THE INFLUENCE OF FLOW CONDITIONING ON THE PROVING PERFORMANCE OF LIQUID ULTRASONIC METERS

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1 INTRODUCTION

For oil custody transfer applications turbine meters are commonly used in conjunction with pipe provers or small volume (piston) provers in order to achieve traceable calibration in the field. With the increasing use of liquid ultrasonic meters in these applications, there is often a desire to calibrate ultrasonic meters in the same fashion.

The difference in ultrasonic and turbine meter operating principles, means that their behaviour, and hence their proving requirements, are different. The effects of naturally occurring turbulence on the instantaneous velocity samples of the ultrasonic meter has an influence on the short term repeatability of ultrasonic meters that is not observed in turbine meter data. Furthermore, unless appropriate steps are taken when designing the ultrasonic meter, sample rates, calculation delays, and filtering processes can all have an influence on proving performance when the proving run durations are short.

The factors mentioned above have resulted in a somewhat confused view of what to expect from an ultrasonic meter when it is used with a volumetric prover. This is further complicated by varying interpretations of how 'repeatability' is defined and issues related to the statistical analysis of small sets of samples.

This paper reviews the various factors of importance when calibrating ultrasonic meters with volumetric provers and demonstrates that improved results can be obtained by conditioning the flow.

2 TERMINOLOGY

Paraphrasing the relevant paragraphs of the International Vocabulary of Metrology [1], repeatability can be defined as follows:

The closeness of agreement between measurement results obtained by repeat measurements under a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, over a short period of time.

There are a wide variety of ways in which repeatability can be quantified and therefore it is useful here to describe those that are commonly used and/or most appropriate.

Standard deviation

The standard deviation is a statistical measure of the variability of a data set. As we are dealing with a limited sample of the entire population of data, an estimator called the experimental or sample standard deviation, *s*, is normally used, and this is given by:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (1)$$

where the data set comprises *n* samples, $x_1 - x_n$.

Repeatability

The measure of repeatability defined in ISO 11631 *Measurement of Fluid Flow – Methods of Specifying Flow Meter Performance* [2], is described as the "value below which the absolute difference between two single successive test results obtained with the same flowmeter on the same fluid under the same conditions (same operator, same test facility, and a short interval of time, but without disconnecting or dismounting the flowmeter) can be expected to lie with a probability of 95 %", given by:

$$r = t_{95,n-1}\sqrt{2}\, s \qquad (2)$$

where $t_{95,n-1}$ is the value of Student's *t* for *n*-1 degrees of freedom at 95 % confidence.

Range or spread

As an alternative measure of repeatability, a number of API documents [3, 4 & 5] include a range term, *w*, where

$$w = \max(x_i) - \min(x_i) \qquad (3)$$

On average this range term and the sample standard deviation are related as follows:

$$s = \frac{w}{C_n} \qquad (4)$$

where C_n is a standard deviation to spread conversion factor. This range term is convenient for manual calculations, but serves no beneficial purpose when computations are to be automated.

Uncertainty of the Mean

The uncertainty of the mean, *U*, for a set of n proving runs can be obtained as follows:

$$U = \frac{t_{95,n-1}s}{\sqrt{n}} \qquad (5)$$

When presented together it is obvious that although results obtained from calculation of these terms will have different numerical values, they are all interrelated, and that the sample standard deviation is the common link.

3 THE EFFECTS OF TURBULENCE

Transit time ultrasonic meters generally operate by sending short pulses of ultrasound back and forth across the flow. It is therefore obvious that it is a measurement technique that involves sampling and computation. It follows that for accurate results in short time periods, the sample rate and output update rate become important.

When calibrating with a volumetric prover, it is normal practice to use a pulse output generated by the ultrasonic meter. Sampling rates or pulse output update rates that are too slow can result in poor proving results when the flowrate is changing during the prove run. Although this is indeed an important issue, it has sometimes been over emphasised, owing to the fact that some hardware or software architectures can introduce significant delays between sampling and output updating. What is of more fundamental importance to the proving performance of ultrasonic meters is the role of turbulence.

When calculating a result using sampled data, where each sample has a random uncertainty, it is well known that the standard deviation of the mean can be reduced by increasing the number of samples. Numerically:

$$s = \frac{\sigma}{\sqrt{N}} \tag{6}$$

Where σ is the standard deviation of the individual samples and *s* is the standard deviation of the mean of *N* samples (note that here we are using *N* refer to the sample count for the ultrasonic meter in a given interval, to distinguish it from *n*, the number proving runs). From the above it might appear that all that is necessary is to increase the sample rate such that *N* becomes sufficiently high. This is simple enough to do on the timescale of importance in most processes, such as batch loading of a shuttle tanker. However, during a calibration process, where only small volumes are used, there are limits to how effectively this can be done, and the most important of these is the influence of turbulence.

Turbulence is a feature of most industrial flows and the vast majority of oil custody transfer applications, and for the purpose of this paper we will deal exclusively with turbulent conditions. Simply stated in a turbulent flow the velocity at a particular point will have an average velocity vector that is fairly steady in time, and a turbulent component that is random in time and direction. A detailed venture into the behaviour of turbulent flows is beyond the scope of this paper; it will suffice to say that it is a natural phenomenon that we have to take into consideration when measuring flow with ultrasonic meters.

In terms of the ultrasonic flowmeter, turbulent features or ‘eddies’ cause random velocity fluctuations to be superimposed on the average velocity measured on a path between an individual pair of transducers. Relative to the current state of the art the magnitude of the random fluctuations owing to turbulence will be much larger than any random fluctuations owing to the accuracy of the ultrasonic system.

Turbulence structures in the flow can be of a size that is a significant fraction of the pipe diameter. Individual features such as vortices can grow or dissipate as they move with the flow, but in the short distance that they travel through the measuring system they will remain relatively unchanged. Therefore from the perspective of a path of in the ultrasonic meter, it will see a succession, or ‘train’ of irregular turbulent features passing by. The speed of this train of turbulent features will be similar to the flow velocity, and the number of features that pass in a given period of time will be proportional to that velocity.

Consider now the example of a 6-inch ultrasonic meter that operates at a fixed sampling frequency of 50 Hz (meaning a complete measurement cycle on all paths plus an update to the output is performed 50 times a second). If we choose a fixed volume, say 1 m^3 then at a velocity 10 m/s the meter would sample the flow 274 times during the passage of that volume. At a velocity of 1 m/s the number of samples would increase tenfold to 2741. From Equation 6 above, that would suggest a reduction by a factor of 3.2 in the value of *s*. However, this not what is observed in practice. Instead we find that for a fixed calibration volume the value of *s* is largely insensitive to changes in flow velocity. What this tells us is that turbulence is playing a dominant role and that the frequency of the turbulent features passing through the measurement section is lower than the sampling frequency.

When turbulence plays this dominant role the level of repeatability that is achieved is a function of the number of turbulent features that have been averaged during the period of interest. As the nature of the turbulence is fairly independent of Reynolds number and the number of features that will pass through the meter is proportional to velocity, we find that it is not specifically the length of time that is important, but the volume of the flow that has passed through the meter. In other words, if we must average a given number of turbulent features in order to get the required repeatability of results, the volume required should be the same irrespective of flowrate. Numerically we can replace the *N* in Equation 6 above with N_{eff}, the effective number of independent samples.

$$s = \frac{\sigma}{\sqrt{N_{eff}}} \tag{7}$$

As we have already stated that N_{eff} is proportional to volume, it follows that we can replace it with term that is proportional to volume, i.e.

$$s = \frac{\sigma}{\sqrt{kV}} \tag{8}$$

Where *k* is a constant and *V* is volume. Introducing a the concept of a reference volume, we can then write

$$\sigma = s\sqrt{kV} = s_{ref}\sqrt{kV_{ref}} \tag{9}$$

If for convenience we choose V_{ref} to be 1 cubic meter then can reduce Equation 9 above to

$$s = \frac{s_{ref}}{\sqrt{V}} \tag{10}$$

One thing that becomes clear from the discussion above is that the proper interpretation of any statement regarding the repeatability of an ultrasonic meter requires knowledge of the calibration volume that is associated with the numerical value given.

4 PROVING CALCULATIONS FOR ULTRASONIC METERS

From the above we can write a set of equations that can be used to design a proving system or characterise proving performance for any particular size and model of ultrasonic meter in a given situation, i.e.

Predicted uncertainty for a given prover volume $$U = \frac{t_{95,n-1} s_{ref}}{\sqrt{nV}} \quad (11)$$

Predicted range/spread for a given prover volume $$w = \frac{C_n s_{ref}}{\sqrt{V}} \quad (12)$$

Estimated volume required for a given uncertainty $$V = \frac{1}{n}\left[\frac{t_{95,n-1} s_{ref}}{U}\right]^2 \quad (13)$$

Estimated volume required for a given spread $$V = \left[\frac{C_n s_{ref}}{w}\right]^2 \quad (14)$$

The primary input that is required for this calculation is the value of S_{ref} for a particular meter type and size.

A similar process to that outline above was used during the development of Table B-2 in Chapter 5.8 of the API Manual of Petroleum Measurement Standards [5]. Table B-2 suggests prover volumes required for achieving +/- 0.027% uncertainty of the mean meter factor and is shown as Table 1 below with volume converted to metric units.

Table 1 Recommended prover volume for +/- 0.027% uncertainty from API 5.8 (2005)

Meter size	5 runs	8 runs	10 runs
inches	Prover size (m^3)		
4	5.2	2.4	1.6
6	11.6	5.4	3.5
8	20.7	9.5	6.4
10	32.3	14.9	9.9
12	46.6	21.5	14.2
14	63.4	29.3	19.2
16	82.8	38.3	25.3

By rearranging Equation 11 above and substituting the appropriate values we can calculate the reference standard deviation for a volume of 1 m^3 corresponding with the data in Table 1. When this data is plotted versus the nominal pipe diameter as shown in Figure 1, another assumption embedded in the API recommended volumes becomes apparent: that the reference standard deviation is proportional to pipe diameter.[1] As s_{ref} appears as a squared term in volume calculations of Equations 13 and 14 this means suggested volume in API 5.8 increases in proportion with the diameter squared.

[1] Note that the difference between the 10 run results and the results for 5 and 8 runs in Figure 1 is believed to be the result of a minor calculation error made during the preparation of Table B-2 in the API standard.

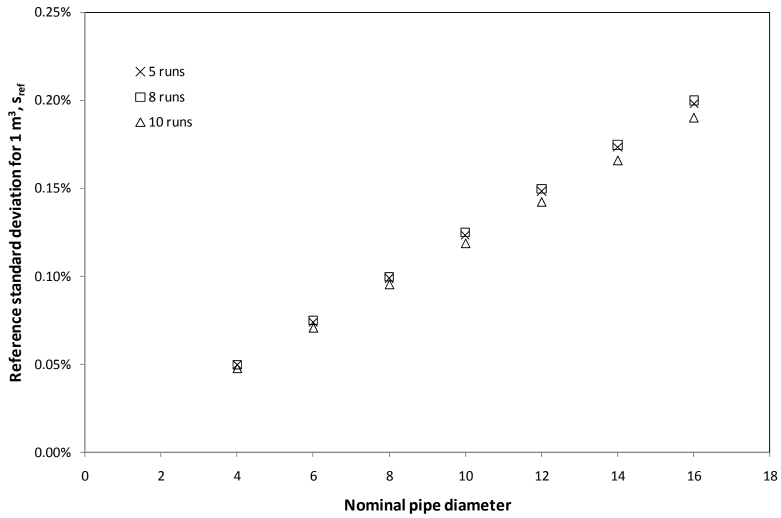

Figure 1 Reference standard deviation derived from the data of API 5.8 Table B-2

From Figure 1 above we can now obtain a value of s_{ref} that could be used in Equations 11 to 14 and it might appear that we have all the information required to design a proving system or to predict the performance of a given system. However, there are several issues still to be addressed, namely:

- The methodology applied here and in API 5.8 will result in a system with average uncertainty or spread equal to what we choose, but will not guarantee a high rate of successful proving
- The API tables do not reflect any variability or uncertainty in the input reference standard deviation, which could result from experimental uncertainty, differences in meter design, or differences in flow conditions in application
- The variability of the prover itself is not explicitly factored into the calculations

These issues will be discussed further in the following sections.

5 THE IMPACT OF SMALL NUMBERS OF RUNS

The default used by the industry for turbine meters is acceptance of a prove result if the spread is within 0.05% in five runs. This is the equivalent of ensuring +/- 0.027% uncertainty in the mean. Although the API Chapter 13 - *Statistical Aspects of Measuring and Sampling* [3] was first published in 1985, it seems that the majority of the industry does not use a larger number of runs or a more flexible scheme in which the number of runs can be varied.

The number of runs we select as a system design target has consequences that are a result of the statistical aspects of meter proving and may not be immediately obvious.

Firstly, if we look at Equation 11 we find that it contains a variable called Student's *t*. The presence of this factor takes care of one aspect of the statistics of small samples. When using a small number of samples there is a greater probability that the calculated mean will fall further away from the true mean value. What Student's *t* is intended to do in this equation is ensure that the calculated uncertainty of the mean accounts for that fact.

This can be nicely illustrated by a numerical example. With reference to Equation 5 a set of 10,000 random meter factors was generated having a mean value of 1 and a standard deviation of 0.02175%, such that the resulting uncertainty for 5 runs using Equation 5 would be equal to +/- 0.027%. Having done this, we can then calculate the standard deviation for each consecutive set of 5 runs, and that can be used to calculate the uncertainty in the mean, again using Equation 5. In this numerical analysis we can also calculate the error of the mean, as we have set the 'true' value equal to 1. Figure 2 below shows a histogram of the error divided by the uncertainty estimated using the standard deviation of 5 runs. If the value is less than 1 then the error is less than the calculated uncertainty and vice versa. When we analyse each group of five consecutive samples, we find that the error is less than the calculated uncertainty 95% of the time, which is what we would expect, having used the appropriate value of *t* for 95% confidence.

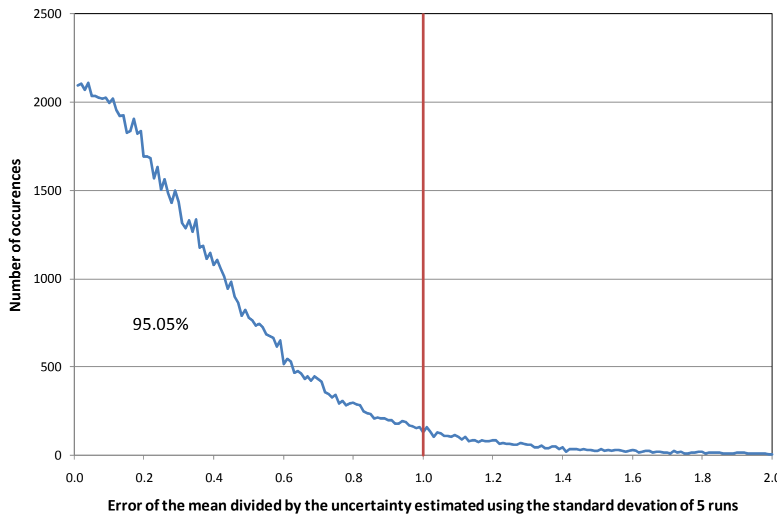

Figure 2 A histogram of error over the calculated uncertainty for $n = 5$

It is no surprise that t is doing the job expected of it in this respect. However, it is worth examining what the impact of *t* is in terms of prover volume requirements. From equation 13 prover volume is proportional to t^2/n. Therefore if we calculate t^2/n and divide by the value of t^2/n for $n = 5$, then the result is the fractional reduction in volume obtained relative to $n = 5$. This is shown in Figure 3 below. From this graph it is clear that via the effect of the reduction in Student's *t*, the volume required reduces more quickly than if we consider the impact of *n* alone, e.g. if we look at $n = 10$, relative to $n = 5$ we have doubled the number of runs, so we might expect the volume required to be half of that at $n = 5$, whereas in fact it is closer to one third.

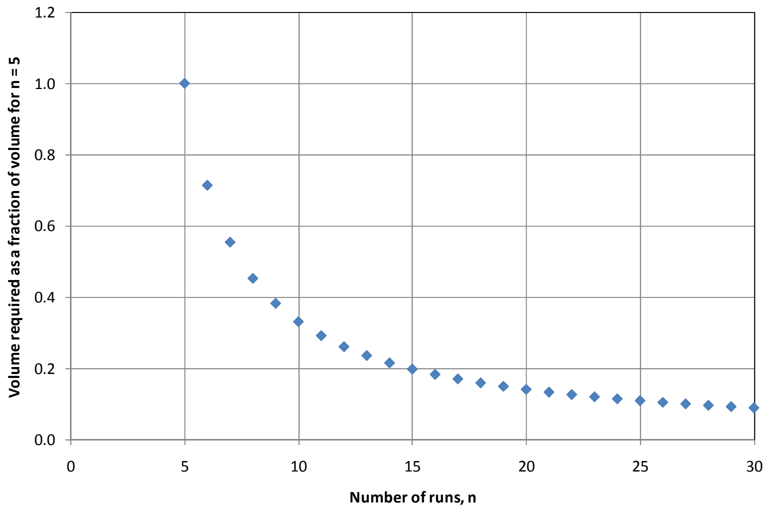

Figure 3 The combined effect of t and n on the required volume

Another important aspect of the statistical analysis of small samples that is not immediately apparent from examination of the equations is the impact of the distribution of the calculated standard deviation on the acceptance of proving data. The issue here is that if we design a system using Equations 13 or 14, then we would expect to achieve the required spread and uncertainty when applying Equations 11 or 12. That seems a reasonable expectation to have, and on average, it would be true. However, as the calculated standard deviation itself has a distribution of values, this will mean that roughly half the time the calculated uncertainty (or spread) will be greater than our target value.

Again this can be nicely illustrated by use of a numerical example. Here we are using the exact same set of 10,000 random meter factors having a mean value of 1 and a standard deviation of 0.02175% as was used for Figure 2. This time however we will plot a histogram of the uncertainty values obtained by calculating the standard deviation of each set of 5 runs. The result is shown in Figure 4 below, and it is immediately apparent that in this case that a large percentage of the prove results would be rejected as the calculated uncertainty is greater than 0.027%.

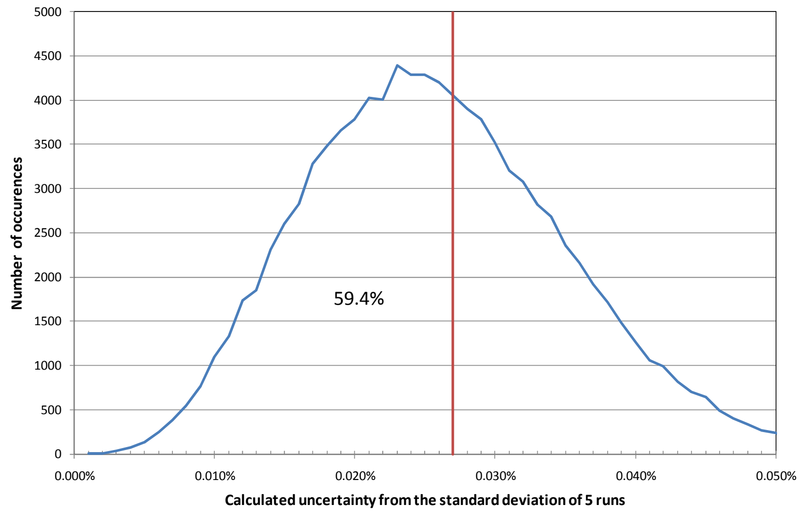

Figure 4 A histogram of the calculated uncertainty for s = 0.02175% and n = 5

Whilst Figure 4 shows that 40 % of the data would be rejected, analysis of the 5 runs means show that 99.5% of the mean values from 5 consecutive runs lie within +/- 0.027%. This may seem somewhat paradoxical but can be summarised as follows.

The data set has the following characteristics:

- 99.5 % of the mean values lie within +/- 0.027 % of the true mean value
- 95 % of the mean values lie within the *calculated uncertainty using the standard deviation of five runs*
- 59.4 % of the values of *calculated uncertainty using the standard deviation of five runs* are less than or equal to +/- 0.027 %

In other words, the fact that we choose to evaluate the standard deviation and uncertainty using only a small number of runs results in a situation where the actual deviation from the mean is expected to be within our desired uncertainty, but that we can only positively verify that it is so around six times out of ten.

If a higher proving success rate is required then the target standard deviation must be reduced, which will in fact reduce the average uncertainty to less than the value that we are using as our acceptance limit. Again using our numerical example, it was found that reducing the standard deviation from 0.02175 % to 0.013 % resulted in 95 % of the 5 run uncertainty values being less than or equal to 0.027 %, with the resulting mean uncertainty value being 0.015 %.

As s_{ref} is a characteristic of the meter and the process conditions, and cannot easily be altered, then if it is deemed necessary to reduce the standard deviation we have to increase the volume accordingly, i.e.

$$s_{ref} = constant = s\sqrt{V} = \frac{s}{k}\sqrt{k^2 V} \tag{15}$$

Therefore if we wish to have a higher success rate we have to add a multiplying factor to the volume calculations in Equations 13 and 14. For our example above of 95 % success in 5 runs, this factor is calculated as follows:

$$k = \frac{0.02175\ \%}{0.013\ \%}, k^2 = 2.8$$

In other words to achieve a success rate where 95% of proving runs can be demonstrated to meet the target uncertainty, a factor of 2.8 has to be added to the volume estimated using Equation 13.

In this section of the paper we have talked specifically about standard deviation and uncertainty. However the same observations apply if the spread, *w*, is used. In fact, as the spread is utilised as an estimator for the standard deviation, the results based on spread are slightly poorer, with only 52 % of the spread values being less than 0.05 % in five runs when the standard deviation was set to 0.02175 %.

If the number of runs is increased beyond 5, the default situation in terms of success rate is not changed substantially, i.e. as we are effectively targeting the average standard deviation, there will be a distribution of results both above and below the average, and the success rate will be approximately 50 %.

Again this can be illustrated by means of a numerical example. This time the 10,000 random meter factors were generated having a mean value of 1 and a standard deviation of 0.03774 %, such that the resulting uncertainty for 10 runs from Equation 5 would be equal to +/- 0.027 %. Figure 5 below shows the resulting distribution of calculated uncertainty, compared with the earlier result obtained with sets of five runs. Similar to the 5 run case, only 56 % of the results fall below the 0.027 % uncertainty limit. However, what is also clear from Figure 5 is that the uncertainty calculated using ten samples produces a narrower distribution of results. This means that if a higher success rate is required, then the multiplying factor that has to be applied to the volume will be less than in the case of $n = 5$.

In the same manner as for the 5 runs analysis, the standard deviation used for the 10 run analysis was adjusted until a success rate of 95 % was achieved. In the case of the ten run analysis, this was achieved with a standard deviation of 0.02757 %. Calculating the multiplying factor we find:

$$k = \frac{0.03774\ \%}{0.02757\ \%}, k^2 = 1.87$$

i.e. in this case we only have to increase the volume by a factor of 1.87 compared with the 2.8 required for case of $n = 5$.

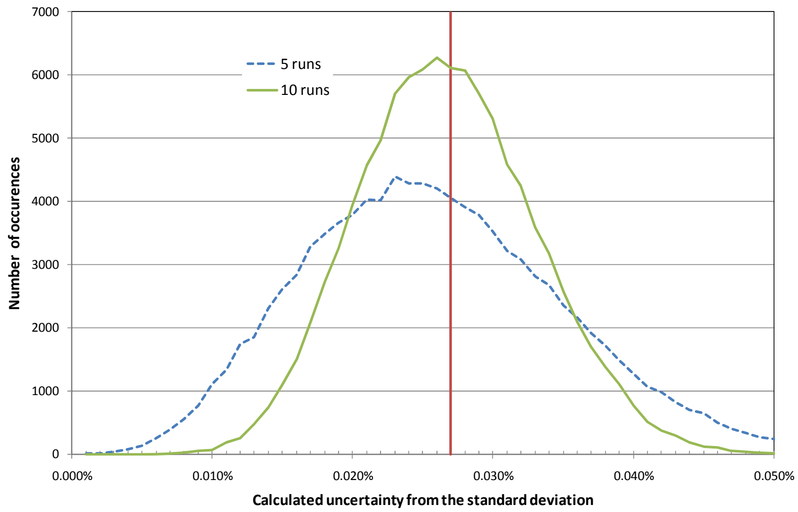

Figure 5 A histogram showing the distribution of calculated uncertainty for n = 5 and n = 10

When the above factors are taken into consideration, we find that if we wish to design a system to prove with a 95 % success rate, the volume required to do this in 5 runs is approximately 4.5 times larger than the volume required to achieve the same performance in 10 runs. It is important to note that these considerations relate only to the statistical properties of problem, and are independent of the actual meter performance.

6 EXPERIMENTAL EVALUATION OF METER REPEATABILITY

As discussed in the earlier sections, the standard deviation is the common link between the various methods of describing meter or proving repeatability, and if this is normalised to volume of one cubic meter then we have a convenient measure that can easily be used for comparison purposes when meter designs, set up parameters or flow conditions are varied. Therefore the results in this paper will be presented in the form of the reference standard deviation:

$$s_{ref} = s\sqrt{V} \tag{16}$$

During the test programmes carried out the standard deviation has typically been determined from a set of between 30 and 100 repeat test points at a given condition. This relatively large value of n was used to limit the width of the probability distribution related to the resulting standard deviation.

6.1 Test facilities

Tests were carried out at the Caldon Ultrasonics Technology Centre in Pittsburgh, USA. This facility has ISO17025 accreditation from NVLAP, a CMC certification from NMi and has had its traceability and uncertainty verified in a successful intercomparison with the UK National Standard oil flow facilities at NEL.

The facility has been described previously [6], so only the pertinent details will be shared here. The facility has two volumetric standards, a 10 m^3 unidirectional ball prover and a 0.12 m^3 small volume prover (SVP). The calibrated section of the ball prover has four detector switches with the result that calibrated volumes of nominally 3.3, 6.6 and 10 m^3 are available. The NVLAP accredited uncertainties are 0.03, 0.04 and 0.07 % for the 0.12, 10 and 3.3 m^3 volumes respectively. Note that these uncertainties describe overall uncertainties, and hence the repeatability of the test standard will be better in each case.

Here we will present results for changes in sample frequency, flowrate, number of paths, and flow conditioning. Further tests, designed to investigate the issues of time delays and the effects of applying and correcting for time constants in the meter electronics, have been discussed in previous papers [7 & 8].

All of the meters used for the tests described in this paper were of 6-inch nominal diameter. Other sizes have also been subjected to repeatability tests but for the purpose of ease of comparison the results presented are limited to the 6-inch size.

Full-bore Caldon LEFM 240C (4-path) and 280C (8-path) meters were tested in addition to a 6-inch pipe diameter Caldon 280CiRN with reducing nozzle and a throat diameter of 3.83 inches, as illustrated in Figure 6. The 280CiRN was also reconfigured for testing in a 4-path format. In addition to the ultrasonic meters, a 6-inch turbine meter was also tested using the ball prover.

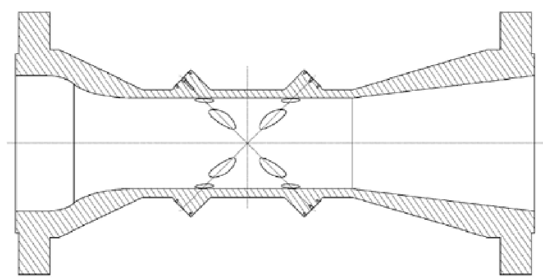

Figure 6 A schematic of an 8-path Caldon meter with reducing nozzle inlet

Tests were conducted at flowrates in the range of 185 and 600 m3/hr using an oil of approximately 2.7 cSt viscosity, resulting in pipe velocities ranging from 3 to 9 m/s and pipe Reynolds numbers in the region of 150 000 and 500 000.

Caldon meters operate at a high sample and update rate in comparison to some other ultrasonic meters. The tests here were conducted with sampling and update rates set to between 25 and 100 Hz. In Caldon meters each measurement cycle involves determining the upstream and downstream transit times for each individual path, computing the flowrate and updating the output. This means that if a sampling and update rate of 100 Hz is stated for a 4-path Caldon meter then individual transit time measurements are being made 800 times a second.

6.2 Results

Figure 7 below show the results in terms of the reference standard deviation (normalised to a volume of 1 m^3) versus flowrate for a 4-path full-bore Caldon meter. Note that the tests were conducted at three different flowrates using 4 different reference volumes.

Also shown on the graph is a dotted line representing the reference standard deviation associated with the recommended volume in API Ch. 5.8 Table B-2 (taken from Figure 1). It is clear that the 4-path full-bore meter results are fairly consistent with this datum, although using the root-mean-square (RMS) value from Figure 7, the predicted volume would be 23% less than that given in Table 1.

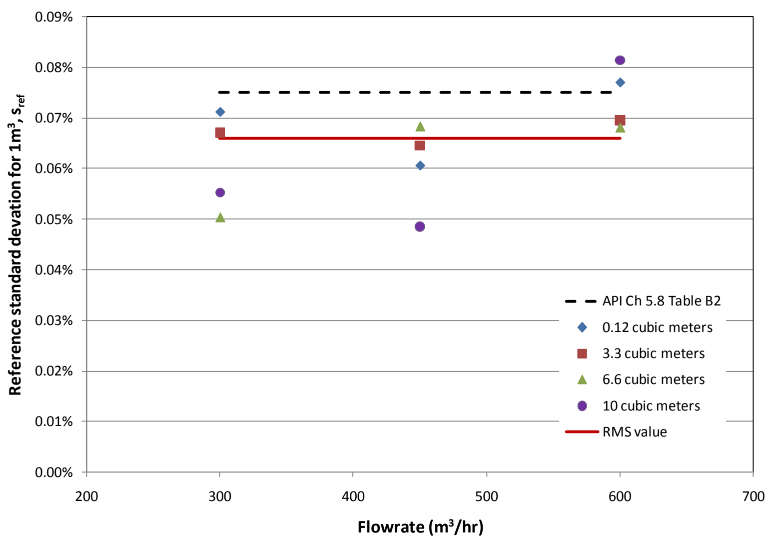

Figure 7 Repeatability in terms of s_{ref} for a 4-path Caldon meter

Figure 8 shows the data in the same format as Figure 7 above for the 8-path full-bore Caldon meter. It can be observed that the results for the 8-path meter are slightly better than for the 4-path meter, but that the improvement is not as dramatic as might be expected. Using the RMS value from Figure 8, the predicted volume would be 30 % less than that given in Table 1.

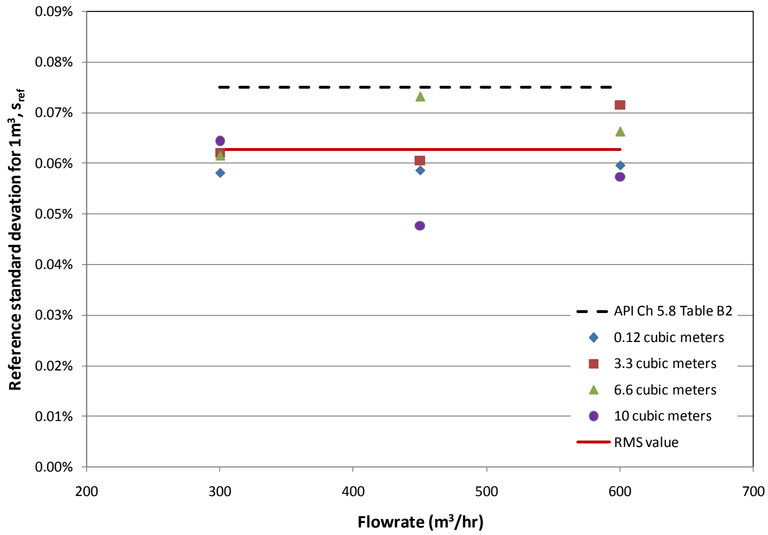

Figure 8 Repeatability in terms of s_{ref} for an 8-path Caldon meter

Figure 9 shows the data in the same format as before for the turbine meter. Note that the turbine meter was only tested against the ball prover. It can be observed that the results for the turbine meter are significantly lower than the 4 or 8-path full-bore meter results. Carrying out a comparison using the RMS value from Figure 9, we find that the API Table B-2 volume is almost 6 times greater than what we would predict for the turbine meter from these results.

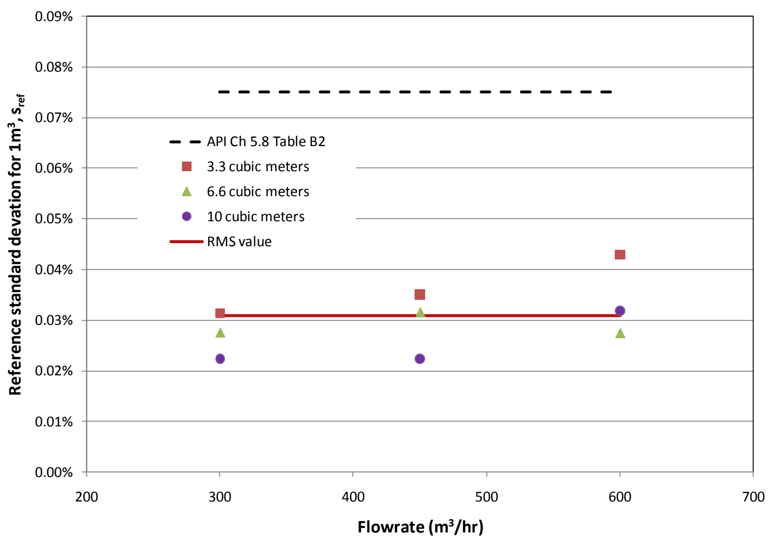

Figure 9 Repeatability in terms of s_{ref} for a turbine meter

It is well known the field of wind-tunnel design that nozzles can have a beneficial stabilising effect on flow that reduces turbulence. Therefore, when the Caldon CiRN flowmeters were under development for heavy oil applications it was expected, and indeed observed, that their short-term repeatability would be better than that of a standard full-bore meter. Owing to this beneficial effect, a 6-inch reducing nozzle meter was selected for an extensive series of tests against the Caldon laboratory SVP.

Figure 10 below compares path velocity standard deviations of a standard (full-bore) 4-path ultrasonic meter with those from the meter employing the reducing nozzle (RN). It can be observed that the variability of the velocity measurements is significantly reduced when the nozzle is employed.

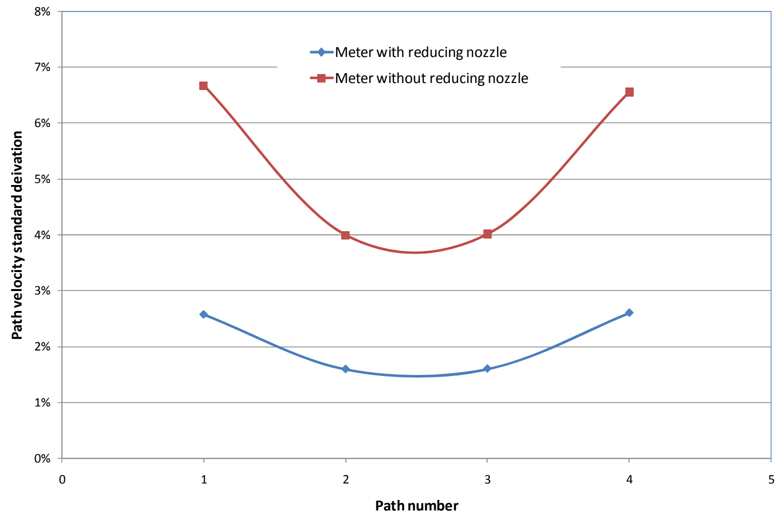

Figure 10 Path velocity standard deviations with and without a reducing nozzle

Figure 11 shows s_{ref} plotted versus flowrate for the 4-path and 8-path RN meter. Also shown for reference is the result for the turbine meter. The first thing that can be easily observed is that the design of meter that employs the reducing nozzle produces results with much better repeatability than before, lower even than the results for the turbine meter versus the ball prover. Although this is not a like-for-like comparison as the ultrasonic meter results were obtained versus the SVP, it does demonstrate that ultrasonic technology has the capability to complete with turbine meters in terms of repeatability.

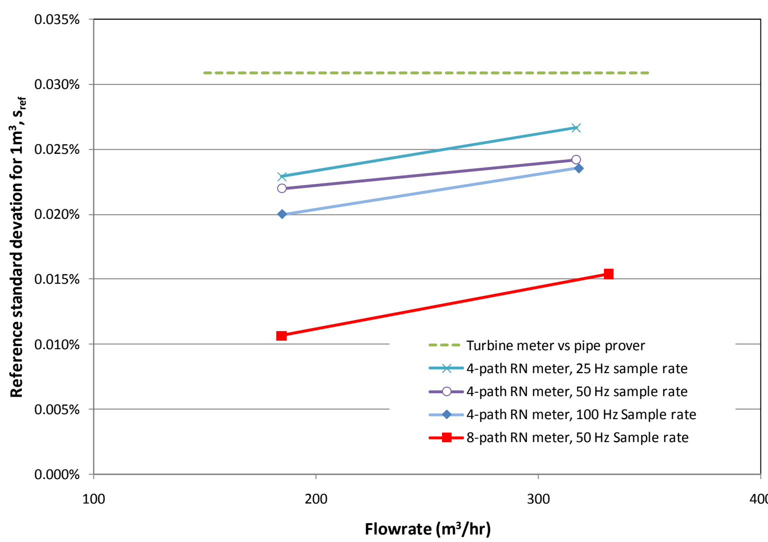

Figure 11 Repeatability in terms of s_{ref} 4-path and 8-path Caldon RN flowmeters

Also shown in Figure 11, the sample rate of the 4-path reduced nozzle meter was varied from 25 to 100 Hz, and although there is some improvement in results, the reduction in standard deviation when going from 25 to 100 Hz is not the factor of 2 that would be predicted using Equation 6, confirming that turbulence is still the dominant factor in determining the repeatability.

When 4-path and 8path meters with reducing nozzles are compared, then it is apparent that for the 8-path RN meter the value of s_{ref} is significantly lower than for the 4-path RN meter. This is interested to observe, as this difference was not apparent when the full-bore 4 and 8-path meters were compared. This result informs us that once we have conditioned the turbulence by means of the reducing nozzle, the provision of additional paths is of greater benefit than increasing the sample rate. This result suggests that in the full-bore meter there is some correlation of measurements between paths owing to the structure of the turbulence and that this correlation between paths is reduced significantly when the reducing nozzle is employed.

It can also be observed in Figure 11 that there is an apparent increase in S_{ref} with increasing flowrate, suggesting that one or all of the following are true:

- the turbulence is not completely dominant (so there is still some effect of the total number of samples, which is then flowrate and time dependent when the prover volume is constant)
- that the turbulence characteristics vary to some degree with the change in flowrate
- the operation of the prover at a higher velocity has an impact on the proving statistics

This implies some additional complexity that is not captured in the equations we have been using, and therefore suggests that they should be used conservatively when sizing a prover or predicting performance.

All of the preceding discussions have aimed to stress the importance of the relationship between turbulence and the short-term repeatability or proving performance of transit time meters. The results obtained with the reducing nozzle show that if we can reduce turbulence in some way then we can improve the performance of the meter.

The issue with turbulence in relation to ultrasonic meters is that the magnitude and scale of the vortices are large enough that they do not average out over the relevant dimensions and timescales. If however, the vortices can be reduced in size, then they will average out more easily along the length of the ultrasonic path and within the width of the ultrasonic beam. Furthermore, the smaller the vortices, the higher their frequency of passage, and hence more features can be averaged in the same time or volume.

In a straight section of pipe, it is generally accepted that turbulent eddies might be as large as a quarter of the pipe diameter. Therefore, by dividing the flow stream into small passages we would expect to bring about a reduction in both the size and strength of the vortices and hence improve performance. Clearly the smaller the passages are, the greater the improvement in performance might be. Based on these assumptions a ‘honeycomb’ style flow conditioner was made and placed immediately upstream of the flow meter. The conditioner was designed to have passages of around 0.02 of the pipe diameter, and a length of around 10 times the passage diameter. In contrast to rather fragile honeycombs made from thin metal sheets, this conditioner was made by machining holes in solid piece of metal.

Photographs of the conditioner are shown in Figure 12 below. This design of conditioner breaks up large vortices, and forces the flow into streams parallel with the pipe axis. Under some conditions, the flow may even become laminar in the small passages. The conditioner is placed very close to the meter in order that natural turbulence due to wall-sheer effects cannot be properly re-established prior to the measurement point.

In terms of practicality, it is obvious that this conditioner design could trap any sizable fragments of 'trash' in the oil, which suggests that it should be protected by an upstream strainer.

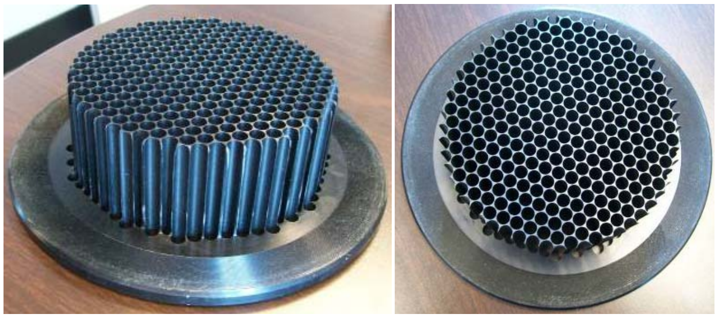

Figure 12 Photographs of the turbulence reducing flow conditioner

As with the reducing nozzle, the beneficial effect of the turbulence conditioner can be observed directly in the meter diagnostics in terms of the path velocity standard deviations, as shown in Figure 13 below.

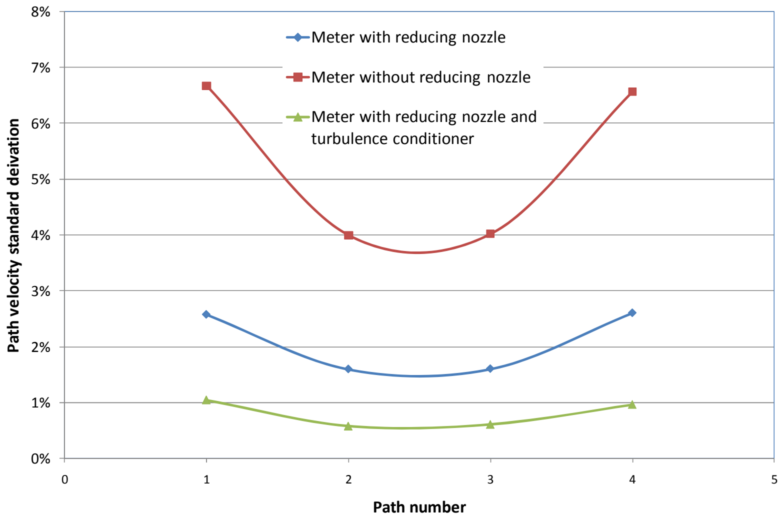

Figure 13 Path velocity standard deviations: full bore, RN and RN + turbulence conditioner

Figure 14 shows the results from tests conducted using the turbulence conditioner, compared with those done with no conditioning. It can be observed that by adding the turbulence conditioner the reference standard deviation is reduced further by as much as a factor of around 2, which results in a reduction of the required prover volume by a factor of 4. This result is significant for two reasons. Firstly, it very clearly provides further evidence of the important role of turbulence in the proving performance of ultrasonic meters. Secondly it shows that the suggested proving volumes given in API Ch 5.8 Table B-2 can be reduced dramatically if various performance improvement measures are taken together.

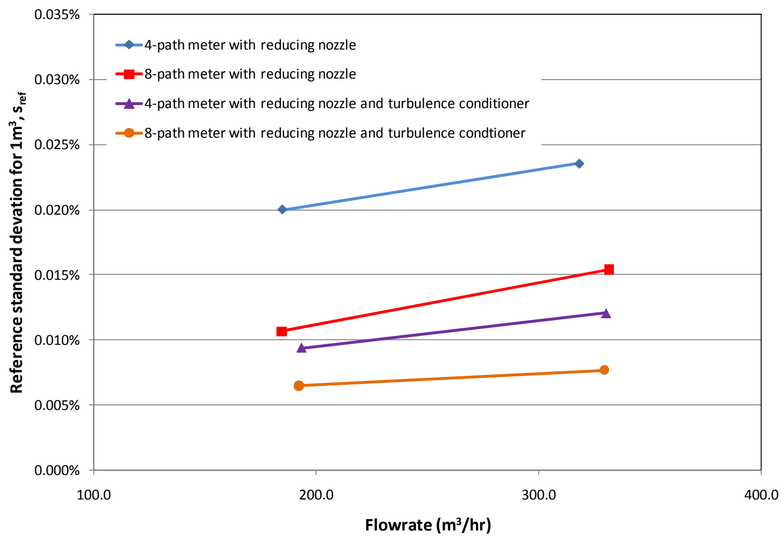

Figure 14 RN meter with and without upstream turbulence conditioning

7 DISCUSSION AND CONCLUSIONS

There are a large number of factors involved when considering calibrating ultrasonic meters directly against volumetric proving devices. These factors are discussed again here briefly prior to concluding the paper.

A prerequisite is that the meter be designed with a sufficiently fast sample and output update rate in order that there are no significant errors introduced by lack of synchronisation. Data presented in this paper obtained directly against a small volume prover of 0.12 m^3 clearly demonstrates that this can be achieved.

It has been shown that there are consequences associated with the selection of the number of proving runs. It should be reiterated that the impact of this aspect of proving methodology is independent of meter performance or indeed meter type. Based on the analysis in this paper it is recommended that a minimum of 10 runs be used to reduce the allowance that has to be made for the statistics of small samples.

The well known equations that appear in API documents can be manipulated to produce design calculations for provers that require only a standard deviation that can be determined experimentally, and input selections regarding the target uncertainty and the desired number of prove runs. However, this approach will typically yield a success rate of around 50 % in terms of the number of acceptable proves. For higher rates of success a multiplying factor has to be applied to the calculated volume, and this factor is dependent on the selected number of runs and the desired success rate. The smaller the number of runs selected the higher this factor will be. This again shows that from a statistical point of view a larger number of runs is desirable.

By normalising the standard deviation from a set of test results to a reference volume of 1 m^3 a reference standard deviation, s_{ref}, is obtained that is convenient for comparisons and for use in estimation of required prover volumes or expected proving performance. However, it must be recognised that the value of s_{ref} is specific to the meter size and type and is subject to change if the conditions of turbulence in the application are significantly different to conditions under which the value was obtained.

As we have shown in this paper, if appropriate ultrasonic technology is combined with flow conditioning that is specially designed to act upon the turbulence in the flow, dramatic improvements in short-term repeatability can be obtained.

It is also important to remember that the determination of repeatability is itself subject to experimental uncertainty, as captured by the words of A T J Hayward who said in his 1977 booklet on the subject, “Repeatability, it appears, is a rather variable property, and successive measurements of it cannot be expected to agree very closely.” Hayward’s expectation was that three successive measurements of repeatability should agree within a factor of two [9]. This is broadly consistent with the results of the numerical analysis carried out for this paper with n = 10.

Before reaching a final conclusion, there are two issues we will touch upon that have not already been discussed.

The first is the issue of the repeatability of the proving device itself. This is generally considered negligible when determining the repeatability of a flowmeter. However that may not always be true, and if the repeatability of the prover is higher than expected, it too may impact on the overall repeatability of the calibration.

The second issue to be discussed is that of combined prover/master metering, where the proving device is used in conjunction with a master meter, which is usually a turbine flow meter. Whilst the content of this paper is directed towards the use of volumetric provers directly, the information herein applicable to any calibration system. For example, in a prover/master meter system, it is still advisable to use a large value of n. In fact for the comparison of the meter under test and the master meter, there is no set volume, so small volumes can be chosen in order to obtain a large value of n. The only caveat in this respect is that if small volumes are used during master metering, pulse interpolation may be required.

One downside of using a prover/master combination is that it introduces another step into traceability chain and adds another system component on which the uncertainty of the calibration is dependent. Another is that if too large a volume is used when calibrating the ultrasonic meter against the master, this could mask poor repeatability or the onset of a problem. On the plus side, it can be attractive when being used for calibration of a measurement system comprising multiple streams, as the prover can potentially be used once for the master meter, and then the master meter used repeatedly for the individual streams. Given the results presented in this paper, it is even feasible to consider a system where the master meter is ultrasonic.

From the data presented and analysed in this paper it can be concluded that, with appropriate selections and precautions, ultrasonic meters can be calibrated directly against volumetric provers, without placing unreasonable demands on the size of the prover or the number of runs. This is best illustrated by an example contrasting the expectations arising from the recommendations of API Ch. 5.8 versus the data and recommendations contained in this paper.

As API Ch. 5.8 does not explicitly recommend using a larger number of runs, we will consider the ‘default’ industry requirement of achieving 0.05 % spread in 5 runs. Using Table 1, the API recommended volume, which is broadly consistent with what we might expect from a full-bore 4-path meter, suggests a volume of 11.6 m^3, with an implicit success rate of around 50 %. To improve our success rate to around 95 % that volume would have to be increased by a factor of 2.8 to roughly 32.5 m^3.

For our alternative example, we will use the 8-path RN meter with reducing nozzle, but without including the separate turbulence reducing flow conditioner. The worst case result for this meter from Figure 11, is a reference standard deviation of 0.0154 %. Inserting this value of s_{ref} into Equation 11 with $n = 10$ (as per the recommendation for the minimum value n in this paper) and U = +/- 0.027% we obtain a prover volume of 0.166 m^3, with a corresponding success rate of around 50%. Applying a factor of 1.87 to obtain a 95% success rate and adding a further ‘safety factor’ of 1.2 to account for experimental uncertainty, the resulting volume is 0.373 m^3, a quantity that is easily obtained in a few passes of an appropriately sized piston prover, and smaller than the previous example by a factor of 87.

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