Setting the STANDARD
- Integrating Meter Diagnostics Into Flow Metering Standards

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1. Introduction

When industry requires to meter a flow, it requires that flow to be metered correctly. A trusted flow meter which is subsequently found to have given an erroneous flow rate prediction can cause financial penalties, legal arguments, and / or the process to become inefficient. Verification of a flow meter's performance has always been a major aspect of the flow meter engineer's art.

Traditional diagnostic methods to verify a flow meter's serviceability are still widely used today, such as mass balance checks, and the associated liquid prover / check meter techniques. However, these methods have long been known to have severe limitations. The latest generation of flow meters tend to have diagnostic systems that carry out internal checks on the meter's health. Although imperfect these diagnostic systems are a great advance over the traditional check methods. Nevertheless, industry has been very slow on the uptake of such an obviously beneficial development.

In this paper the authors discuss the history of flow meter verification and the issues that hinder the permeation of flow meter diagnostic usage throughout industry. It is argued that the flow meter diagnostic systems have now reached a maturity where they could and should be discussed in considerably more detail in the flow meter standards. Once included in flow meter standards, diagnostic techniques for meter verification will become included in contractual obligations, and applying such techniques which is presently the exception, should gradually become the general rule.

2. Verification vs. Diagnostics

Operators talk of "verifying" that a flow meter is correctly metering a flow. "Verification" is described in dictionaries as:

- To prove, show, find out, or state that (something) is true or correct.

Diagnostics are the methodology utilized to achieve this verification. "Diagnosis" is described in dictionaries as either:

- The act of identifying a problem by examining something, or,
- A statement or conclusion that describes the reason for a problem.

Clearly, the two definitions of diagnostics are quite different propositions to the flow meter engineer. It is an order of magnitude easier to show that ***something*** is wrong, i.e. highlight an unspecified malfunction, compared to also stating precisely ***what*** is wrong.

3. A History of Flow Meter Verification (Diagnostics) Methods

Where there is an industrial requirement to meter a flow there is an inherent requirement to meter it correctly. This obvious observation leads directly to a very practical and difficult problem; how does the operator know a flow meter output is trustworthy!?

Most flow meter designs require calibration at a test facility prior to being shipped to site and installed[1]. However, although a good performance at a calibration laboratory is a prerequisite to a meter's acceptance at site it does not guarantee the meter will have the calibration performance in operation. Many problems can adversely affect a meters performance. If the rigors of industrial use can create various scenarios that adversely affect a flow meter how does the operator check the integrity of the meter output? This conundrum has blighted flow metering since the earliest days.

Early methods of checking a flow meter's integrity are still used today. These include using due diligence, i.e. due care in selecting, calibrating, installing and operating a flow meter, possibly coupled with routine scheduled maintenance.

3.1 Mass Balance Checks

In pipe networks with multiple pipes and flow meters it is possible to check the mass balance across the system. Mass balance checks inherently require knowledge of the process which is a recurring theme in flow meter verification / diagnostics up to the modern age. There were, and still are, severe limitations to the mass balance method. Perceived mass balance issues can be caused not just by meter malfunctions but by incomplete understanding of a process (e.g. flow being diverted down other pipe lines, line pack, or leakage). Also, multiple flow rate uncertainties combine to make a mass balance check across a large pipe network relatively unprecise. Furthermore, even if a mass balance check identifies a problem, it doesn't identify if the problem is loss of fluid from the pipe, or a flow meter error, or which flow meter is in error. In short, these verification / diagnostic methods are external to the meters themselves and even if a problem is suspected these methods can do little to pin point a specific problem. At best, mass balance is too coarse a technique to identify many flow meter errors.

3.1.1 Check Metering – Two Meters in Series

Fig 1. Gas Ultrasonic Check Meter Upstream of Primary Gas Turbine Meter.

An early attempt to improve on such flow meter integrity checks consisted of using check meters, i.e. comparing the outputs of two meters in series in close proximity. This is a mass balance check, but specific to the two meters. However, there are limitations to this approach. If the two meters are of the same design principle they may encounter a common mode problem. That is, they may have similar flow rate errors induced by the same underlying issue thereby masking a flow meter problem instead of highlighting it. A partial solution is to

[1] An exception to this is the orifice meter. Orifice meters are very reproducible. Industries massed orifice meter data has been fitted & ratified by standards boards to create a discharge coefficient prediction in lieu of a calibration. The standards discharge coefficient prediction is therefore just a data fit to massed calibration data. Hence, orifice meters are effectively "pre-calibrated" and not exempt from this discussion.

use dissimilar meters in series (i.e. meters that operate on different physical principles). It is less likely that meters operating on different physical principles will encounter a common mode problem. Figure 1 shows an example of dissimilar flow meters in series; a non-intrusive ultrasonic meter is installed upstream of the turbine meter. The gas ultrasonic meter is a check meter to the primary gas turbine meter.

Dissimilar meters in series is still not an ideal check. It still requires two separate meters, some problems can still affect dissimilar meters in similar ways, and any combination of meters in series produces a check only as good as the combined uncertainty of the two meters flow rate outputs. For example, if both meters have a 1% uncertainty, the meters can only be checked to within their root mean sum uncertainty of √2%. That is, this system has a relatively low sensitivity to any flow prediction bias. This check can only suggest the meter is operational to an uncertainty higher than the meter's uncertainty rating. Unfortunately, this is a recurring theme with flow meter diagnostics, even for the latest internal diagnostic systems. Furthermore, check metering only gives the operator a green or red light on meter serviceability. If there is a problem it should show a discrepancy between the meters, but as a stand-alone check it gives no information on which meter is in error or why. Nevertheless, check metering can be described as a basic verification / diagnostic check.

Check metering is a diagnostic method that can identify if there is a metering problem. If the two meters disagree on the flow rate outside their combined uncertainties, then it is verified that there is a problem. The converse is not true. If the two meters agree on the flow rate within their combined uncertainties then it is only **probable** that the meters are operating correctly. However, there is still a possibility that both meters are in error together due to some common mode problem. This issue highlights a fundamental truth about instrument diagnostics. Diagnostic suites seldom if ever offer absolute proof a meter is fully serviceable, they simply **significantly increase the probability** that the meter is fully serviceable. A consequence of this fact is although diagnostics can be extremely useful, they cannot completely replace the requirement for due diligence and good metering practice.

3.1.2 Check Metering with Liquid Provers

Fig 2. A Liquid Prover

Liquid flow meter "proving" is a form of check metering. The great advantage a liquid prover has over a regular check meter is that its uncertainty is so small that the root sum square of the prover and flow meter being checked is in practical terms the uncertainty of the meter being checked. The disadvantages are that it is a spot check, effectively a periodic re-calibration of a meter in service, and fundamentally the process still just produces the basic diagnostic of showing if the pair of meters disagree for some unspecified reason. Furthermore, due to the intermittent nature of proving, if a discrepancy is found the operator does not know when in the time period between 'proves' the meter malfunction developed. Proving is also limited to liquid flow meters, it isn't practically possible to prove gas meters. Hence, whereas liquid provers most certainly have their place in industry they are not the panacea or benchmark of flow meter diagnostics. As such, industry has been slowly turning to internal ("integrated") flow meter diagnostic systems (particularly for gas flow measurement) to verify a flow meter's performance.

3.2 Integrated (or 'Internal') Diagnostics

Whereas industry still appreciates reductions in flow meter uncertainties for meter designs operating in ideal conditions, much flow meter research has been leaning towards developing and improving internal meter diagnostics. Flow meter verification is becoming as important an aspect of flow metering as the uncertainty of a meter working flawlessly.

In the last twenty years flow meter designs have had great advances in internal diagnostics. There is a slow acceptance of the inherent truths that a flow meter's stated uncertainty is only truly valid when there is a guarantee the meter is operating correctly, and the most assured and precise way to continually guarantee meter serviceability is to use a diagnostic system internal to the meter system. Strictly speaking, a flow meter's uncertainty rating is only as good as its diagnostic system's ability to verify the meter is fully serviceable. As no flow meter's diagnostic system is perfect, this obvious truth leads to a less spoken truth, the uncertainty rating of **any** flow meter is more notional than reality, it is still a faith based measurement. It is a 'best estimate' based on the engineer's judgement when accounting for the meters calibration performance, installation & process conditions, and the capability of its diagnostic system. This is the true state of the art, and the underlying driver for improvements to diagnostic suites. The better the internal diagnostic system and the better the knowledge of the process, the less uncertainty in the flow meters output.

A definition of "external meter diagnostics" is a diagnostic system that uses information external to the meter readings, such as mass balance, the associated method of check meters, or other process information. A definition of "internal meter diagnostics" is a diagnostic system that uses information obtained solely from readings that are generated from sensors internal to the metering system. An internal diagnostic system compares the resulting readings and parameters to known laws of physics[2] and / or known correct performance criteria (sometimes derived from a calibration baseline). Internal and external methods are not mutually exclusive and operators can and do combine both methods.

Internal diagnostics have been developed for various flow meters such as the ultrasonic, DP and Coriolis meters. However, these diagnostics suites tend to be relatively complicated systems. These diagnostic systems (or 'suites') are a great advance in flow metering verification, are well understood by some meter experts, but as yet they are not well understood or utilised by the majority of flow meter operating staff.

4. Challenges with Adopting Modern Flow Meter Integral Diagnostics

In order to understand the diagnostic suite of an ultrasonic, DP or Coriolis meter it is necessary to have a good grounding in the fundamental principles governing the operation of the basic meter designs. Unfortunately, flow meter designs are based on various combinations of fluid mechanics, mechanical, electronics and mathematical principles, and this can be quite

[2] Examples: 1) Ultrasonic meters can prove path serviceability by inter-comparing the speed of sound (SOS) measurements across each path because a homogenous fluid at a given thermodynamic condition has a constant speed of sound regardless of the local path flow velocity. 2) DP meters can prove DP reading integrity by equating the sum of the recovered & permanent pressure loss DPs with the traditional DP as this relationship is a consequence of the 1st law of thermodynamics.

daunting to the average operator, who is not a meter specialist and has many other duties to attend to other then checking the flow meters.

Many operators of flow meters see them as ‘black box’ devices and are content to use them without understanding the details of how the operate. Standard meters predict the flow rate via a flow computer output the operator can read, believe, and use. They do not need a detailed understanding of the internal metering system. This level of understanding hinders the adoption of the present diagnostic suites.

Many operations require (by legal contract) that flow meters are used for fiscal, custody transfer, and allocation flow metering, and hence the operating staff are obliged to have a ***basic*** working knowledge of them. But, the same is not true of the meter’s associated integral diagnostic suites.

Legal contracts tend to state that flow metering will be conducted according to some standards document (e.g. ISO, AGA, API documents etc.). If the stated standards document does not promote the use of the relevant flow meter diagnostics, then use of diagnostics to verify the flow meter will not be required by the legal contracts. As much of industry considers the use of these diagnostics complicated, and they are not being forced by legal requirements to adopt the use of such diagnostics / meter verification, then it is natural that many do not pursue their use. However, such an obviously useful and beneficial advance in technology cannot and will not fail to be adopted in the long term. Obstacles hindering the general adoption of flow meter diagnostic suites include:

- the lack of comment in the standards documents,
    - o and the associated lack of legal requirement,
- the incomplete nature of diagnostic suites,
- confusing operator / machine interfaces,
- operator lack of understanding coupled with technician resistance

4.1 Meter Diagnostics and Standards Documents

There is passing comments to the ultrasonic meter diagnostic suite in AGA 9 [1] & ISO 17089-1 [2]. However, there is no comprehensive description, nor any concise statements on the benefits, or necessity, of applying these diagnostics as part of a comprehensive meter verification process. The DP meter and Coriolis meter standards say significantly less regarding their respective various diagnostics. Therefore, in this 21st Century world, the standards, and hence the legal contracts are promoting use of 20th Century technology.

The reasons for this are varied. One reason is the fact that standards traditionally lag the state of the art (on the grounds that they are meant to discuss mature accepted technology). As yet there has been no strong drive to update relevant flow meter standards to include the now matured diagnostic methodologies. Another reason is different manufacturers use different diagnostic suites (which in reality are very similar) with different user interfaces, which makes the diagnostics more difficult for operators to understand.

Although different manufacturers do have different diagnostics and interfaces, for a given meter type (such as ultrasonic or Coriolis meters), or a given meter sub-system (such as DP transmitters), the diagnostics and user interface tend to be a variation on a common theme. This perception of difference is in part caused by the meter manufacturers aim to be seen as different and unique. They tend to want their diagnostics to be seen as different and better than their competitor for commercial reasons. However, in many cases they are close enough that a generic description in a standard document is possible. All that is really hindering such a development in the relevant standards is the political will. Such an addition to the standards would benefit the meter operators, who in the long run would then adopt the very useful tool of internal diagnostics.

4.2 The Incomplete Nature of Flow Meter Diagnostic Suites

"*Part of the problem is when we bring in a new technology we expect it to be perfect in a way that we don't expect the world that we're familiar with to be perfect.*" - Esther Dyson.

Great advances in the diagnostic suites of various flow meter designs have made in the last twenty years. Further technical developments will undoubtedly be beneficial to further persuading industry to adopt flow meter diagnostics as a verification tool. However, although flow meter diagnostic suites are very useful at telling an operator if the meter has a problem they are not "all seeing". No developer of a diagnostic suite can guarantee (or will ever guarantee) that it will see any and all problem/s, from any source, before a flow meter bias in excess of the meters stated uncertainty is exceeded.

For any given generic flow meter its internal diagnostic system does not have the same sensitivity to different problems. Different problems can induce different flow rate prediction biases before the diagnostic system can identify that a problem exists[3]. Furthermore, no diagnostic system of any flow meter type can guarantee it will see ***all*** potential problems.

The fact that diagnostic systems are inherently imperfect has been cited as one reason they are not adopted. But this is a weak argument. Such an argument is practically saying, "… if it cannot tell me ***everything*** I'd rather know ***nothing***." Ignorance is bliss. Such an argument cannot stand for long when discussing commercially sensitive metering applications.

4.3 Desired Improvements in Meter Diagnostic Suites and Their Operator / Machine Interface

"*It takes a lot of hard work to make something simple, to truly understand the underlying challenges and come up with elegant solutions.*" – Steve Jobs

A significant problem with industry adopting internal flow meter diagnostics has been that the advance in flow meter diagnostic suites has not generally been matched with advances in the machine / operator interface, nor operator training[4]. It is unreasonable to assume that the average operator has advanced knowledge of a flow meter operation principle and its associated diagnostics suite. Hence, just as many flow meter operators wish to simply receive a flow rate prediction from his "black box" flow meter, he would also appreciate a ***simple*** diagnostic output. Complex diagnostics screens may contain very valuable information, but it's of little practical use if the average operator does not understand what it means. Presently, diagnostic suites make the flow meter far 'smarter' but also far more difficult to understand and use.

Let us consider an "ease of use vs. smartness" graph (as used by the late Steve Jobs of Apple to discuss smart phones). Figure 3 shows the industry perception of where standard traditional flow meters are. Not so smart but easy to use. It also shows the industry perception of where present flow meters with diagnostics are. Quite smart, but difficult to use. The long term goal

[3] Can a diagnostic suite guarantee the flow rate prediction to within "x%"? Unfortunately, the answer (as opposed to a salesman's answer) is ***always*** **no**. There are philosophical arguments that suggest it is a panacea that is impossible to reach. Improving diagnostics can approach this ideal asymptotically but will never actually reach that ability.

[4] It does go both ways. Whereas the meter manufacturer could simplify the diagnostic output to make it easier for the end user to understand, there is some onus on the end users to put in some effort to improve their understanding by actively training on how to read the diagnostic output.

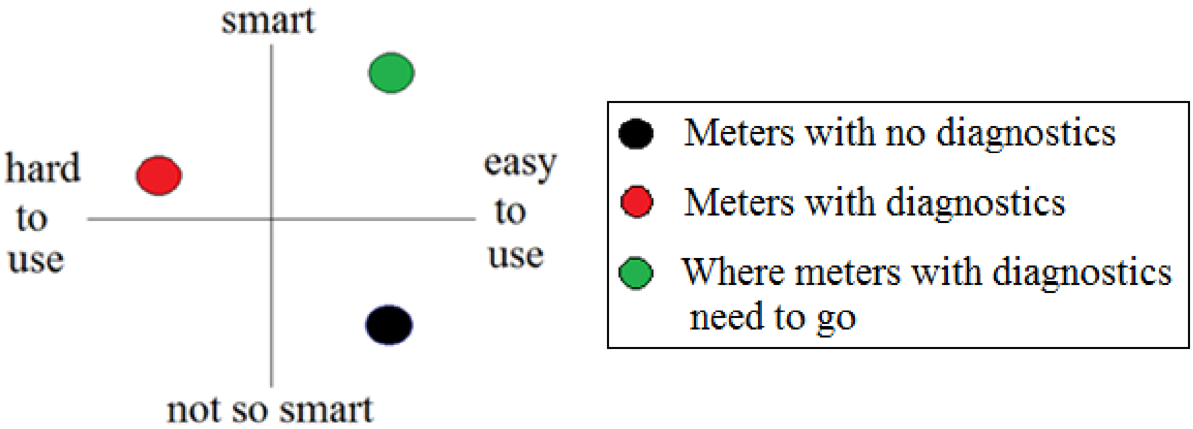

Fig 3. Perceived Meter Diagnostics Usefulness vs. Ease of Use

of industry must be to make flow meters with diagnostics very smart and easy to use. This will only be achieved by both meter manufacturers improving their diagnostic suite, improving the operator interface (to make it more user friendly), and by training of the operating staff.

The authors have noted that some meter manufacturers presently think that their diagnostic interface is just fine, and the onus is on the end users to learn the meaning of their diagnostic display. After many years of practice and familiarity, some are so used to their diagnostic display that its meaning is obvious to them. They cannot see a need for a simpler representation of the diagnostics. They attempt to educate the users on what the complex display means. However, this is effectively asking the non-specialist end user to become a specialist. The client is being told to put the effort in to work with their system, rather than they put the effort in to work with the client's needs. In reality, the essential long term requirement of industry is to significantly simplify the diagnostic output display. This of course is easier said than done. It is difficult to simplify a complex system, and this is why it is still a major issue. Regardless of difficulty, such is the obvious benefit to industry, and such is the marketability of user friendly diagnostics, that it is inevitable that this will be achieved to a certain degree in the long run. The question then, is when, not if these developments will take place.

Figure 3 indicates that the authors consider it necessary that there is not only an improvement in the ease of use of diagnostics but an increase in the diagnostic capability. Presently, many flow meter diagnostic suites can indicate that there is a problem, but few make any serious effort to tell the operator what that problem is. This is partially as the meter manufacturers are seldom pushed to do so, and partially as the state of the art of diagnostic suites makes this a very difficult challenge. Nevertheless, various diagnostic suites allow the operator the ability to eliminate certain common problems while short listing other common problems. Hence, the present state of the art potentially allows some diagnostic suites to make at least limited predictions on the likely causes of a problem. Few however do.

4.4 Psychological Resistance

4.4.1 Technician Resistance – Fear of Change (Resulting in Redundancy)

Technicians providing flow meter maintenance are a mandatory requirement for any reputable hydrocarbon company. As such, senior technicians in hydrocarbon production and transmission companies can become the companies flow metering specialists. Any new metering development is often passed by these company experts for their opinion. However, these metering technicians can perceive diagnostics as a potential threat to their and their teams livelihood. It is not always in their personal interest to highlight the great benefits, they can perceive a flow computer with diagnostics as a “technician in a box”. That is, technology coming to make them redundant. It is only natural that there is resistance.

Many operators have too few flow meter technicians for too large a number of meters, spread over too far an area. Typically most of these meters have no diagnostics, or if they have diagnostics they are not monitored as they are not fully understood. As such the technician can be blind to many problems and is rather inefficient as he carries out routine scheduled maintenance on meter after meter that did not need maintenance[5], while other meters with unseen problems are untouched. The use of diagnostics would allow this technician to carry out the philosophy “… if it ain’t broke don’t fix it”, while continually going to the meters that do need work. That is, diagnostics allow the technician to carry out a Condition Based Maintenance (“CBM”) scheme. CBM schemes are far more efficient, making the technicians efforts far more valuable to his employer. CBM also reduces unnecessary staff exposure to high pressure hydrocarbon systems. If there is proof that a meter does not need maintenance then there is no need to break containment. Yet, by human nature technicians tend to be nervous of the introduction of diagnostics, as it is change. Perhaps they are correct, a portion of them may in the long run be no longer required. But this is the nature of progress, in the end a good idea cannot be stopped, only delayed.

4.4.2. What You Don’t Know Won’t Hurt You / Plausible Deniability

The vast majority of meter operator staff / technicians naturally want to do a good job, be part of a good team, and want the meters to operate correctly. They take pride and satisfaction from their work. But, naturally they also want a quite life and to defend their job function. Their management too want a quite life. Nobody likes problems. Management like to hear that all is well. Successful mass balance check across plants, agreement between buyer and seller metering stations, no metering alarms etc., all lead to a happy management and harmony among the team. Ignorance is bliss. **But**, if you have comprehensive flow meter diagnostic suites, they just might find a problem, a problem you otherwise would have been ignorant of. To know of a problem, is to give the technician the conundrum of what to do about it?

The product being flow metered is not the property of the meter operator staff / technicians. Not at least in a financial sense. The meter operator staff typically get paid regardless of their employers profit levels. If the operator is losing money by giving product away due to an under-reading meter, or accidentally over charging due to an over-reading meter, it doesn’t directly financially affect the metering staff. If a flow meter diagnostic system shows a problem they otherwise wouldn’t have noticed, the diagnostic system has ***created a dilemma*** they would otherwise not have had to deal with. Now, thanks to the diagnostic suite, if they admit such a problem they get the satisfaction of doing their job properly and honourably, but potentially give themselves the pressure of fixing it (while perhaps being unfairly blamed by a demanding management). If they do not admit such a problem they know they are not doing their job properly and honourably, but they avoid the pressure of fixing it (and perhaps being unfairly blamed). However, if they can avoid using flow meter diagnostics in the first place then “ignorance is bliss”, and they may never face this dilemma. This is a rather cynical

[5] Routine scheduled maintenance can cause as many problems as it solves. For example, an orifice meter may operating correctly before scheduled maintenance and after the maintenance the technician leaves it with a problem, e.g. a plate re-installed backwards, a not completely re-sealed equalization valve on the 5 way manifold etc.

observation, but it's also human nature, and therefore undoubtedly a real issue. So, here again, some technicians responsible for flow meters have natural reasons for not wanting diagnostic systems. Still, many technicians want flow meter diagnostics regardless of these problems. Many promote the use of diagnostics to senior management, but find some of their senior management obstructive.

4.4.3 Resistance from Some Senior Management

"*New ideas pass through three periods: 1) It can't be done. 2) It probably can be done, but it's not worth doing. 3) I knew it was a good idea all along!* " – Arthur C. Clarke

Most operator management who are in charge of, or advise on, flow meter issues served their time over several decades as instrument technicians or engineers. They are well versed, and opinionated, on how flow metering should be conducted. However, along with the valuable experience age brings, it also brings a greater resistance to change, and a tendency to not follow or understand new technology as well as the younger generation who are brought up with it. With flow meter diagnostics being one of the latest, most significant and complex changes in flow meter technology for many years, it is only natural that many (although not all) senior engineers with the authority to drive flow meter diagnostic use have not been proactive in doing so.

There is an exception to this. Ultrasonic meters have been extensively marketed for the last two decades. The ultrasonic meter diagnostic suite was one of several claimed benefits. Many middle managers of the time 'hanged their hat' on the new ultrasonic meter technology, and these managers are now senior managers. Nevertheless, it is curious that even though they still promote these claimed benefits, few actively drive the use of ultrasonic meter diagnostics in practice. For other meter designs, such as Coriolis and DP meters, the proponents of diagnostics amongst senior instrument / flow meter engineers is significantly less, probably as fewer have any personal 'buy in' to those technologies, and not all fully understand them. Nevertheless, for hydrocarbon industry flow metering practice to evolve to include the benefits of diagnostics it is necessary that the senior managers of the major operators support diagnostic suite use with generic meters. This will be achieved in the long run, by some senior managers realising their benefit, but also by the natural process described by Max Planck:

"*A new scientific truth does not triumph by convincing it's opponents and making them see the light, but rather it's opponents eventually die, and a new generation grows up that is familiar with it.*"

The hydrocarbon industry has been long used to operating without flow meter diagnostics. The contracts (and standards) do not tend to demand the use of diagnostics. Adding meter diagnostics may add capital cost, i.e. in the case where the diagnostics are supplied external to the basic meter, such as proving or check meters, or a stand-alone optional diagnostics system procured separately to the basic meter. Diagnostics will add operating costs in the form of staff training and time. Hence, some managers can resist due to the perceived increase to the project budget.

In an effort to reduce in-house engineering staff costs many operators now out-source large engineering projects (such as refineries, platforms, metering stations etc.). This makes the budget issue more acute. By senior management policy operators do not get involved in detailed engineering design decisions of these large projects. That is left to the bidding engineering house contractors. However, such is the competitive nature between these engineering houses, that for fear of losing a contract on price, they will not add any equipment beyond the basic requirements of the “cookie cutter” specifications specifically requested by the clients. Hence, the operators tend to trust the engineering houses judgement, but the engineering house doesn’t use any judgement regarding extra equipment (such as meter diagnostic considerations) for fear of over bidding and losing the job. Therefore, metering diagnostics equipment like provers, check metering (including ultrasonic meter Z configurations), or diagnostic systems not automatically supplied with a flow meter are often not considered. The operator and the engineering house may both individually think the addition sensible, but due to the political set up of the relationship neither party has the authority to add the diagnostics. They both claim it’s the other party’s responsibility. Inclusion in the standards and therefore contracts would induce operators to specify the relevant flow meter diagnostic systems in the system specification and therefore help alleviate this issue.

4.5 The Problems of Selling Insurance Policies

Fundamentally a flow meter diagnostic system is an insurance policy. A diagnostic suite is not required for the flow meter to be fully functional. Industry has long been using flow meters with no diagnostics. If there is no flow metering problem, the meter operates without diagnostics just as well as it does with diagnostics. Hence, you do not need diagnostics to meter a flow rate correctly. You just require diagnostics to give a significantly greater level of certainty to the flow rate prediction uncertainty, and to tell you of the occasion when a meter malfunctions.

The decision to buy into a flow meter diagnostic methodology is inherently a decision to buy flow meter malfunction insurance. To the neutral 3rd party observer such insurance is obviously beneficial. It can (and will) reduce the uncertainty in the operators product (and therefore money) flow. That is, it will reduce exposure to potential large financial losses if a meter under-reads, or perhaps law suites when the operator has over-charged due to an over-reading. Nevertheless, selling the concept of insurance to a conservative industry that often operates on inertia and habit can be difficult.

The application of flow meter diagnostics may take a paradigm shift in the long established way that some operators think about their needs. Mis-measurement of fiscal, custody transfer and allocation flows has always periodically occurred, long before comprehensive flow meter diagnostics were available. Hence, industry has long accepted the inefficiency of finding a flow metering bias, not knowing when the bias developed, and therefore compromising on a mis-measurement / reallocation agreement between the affected parties. All parties are exposed to the uncertainty of a resulting profit or loss. So entrained and routine is this process in some organisations, that they have become blinded to the fact that this is now becoming an obsolete methodology of conducting their affairs, a legal artefact from an early period in technology when there was no alternative.

While inspecting a large high pressure high flow custody transfer meter, one of the authors enquired about use of diagnostics. The response was: “Why would we need to bother with that? We check the meter every few months. If there is a problem I just write a mis-measurement report, they re-allocate funds, and everything is fine.” The facts that:

- they may not know the amount of bias induced by the problem found,
- they don’t usually know when the problem appeared between checks,
- they may not notice a problem without diagnostics even with standard checks,
- and hence they don’t know the financial cost of such a mis-measurement,

seemed lost on them. As was the fact that with diagnostics they would know immediately when a problem appeared, and could have fixed it then, before exposure to measurement uncertainty was an issue. Again, exposure to such mis-measurement usually does not directly affect the individual meter technician's personal finances. They get paid regardless, as long as they follow the antiquated standard procedures. If the industry is to be brought into the 21st Century, if the industry is to adopt flow meter diagnostics due the obvious advantages they offer, a paradigm shift is required.

5. Examples of the Present State of the Art of Flow Meter Diagnostic Technologies

Flow meter diagnostics can only be considered as mature enough for general use and inclusion in standards if they are generally accepted as potentially useful in most metering applications. Various diagnostic methodologies for ultrasonic and DP meters at least have been about for many years and can certainly be considered mature.

In this section the authors show a few sample examples from the positive feedback from certain parts of the industry. (It is difficult to find any negative feedback from any source from a technical perspective.) It is assumed that the reader has a basic understanding of flow meter diagnostics. Detailed descriptions of ultrasonic and DP meter diagnostics can be found throughout the industry literature. Sample documents for further reading are Lansing [3 & 4] for ultrasonic meter diagnostics, Skelton [5] and Rabone [6] for DP meter diagnostics, and Wehr [7, 8] for DP transmitter diagnostics. This is a very small sample. There are many more detailed meter diagnostic documents by multiple authors and organizations that can be found by rudimentary literature search.

Flow prediction biases tend to be induced by two distinct root causes. One is a meter system malfunction problem (e.g. a malfunctioning sub-system such as an ultrasonic transducer or DP transmitter, or wrong geometry or calibration information supplied to the flow computer). The other is a flow condition induced problem on a correctly operating metering system (e.g. disturbed flow, contamination, two-phase flow etc.) However, in some cases the flow condition issue can in turn induce a meter system malfunction (e.g. erosion, contamination build up, partially blocked flow conditioner, blocked pressure ports etc.) The state of the art of flow meter diagnostics can typically identify when the meter has a problem. For a given flow meter diagnostic system it sometimes can identify (or 'short list') what that problem is, and sometimes it cannot identify the possible source of the problem. This issue is one of the R&D aims of meter manufacturers. Nevertheless, a generic alarm stating the meter has a problem and is therefore probably misreading is still very valuable. The examples below are a mixture of these three general cases.

Each generic flow meter type has its own unique diagnostic suite based on the physical principles of that meter type. It is therefore not possible, or relevant, to try and compare different meters diagnostic systems. For example, an ultrasonic meter diagnostic suite can see small changes in velocity profile, while a Venturi DP meter diagnostic suite cannot. However, ISO 5167-5 indicates that a cone meter flow rate prediction is rather resistant to this problem, whereas ISO 17089-1 indicates ultrasonic meter flow rate prediction is very sensitive to the problem. So it can hardly be claimed that an ultrasonic meter's diagnostic capability to see small flow disturbances that effect it significantly is any real advantage over the cone meter's inability to see this issue that does not significantly affect it. In general, different flow meter types diagnostic systems cannot be directly compared.

Most flow meter's diagnostic suite can have the diagnostic checks broken into two categories, i.e. 'absolute' and 'relative' diagnostic checks. An absolute diagnostic check consists of comparing a known baseline to a meter result. This known baseline may be set by a physical law, or by a fixed calibration result. A relative diagnostic check consists of trending a parameter, i.e. checking the performance of a specific parameter over time, a 'then' and now' comparison. Examples of absolute diagnostic checks are the ultrasonic meter Speed of Sound (SOS) measurement compared to an external equation of state SOS prediction check, and the DP meter DP reading integrity check. Both compare the results to known physical laws. Examples of relative diagnostics is the ultrasonic meter trending of gain, signal to noise ratio, path performance etc., and the similar diagnostics of the trending of a DP meter's DP reading standard deviations. Absolute diagnostic checks tend to be more powerful than relative diagnostic checks, as they are less subjective, but trending diagnostics are still very useful. Most flow meter diagnostic suites combine both. In these examples both types are shown.

5.1. A Proving Example – Wax Deposits on a Turbine Meter

Proving on site is a diagnostic that has been available for around 50 years. It shows change in meter performance, i.e. if there is a shift due either an installation effect, or a change in flow conditions with time then a proving will demonstrate this not just only qualitatively but also quantitatively. Furthermore, proving is effectively a periodic re-calibration of the meter within a resolution that is acceptable at present for custody transfer metering levels. A good proving system should be able to determine the new calibration to within 0.06-0.1%.

A prover system further acts as a very competent diagnostic for meters such as turbine meters, where it is known that such a meter should repeat during proving to within a given value, usually set in practical terms to a spread of 0.05% in 5 runs for a fixed set of flow conditions. If a turbine meter does not meet this criterion, then it is known that either the meter has mechanical issues, the flow conditions are bad or have changed, or the prover has a problem. This combined with a control chart is an excellent method of providing a "quantitative diagnostic".

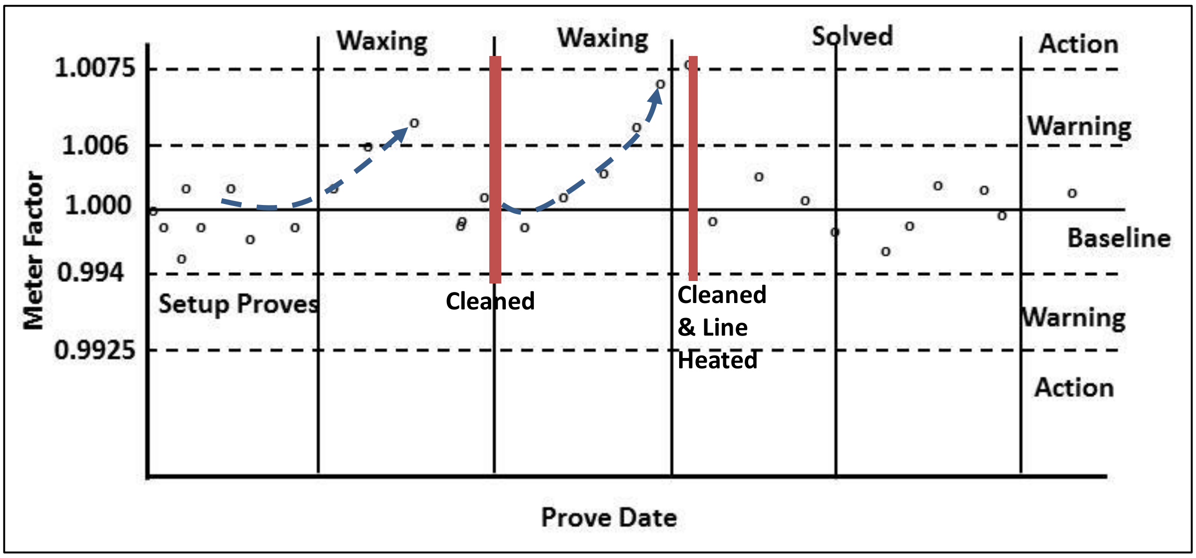

Fig 4. Control Chart for a Turbine Affected by Wax Build-up

Figure 4, shows an example of a turbine meter measuring where the meter has a buildup of wax. In this example, the problem is inherently a flow condition problem (i.e. it contains wax) but this problem then causes the meter to mechanically have a problem (as the wax deposits on the meter). The proving shows the meter calibration change as a quantitative value, while giving the operator a warning that the meter is experiencing a significant issue. The prover is a good diagnostic system for identifying something is wrong. However, like most diagnostics it does not state what the source of the problem is. It takes process knowledge, and / or manual intervention, to identify the problem (in this case wax deposits).

Although the prover is a good diagnostic system for liquid flow metering it does have drawbacks. Prover systems are only available for liquid applications. Provers are expensive, requiring good operational maintenance and skilled staff to operate. It is not a practical proposition to run provers continuously, and therefore proving is a "spot check" where the operator is still blind in-between the periodic proves. When a prove shows a problem has induced a meter performance shift since the last prove (with a subsequent mis-measurement), the operator does not know when that problem appeared and at what rate it developed. The mis-measurement has to be solved retrospectively, and usually with some guess work and approximations, never a satisfactory situation for a high value product sales meter.

A significant modern issue is the lack of prover compatibility with the modern Coriolis and ultrasonic liquid flow meters. By the physical principles of how they operate both these meter types have inferior repeatability compared to turbine meters. Poor repeatability between proves is a good diagnostic for liquid turbine meters. However, poor repeatability is not a good diagnostic for liquid Coriolis and ultrasonic meters. The repeatability of these meters can vary widely and unlike turbine meters repeatability is not a true diagnostic of performance. In practical terms this results in two issues:

- The prover requires a large number of proves, making the mechanical parts, such as the four way valve, work harder per prove with consequent maintenance issues.
- Keeping the repeat proves at constant flow conditions is difficult to achieve on site.

A further issue is several turbine meters can be replaced by one larger ultrasonic meter. Compared to the prover size required to test one smaller turbine meter at a time, proving a single larger meter requires a larger prover with the associated larger cost and footprint[6]. Proving therefore becomes a practical issue, and in finding some way to resolve this, internal flow meter diagnostics have come to the forefront. Thus operators hope that the internal meter diagnostics can identify any metering issue as it arises, so as they can decide whether maintenance or recalibration is required.

5b. <u>An Ultrasonic Meter Integral Diagnostic Example – Gas Trapped in Transducer Pocket</u>

A liquid test facility calibrated an ultrasonic meter. The ultrasonic meter's diagnostic output was recorded during the calibration. The meter was calibrated at a high flow rate first, and then the flow was reduced. A distinct step in meter factor was found between the high flow rate and lower flow rates. When the flow rate was subsequently increased again to the high flow rate, the meter factor remained similar to that found for the lower flow rates. That is, there was a shift in the high flow rate meter factor between the two high flow calibration results. Figure 5 shows these results. Note the step calibration change between the original high flow rate and lower flow rate results. What caused the initial higher meter factor during the initial high flow rate test?

[6] There are always pros and cons to any engineering system. The increase in prover size required to prove large ultrasonic meters is a disadvantage of using a single large ultrasonic meter instead of a bank of smaller turbine meters. Ultrasonic meter marketers have responded by claiming ultrasonic meters do not need proved like turbine or PD meters as they have no moving parts. However, such claims are tantamount to claiming an ultrasonic meter will never malfunction for any reason. This is obviously not true, ultrasonic meters are adversely affected by pipe fouling, flow disturbances, flow conditions out with the calibration range etc., and hence they too benefit from periodic proving.

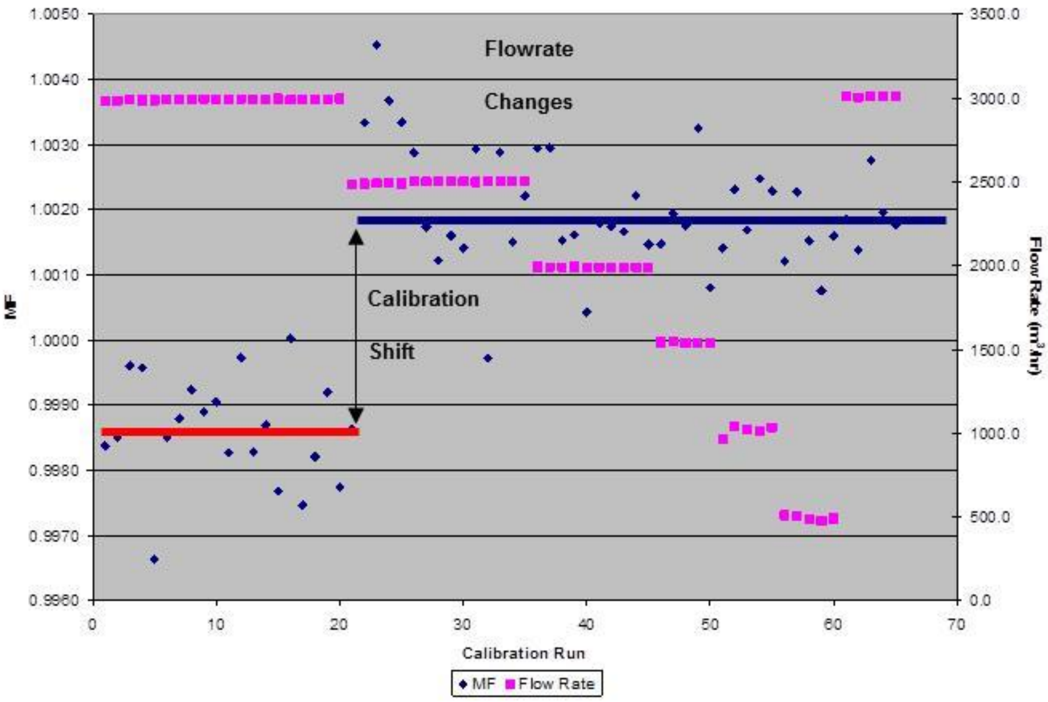

Fig 1. Change in an Ultrasonic Meter Calibration Meter Factor

The ultrasonic meter diagnostic suite has various diagnostic checks. Different diagnostic checks are more sensitive to specific problems than others. That is, the diagnostic check within the over-all suite that is most sensitive to any specific problem depends on the specific problem. In this case study, let us consider the Signal to Noise Ratio (SNR), gain (the drive voltage to give an acceptable signal strength), and the individual path velocities. Diagnostic results of interest are:

- at the time of meter factor change there was a significant change in the SNR, Gain and path velocity data,
- the top path in particular exhibited a significant difference to the other paths - **a warning from the outset that the meter had a possible issue**,
- the top path SNR was low, showing a poor signal level compared to the noise,
- the top path transducer gain was very high, showing that the meter was trying to push up the signal level to compensate,
- the velocity of the top path was different to its equivalent path.

The meter diagnostics were clearly showing that the top path was experiencing an issue at the start of the calibration. The diagnostic warnings disappeared at lower flows, suggesting the problem was only temporary. Process knowledge (external to the meter diagnostics) allows us to surmise that air could be trapped in the liquid flow. Therefore, a likely reason for such a diagnostic response is that air, which will gather at the top of the pipe, may have become trapped in an upper paths transducer port. The flow rate changes are likely to have flushed the gas free, and hence the problem soon disappeared.

There can be a tendency amongst diagnostic proponents (and ultrasonic meter salesmen) to claim in such situations that the ultrasonic meter self-diagnosed that there was air tapped in the transducer port. However, such claims exaggerate the ability of flow meter diagnostics. In truth, the ultrasonic meter only self-diagnosed that the top chord had a temporary problem. It was the skill of the operator, coupled with both the process knowledge and ultrasonic meter diagnostics suite output that allowed the operator to come to the conclusion of what the specific problem was. Nevertheless, the ultrasonic meter diagnostic warning that *something* was wrong (and that it was a problem specifically with the top path) was the catalyst for the problem being found a solved.

This is another example of the problem being inherently a flow condition problem (i.e. gas entrained in the liquid) but this problem then causing the meter to mechanically have a problem (i.e. gas trapped in the transducer port causing the transducer a problem due to the significant difference in gas and liquid acoustic impedance).

5c. An Ultrasonic Meter Integral Diagnostic Example – Flow Profile Issues

An operator was periodically proving a 4 path liquid ultrasonic meter. After several years of successful quarterly proving the prove indicated a significant shift in meter performance. The meter factor shift was approximately 0.8%. The operator immediately surmised that there was a fault with the flow meter.

Figure 6 shows a sketch of the meter installation, flow passes through two bends approximately 15 diameters upstream if the meter. To mitigate the bends a 19 tube, tube bundle was mounted upstream, 10 diameters between the tube bundle inlet and meter inlet, similar to the installation recommended by API 5.8. In this installation there was no access to log the meters internal diagnostics, it could only be done by taking a laptop to the meter, and downloading a snapshot. That is, the operator did not monitor the flow meter's internal diagnostics.

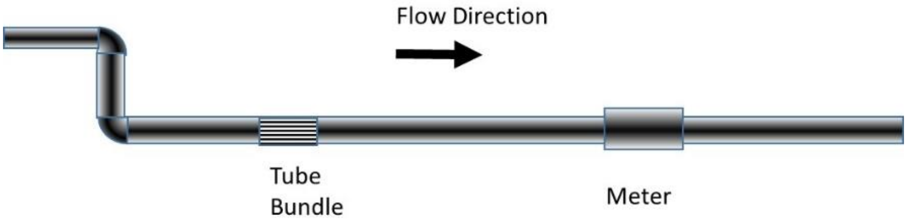

Fig 6. USM Installation

The auditors first course of action was to review the prover data. The prover was calibrated with turbine meters by an external US proving company with a generally good record. The water draw data appeared in order. The turbine master meter calibrations and history were acceptable. The temperature and pressure calibration certificates were up to date. The records showed that they had checked the critical valves. The prove appeared correct, not totally confirmed, but a very high probability. Suspicion turned to the ultrasonic meter.

Due to the unspecified problem identified by the prover, and the assumption that the ultrasonic meter must have malfunctioned, the ultrasonic meter's internal diagnostics were reviewed. Fortunately, the ultrasonic meter had had a diagnostic baseline recorded during its commissioning. The present results could therefore be compared to this diagnostic baseline. The majority of the diagnostic checks had not shifted from this baseline significantly. The SNR, gain & SOS checks had no significant change. The 'turbulence' diagnostic showed a marginal shift. However, the diagnostic check sensitive to this problem was the flow profile.

Figures 7a & 7b shows the difference between the commissioned profile and the profile during the investigation. At commissioning the profile appears symmetrical (as it should), but during the investigation the profile was asymmetric. Therefore, the ultrasonic meter's diagnostic result showed that there had been a shift in the meters velocity profile. That is, the

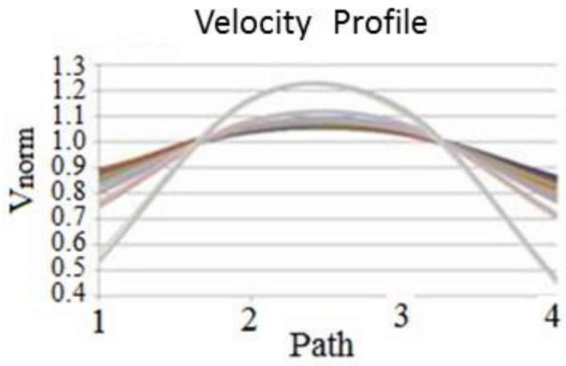

Fig 7a Commissioned Profile

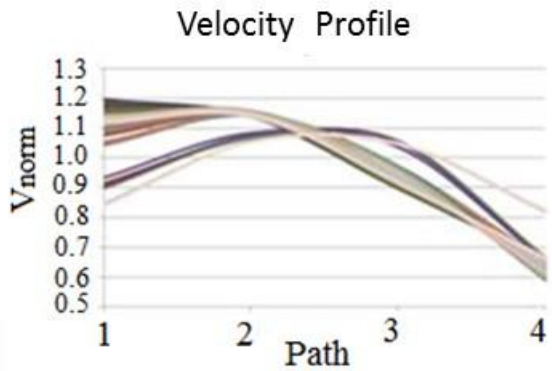

Fig 7b Profile after Tube Bundle Lost

ultrasonic meter diagnostics specifically identified that the meter is receiving a disturbed flow profile. This typically means the ultrasonic meter mis-measures the flow, although it is not possible to derive from the meter diagnostics the induced flow rate bias.

By combining the ultrasonic meter diagnostic output with knowledge of the process, the first prediction of the trained flow meter auditor was that the tube bundle was partially blocked. That would create a disturbed flow and account for the meter's diagnostic response. The meter operators were not trained in understanding the ultrasonic meter diagnostics and had to trust the auditor. In winter conditions the line was dismantled to inspect the tube bundle. The auditor was only partially correct. Yes, the ultrasonic meter diagnostics were correct in indicating there was a flow disturbance, but it was not due to a partially blocked tube bundle, it was due to the tube bundle being absent. The tube bundle had become detached and had passed through the meter and been caught by a downstream bend. So what does this simple example teach us?

a. Proving on a quarterly basis only catches a major event at the time of the prove, and that the error can be in place for an indeterminate time between the proves.

b. If the flow meter diagnostics had been continually monitored (by software which can send an alarm to operator staff trained in the diagnostic system) a large and significant event such as a tube bundle disappearing downstream, would certainly have been immediately noticed.

c. The diagnostic alarm could not confirm the precise cause of the problem, but significantly it would have correctly identified that a problem may exist and the meter needs to be immediately re-proved.

d. After such a re-prove (i.e. recalibration), it would be possible to back calculate from the before and after meter performance the flow rate prediction bias induced by the adverse event.

e. For flow meter diagnostics to be of any use the staff operating the meter need to understand their meaning. In this case the operating staff did not understand the ultrasonic meter diagnostics and hence it is probable even if diagnostic results were recorded the staff would not have realized there was a problem.

The main reasons cited by the operator for not utilizing the ultrasonic meter diagnostic suite was that they believed the prover would be good enough to see any problems, nobody on staff understood the ultrasonic diagnostics, and their use was not demanded in the contract or local regulatory requirements. Both the contract and regulatory requirements followed the recommendations of standards.

5d. An Orifice Meter Integral Diagnostic Example – Contamination

Orifice meters have been used widely throughout industry for a century. As with liquid flow meter proving, it has long been known there should be site checks for gas orifice meters, particularly for custody transfer applications. An early form of orifice meter diagnosis was the creation of the orifice plate fitting which allowed the plate to be periodically removed and inspected. Instrumentation could be periodically re-calibrated. These processes gave a good indication of the meter performance. However, as with liquid provers, such techniques are "spot checks" that leave the operator blind to problems that occur between such checks. Again, what was needed were internal meter diagnostics that could continually monitor the orifice meter. Such techniques now exist. DP transmitters (a vital sub-system of DP meters) now have internal diagnostics that monitor their health. More recently a DP meter diagnostic system based on pressure field monitoring has been developed. This case study uses the orifice meter pressure field monitoring diagnostics (and was previously presented at the North Sea Flow Measurement workshop by Rabone [6] in 2012)

Fig 8. Orifice Meter Run

Fig 9. Plate Inspection - Contamination.

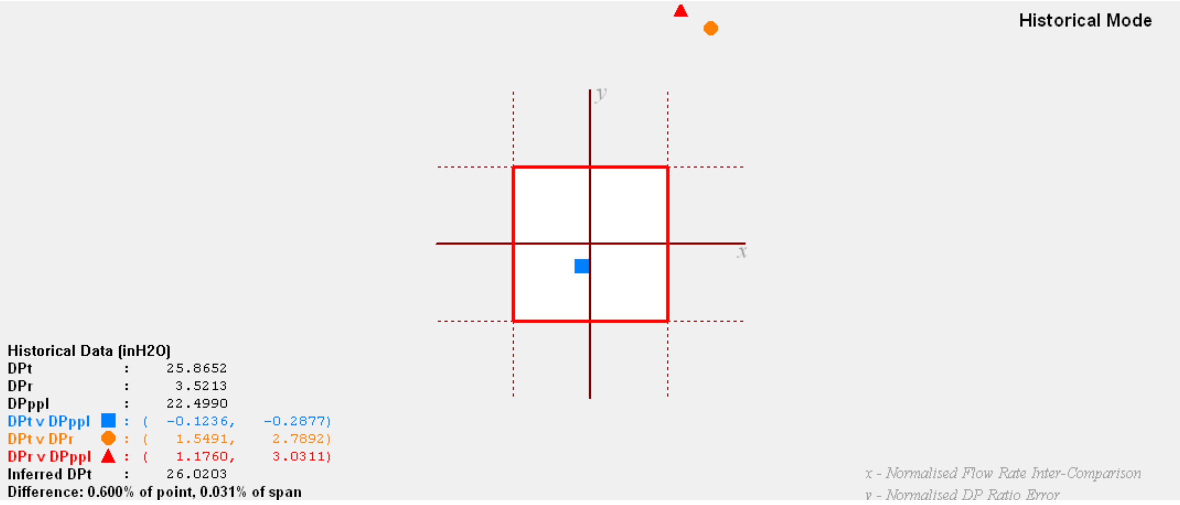

Fig 10. Orifice Meter Diagnostic Display Screenshot.

A 6" orifice meter was audited. The DP meter pressure field monitoring diagnostic system 'Prognosis' was installed as the initial part of the audit. Figure 8 shows the meter run prior to the installation of the diagnostic system. Figure 10 shows a screenshot from the diagnostic display. The diagnostic result immediately showed that the meter had a problem (i.e. note the two points outside the box in Figure 10). Like the ultrasonic meter diagnostic suite, this DP meter diagnostic suite cannot always tell the operator what the specific problem is, but from the diagnostic output pattern coupled with operator process knowledge the problem can be identified. The particular diagnostic pattern was indicative of a few potential problems. This short list included possible contamination of the meter run. It was known from process knowledge that contamination was a possibility. The meter was subsequently inspected. Figure 9 shows a photograph of the plate. The plate was contaminated. A subsequent borescope investigation of the meter run showed meter run contamination.

Contamination causes all flow meters to mis-measure the flow. The operator was unaware that the meter flow rate output was in error prior to the installation of the diagnostic system and the subsequent audit. If the operator had used such a diagnostic system from the outset, and been trained to understand the diagnostic display, they would not have been blind to the developing problem and would have known to intervene long before the problem was accidentally found by a scheduled audit.

This is another example of the problem being inherently a flow condition problem (i.e. contaminate in the flow) but this problem then causing the meter to mechanically have a problem (i.e. contamination build up in the meter).

5e. An Orifice Meter Integral Diagnostic Example – DP Reading Error

Three 12" orifice meters are used to meter gas being supplied to a power station (see Rabone [9]). The operator installed the pressure field monitoring diagnostic system "Prognosis". On commission of the meters (with the diagnostic system) two of the three orifice meter diagnostic systems gave no diagnostic alarm. That is, for these two meters the seven DP meter diagnostic checks found no issues. The results are represented in the diagnostic display as seven co-ordinates (giving four points) on a graph. If the points are inside a box there is no alarm. The meters with no problem showed a diagnostic result like that shown in Figure 11. However, one of the three meters showed the diagnostic result reproduced in Figure 12. One of the diagnostic checks is indicating a meter problem.

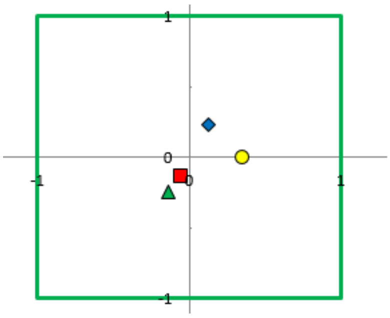

Fig 11. Normal Operation Result.

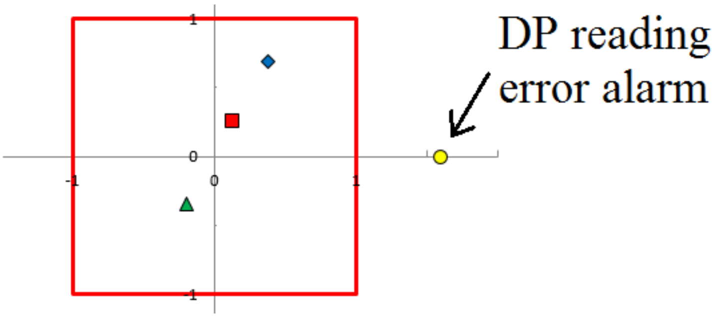

Fig 12. Abnormal Operation Diagnostic Result.

This DP meter diagnostic pattern shown in Figure 12 specifically indicates that one of the DP readings is erroneous. The operator checked the DP transmitters and stated that they looked okay. The DP transmitter internal diagnostics showed no problem. However, the diagnostics DP integrity check is an absolute diagnostic check, based on the 1st law of thermodynamics. Hence, a DP reading was wrong, regardless of the initial maintenance check suggesting otherwise. The operator understood this, and on second review found a minor scaling issue in the flow computer that was causing an incorrect conversion of the DP signal. The primary DP reading used to measure the flow rate was being over-predicted by +1.6%. The associated flow rate prediction bias was +0.8%.

This case study is an example of where the problem was not induced by flow conditions but by the metering equipment. In this case the diagnostics were very close to identifying the precise problem and no process knowledge was required.

This example shows that internal meter diagnostic suites are sometimes more useful than due diligence, spot checks, or check metering by external systems. For example, if this orifice meter had an ultrasonic meter in series as a check meter the problem may still not have been seen. API 14.3 estimates the typical uncertainty of an orifice meter at about 0.7%. ISO 17089-1 states the typical uncertainty of a custody transfer ultrasonic meter as 0.7%. So the root mean sum of these meters uncertainties is approximately 1%. That is, these meters in series could only indicate a metering problem when the discrepancy between them is > 1%. The discrepancy here was 'only' +0.8%, below the threshold of many check metering systems, but high enough to cause significant financial mis-measurement.

Even after maintenance the initial response of the competent maintenance crew carrying out standard instrument checks was to say the DP readings were okay. It took their trust in the meter internal diagnostic system to make them look again, closer. Only due to their trust in the meter's internal diagnostic system did they save themselves from mis-measuring the flow.

5f A Venturi Meter Diagnostic Example – Showing the Calibration Report to be Wrong

An 8", 0.4 beta Venturi meter (Fig 13), was calibrated with natural gas flow. The calibration included setting the baseline of the pressure field monitoring diagnostic system. After multiple witnesses had confirmed the calibration was correct and complete, the standard Cd vs. Re calibration report was written and released. No comments or issues were raised by *any* party on the integrity of the calibration report.

Fig 13. 8", 0.4 Beta Ratio Venturi meter Under Calibration

At a later diagnostic system FAT, the diagnostic system software was checked by entering the meter geometry, calibration diagnostic parameters, and sample data from the calibration report. As the diagnostic system had been calibrated to this very data the diagnostic system should by default show no problem. However**,** the diagnostic system signaled a malfunction. Figure 14 shows the resulting diagnostic plot.

There is a short list of possible malfunctions that cause such a Venturi meter pressure field monitoring diagnostic pattern. The first on the list was incorrect geometry, either too small an inlet diameter or too large a throat diameter. The geometry in the calibration report was therefore compared to the actual meter geometry from the manufacturer. The true 8", 0.4 beta Venturi meter throat diameter was found to be 73.**0**2mm. The meter had been calibrated with the correct geometry. However, the calibration report erroneous stated the throat diameter of 73.**6**2mm. The diagnostic system had subsequently been given the wrong geometry read from the report. *The flow computer for this meter in service would most likely have been given the wrong geometry from the same report*. The effect on the meter flow rate prediction would have been to over-read the flow. The Venturi meter internal diagnostic system saw the problem before mis-measurement occurred. Conversely, standard practice of due diligence by

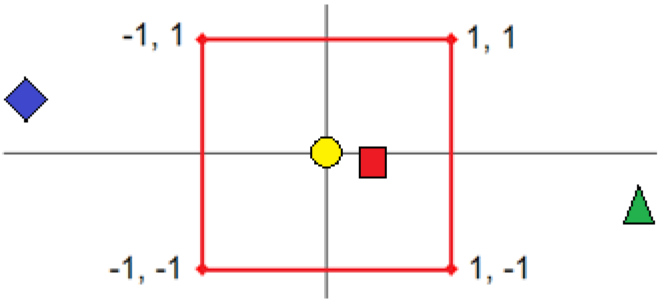

Fig 14. Diagnostic Result During Factory Acceptance Test of Diagnostic System

multiple experienced competent witnesses checking the report failed to see the problem. Without diagnostics the problem may have *permanently* would have gone unnoticed. Further details of this example are discussed by Rabone [6].

This case study is an example of where the problem was not induced by flow conditions but by the metering equipment (and more precisely human error). In this case the diagnostics were very close to identifying the precise problem and no process knowledge was required. This example shows that internal meter diagnostic suites are sometimes more useful than due diligence. No matter how diligent operators are they are human and mistakes can creep through. Automated checks from diagnostic systems do not make such errors.

5g A Coriolis Meter Diagnostic Example – Gas in the Liquid Flow

Coriolis meters have an established diagnostic suite. The Coriolis meter manufacturers talk of in-situ verification by using the Coriolis meter internal meter checks (i.e. diagnostic suit).

For liquid flow particularly, the Coriolis meter's density output can be monitored for fluctuations and compared to the expected liquid density. As the liquid density is usually know by the operator to a high degree of certainty, and the Coriolis meter liquid density measurement has a low uncertainty, any significant difference between the values suggests a problem exists[7]. (This is another example of how many diagnostics rely on operator process knowledge.)

The measured stiffness of Coriolis meter vibrating tubes in operation can be compared to the original factory baseline value. Changes in stiffness can represent corrosion, erosion, or deformation of the tubes.

Another main Coriolis meter diagnostic check is that of monitoring the drive gain. Drive Gain is a measure of the amount of power the transmitter requires to keep the tubes resonating. Drive gain is stated as a percentage of the total power available to the transmitter. For given fluid properties, it takes a set amount of power to keep the tubes resonating. If the fluid consistency is constant, and the flow is constant, the drive gain should be constant. Changes in fluid density and / or two-phase flow cause shifts in drive gain. Therefore, drive gain can be used to monitor fluid consistency. Shifts in drive gain can indicate qualitative shifts in fluid properties. However, fluid properties are not the only factor that influences drive gain. Drive gain is also affected by the physical condition of the vibrating tubes. If these tubes are damaged or changed (e.g. by erosion, corrosion, overpressure, hydraulic shock,

[7] Liquid Coriolis meters give low uncertainty flow density measurement. However, as moderate to low pressure gas flow has such a small density compared to liquid densities, the gas Coriolis meter density measurement has a much higher uncertainty. This, coupled with the fact that the independent gas density measurement uncertainty is also higher than an independently measured liquid density uncertainty, means that this diagnostics is very useful with liquid flow but less useful with gas flow.

contamination deposit etc.) the drive gain required will shift. Most damage or changes to the vibrating tubes is non-symmetrical in nature, and this can make resonance very difficult to attain, resulting in an unstable (or possible saturated) drive gain.

A Coriolis meter drive gain value is application dependent. Stable flow conditions produce a stable drive gain. If the drive gain has significant fluctuations, say 10% or more, the measurement might be still be acceptable, but the meter uncertainty may higher than the specified uncertainty rating. A higher drive gain indicates more energy required to overcome higher damping of the vibrating tubes. Gas entrained in liquid flow is one adverse operating condition (amongst others) that induces higher tube damping.

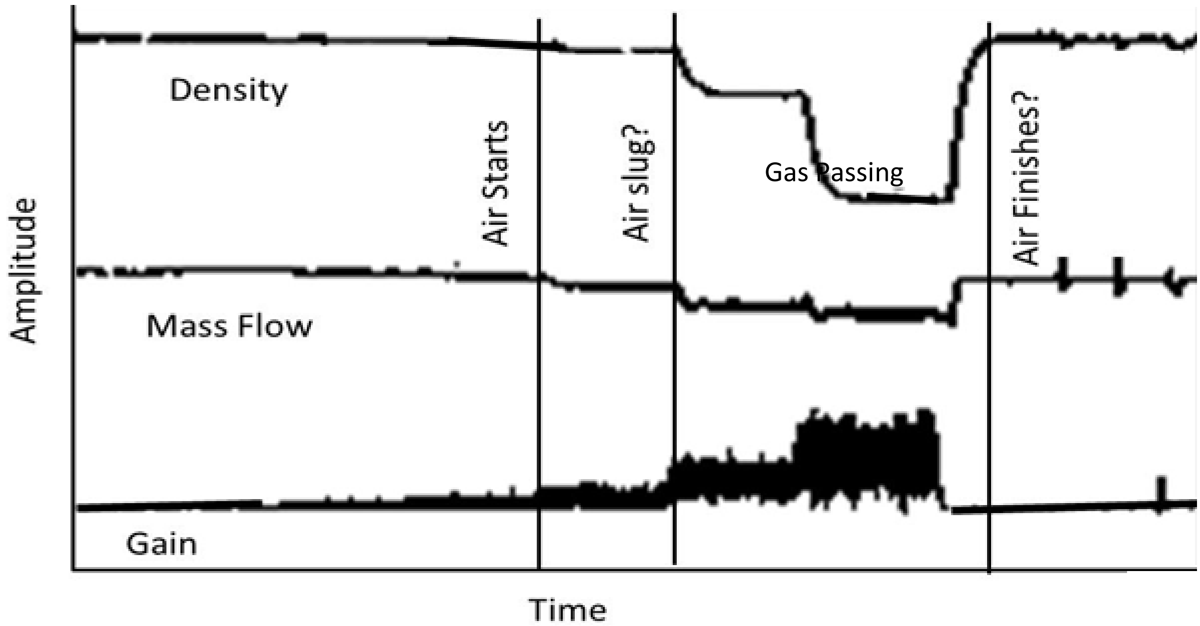

Fig 15. Coriolis Diagnostic Showing Gas in the Liquid Flow

Figure 15 shows sample trending data from a liquid Coriolis meter. The primary meter outputs of mass flow rate and density measurement are shown along with the drive gain, all plotted against time. The initial conditions are steady. The initial conditions give a density measurement that can be compared to process knowledge, i.e. an external density measurement, and shown to be correct, giving confidence in the meters operation and mass flow prediction. The drive gain is stable (i.e. has a small standard deviation) and low, as expected. Then trending shows all three outputs to significantly change together. It is suspected that this particular combination of diagnostic results indicates the liquid flow becoming a two-phase flow. The mass flow rate and density predictions begin to drop as the drive gain magnitude and standard deviation significantly increases. Then these effects magnify. This is suspected to be a two-phase flow, i.e. gas passing. The density measurement and mass flow rate prediction drop as would be expected with gas in a liquid flow, although these meter cannot be expected to be the average actual flow values! Then, the meter outputs return to their original values, indicative of the gas having passed, and the flow being single phase liquid flow again.

The transient nature of the response (shown by trending) indicates that the issue is likely a flow condition issue as mechanical problems do not tend to fix themselves. Although ‘absolute’ diagnostic checks are generally more powerful than relative / trending diagnostics (as they are less subjective), this example shows that relative / trending diagnostics have an important contribution to make to diagnostic suites. As the trending allows mechanical problems to be considered unlikely the result strongly suggests two-phase flow.

The precise effect of two-phase flow on any Coriolis meter is design, fluid property and flow condition dependent. Drive gain is a good qualitative indicator that something has changed. However, Coriolis meter drive gain is influenced in complex interactive ways by various considerations and therefore it cannot offer any detail quantitative information.

This case study is an example of where the problem was induced by flow conditions and not the metering equipment. The flow conditions did not damage the meter in any way.

6. Existing Authoritative Flow Meter Documentation - Comments on Flow Meter Diagnostics

There are limited comments in the authoritative literature promoting the use of flow meter diagnostics. However, it is interesting to note that although these documents support the use of meter diagnostics they tend to stop some way short of demanding their use, while they demand adherence to other good meter practice. As we will see below (in quotes from sample text) the organization and committees that wrote these authoritative documents clearly understand that the use of internal flow meter diagnostic systems are as important as adhering to good standard meter practice if mis-measurement is to be avoided. However, these documents (which at least address diagnostics – many authoritative documents don't) only promote diagnostic use with words like 'should' and 'can', while other good practice is described with language like 'shall' and 'must'. In the following examples the bold underlined italics are added by these authors to highlight the optional aspect of the suggestions.

DECC "Guidance Notes for Petroleum Measurement, Issue 8", released in 2012

For DP meters in section 6.7.7 DECC states:

> "The use of diagnostic systems based on the use of an additional measurement of the fully-recovered pressure is gradually becoming well established. Experience has shown that this technique enables the Operator to detect significant deviations from normal operating conditions as they arise. It ***may*** therefore form the basis of a condition-based maintenance strategy, as described in Chapter 4 of these Guidelines; DECC has already agreed to the adoption of such a strategy at a major UK terminal. Operators of new developments are ***strongly encouraged*** to consider the adoption of such a strategy. The provision of an extra pressure tapping costs relatively little at the design and manufacturing stages, but ***may*** permit significant operational savings to be made during the life of the field."

For ultrasonic meters (called "USFMs") in section 6.8.12 DECC states:

> "…condition-based maintenance (CBM) of gas USFMs ***may*** be the most appropriate strategy in many instances."

Therefore diagnostic use is optional, while other good practice is not. DECC explain that by 2012 they had agreed to a condition based maintenance strategy on one orifice meter station and one ultrasonic meter station based on these meters respective internal meter diagnostics.

The Alberta Energy Regulator's Directive 17, "Measurement Requirements for Oil & Gas Operations", released 2015

In section 2.5.2 (on gas meter internal inspection) Canada's Directive 17 states an exception (#9) to the demanded routine scheduled maintenance / re-calibration period for a gas meter:

> "Internal metering diagnostics ***may*** be used to determine if the structural integrity of the primary measurement element is within acceptable operating parameters and checked at the same required intervals as an internal inspection. Then internal inspection is not required until an alarm or error is generated by the device or as recommended by the manufacturer."

In section 2.6 (on liquid meters) Directive 17 repeats this statement. In section 12.3 (on production measurement) Directive 17 states:

> "Verification ***can*** be achieved using…. internal diagnostics of the measurement device if present to check the structural integrity of the primary measurement element"

Again, diagnostic use is optional while other good practice is not.

ISO 17089-1 "Measurement of Fluid Flow in Closed Conduits – Ultrasonic Meters for Gas – Part 1: Meters for Custody Transfer and Allocation Measurement", 1st Edition.

This ISO standard discusses the use of the meter's diagnostics in considerably more detail than most flow meter standards. However, again it is curious to note how much the authors clearly understand the importance of the internal meter diagnostics and yet hold back from demanding their use. The language surrounding the diagnostic system is promotional, whereas the language discussing operation of the primary meter system itself is authoritative. The text repeatedly alludes to the fact that if the operator is to achieve the minimum flow rate prediction uncertainty technically achievable he needs to use the meter's internal diagnostics. But the text does not take that leap to state this fact outright. Sample text from ISO 17089:

In the scope:

> "This part of ISO 17089 specifies requirements and recommendations for ultrasonic gas flowmeters (USMs)…"

That is, in the scope, the scene is set where aspects of use of the ultrasonic meter will be ***requirements*** of the standard, i.e. ***instructions*** to the operator, and other aspects of use of the ultrasonic meter are only ***recommendations***, i.e. suggestions as a good idea. The operators are free to ignore those recommendations and still claim the meter installation is compliant with this standard. It is notable that virtually all comments on the universally accepted ultrasonic meter diagnostics system are all firmly in the recommendation camp, where they are free to be ignored. For example:

In the Introduction:

> "USMs ***can*** deliver extended diagnostic information through which it ***may*** be possible to demonstrate the functionality of an USM." And,
>
> "Due to the extended diagnostic capabilities, this part of ISO 17089 ***advocates the addition and use of*** automated diagnostics instead of labour-intensive quality checks."

In Section 7.4.1:

> "… the theoretical speed of sound (TSOS) ***can*** be compared with the measured value *[MSOS]*. The SOS is an excellent tool..."

In Section 7.4.1.1:

> "If both MSOS and TSOS are available, they ***may*** be compared …"

In Section 7.4.1.1:

> "Although the SOS is one of the most important parameters to be used in verification, there are many more parameters which ***may*** be monitored in order to ensure optimum performance…"

Again, diagnostic use is optional while other good practice is not. This standards document is one of the best available standards for promoting and discussing the benefits internal flow meter diagnostics. However, even here, virtually nowhere does this ISO text demand the use of these diagnostics. Some the wording is deliberately weak. Even if use of the meter diagnostics are not to be demanded, wordage like "can" and "may" is significantly weaker than, "should" and "it is highly recommended".

Why is this? After years of research, development and field experience are the subject specialists who write flow meter standards really still unsure if such internal meter diagnostics can demonstrate flow meter functionality!? That is what such text infers. However, these authors think not. There is now abundant evidence over many years, from multiple manufacturers, laboratory and field results from multiple independent parties (including users), to show that flow meter internal diagnostics have come of age. The authors of the standards are the same individuals that independently publish results for their respective companies showing flow meter internal diagnostics to be invaluable.

Perhaps this is a legacy issue, with diagnostic suites tending to be newer attributes to the original meter designs. The standards committees (even those working on current draft standards) are notoriously conservative and still baulk at demanding adherence to even the most established meter diagnostics. No flow meter standards committee working on any flow meter technology as yet has stepped up and made the not so bold step of stating what is now surely self-evident. That is, flow meter diagnostics have come of age and now should be an integral part of flow meter best practice. There is no real technical argument against using modern flow meter internal diagnostics. So surely it is time standards said as much?

Flow meter diagnostics can now be made integral to the meters such that future generations will automatically see them as integrated vital parts of the core meter system. Today, there is still a lingering historic perception that somehow these diagnostic systems are superfluous, not essential to guarantee the correct operation of the meter, but it is fast becoming a false perception. Technology has moved on, and such an obviously beneficial advance cannot, and will not be ignored indefinitely. Sooner rather then later, these diagnostic systems will become engrained in the operators mind as essential to professional flow meter operation conduct, and they will be automatically used. The sooner the flow meter standards board grasp this reality and make authoritarian demands about the use of diagnostics the quicker this change in mind set and practice will occur, to the benefit of all industry.

7. Comments

Under ideal (calibration) flow conditions many modern flow meter types have low uncertainty, and their internal diagnostic systems are capable of seeing many common problems before significant flow rate prediction errors occur. As long as the operator applies the meter's internal diagnostics flow metering has never been so assured. Time and time again internal flow meter diagnostics have repeatedly proven themselves invaluable. They are vital to gain maximum assurance of low uncertainty flow metering. However, the majority of industry still does not understand or use these internal meter diagnostics. Industry still tends to run the majority of flow meters "blind".

Various common flow meter designs now have good diagnostic capabilities that are very capable at identifying when the meter has malfunctioned. They often cannot state what the problem is, or the size of the flow prediction bias. However, the diagnostic output of many meters is now good enough that when the pattern of the diagnostic suite output is cross referenced with process knowledge a competent operator can often deduce the specific flow condition or meter problem. (Without the diagnostics a competent operator is often effectively blind, even with good process knowledge, and often cannot even deduce the meter is in error.)

The authors have not discussed in the paper some further advantages of the use of diagnostics that are worthy of mention. The active use and collection of diagnostic data allows an auditor to be able to review the historical performance of metering systems, giving a greater degree of confidence in the operation. Further, the active use of diagnostics helps streamline the maintenance and efficient operation of metering, which generally contributes towards the correct operation, and sustainability of a good uncertainty of measurement.

These diagnostic advances represent a significant improvement in flow meter technology over the last two decades. However, many operator staff do not understand the physical principles of these various flow meter internal diagnostic suites, and they do not understanding the need, or the implications of using these diagnostics. There is a lack of expertise in interpreting these diagnostics. Even when some do understand the physical principles, it can still be difficult to understand the various complex ways in which the different manufacturers present their diagnostic results. These factors all contribute to the poor uptake of diagnostic use. All these issues are consequences of the core issue: the lack of standardization.

Without standardization there is no political pressure for operators to even use flow meter diagnostics, never mind for these issues to be resolved. With standardization, use of internal meter diagnostics will become included in contracts and fiscal regulators will then enforce their use. This in turn will drive the permeation of flow meter internal diagnostics into the main stream of industrial flow metering to the long term benefit of industry and society.

Flow meter internal diagnostics are one of the most guaranteed ways of knowing when a meter has malfunctioned. (Some traditional external diagnostic methods have significant limitations.) Internal diagnostic systems of various meters (and sub-systems of meters) are now mature, and their inclusion in the relevant standards is due. There are two types of comment in industry standards, requirements and recommendations. To comply with a standard an operator must follow the requirements, but is not obliged to follow the recommendations. Therefore, although it is preferable for diagnostics to be recommended in a standard rather than for them to be not discussed at all, for full impact it is preferable that internal flow meter diagnostics should be stated as a requirement in standards. Then their subsequent inclusion in contracts will slowly dismantle the present remaining political obstacles.

Inclusion in standards, and therefore contracts, would inevitably result in a significant increase in use. This in turn would offer meter manufacturers commercial incentive to put more resources into further developing flow meter diagnostics. It would also produce more scrutiny of the various meter manufacturer’s diagnostic claims and in turn control their claims. This increase in use would focus the industry into developing better, clearer, simpler more intuitive user friendly ways of displaying diagnostic outputs. Such a development would inherently make flow meter diagnostics more accessible and understandable to more meter operators. Standardization of flow meter internal diagnostics and their displays would also facilitate an increase in formal meter operator training which in turn would further increase their use.

The authors can only think of a couple of minor potential disadvantages. The first is that as a diagnostic system is inherently imperfect, of course there will be occasions where it could give a false alarm (i.e. "cry wolf"). This is inevitable. However, these cases would be relatively few, especially if the operator is initially pragmatic about choosing the sensitivity settings of the diagnostic output until he has experience with the system. The second is the perceived cost of change. Diagnostic systems can add cost to a metering system in some cases via capital cost, and in most cases due to the required training and duties of the operators to monitor these diagnostics. However, these capital and training costs are typically a modest investment, in the hydrocarbon industry they are small relative to the potential savings by avoiding mis-measurement. Furthermore, nobody would expect an operator to continually monitor a diagnostic system. Modern diagnostic systems run in the background unmonitored until the operator chooses to periodically look, or they are alerted of a problem by the diagnostic system. Therefore, these few claimed disadvantages are more false perception than reality.

Such is the benefit that modern flow meter diagnostics bring to industry that it is obviously only a matter of time (although a rather long time) before they are universally adopted. In the long run operators will come to wonder how they managed without them. The sooner their use permeates throughout industry the better for industry. A catalyst to accelerating their use is their inclusion in the industry standards as required practice. This development would help the conservative hydrocarbon industry depart from its habit of using 20th Century metering methods and bring its metering methods into the 21st Century.

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