the overall performance of Coriolis meters when proved with a small volume prover. Average MF and repeatability results will be presented for a range of flow rates and (small) prover sizes. Recommendations are made to optimize the response time of meters to accommodate the small size of the provers and also how to utilize averaging techniques to achieve acceptable repeatability.

2 CORIOLIS METER PERFORMANCE

Coriolis meters are largely unaffected by process conditions including temperature, pressure, density and viscosity. An illustration of performance is shown in Figure 1.

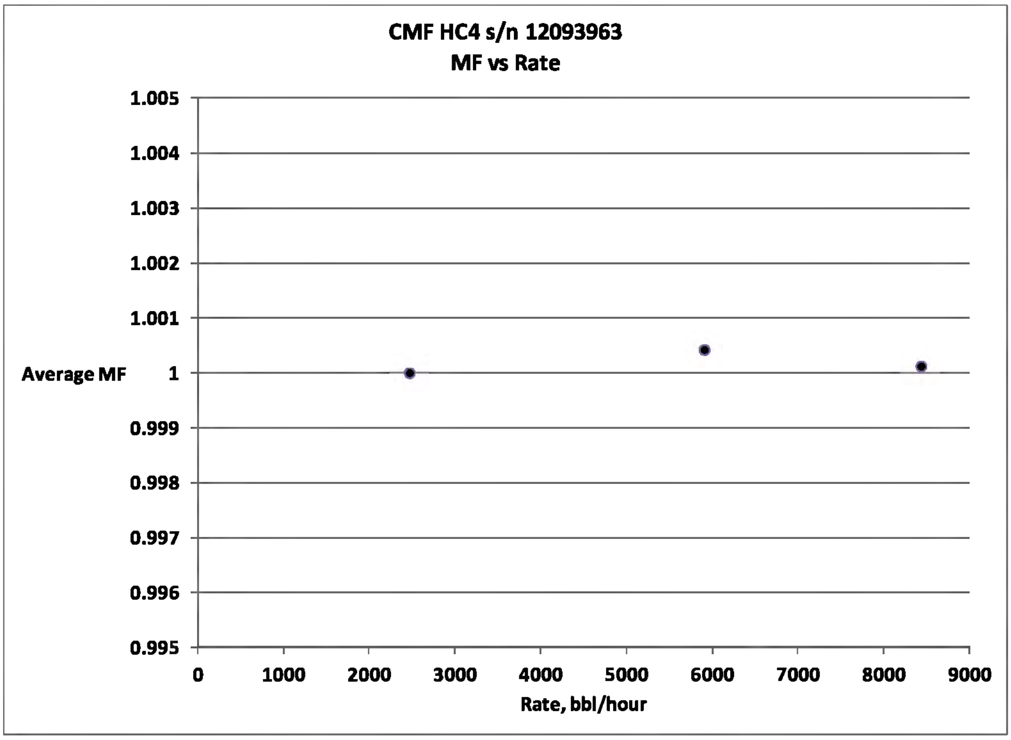


Figure 1 – Micro Motion CMF HC4 Flow Test

Conditions during the test were as follows:

Table 1 – Operating Conditions during Flow Test of Fig. 1

Rate, bbl/h	Re	Avg Volumetric MF	Avg Temp, °C	Avg Pressure, barg	Viscosity, cSt
2469	8,000	1.0000	25.2	2.9	75
5906	20,000	1.0004	24.5	3.4	75
8432	40,000	1.0001	33.4	4.3	45

The test was performed on a Micro Motion CMFHC4 which has a nominal flow rate of 13,000 bbl/hour. A 24" Daniel Compact Prover at Emerson's Micro Motion facility in Boulder, Colorado serves as the reference. Test fluid was mineral oil; notice that temperature and pressure rise considerably as the flow rate increases. This is because the facility is closed-loop and the heat exchanger doesn't reject 100% of the heat generated by the pump, especially at the highest rates. The maximum system rate is limited to 8400 bbl/hour due to pump capacity. No changes to meter parameters (e.g. meter zero or MF) were made during the test and the calibration constants were established on water. The prover's measuring volume is traceable to the Daniel factory water draw. Linearity errors of less than 0.05% as shown here are typical.

3 SMALL VOLUME PROVERS

Small volume provers have been in the marketplace for at least 30 years and have steadily gained acceptance as a viable reference standard for custody transfer, refer to Figure 2. The use of small provers coinciding with the release of high flow Coriolis meters larger than 8″ has created a need for a better understanding of the interaction between the two technologies.

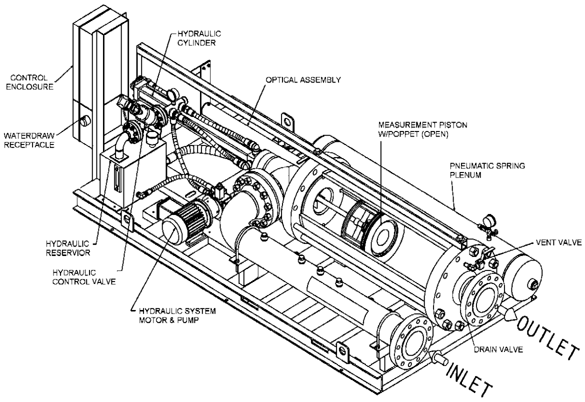


Figure 2 – Daniel Compact Prover

The flight time of the piston in a small volume prover can be as short as 0.5 seconds. Additionally, the time between when the piston launches and the first detector (pre run time) can be as short as 0.25 seconds. The very short times, coupled with the fact that the flow is disturbed by the piston when it launches creates challenges for Coriolis meters.

Figure 3 is an example of the changing flow rate as the piston launches. Four complete prover cycles are shown. Each time the piston launches the rate increases by 500 bbl/hour. Rate increases because the overall pressure loss of the system is lower when the piston is moving and the plenum pressure had not been optimized. In some instances the rate will decrease, such as a pipe prover because the ball adds resistance to the flow. Regardless of an increase or decrease in flow, the meter response time must be fast enough to have fully responded to the change imparted by the prover. For example, if the pre-run time is 0.25 seconds the meter has 0.25 seconds to fully respond to the flow change

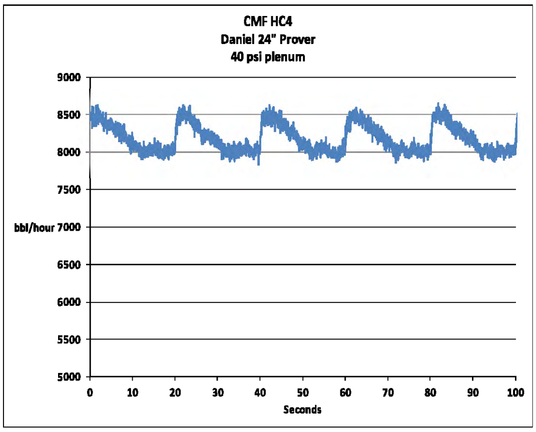


Figure 3 – Example of Changing Rate during Prover Pison Launch

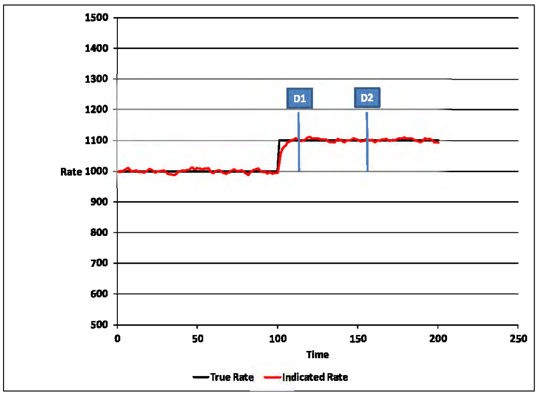


Figure 4 – Example of Adequate Meter Response Time

before the first detector is encountered. An example of good response time is shown in Figure 4, and results in an accurate MF.

Notice that meter flow indication (red) is equal to the true flow when the piston passes the first detector (D1). Figure 5 shows what happens when meter response time is too slow. The small area between the true rate and indicated rate is not “seen” by the meter and is therefore not totalized correctly. This phenomenon artificially creates a MF>1.000 (note that MF will be less than 1.000 if the rate change is negative). Adequate response time is critical to accurate proving.

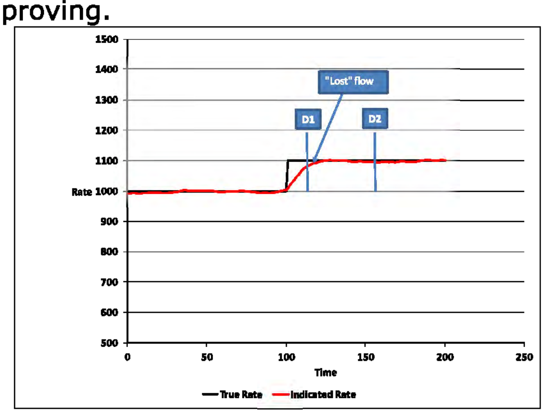


Figure 5 – Example of Inadequate (slow) Meter Response Time

Because a prover is a fixed volume device, the pre-run time and pass time between detectors changes with rate. For instance, a 2 barrel prover at 5,000 bbl/hour has a pass time of $\frac{2}{\left(\frac{5,000}{3600}\right)} = 1.4\,seconds$. At 10,000 bbl/hour the pass time is 0.72 seconds. Likewise, the pre-run time is half when the pass time is half.

An example of changing pass time vs. Rate for the Daniel 24” prover is shown in Figure 6. The importance of understanding the pass time vs. rate dependence will be discussed in the section “Coriolis Meter Repeatability and Uncertainty”.

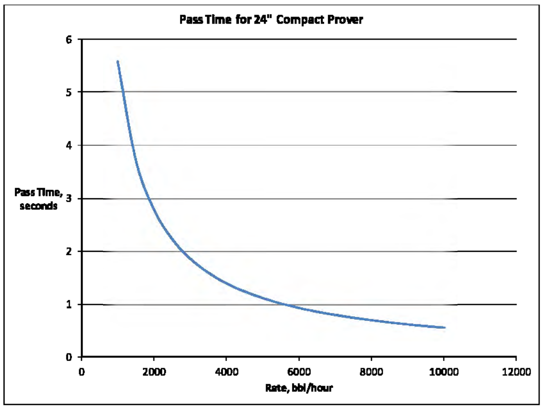


Figure 6 – Pass Time vs. Rate for the Daniel 24” Compact Prover

4 CORIOLIS METER RESPONSE TIME REQUIREMENTS

A meter must have adequate response time to avoid bias errors associated with the short pre run time of a small volume prover. The pass time and pre run time of the prover during the test of Figure 1 are shown in Table 2.

Table 2 – Pass Time and Pre Run Times for Test Shown in Figure 1

Rate, bbl/h	Re	Avg Volumetric MF	Pass time, seconds	Pre Run Time, seconds
2469	8,000	1.0000	2.19	1.09
5906	20,000	1.0004	0.91	0.46
8432	40,000	1.0001	0.64	0.32

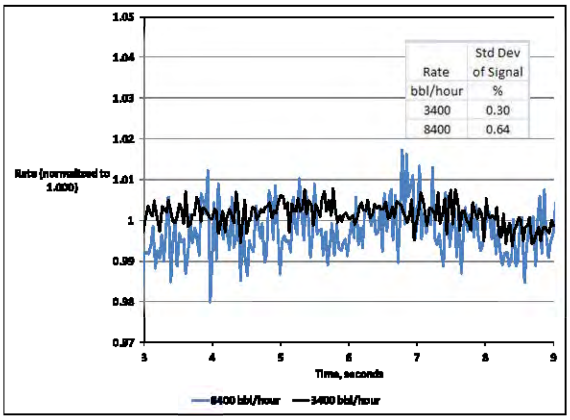
The good linearity and lack of any MF trend substantiates that for pre run time of 0.32 seconds the response time is adequate. If a trend in MF had been observed it would have been indicative of response time that was too slow.

The Micro Motion CMFHC4 (and all smaller meters, too) have a stated 99% response time of better than 0.05 seconds. A meter response time of 0.05 seconds allows for pre run times as short as 0.1 seconds, although most small volume provers are limited to a minimum pre run of approximate 0.25 seconds. When configured for the fastest response time and no damping, Micro Motion meters have no issues with the short pre run time of small provers.

5 SIGNAL TO NOISE IN CORIOLIS METERS

Coriolis meters measure two dynamic signals – phase (or delta T) and frequency. The signals are sampled at a very high rate (up to 48 kHz) then filtered using sophisticated DSP techniques to improve the signal-to-noise ratio as much as possible. In a system where fast response time is important (e.g. proving) any time-based averaging (damping) is not recommended.

System noise can originate from many sources: cavitating valves and strainers, pumps, mixers and even the flow turbulent velocity itself. Each of these noise sources can influence the signal stability of a Coriolis meter, especially as the velocity gets high (greater than 10 m/s). Figure 7 shows typical signal noise response of Coriolis meter at two flow rates.



Rate bbl/hour	Std Dev of Signal %
3400	0.30
8400	0.64

Figure 7 - Signal Noise at 3400 & 8400 bbl/hour

The signal noise at 8400 bbl/hour is approximately twice the noise at 3400 bbl/hour. The relationship between noise and rate is complex, but it is directionally correct to say that noise increases with rate. The implication is that as rate increases signal noise will impact proving repeatability. Concurrently, as rate increases the prover pass time decreases. The two effects on repeatability are normally convolved together and it is difficult to separate them. The next section describes modifications made to the prover at Emerson to study the impacts of rate change and prover pass time separately.

6 PROVER MODIFICATIONS AT EMERSON

In all commercially available provers there is at least one set of photo detector switches (in some models there are two). Referring to Figure 6, as rate increase the pass time decreases. Since the meter signal noise changes as rate increases at the same time, we needed a way to study the effects of changing rate independently of pass time (prover size). The solution was to add adjustable detectors to the optical assembly, which made the measuring volume of the prover adjustable. The modifications allowed us to study the affect of different size provers simply by changing the location of the detectors. Specifically, the modifications were made to study the affect of different pass times on repeatability while holding flow rate constant. Conversely, we can study the affect of different rates for the same pass time. Figure 8 is a photograph of the modifications.

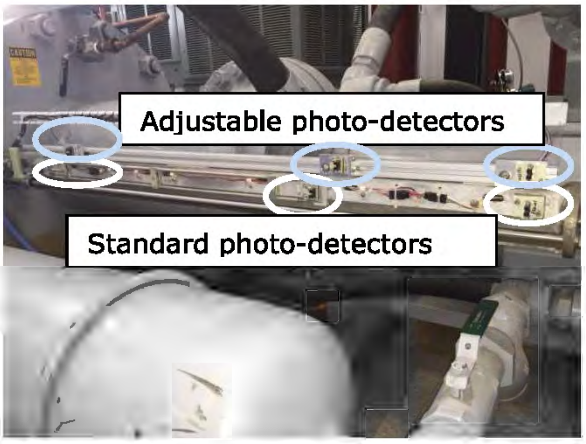


Figure 8 – 24" Prover with Adjustable Photo Detectors

A very important caveat – by using adjustable photo detectors there is no water draw calibration reference. The study using the adjustable detectors was intended to only quantify the affect of rate and pass time on repeatability.

For definition purposes, a pass is the time between detectors (sometimes referred to as flight time). A run is one or more passes averaged together.

7 CORIOLIS METER REPEATABILITY AND UNCERTAINTY RESULTS

The Coriolis measurement is a dynamic, time-based measurement and requires some amount of averaging to determine the correct MF. A large part of the challenge in proving is to minimize the uncertainty (API suggests less than ±0.027%, which is derived from 0.05% repeatability of 5-in-a-row). The uncertainty calculation is simple:

$$\boldsymbol{MF\ Uncertainty} = \pm\frac{\mathbf{2}\boldsymbol{\sigma}}{\sqrt{\boldsymbol{n}}} \tag{1}$$

Where σ is the population standard deviation of the meter signal variation and "2" is the coverage factor for 95% confidence. Normally, "n" is considered to be the number of passes (or runs); however, each pass is itself an average of a number of samples internal to the meter. If the pass time is too short there are not enough samples to drive the uncertainty to an acceptable level. The number of internal samples and the sample rate is not of much value to the user but since the sample rate is fixed, the number of samples is directly proportional to time, which is a more useful quantity. When proving, pass time (in seconds) and total run time (passes averaged together) are the relevant quantities.

A large test plan using a Micro Motion CMFHC4 was conducted to quantify how flow rate and pass time impact meter repeatability. The HC4 was chosen because its low pressure drop allowed testing up to the maximum rate of 8400 bbl/hour. The test plan and results are shown in Table 3.

Table 3 – Test Plan and Results of Pass Time Study

Test No.	Rate, bbl/hour	Pass Time, seconds	Pre Run Time, seconds	No. of Passes	Std Dev of MF, %
1	3000	1.43	0.50	100	0.024
2	3000	1.19	0.50	100	0.030
3	3000	0.95	0.50	100	0.032
4	3000	0.72	0.50	100	0.041
5	3000	0.48	0.50	100	0.044
6	3000	0.24	0.50	100	0.070
7	3000	0.13	0.50	100	0.102
8	5000	1.01	0.50	100	0.043
9	5000	0.85	0.50	100	0.041
10	5000	0.67	0.50	100	0.042
11	5000	0.46	0.50	100	0.062
12	5000	0.34	0.50	100	0.068
13	5000	0.17	0.50	100	0.120
14	5000	0.08	0.50	100	0.177
15	8400	0.24	0.50	50	0.211
16	8400	0.35	0.50	50	0.162
17	8400	0.59	0.50	50	0.109
18	8400	0.65	0.50	50	0.117

The number of passes was limited to 50 at 8400 bbl/hour due to temperature rise considerations. Given the large number of samples for each test, the sample standard deviation will be assumed to be the population standard deviation. For brevity, the data isn't shown but each population of data in Table 3 is normally distributed.

For a given flow rate, Equation 1 predicts that the MF repeatability (2*Std Dev) is related to $\frac{1}{\sqrt{pass\ time}}$, recalling that each pass is an average and subject to the integration time. This is illustrated graphically in Figure 9 using the data collected at 3000 bbl/hour.

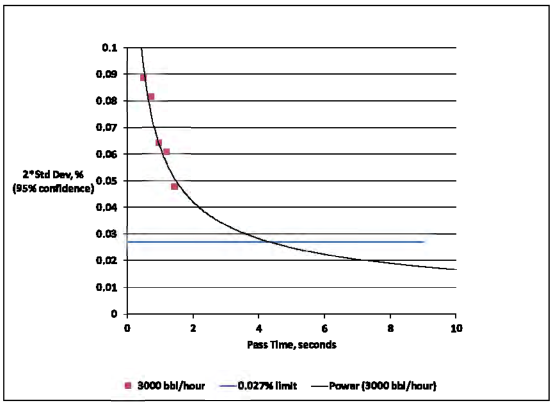


Figure 9 – Repeatability vs. Pass Time at 3000 bbl/hour (95% confidence limit)

The interpretation of Figure 9 is: a pass time of 4.5 seconds is required to make 2*(std dev) equal to ±0.027%. In other words, if the pass time is 4.5 seconds, the uncertainty of the measurement will be ±0.027% with a confidence limit of 95%. Equivalently, ten 0.45 seconds passes averaged together for one run will give exactly the same uncertainty. A 95% level of confidence assures that the meter will pass 5-in-a-row repeatability nearly every time it is proved. Although 95% confidence is the normal industry standard, adhering strictly to a high confidence limit has the potential to result in many passes per run. For instance, if our prover was ½ the size (32 gallons instead of 65), then ten passes per run would have been required to achieve 5-in-a-row repeatabilty within 0.05%.

Figure 10 represents the same data as shown in Figure 9 but at a confidence limit of 68% (1*std dev). Relaxing the confidence limit does not mean less uncertainty, rather it means that 68% (instead of 95%) of the time the expected uncertainty will be within ±0.027%. Another way to say this: if the prove requirement is 5-in-a-row at 0.05%, approximately 2/3 of the proves will pass with single pass runs (no averaging is required).

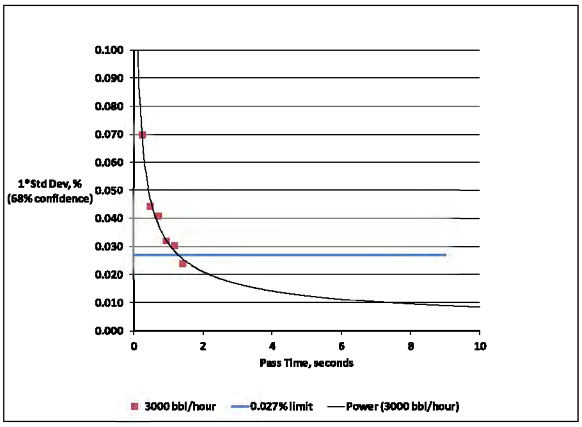


Figure 10 - Repeatability vs. Pass Time at 3000 bbl/hour (68% confidence limit)

Using the 68% confidence data of Figure 10, pass time should be at least 1.4 seconds. This says that the 24" Compact Prover is large enough to give good repeatability results at 3000 bbl/hour with no averaging.

Point no. 1 from Table 3 was analysed by grouping the 100 data points into 20 groups of five. Each group of five was evaluated for repeatability, requiring the range to be better than 0.05%. Of the 20 groups, 10 passed 0.05% repeatability, which is in-line with statistical theory. While not strictly in-line with API guidelines, analysing to 68% confidence strikes a reasonable balance that minimizes the number of required passes while maintaining required uncertainty.

Figure 11 shows all of the data for all rates that are summarized in Table 3.

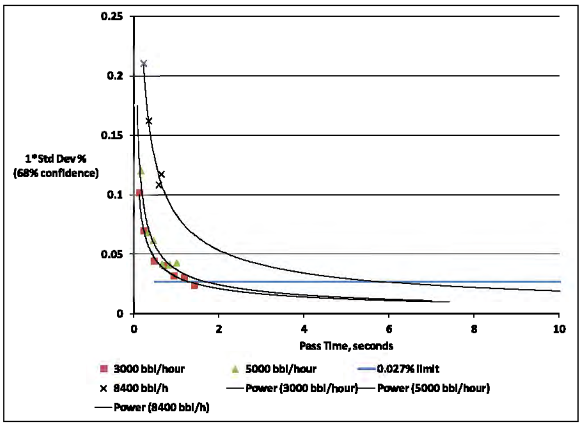


Figure 11 - Repeatability vs. Pass Time for all Rates (68% confidence limit)

At the highest rate of 8400 bbl/hour a total pass time of 6 seconds is necessary to achieve ±0.027% uncertainty. For example, a prover that has a 1 second pass time at 8400 bbl/hour will require six passes to be averaged together for a single run. Approximately 2/3 of the time the meter will prove with 5-in-a-row within 0.05%. The total number of passes required is 30 (six passes per run and five runs).

8 SUMMARY OF REPEATABILITY AND UNCERTAINTY STUDY

By evaluating the intersection point between the data in Figures 9, 10 & 11 and 0.027%, a relationship is drawn between total pass time and flow rate. Figure 12 provides a guideline for estimating the required number of passes per run and ultimately guidance for sizing small volume provers.

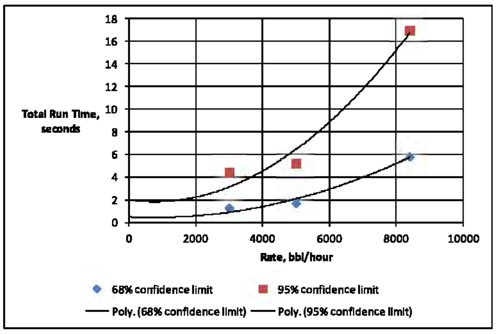


Figure 12 – Run Time Estimates for CMF HC4 vs. Flow Rate

The case for using a 68% confidence limit also is apparent. Especially at high flow rates the total run time is significantly less at 68% confidence vs. 95%.

The data presented in this paper was collected on the laboratory at Emerson in Boulder, Colorado. Although representative of CMFHC4 performance, field performance may vary.

9 SUMMARY AND RECOMMENDATIONS

Coriolis meters are an excellent choice for custody transfer applications that are proven in-situ. When using a small prover it is important to understand the fundamentals of Coriolis meter performance to get optimum performance:

- Minimize noise sources. This is especially important at flow rates above 10 m/s where cavitation from strainers, valves, etc. and other high velocity noise sources can influence repeatability.
- Configure the meter for its fastest response time.
- Minimize time-based damping.
- The number of passes per run will depend on the prover volume and the flow rate. Use Figure 12 to help make averaging and prover sizing decisions.
- When evaluating repeatability, use a confidence limit of 68% (1 standard deviation). This minimizes the number of passes required while maintaining required uncertainty of ±0.027%.
- Data presented in this paper is specific to the Micro Motion CMFHC4. Further testing is planned for additional sizes.

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.