Calibrating and Testing Custody Transfer Hydrocarbon Liquid Meters.

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1 INTRODUCTION

Before discussing calibration and testing meters we should first attempt to define these activities:

Calibration is formally defined by BIPM as an "Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties (of the calibrated instrument or secondary standard) and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication."[1]
In reality this implies that calibration is really a comparison of two methods, one of which is an **accepted standard**, using measurement uncertainty of the methods to define that comparison.

Testing has a wider meaning with a more general definition such as "finding out how well something works", often trying to define the limits of operation. In metering we tend to be more concerned with **Type testing** sometimes called Conformance testing, conformity assessment or compliance testing. It is testing or other activities that determine whether a meter complies with the requirements of a specification, technical standard, contract, or regulation. For example whether a meter performance conforms to OIML R117 standard.
Perhaps the biggest differences between the two are that Calibration of a meter implies an operation on each produced meter under some defined "ideal" flow conditions, whereas Type testing implies that the conditions may be varied from "ideal" and the testing will be carried out on a representative sample.
This paper reviews the needs, requirements, downsides and end result of calibration and testing to the ever reducing uncertainty being applied to custody transfer meters for hydrocarbon measurement.

2 UNCERTAINTY AND REALITY

Over the years the level of claimed uncertainty has been reducing sometimes without any practical reality. We are staggering towards claiming values of better than 0.1% total measurement uncertainty for meters that are not even proved on site. Those of us that have dealt with practical proving on site would I expect feel that in reality even the prover on site is struggling to achieve better than uncertainty of around 0.1%. To make the assumption without proving of better than 0.1% uncertainty is really a big ask, particularly as the "Gorilla in the room" the installation effect has to be addressed. However that is the game we now play. Many operations now seems to feel that the running cost, medium to long term reliability and management effort of prover systems is not a good return on investment. However, to achieve such uncertainties, without a prover, it is very clear that certain criteria must be achieved:
The meter has now to be very good, an emotive term that implies:

- It has to be able to withstand the vagaries of many installation variations without a change in performance, or at least a defined acceptable change. (Type testing may be one method to confirm this?),

- The installation must be well controlled and defined (Even with the ability to withstand installation changes it is best to ensure that the conditions are well defined, the correct upstream piping, flow conditioners etc.)
- The meter must have a well-defined range related performance. (Linearity must be under control over the specified range, again one method of determining this is type testing, but the major issue is good calibration)
- The base value of the meter has to be within a known tolerance, and this tolerance has to be valid over the range of operation of the meter. (This is where proper calibration now comes in, and is essential to the control and definition of the base value.)
- This base value **must have a relevance** to the meter operation.

3 WHY DO WE NEED TO CALIBRATE?

This has been briefly noted in the previous section, now we need to see the reasons in detail. The questions we need to answer are, do we need to calibrate and at what level and conditions should this calibration be carried out.

3.1 Base Calibration of the Meter

In general all meters when produced have an output that has to be modified to bring it into the specification. It is difficult, if not impossible to produce meters with the precision to meet the level of uncertainty we require without some form of calibration, external correction, to make the meter give an acceptable answer. Over the years there have been many attempts to produce to this level of precision, and be able to send meters out of the door straight from manufacture. Early on it was felt that Vortex Shedding flow meters could be produced this way, with just checks on the dimensions to take out those failing to meet the dimensional specification, but the best that I have seen was a spread of 0.65%. Figure 1 shows the raw calibration of eight 12” ultrasonic flowmeters at a Reynolds number of 700,000, where the meter was considered linear. It can be seen that meters all show a shift from the predicted meter factor, but more importantly the spread was in the order of 0.75%. It should be noted that we can play statistics to show that the standard deviation is relatively a lower figure, but we have to remember that each meter is an individual, and so spread has to be used to keep us in the land of reality, because the performance of each meter matters. If we do an uncertainty to say 95% confidence limits, for example, do you want to be the user who gets the meter that is in the 5%.

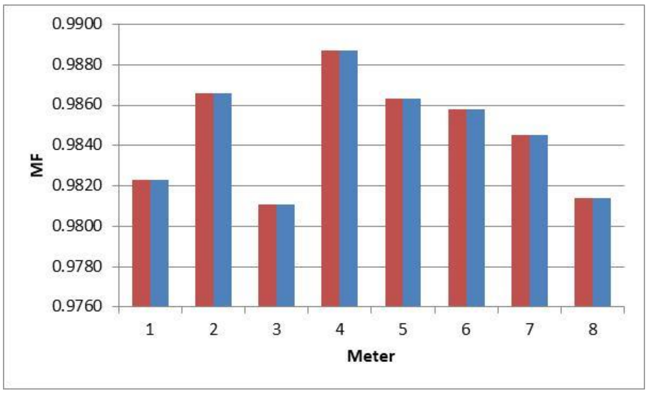

Figure 1 Meter Factor Variation of 12" USMs

To a certain extend this method is used for Orifice plates via ISO5167. Although it could be said that high quality dimensional tolerances are used to control the end result. The calibration is based on a large amount of empirical data compiled into a data fitting equation. The claimed uncertainty is of however high compared to the liquid uncertainty we are discussing. Only by performing a full calibration could the device come close to meeting the current performance specifications, providing that the calibration facility can provide an adequate uncertainty. (It is common to hear in gas measurement that the uncertainty of meters is limited by the calibration facility an interesting and unsubstantiated take on calibration)
Summarising, the point has been now made that we need to calibrate meters just to find their base factor if we want the best achievable uncertainty, but are there more reasons to calibrate?

3.2 The Non-Linearity of Meters

The issue now is, does the meter meet whatever criteria are set for it under ideal flow conditions without any further calibration? Could we, for example get away with just a single point calibration to identify the shift needed to bring the meter to the “correct value”?
Here we begin to run into the issue of belief and reality. Coming to terms with the real performance of meters is difficult. When a new meter is produced there is always a hope that it will require a minimum of effort to produce and get into the field. But it is clear that most meters do not come out of production with a perfect relationship (usually a direct linear relationship of meter output to flow over the full operating range) with the fluid passing through it. One obvious issue is Reynolds number. Data shows that all of the major flowmeter types used in Custody transfer have a non-linearity to some degree that is a function of Reynolds number. Interestingly USM manufacturers have, for example learnt to live with Reynolds number as a factor that makes it problematic to produce the meters without a detailed calibration. It has taken Coriolis meters much longer to acknowledge the issue, and some still do not reached that point.
Two Reynolds number examples are shown in figures 2 and 3. Figure 2 shows the calibrations of five 4” OGM meter “out of the box”. Several issues are very clear from the graph:

- The first is that the linearity is of the order of +/-0.5% across most of the range shown. This was a meter that is specified to be a +/- 0.15% meter and so quite clearly it has to be modified to meet that performance. If it was a Turbine meter, the blades would be shaped, for a USM the meter has to be matched to Reynolds number and curve fitted.

- The second point of issue is there is a variation in the shape of all meters. This is typical of most meters. It gets worse as the size reduces because of the tolerances, but the implication is again the need to calibrate each meter, and over the range the meter will operate.
- The last issue the graph shows is not so related to the paper, but to our concept of flow profile and transition. It can be seen that the non-linearity starts at around a Reynolds number of 60,000. On reviewing the data for other sizes of the same meter the same can be seen, similarly with other meter designs, all start the non-linearity around 50,000 to 60,000 Reynolds number. My colleague Julian Porre came up with a good term to describe what is happening, he called it "pre-transition". It is almost as though the profile is preparing itself for the transition region. It does say that the idea of 10,000 as a safe lower point for meters may be too low. Looking back at data for USMs generally this would seem to me to be a very interesting area of research for pipe flows, as I am sure it applies to other meter types.
- The graph also shows the recalibration after it has been linearised to within +/-0.1%

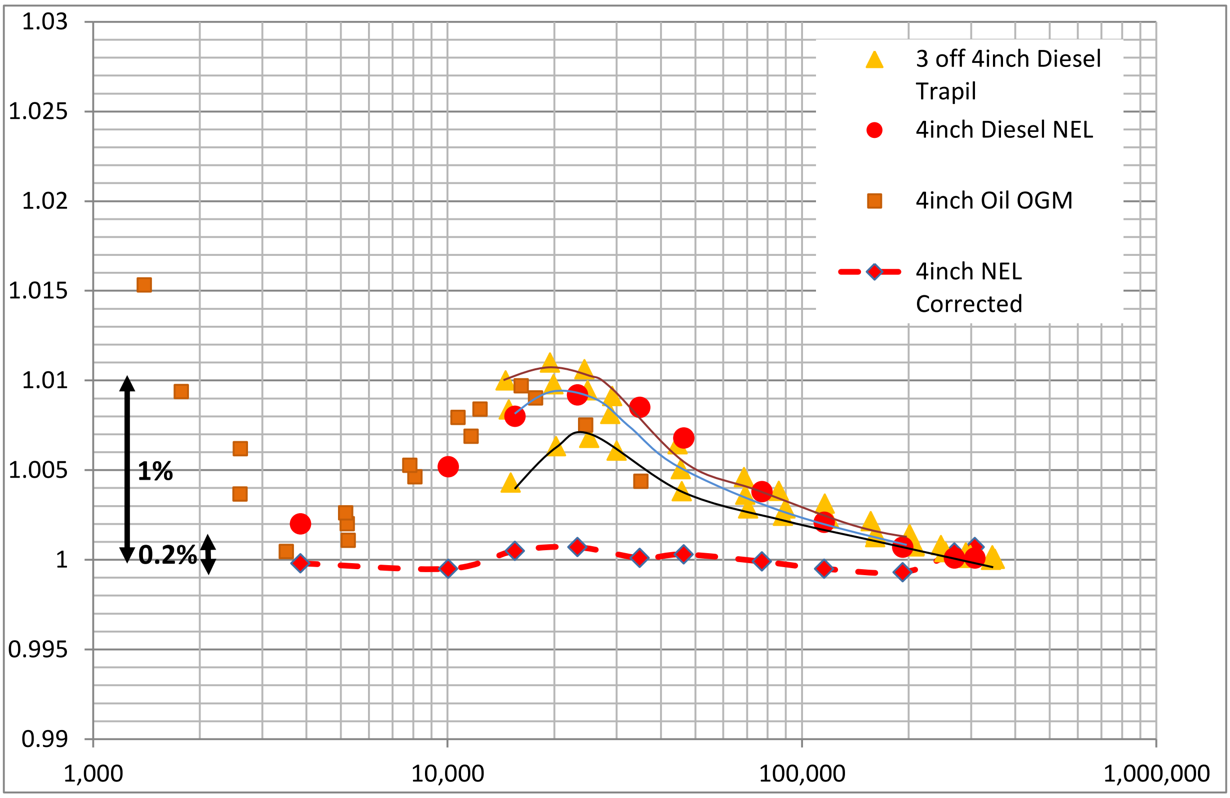

Figure 2 Base Calibration of five 4" OGM Meters

Figure 3 shows the calibration[2] of a standard 4" Coriolis meter, interestingly it obviously has a non-linearity though the transition region, but also it appears to start at the "pre-transition" point of around a Reynolds number of 50000. (Coincidence I think not!) I do not have any data as to the stability with manufacture, but it would be expected that there would be some difference for individual meters in line with manufacturing tolerances, and so it would be expected that for very low uncertainty measurement all meters need to be calibrated.

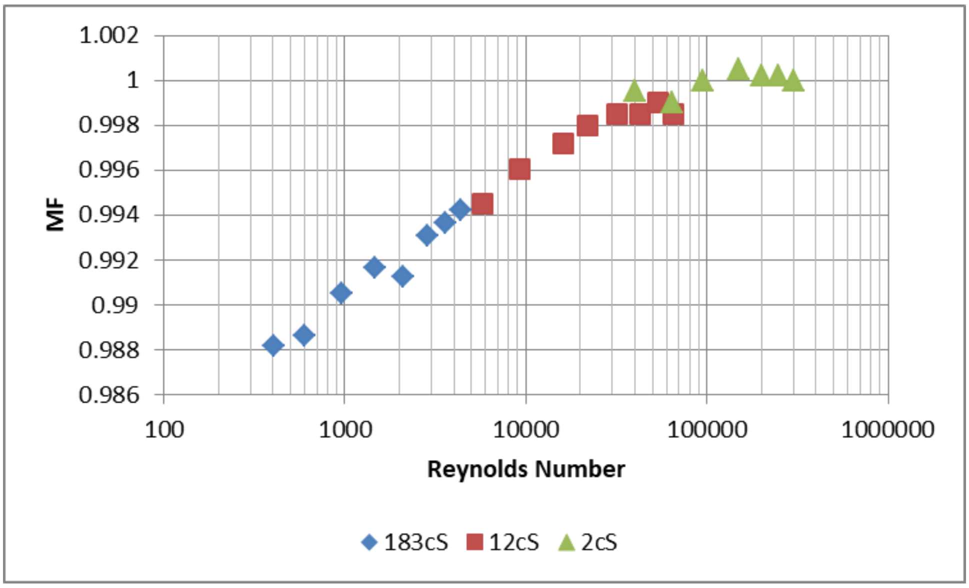

Figure 3 Calibration Against Reynolds Number of a 4" Coriolis Meter

Reynolds number is not the only issue; other areas of non-linear performance are a result of the physical changes that effect the meter, such as temperature and pressure. Others are design issues such as bearing friction with turbines and PD meters, resolution of the meter, zero settings for USMs and Coriolis meters. Finally there are issues of the fluid integrity. By this I mean that most meters discussed here are fundamentally designed for single phase measurement. There is pressure to use these meters in an environment where the main measurement fluid is no longer single phase, but maybe a water oil combination, under these circumstances it should be clear to us that some form of testing/calibration is required to achieve an "idea" of the meter performance.

All of these factors contribute towards the meter not performing in either a predictable or a linear way. Some have a good theoretical basis for correction, factors such as material expansion and stress corrections may not need to be calibrated, but be part of a type test acceptance, but others do not have an exact replication within the uncertainty requirements and so require a detailed correction that can only be produced by a good calibration. This can be clearly seen in the calibration of a turbine meter with different volumes of water in oil, figure 4[3]. The uncertainty of the calibration is higher than that expected for a single phase fluid, but it does give a good indication of the expected performance, particularly at low flows, which at least would give the end user an indication of the limits.

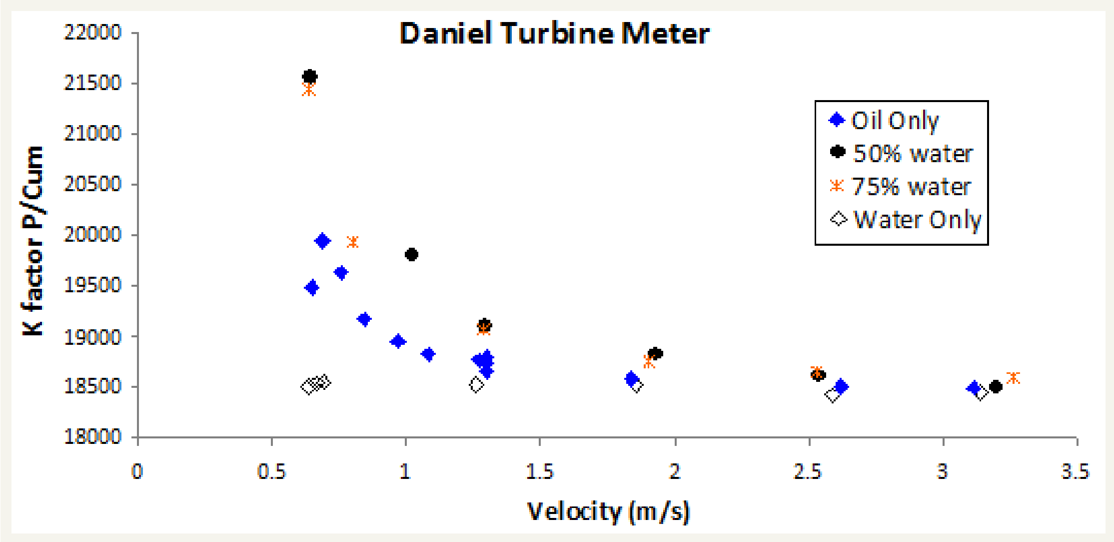

Figure 4 Calibration of a Turbine Meter with Water in Oil Mixture

To summarise, if we were talking about 1% uncertainty measurements, then I think we would be happy to accept modest calibration requirements, but we are not, we are dealing with 0.1%. We are moving ever closer to what a good friend of mine, Dr. Alan Haywood believed, a "God given limit" to a meters performance. I may not agree with that actual words but the sentiment is well taken. When we are nearing these limits it is clear that we have to be very precise in our methodology, and detailed correct calibration is one of the areas where this particularly applies.

4.0 TESTING-TYPE TESTING

Type testing is usually associated with a standard which will define the potential performance to be obtained. Both are there to help the user understand the requirements and performance for a particular device, and to guide designers and manufacturers as to the appropriate methods to achieve the ends set out by the standard. With flow measurement the need for appropriate standards and type testing is more relevant than many other devices because of the lack of good theoretical background, requiring that the knowledge of meter performance be determined more by experience than for other devices, such as thermometers and pressure measuring instruments. The range of variables that effect a given flowmeter design, whether it be a USM, Coriolis, turbine, positive displacement or orifice meter is large, and generally only available through experimental data, the most economically expensive method to confirm the performance. The consequence is that it often takes many years to collect and interpret the data in a way that is useable for non-experts.

Necessarily most standards can only give a set of criteria that should be met by a design, or meter type, it is then left to the designer/manufacturer to provide evidence that their meter conforms to that standard. This can be a chaotic experience, as the presentation of this data can be in many forms, and often heavily influenced by a sales approach, which necessarily presents the data in the best possible light. A controlled "type testing" is one way in which there can be a standardised presentation of data from all manufactures, hopefully showing the similarities and distinctions between the products in a clear light. From the manufacturers point of view it should be an opportunity to clearly show that their meters meet the standard.

4.1 Comments on Type Testing

It needs to be asked of the current type testing methods , are they giving the end user, the main person requiring this data, a real indication of quality of the meter performance? It should be noted that type testing quality will be first determined by the quality of the standard. It implies that the standard should be a performance based standard, and so OIML would be a better basis than the majority of API standards, which are really technical contract documents.
We need to consider what features are needed for a good basis of comparison of meter performance:

4.11 Batch Sampling or Sample size

At present it is usual to review the calibration characteristics of a single meter of a given size. At worst this can lead to the use of "super" meters being presented for testing, at best it does not give a clear picture of how representative this meter is of the general population of meters of this design. There should be some safeguard, possibly by requiring the data for a number of meters of the same size and design to be calibrated and the performance checked, possibly picked at random, if this is physically possible. Determining sample size is a very important issue because samples that are too large may waste time, resources and money, while samples that are too small may lead to inaccurate results. In many cases, we can easily determine the minimum sample size needed to estimate a process parameter, such as the population mean. It may be for example sufficient to do this for one size only, as being representative of the rest of the meters in the range. It would also allow the producer to choose a size range that is likely to have the largest number of meters available.

4.12 Meter Sizes

Currently there is no clear indication as to the number of meters and sizes required for testing, when there is a range of sizes for meters. If every size had to be tested, in the most common sizes this would lead to testing a minimum of 10 meters. While this would be good business for the calibration and type test facilities, the cost burden would be excessive, particularly for the large size meter calibration on liquid. There needs to be some agreed method of determining the number of sizes that are representative of meter design. Perhaps there should be the smallest, the largest and one in between? Often the larger meters are only built rarely, is it feasible to allow a meter, say 20" diameter to represent the 30". There needs to be some consensus as to the methodology to determine the meters required to represent the range. At present it is by negotiation.

4.13 Design Variations

Often there are differences in design with for example size. For example it is often more difficult to make a design of USM that can have the same path arrangement because of the size of transducers. This leads to the question, at what point should type testing review these variations and should they be tested as part of the type test procedure. There needs to be at the very least some reference to these changes within the type test regime to make it valid.

4.14 Proving

Any performance standards should have a reference to proving of liquid meters. It is an area of great debate between suppliers and users, and would do well to have a set of performance requirements to enable a direct comparison of meter designs.

4.15 Installation

Installation is a necessary issue relating to type testing of meters, particularly in non-proved systems. There are of a variety of configurations and designs of meter even of the same type. They do not react the same way with different installations. On the gas side OIML R137 and ISO 17089 have tests for performance with installation. On the liquid side, there is not a general standard relating to installation and so putting together a definitive type test is difficult. There are many variations of installation from fluid mechanical to mechanical such as stressing and vibration. On the fluid mechanical side even a simple installation such as a bend has many variations, distance downstream, axial orientation. The latter can be seen in figure 5, the theoretical change in performance of a 4 path USM[4] as it is rotated downstream of a bend. So with type testing this has to be acknowledged, giving more variations and consequent cost. Even the rotated paths of the 32 path OGM meter has still some residual error.

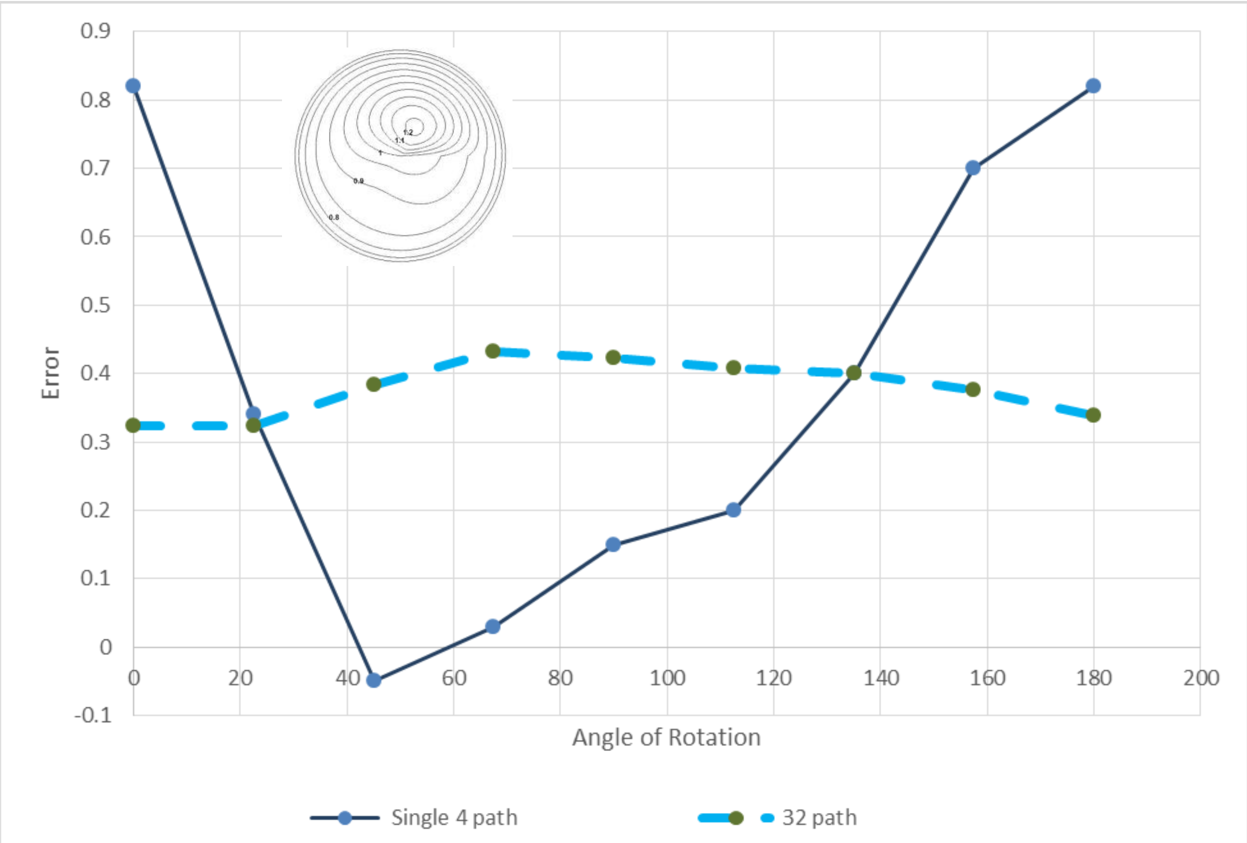

Figure 5 Theoretical Effect on Rotating the Paths of a Four Path Meter With a Non-Symetrical Disturbance

4.16 The Complete Story

There are also other issues to be tackled such as**:**
Environment, Electrical and Mechanical Performance, Type Test Approval Organizations and Calibration Facilities and Software are other major issues, but

these are not within the remit of this paper, but need to be considered as part of the full type testing criteria.

5.0 CALIBRATION, TYPE TESTING AND ON-SITE PROVING- THE RELATIONSHIP.

We need now to bring these together with the reality of site operation, and in particular the influence of the Prover.

5.1 Proving

Let us start with a working definition of Meter proving. "Meter proving is the physical testing of the performance of a liquid meter in a liquid service. The main purpose of the test is to assure accuracy". It is fundamental a confirmation of the performance of a meter under operational conditions. The basic principles of proving a liquid meter are the same whether it is a Ultrasonic meter, Coriolis meter, turbine meter, or a positive displacement meter. Each type of meter has its own characteristics when being proved, but the basic principles are the same. In theory then perhaps the obvious way to attack the need for calibration is prove the meter on site. Then we can, with a good prover, shift the meter base factor to be correct within a known uncertainty, linearise the meter by checking it, there is obviously a need to be able to change the fluid properties, flowrate, viscosity etc during the proving exercise, an onsite calibration, or be able to prove at each change. Also we can generally negate the concerns over installation. There is a need, however, either to have access to the meter "black box" to implement the changes or maybe a more sophisticated use of a flow computer to carry out these changes away from the meter. Quite clearly this stands the best chance of achieving a **quantifiable uncertainty.** The measurement issue without proving is always attributing an uncertainty to the installation, which pulls us into the realms of conjecture hopefully, backed up by so reasonable basis of data.

5.2 The Real Responsibility for the Meter Performance

The big issues with moving calibration out to the field are basically the management, logistics and responsibility of the calibration. If proving becomes more than a confirmation of the performance of the meter and is now taking on the full "characterisation", we have to ask who is responsible for the veracity of the results. Further, it becomes a major logistical exercise to carry out the tests, which may take a good length of time to complete. An example from my life happened in the 1990s with a turbine meter system I audited. The temperature of the oil, supplied from storage tanks, changed through the year from around -10^{0}C to 40^{0}C, with a consequent viscosity variation of around 5-30cS. The meters were flat bladed and changed calibration through the year. Because the prover was to be only used sparingly a table had to be constructed of the Meter Factors through the year against temperature. This became complex as the system had to be designed to allow the meters to be calibrated at different viscosities, and the data used over a gven band of viscosites to reduce the meter uncertainty due to calibration change with viscosity. Up to 5 bands are allowed. For the initial tests the bands were arbitrarilly taken as 5 centistokes, see table in figure 5. The main problem however was to determine a method of predicting the optimum band size for the future. A semi-empirical method developed that relied on there being a linear relationship between the viscosity and Meter factor inside the required viscosity range.

Band 1 --------------- 5-10 cs
Band 2 --------------- 11 to 15 cs
Band 3 --------------- 16 to 20 cs
Band 4 --------------- 21 to 25 cs
band 5 --------------- 26 to 30 cs

Figure 6 Table for Change in K Factor with Viscosity

The work involved in doing this can be seen in the table for one of the 12 meters, which after a year had still not achieved the full data collection.

METER No. 3211

Turb.Met. Tag. No.	**Turb.Met. Flow Range**	**Factory K-Factor**	**Calibrat. Flow Range**	**Calibration Meter Factor MF**	**Viscosity (cst)**	**MF fact. deviat. due to viscosity %**	**Density (kg/m3)**	**Range**
FT 3211	486-4088	652.501	3160	1.00460	9.2600			1
		652.501	2376	1.00530	9.2000	**61.28**		1
		652.501	1598	1.00625	9.6900	**5.78**		1
		652.501	1191	1.00720	9.2500	**4.96**		1
		652.501	793	1.00895	9.6900	**3.53**		1
Average				**1.00646**	**9.42**			
FT 3211	486-4088	652.501	3177	1.00490	14.11		861.60	2
		652.501	2383	1.00480	14.56		862.00	2
		652.501	1603	1.00540	14.61		862.00	2
		652.501	1189	1.00630	14.70		862.00	2
		652.501	797	1.00780	14.69		862.00	2
Average				**1.00608**	**14.6400**			
FT 3211	486-4088	652.501	3205	1.00510	18.53		862.50	3
		652.501	2431	1.00530	17.81		858.70	3
		652.501	1588	1.00630	17.93		858.70	3
		652.501	1187	1.00680	18.04		859.10	3
		652.501	798	1.00880	18.14		859.00	3
Average				**1.00646**	**18.09**			
FT 3211	486-4088	652.501	3205	1.00460	22.47		875.60	4
		652.501	2431	1.00540	20.81		874.60	4
		652.501	1600					4
		652.501	1200					4
		652.501	800					4
Average				**1.00500**	**21.64**			
FT 3211	486-4088	652.501	3200					5
		652.501	2400					5
		652.501	1606	1.00770	25.53		884.10	5
		652.501	1207	1.00900	26.12		884.80	5
		652.501	820	1.01140	26.02		884.70	5
Average				**1.00937**	**25.89**			

Figure 7 The Proving of A Turbine Through the year

Obviously the complete calibration/characterisation of the meters took nearly a year. During this time the **responsibility for the data collection and use changed from the supplier to the end user**. The pressures on the method changed from trying to get the system accepted to getting oil on the tankers. On site the metrology, standards, independence and controls necessarily become strained and loose compared to a calibration facility, and so the reality is that what has been gained by proving can start to be eroded. The issue therefore is really a question of balance, proving can definitely give greater confidence in the performance, but it must be controlled and it should be the responsibility of manufacturers to provide a meter that ready for proving.

5.0 FINALE- HOW SHOULD THE PIECES FIT TOGETHER

So how do they fit together in practical terms?

1. Calibration should ensure that the meter "under ideal conditions" meets the specification over the proposed range of operation of the meter and is corrected in a stable way to ensure the best possible performance on site.
2. Type Testing should define that it meets specification under ideal conditions and the limits to be expected in the operation of the meter when used outside of the ideal conditions.
3. Proving is the icing on the cake, it ensures that when transferred from the ideal conditions the meter either meets performance, or allows it to be modified in a minor way to correct it to meet the performance. **Proving should not be used to solve the inadequacies of a meter or its calibration**.

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