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Different Requirements and Methods for Calibrating Gas and Liquid Ultrasonic Flow Custody Transfer Meters

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1 INTRODUCTION

There is one common purpose for "wet" calibrating Gas and liquid USMs, the fact that current measurements of the distance between and the angle of the transducers is not sufficient to allow for a prediction of the calibration factor within the required uncertainty limits. Both types of meter still require a base calibration to locate a basic meter factor. From this point on their philosophy and requirements diverge.

Perhaps the over-riding feature is Reynolds number. For liquid meters, with the exception of very light oils, such as LNG etc, the Reynolds number is below 10^6, but for gas measurement the range of Reynolds numbers is generally above $5x10^6$. In fluid mechanics, generally, low Reynolds number produces more variation and issues in performance than at higher Reynolds numbers.

The paper concentrates on issues regarding the calibration of both types of meter, highlighting the operational factors that influence the differences. It also discusses the methods available for calibration, and the consequent traceability and uncertainty chain, which, in spite of the same basic principle, result in a different level of performance, uncertainty, attributed to the gas and liquid meters. Further, the paper discusses the differences in standards and detail of such concepts as repeatability between the two methods of calibration.

2 BASE CALIBRATION REQUIREMENTS

The present designs of USMs need calibration. The common reason for both Gas and Liquid meter calibration is the need to find the base meter factor. This is because the manufacture and measurement of the component parts of the meters are still not adequate to predict the MF to the required uncertainty from physical measurement alone. Remembering that for liquids the end uncertainty for the meter is likely to be between 0.15 - 0.2%, and for a gas meter in the order of 0.3%, then the detail of the calibration method is all important. For example, in table 1 the effect of change in transducer path angle can be seen. For a liquid meter the effect is generally less than for gas meters. The effect of path angle on the measure flowrate from the base equation is given by:

$$Difference\ is \propto \frac{1}{(sine\theta cos\theta)} \quad \text{------------------------ [1]}$$

Where θ is the angle of transmission of the ultrasound.

For a liquid meter the path angle is in the order of 45^o with a resulting variation in the order of 0.06%/degree. A gas meter typically has a steeper angle, around 60^o giving a path angle variation in the order of 2%/degree. The angle is a difficult measurement particularly on smaller meters, the logistics of the measurement method and the tolerances on transducer position create the variation in angle which needs compensation by wet calibration.
Meter diameter, while easier to measure, is still an issue as it is a D^3 effect, due to the base equation having the distance between the transducers as a function of the velocity calculation. The smaller the meter, the more difficult the physical measurement becomes.

Liquid Meter			Gas Meter		
Tranmission Angle	1/sinCos	% Difference from base angle	Tranmission Angle	1/sinCos	% Difference from base angle
44.5	2.000305	-0.02	59.5	2.286708	0.98
44.6	2.000195	-0.01	59.6	2.291155	0.79
44.7	2.00011	-0.01	59.7	2.295648	0.60
44.8	2.000049	0.00	59.8	2.300186	0.40
44.9	2.000012	0.00	59.9	2.30477	0.20
45	2	0.00	60	2.309401	0.00
45.1	2.000012	0.00	60.1	2.314079	-0.20
45.2	2.000049	0.00	60.2	2.318804	-0.41
45.3	2.00011	-0.01	60.3	2.323576	-0.61
45.4	2.000195	-0.01	60.4	2.328397	-0.82
45.5	2.000305	-0.02	60.5	2.333267	-1.03

Table1 % Variation in Calibration Due to Angle Change

A typical variation of the raw calibration of 20" diameter liquid meters is shown in figure 1. The spread of the data is 0.44%, and the standard deviation is 0.11%. This data was taken at a Reynolds number of 750,000. These meters were 4 path Gaussian meters using the Jacobian solution for the spacing. The theoretical meter factor before correction is 0.998, the mean of the meters came out to 0.9966. The difference is due to a combination of Reynolds number, measurement errors and effect of transducer ports, the flow in the ports and more particularly the difficulty in reproducing the edges of the ports.

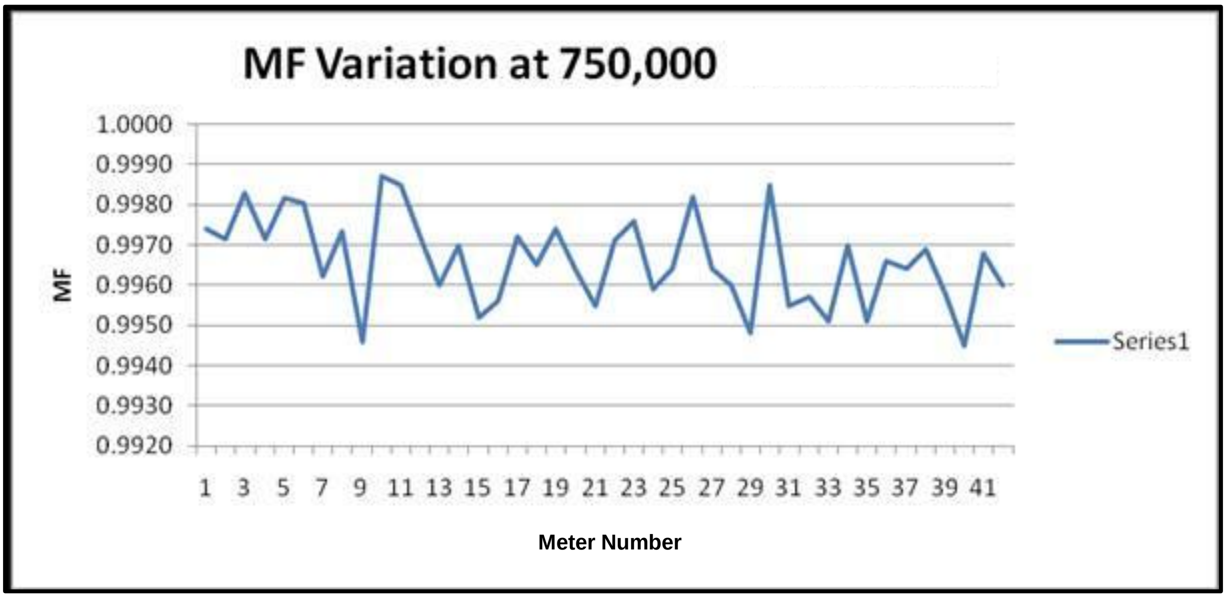

Figure 1a Variation In MF of the Raw Calibration of 20" Liquid Meter Factors (Courtesy of Cameron Caldon)

The variation of 31, gas USMs calibrated at CEESI is shown in figure 1b. As can be seen the spread data is wider than for the 20" liquid meters. This is partly size difference, but also the ability to measure the meters accurately enough to get a consistent dry calibration value of MF.

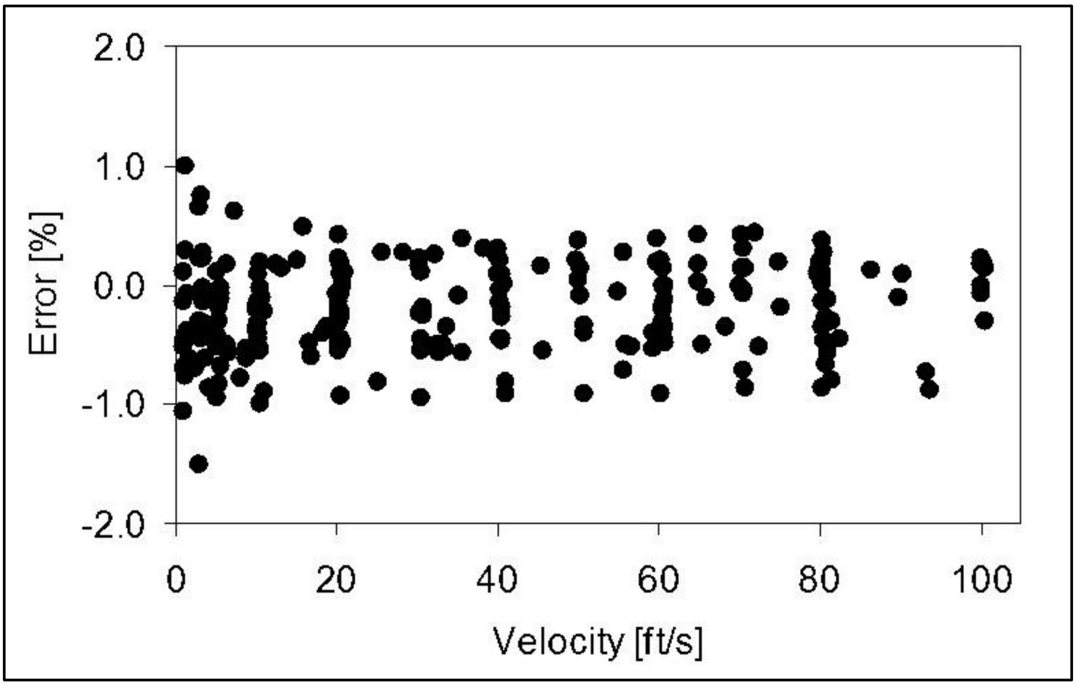

Figure 1b Variation in Meter factor of 31 10" Gas Meters

While the main common reason for calibration is the need to find the correct meter factor, there is a secondary reason. It is a very good final test for catching errors in assembly, and more particularly any last minute software errors. It should be remembered that these are now sophisticated machines with large complex software bases, often with continuous changes. A quality flow test will help ensure that there is a fall-back position to finally check that the meter is operating satisfactorily.

A further issue that can be held in common is the calibration taking out the influence of installation. This is not a reason for proved liquid meters, but where they are unproven in the field then the issue is the same as for gas meters, what is the effect of installation? The standards are more specific for gas meters, because of the experience of not having provers to fall back on. But the question remains, how to calibrate the meter such that it will retain the calibration in the field? The issues with transfer of calibration are briefly discussed later.

It is worth making the point at this stage, that both Gas and liquid meters work essentially on the same principle, they even in most cases have the same transducer spacing's, but the generally accepted uncertainty of a gas meter is around twice the equivalent liquid meter. This not because of the issues of more difficult signal detection in gas meters, or the lower resolution of time due to lower frequencies, modern electronics and software reduce these considerations to minor issues, it is the calibration process. The major reason is the calibration uncertainty. This will be discussed in detail later but, essentially, the traceability chain for a liquid calibration is smaller than for gas, with the inevitable increase in the base calibration uncertainty. Essentially it is difficult to catch gas in a bucket and determine its volume or mass!

3.0 DIFFERENCES IN CALIBRATION TECHNIGUES DUE TO METER PERFORMANCE.

We have stated that the principle of the gas and liquid USMs are similar and certainly the basic theory of operation is the same, the transit time methodology is the same. The significant difference is in the fluid mechanics in the form of Reynolds number. This appears in several forms as an issue. In general, it can be stated for fluid mechanics, providing such effects as Mach number do not come into play, the stability of fluid mechanical processes becomes better as the Reynolds number increases. For example changes in pipe profile become less pronounced and separated flow becomes more stable. In the case of ultrasonic flow meters, the calibration becomes more linear, largely because the fluid mechanical effects become more stable.

3.1 Gas Meters

For a gas meter the concept of calibration is simple, the meter is calibrated “as found”, figure 2, any correction for the offset due to physical measurement errors is taken out, the meter is recalibrated in the “as left” condition. Generally, the meter linearity is within the specification when calibrated ‘as found”, but the meter may be linearized to give a performance that is well within the the specified range. It should be noted that the curve plotted as Reynolds number and velocity in figure 2 are essentially the same. The linearization of a gas ultrasonic flowmeter, therefore, generally uses flow velocity as the “base”, an easy and stable function to determine.

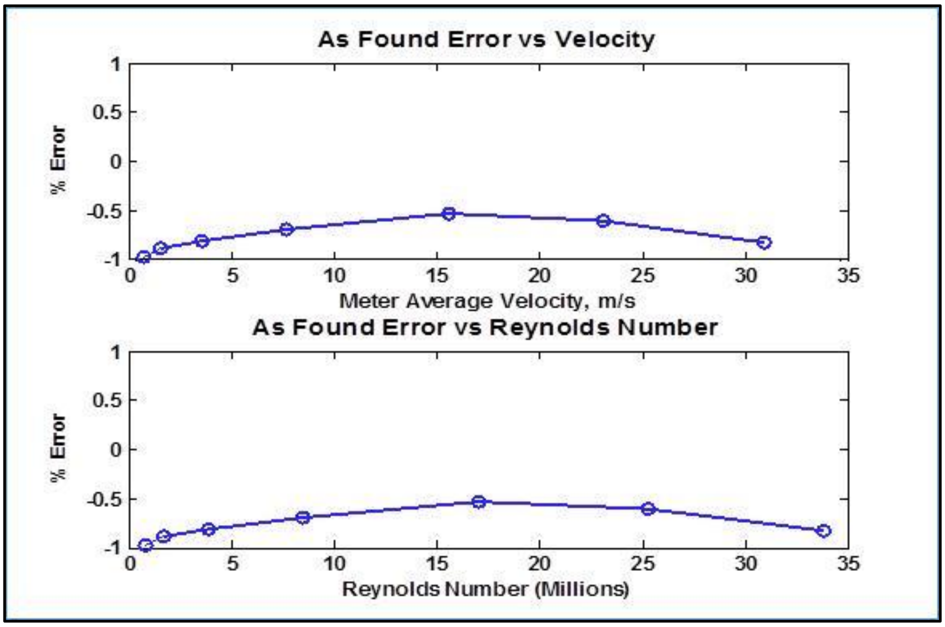

Figure 2 “As Found” Calibration of an 8” Gas USM (Courtesy Cameron Caldon)

3.2 Liquid Meters

The factor effecting liquid ultrasonic flow meters is very different. With the exception of measurement of LNG and lighter oils, the Reynolds numbers can vary from below 10^6 down to the laminar region, less than 10^3, and also through the transition region. Throughout this range the meter calibration has several regimes, the effect depending on the meter design.

Figure 3 shows the various flow regimes through which an oil ultrasonic flowmeter has to pass. From 10^6 down to around 10^4 the flow is essentially turbulent, somewhere below 10^4, dependent upon pipe roughness, installation effects and the properties of the fluid, the flow becomes turbulent, and the fluid switches between laminar and turbulent, and finally at somewhere around $2x10^3$ the flow becomes generally laminar. Within the turbulent region USMs may not be totally linear within the bounds of the requirements for the meter specification, but have stable calibrations, making it possible to characterise them to bring them into specification. The degree of characterisation is a function of the design, and will include such issues as transducer spacing, transducer size, port design and spacing and consistency of the machining of the ports. Figure 3 shows the typical curves for two solutions of the Gaussian quadrature spaced meters with 4 paths. While it would appear the obvious solution is the Legendre, pragmatism such as producing the meters, the Legendre spacing takes the transducers further out towards the walls, and the fact that the Jacobian spacing is more stable in the transition region will influence the choice of design. Other spacing’s and numbers of paths will have different fundamental curves. They are generally characterised either by calculation of Reynolds number or by some form of determination of the profile change with Reynolds number, profile factor or flatness ratio, the ratio of the inner and outer paths.

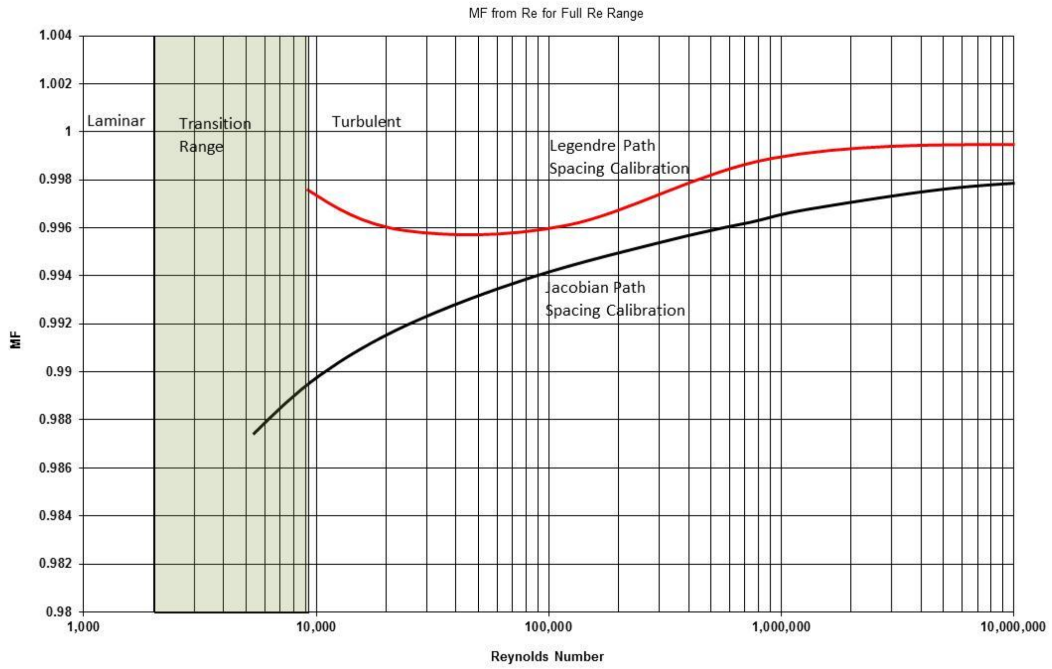

Figure 3 Typical Calibration of Liquid USMs.

To characterise the meter clearly requires a good knowledge of the calibration curve over the operational flow range, and calibration now is a key function to determine the characteristics of the curve. A calibration over a limited range is only acceptable if the shape of the curve is exact and repeatable. It should be remembered that these meters are for uncertainties in the region of 0.2%, any misjudgement of the curve shape will lead to errors in the meter performance. Can meters that are being proved on site not have a calibration? Apart from the fact that the calibration is a good FAT, removing the effect of the curve on site using conventional turbine meter type linearization is likely to lead to errors as the curve is essentially Reynolds number based.

The transition region represents further calibration problems as USMs with straight through bores become less repeatable and linear. The amount of deviation depends on the design, but will always be an issue. It should be remembered that the start and finish of transition depends very much on installation factors, and so it would be expected that a calibration of a meter in this regime would not necessarily repeat on site. These comments do not appear to be true for reduced bore meters designed to condition the flow though the working section and reduce significantly the effects of transition flow..

In the laminar region stability returns and unless there are temperature gradient issues the primary purpose for calibration changes from determining the calibration curve, to demonstrating that the signals from the transducers will travel through to the receiver because of high viscosity effects.

4.0 CALIBRATION METHODS

Both gas and liquid calibrations require a reference measurement for the calibration, it is through this reference that a traceability chain can be established back to the national standard. Generally, the traceability chain for liquid measurement is shorter than for gas. The calibration "effect" is probably the major source of diiference in uncertainty between liquid and Gas meter

4.1.1 Gas Meter Calibration

The calibration of large meters, above 2", uses master meters for the calibration method of the USM. For small meters it is possible to use more direct measurement, such as weighing the gas or determining the volume. This leads to longer traceability chains for large meter calibration and consequently higher uncertainties.

The process used to calibrate large meters is called "Bootstrapping". Bootstrapping is the process of utilizing small meters in parallel to calibrate a larger meter which would then be used with other larger meters to calibrate the final meter. The smallest meters in the chain can be calibrated against a direct mass or volume. Several are then used in parallel to give the full range of calibration of the next size of meter in the chain.

One example of this is the CEESI 1" Critical Flow Venturis, CFVs, used to calibrate the 12" working turbine standards in the Iowa facility (called Gold Standards). These meters used to calibrate a total of 17 other 1" CFVs. A combination of the 4 Gold Standards, and 4 of the other meters, chosen from the 17, for a total of 8, are then used to calibrate each individual 12" turbine meter standard. This process, in one form or another, is used in all the major gas calibration facilities. An example of the bootstrapping method is shown in Figure 4. Point 1 is the layout with 5 smaller meters, in point 2 flow passes through one small meter and one larger meter, point 3 the flow goes through two smaller meters and through the same large meter. This is continued until all of the small meters have been used to calibrate the large meter over its full range. The process would then be repeated for the next large meter. Finally, all the larger meters will be calibrated and can then be used in the same fashion to calibrate the meter under test.

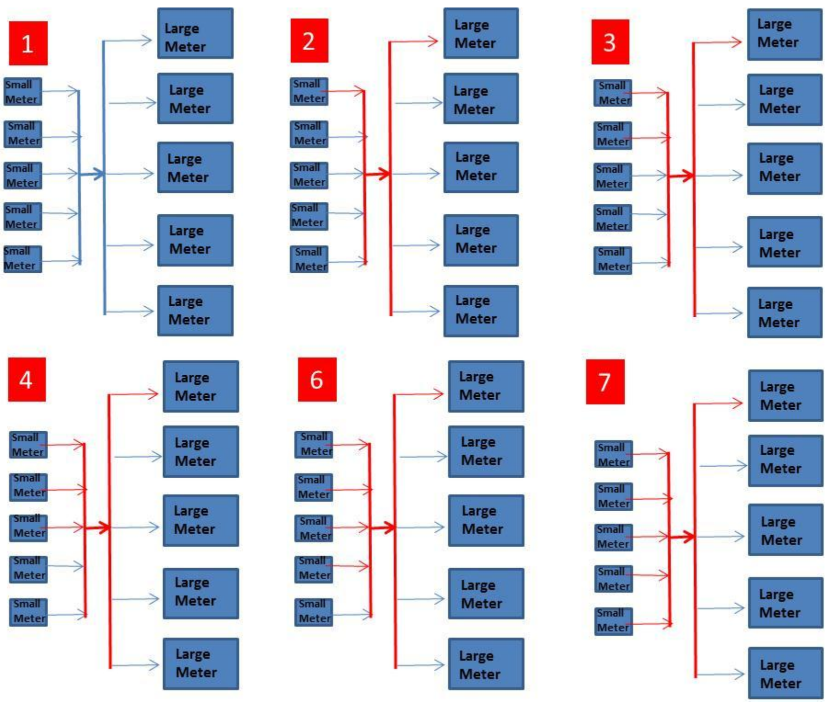

Figure 4 Bootstrapping Method

With regard to traceability we will consider the large CEESI calibration at IOWA, although to achieve the full traceability it will bring in the smaller facilities available at Nunn. The Iowa facility uses gas from a main trunk line passing through Garner. The gas is currently Trans-Canada gas. Gas is diverted through the flow facility and back to the main line. The top flow and pressure are, to a large extent, controlled by the flow conditions in the pipe line, as is its capacity. This is the same with most other facilities around the world, Ruhrgas, Westerbork etc. The facility is shown in figure 5.

Figure 5 CEESI Iowa Gas Calibration Facility

The consequent traceability chain is shown in figure 6, starting at the top with NIST Mass standard, via the primary flow standard at Nunn, then to the CVFs, to the turbine meters and finally the meter under test.

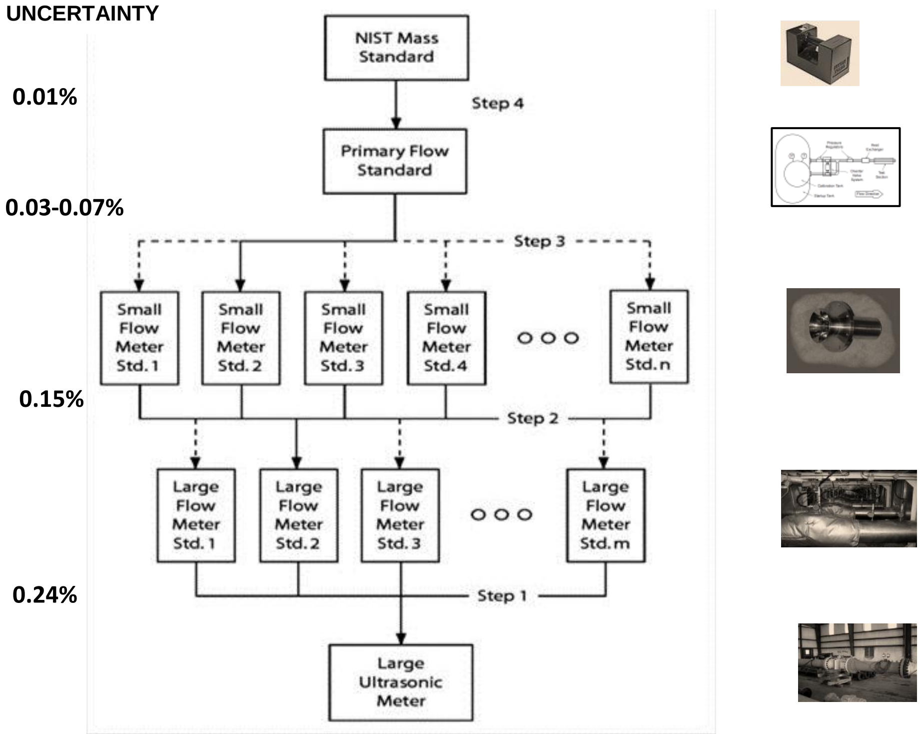

Figure 6 Traceability Chain for CEESI Iowa Gas Calibration Facility

It can be seen that the overall uncertainty attributable to the calibration is 0.24%

4.1.2 Liquid Meter Calibration

There are a number of methods of calibrating liquid meters, here we concentrate on the most common oil calibration method, the use of provers. The traceability chains are shorter, particularly the weighing system with a consequent reduction in uncertainty. Further the calibration methods are more direct rather than by building up uncertainty with the boot strapping. For weighbridge based calibration it should be noted that the traceability chain is even shorter and unless master meters are required, a lower uncertainty than for volumetric methods can be achieved. Figure 7 shows a typical oil calibration facility using two types of prover, a line prover and small volume prover.

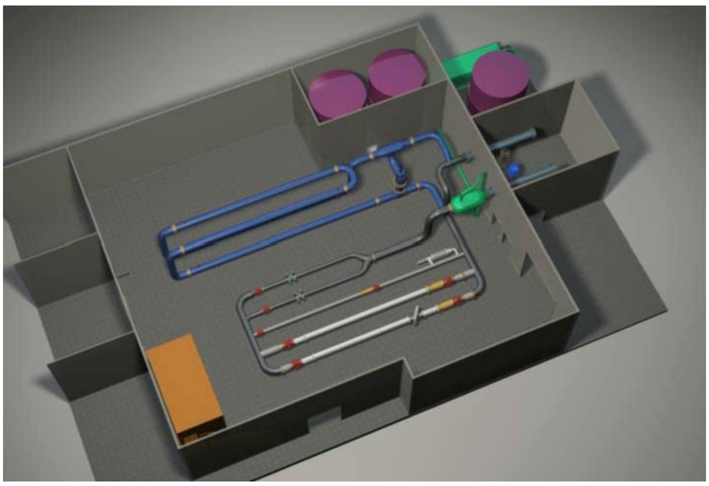

Figure 7 Oil Calibration Facility

The traceability chain for the prover system is shown in figure 8. The end uncertainty is around a fifth of the gas facility.

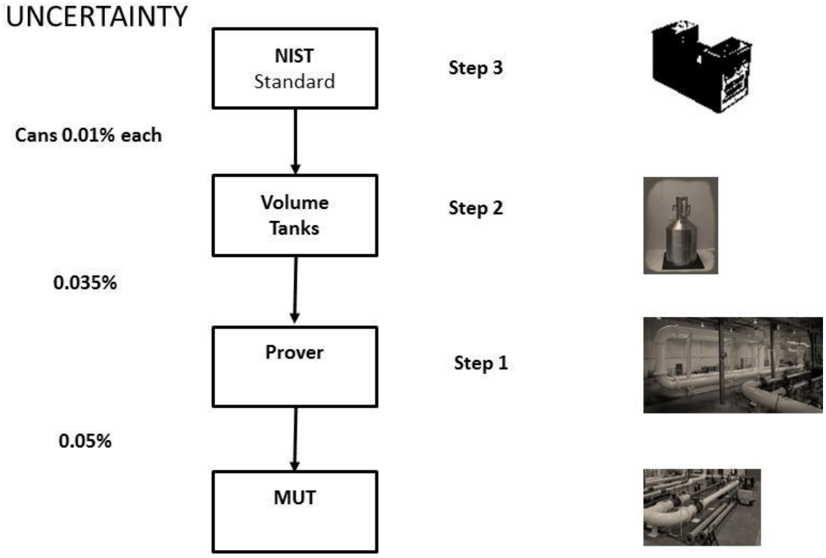

Figure 8 Traceability Chain of a Oil Calibration Facility

4.3 Summary of Uncertainties

A summary of the potential uncertainties of both gas and liquid facilities for measurement of large meters is shown in table 2.

FUNCTION	UNCERTAINTY
GAS	0.2-0.3%
LIQUID	
Direct Volume	0.03-0.05%
Direct Mass	0.02%
MM Volume	0.08%

Table 2 Summary of Typical Gas and Liquid Facility Uncertainties

5.0 CALIBRATION STANDARDS

Another difference in the calibration of gas and liquid USMs, is the standards available to specify the method and requirements of calibration. The AGA 9 has some very clear standards which include performance standards and guidelines for calibration. On the liquid side OIML R117, has performance standards, although they are not specific to USMs, but does not give a good indication of calibration methods. API 5.8 gives no help with calibration, other than to point towards the API chapter on proving.

5.1 Gas Standards and Calibration Requirements

For Gas Calibration the most common standard is AGA9. It contains details on calibration and the expected performance.

It starts off with the expected meter performance requirements, stating that calibration of the meter is recommended as per section 6.4, which is the calibration section. The meter must meet minimum performance requirements before adjusting meter factor(s). The performance requirements are laid out in a graph, similar to figure 9.

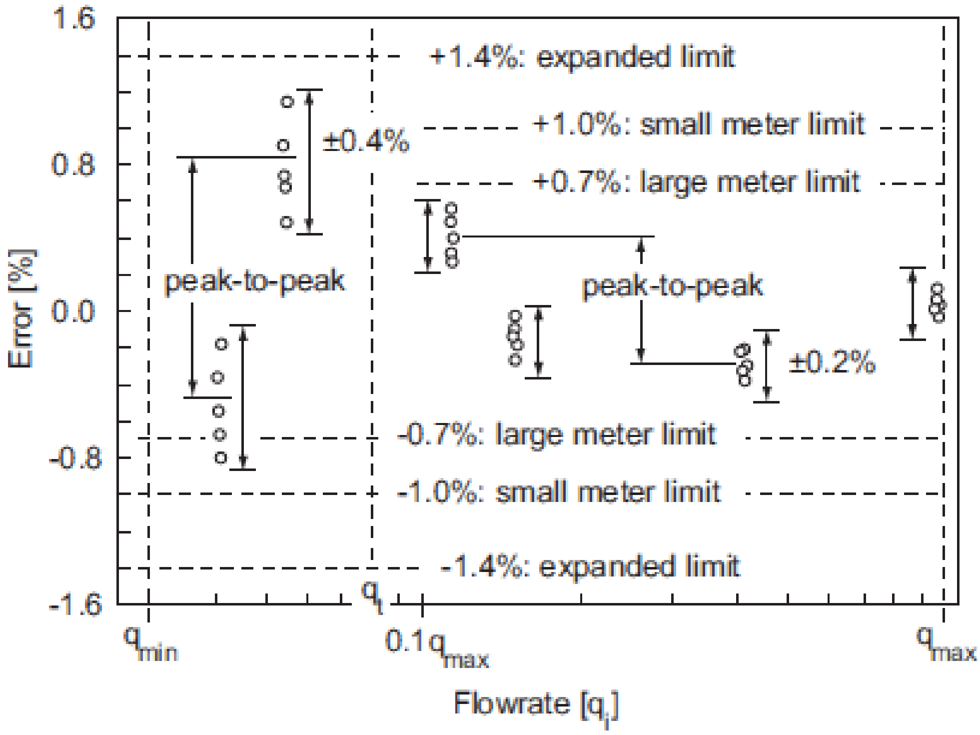

Figure 9 Representation of the Performance Requirements in AGA9

There are two sets of performances quoted for large meter, 12" (nominal) meters and larger,and Small meters, less than 12" (nominal).
Defining:
q_{max}: maximum flow limit
q_t: transition flow limit ($q_t < 0.1q_{max}$)
q_{min}: minimum flow limit
q_I: indicated UUT flow
The peak to peak limits are:
± 1.0% for qt ≤ qi ≤ qmax(small meter, = 10")
± 0.7% for qt ≤ qi ≤ qmax(large meter, = 12")
± 1.4% for q min ≤ qi ≤ q t

As can be seen there is a detailed performance defined and it is against this performance that a gas USM is calibrated. This includes repeatability's, (spreads) and linearity.The standard also includes such items as calibration facility preparation, with such items as:

- Inspect the meter for damage during transport.
- Ensure meter configuration (components and electronics) match that specified by the user.
- Identify any problems encountered with the meter (i.e., perform zero-flow test prior to flow-calibration).
- Configure the calibration such that UM is calibrated using the output specified by the user.

The calibration is further stated with the following requirements:

- At least one verification point.
- At least one sound speed check.
- Data collection interval of 120 seconds.
- Calibration adjustment factor must account for meter package dependent changes in meter performance.

- Calibration factor adjustment, “further investigation is recommended”:
  - exceeds 1.0% (large UM) or 1.3% (small UM) between q t
  - not absolute grounds for rejection of metering package.

The standard also includes a section of what should be contained in the report, zero flow verification, piping installation, package configurations and methods available for meter factor adjustment.

The calibration method is usually:
- “As Found” calibration with7 Flows across the range
- “As Left” calibration 2 points to check the corrections
- All the data is available as part of the calibration certificate, including both the As Found and As Left data and diagnostic data to allow for finger printing at meter commissioning etc.

The standard leaves very little to the discretion of the calibrator, meter producer or the user, if it is chosen as the basis of calibration.

5.1 Liquid Calibration

For Liquid Calibration the standards are less clear. The two major standards used around the world currently for liquid USMs, API MPMS Chapter 5.8 and OIML R117, say little or nothing about calibration.

A word search of OIML R117 failed to turn up the word calibration. The OIML standard does contain three issues that relate to the meter performance, an uncertainty, including the calibration laboratory, repeatability, normally taken as a spread of 0.12% in 3 runs, and flow ranges. Unlike AGA 3, there is no direct reference to any calibration procedures.

API does not state any performance criteria for calibration, other than proving, no uncertainty or calibration. The standard used in this case for repeatability is an uncertainty of the repeats should 0.027% or less.

There appears to be no publication that mandates such issues as to what is an acceptable repeatability, how many points should be taken, whether there should be an As Found, and As Left calibration, how to define the ranges or whether there should be within the calibration some range related to the operational conditions.

The normal practice is to try to get customer acceptance of the OIML repeatability condition, as it is much easier with USMs to get a calibration accepted. If using provers or small volume weigh tanks then achieving the API repeatability can be a sole destroying activity, as it can take a large number of runs. The range and number of points is usually 5 or 6 over the full range but may, at the users request, end up as 10 points, or have the points biased towards the main operational flows. It is usual practice to use Reynolds number as the base for the range of calibration. This may not necessarily be the same flowrates as the operational conditions.

6.0 TRANSFER OF CALIBRATION TO THE FIELD

The objective of this paper was not to discuss this in any detail, however, it is an important subject and worthy of some discussion. USMs like all other meters have some form of installation effect, such that the transfer of the calibration from the calibration facility to the field will have some effect depending on the design and installation conditions.

For small liquid meters the installation effect is mitigated by the use of site proving, in this case the calibration is really a linearization, and the main effect is likely to be the fluid properties, and is the linearization method strong enough to allow sensible proving. For non-proved liquid meters the issue of transfer of calibration is the same as for gas, with the added linearization proviso. The major issue is how to calibrate the meter such that there is a minimum effect of installation during the transfer. Gas meters, which have a greater history of this issue than liquid resolve the situation by usually calibrating with the complete meter section, usually a specific upstream pipe that will be used in operation, and of adequate length to ensure the minimum errors due to installation. It is usual practice to include a flow conditioner as part of the package. The level of installed uncertainty, or confidence in the installed calibration, will be influenced by the method of transportation of the meter. If the meter is kept bolted in place with the pipework and flow conditioner, then there will be the greatest confidence in the end result. Removal of the pipework, even with location dowelling, will lessen the confidence. Using “mock” pipe work for the upstream meter run will further lessen the confidence in the meter performance on site.

An extreme case of trying to replicate the site conditions is to carry out model tests of the site. This is usual practice in the US nuclear industry, where complex installation conditions, figure 10 are used to give a bounding of the installed uncertainty likely to be achieved in practice.

Figure 10, A Modelled Nuclear Installation

7.0 EXTRAPOLATION

While extrapolation of data is not a calibration, it does require calibration to be able to make the extrapolation. It does imply that an assumption is made about the shape of the calibration curve without any data, other than history to back it up. It deserves a complete paper on its own, but a few comments are made here about the process.

There are times when the meter cannot be calibrated over the required Reynolds number range.

- LNG meters, a high Reynolds number that cannot be duplicated at any world calibration facility.
- Large meters cannot achieve the Reynolds number on calibration because few calibration facilities can reach the flowrates required.
- Very high viscosity, calibration facilities have difficulty pumping highly viscous oil.

In these cases the meter calibration will have to be carried out at flows as close to the operational range as possible and then the data extrapolated to the operational range.
The assumption that has to be made is the extrapolated data follows the curve of the meter at the end of calibration. Often the assumption is that the meter is now completely linear, a feature of many Reynolds number based meters as they increase in Reynolds number. The problem comes if there is an unexpected discontinuity in the calibration. This, of course will never be known until tests can be carried out at the extrapolated flowrates or the meter shows differences to the expected performance by, for example, a mass balance of the system. If this method has to be used then it is imperative that the following is shown:

- The method of extrapolation in detail.
- The data to back up the extrapolation.
- And importantly an independent assessment of the extrapolation method and how strong it will be in the application.

The uncertainty for extrapolated meters will always be greater than for a meter calibrated over the operational range.

8.0 CONCLUSIONS

- While the principles are the same the calibration methodology is quite different.
- Much of the higher uncertainty of gas meters comes from the calibration methods.
- The concept of bootstrapping is essential to large gas measurement making uncertainties larger than liquid calibration.
- Linearization is more essential for liquid meter designs than gas, requiring:
  - More attention to the detail of calibration of liquid meters.
  - Calibration over a range that is representative of the operational conditions.
- The standards for gas USMs are more applicable to calibration than those available for liquid.
- A liquid USM calibration standard similar to the AGA9 format would be a useful addition to the world on metering.
- Until calibration facilities for gas can improve significantly the uncertainty of Gas USM will always be inferior to liquid USMs.

9.0 REFERENCES

1.0 AGA Report No. 9 “Measurement of Gas by Multipath Ultrasonic Meters” Second Edition April 2007.
2.0 OIML R117-1 “ Dynamic Measuring Systems for Liquids other than Water” Part 1 Metrological and technical requirements, Edition 2007.
3.0 Manual of Petroleum Measurement Standards, Chapter 5- Metering Section 8 “Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters Using Transit Time Technology”, 2011.
4.0 Kegel. T, “Ultrasonic Meter Performance Results”, CEESI Training.
5.0 Clancy. J, “Overview of AGA 9 Revisions” CEESI Training.
6.0 Brown G, Estrada H, Augenstein D, Cousins T, “LNG Allocation Metering Using 8-Path Ultrasonic Meters” NSFMWS 2007
7.0 Fisher S, Spink P, “Ultrasonic as a Standard for Volumetric Flow measurement” Modern Developments in Flow Measurement, AERE 1971.
8.0 Augenstein D, Cousins T, “Validating the Accuracy of Multi-Path Transit Time Ultrasonic Flowmeters” ISFFM 2009
9.0 Brown G, Augenstein D, Griffith B, Cousins T, “Comparison of Multipath Ultrasonic Meter Calibration Data from Two Liquid Hydrocarbon Facilities and One Water Facility” CEESI Denver Workshop 2010
10.0 Cousins T, “Presentation of Caldon Ultrasonic Meter Technology For Liquid Custody Transfer Applications.” CEESI Denver Workshop 2010
11.0 Cousins T, “HOW SAFE IS LINEARISATION OF FLOW METERS?” ISFFM, Denver, 2012