Further Developments In The Design & Implementation Of An Advanced Online Condition Based Monitoring System & A Dirty Meter Prediction Model For Custody Transfer Ultrasonic Gas Flow Meters

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1.0 Introduction - Dirty Meter

1.1 What is a dirty meter

After installation a calibrated ultrasonic flow measurement meter may begin to experience minute changes in measurement accuracy due to accumulation and deposition of foreign material in the meter tube, meter runs and piping. Even in pipeline quality gas, foreign materials may still be present. These are often carried over from processing, compression, or formed due to chemical and biological reactions between the natural gas, its constituents and the gas transport system. Any measurement device in the natural gas stream begins to be coated from the moment of installation until the moment it is taken out of service. The nature and character of the coatings continues to be a vast field of study. It should be understood that the coating material, thickness and apparent roughness does not need to remain constant over the service period of the flow meter nor of a consistent composition. It is also postulated that a dirty meter may or may not be fouled symmetrically thus adding to the over all complexity and understanding of this phenomenon.

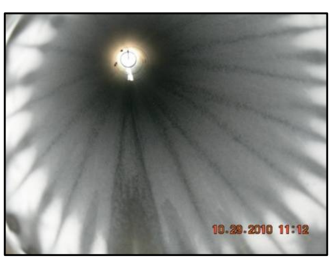


Fig. 1
Jet stream of contamination

Fig. 2
Circumferential Buildup

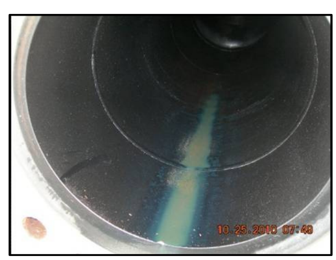


Fig. 3
Residual Bottom contamination

1.2 Why does a dirty meter occur

The nature and extent of fouling materials in pipeline quality gas are many and varied. At this juncture all of the mechanisms that cause foreign matter to form in the natural gas transmission piping system are not known. However, some types of residual fouling such as compressor oil, glycol and odorant residue can be carried over from processing activity. Alternatively, Corrosion/erosion and crystallization formation may occur due to reactions between the gases themselves and the transportation system.

The physical properties of the foreign material may also be very different in appearance & consistency. Extremes ranging from fine, dry powder, that leave a light dusting on the pipe wall, to grease and paste like substances that adhere to themselves have all been encountered in the past.

Therefore, the origin of the gas, the processing techniques, the operating regimes and the materials of construction can all contribute to existence of fouling in the system. For that reason, 'Understanding one's process' is a must as we embark on the prediction process of flow meter error shift in dirty applications.

1.3 Present day techniques of detecting a dirty meter

From inception, ultrasonic transit time flow meters have almost always had on board diagnostics in one form or another. As technology moved from analog to digital, the amount of diagnostics increased in volume, accessibility and complexity. As the meter continued to evolve, algorithms began to be developed that not only looked at the trends of singular diagnostics but rather combinations of diagnostics in sequences. All in pursuit of one goal, to better understand the behavior and performance of the flow meter over time.

Initially, diagnostic monitoring required the connection of a personal computer to the flow meter to capture live instantaneous data on a 'spot check' basis. Connecting periodically to verify performance began to build confidence in what was a relatively new technology, operating in a somewhat conservative industry. As the value of spot checks became better understood, it often evolved into a more rigorous routine such as monthly verifications. This is not surprising given the revenue that was passing through the meter; Confidence in the measurement was imperative.

With more data to obtain and process, often from meters in remote locations, applications began using modems and remote communication in order to obtain the diagnostics. Data logging was also internalized into some of the flow meter electronics such that they could either be collected at a convenient time elected by the end user or accessed & retrieved remotely. Improved internal network connectivity has enabled the natural gas industry to begin developing continuous monitoring systems that are not hindered by memory limitations, and that ultimately analyze the flow meter in real time. These continuous monitoring systems not only look at changes in basic diagnostics and trends over time, but also have the intelligence to compare trends and instantaneous data to milestone events. Some of the active comparisons look at 'current' data and compare it with 'original manufactured characteristics' (often referred to as the meter fingerprint), while others look at characteristics of the calibration facility and compare them against those in the field. These types of comparisons give the continuous based monitoring system a number of references to work with and to evaluate the significance of any diagnostic parameter shift.

From an end user perspective, any significant change in diagnostic values may indicate that there has been a change in either the metering equipment itself, the environment in which it has been operated, or the operating regime itself. As a result, any such change may or may not have an impact on the overall measurement accuracy. The ultimate goal is to derive a method, be it formula, calculations, algorithm and/or equipment, to not only detect this change quickly & precisely, but to also quantify the effect on the flow meter measurement accuracy.

In addition to the developments above, positive steps have also been made utilizing predictive modeling techniques. These models typically rely upon historical measurements and observations from a particular metering station or meter run to predict future performance or behavior.

Although this level of sophistication is desired, and advances have indeed been made on both counts, at this moment in time no known manufacturer or end user has formulated a total solution.

Perhaps the combination of live diagnostics and predictive modeling may now enable us to take the next step toward the ultimate goal of real time error reduction under the effect of dirty meter conditions.

1.4 Diagnostics

Some of the common diagnostics shared amongst most of the ultrasonic transit time flow meters are; measured speed of sound versus theoretical calculation of the speed of sound (AGA10 check), automatic gain control of the acoustic signal, noise level, signal to noise ratio calculations, individual gas velocities as seen by each acoustic path, gas velocity ratios of individual paths to an average, average measured speed of sound relative to individual measured speed of sound to mention a few. Other derived diagnostics include the calculations of flow profile factors, asymmetry, and calculated turbulence as well as swirl angle. Many of these diagnostics have a notable yet individual response after an ultrasonic meter is installed and begins its exposure to fouling by foreign material.

2.0 Dirty meter prediction models

The rationale for developing a model for predicting flow measurement error is to allow the operator to make better informed decisions regarding service intervals or stream switching rather than simply following a ‘time’ or ‘calendar’ based regime.

Given that one can estimate the error produced by a change in a diagnostic parameter set such as profile factor & chord velocity ratios, the operator can then make a value weighted decision for maintenance or recalibration. An example of a value weighted decision would be taking action to clean a meter when the estimated meter error reaches 1% for example. By making confident estimates of meter error from logged measurement data, costly and laborious field breakdown inspections may be avoided or managed more effectively. In addition, Lost & Unaccounted for gas (LAUF) may be minimized.

2.1 A Velocity Profile Model

Several velocity profile models have been developed in the past and much has been published on the effects of pipe roughness as it pertains to the shape of a pipe velocity profile. The actual velocity profile measured by the meters may be influenced by many things; The upstream piping conditions, pipe roughness, Reynolds number for the operating condition, buildup or contamination, and if applicable, the shaping influence of a flow conditioner installed upstream of the meter to mention a few.
In 2010, Witte [1] chose to use a velocity profile equation developed by Morrison and Morrow [2] and then modified it to fit actual run data produced by a particular set of meters,

$$U = Ucl\left[\frac{y}{R}\right]^{\frac{1}{n.\alpha}}$$

where U is the velocity at a distance y from the pipe wall, Ucl is the centerline pipe velocity, R is the pipe radius, n is a power law exponent, and α is a constant used to correct n to fit the calculated baseline velocity profile to the actual logged velocity measurement data from the ultrasonic meter.

The power law exponent, n as developed by Morrison and Morrow [2] is given as,

$$n = -23.397 + \frac{1.408}{\sqrt{f}} + \frac{66.89\ln\left[Log(\mathrm{Re})\right]}{Log(\mathrm{Re})}$$

Where f is the Moody friction factor and Re is the Reynolds Number.

The power law exponent correction factor α has a value which is empirically derived from actual log data and is a function of the type of flow conditioning plate located upstream of the ultrasonic meter being evaluated.

The exponent n is also a function of pipe wall roughness as described by Morrison and Morrow[2]. Reynolds Number for the observed flowing condition is calculated from a molar analysis of the gas, pressure, temperature, pipe diameter and flowing velocity.

2.2 Mean Velocity Calculation

In previous work, two ultrasonic meter designs had been considered. Those were the Instromet reflective type and the Westinghouse chordal measurement design (which is the basis for the Daniel and Sick Maihak ultrasonic meters). For this paper the focus is exclusively on the Instromet reflective type meter as the recent enhancements to the model have been made in conjunction with the study on this type of meter installed at an El Paso facility.

The mean velocity for the Instromet meter is calculated as follows:

$$Vavg = 0.15(Vaxial) + 0.85(Vswirl)$$

Where *Vaxial* is the average axial path velocity measurement and *Vswirl* is the average swirl path velocity.

The calculated mean velocity is corrected by a final factor which may be a constant across the flow range, a different factor as a function of flowing velocity, or a factor determined as the result of a polynomial calculation which is a function of flowing velocity. The particular case that applies is determined by the version of meter being evaluated and how it is configured for the application.

The remainder of the assembly of the error calculation model requires the calculation of flow rate at the clean condition and a calculation of flow rate of the meter in the dirty condition. Flow measurement error is determined to be percent deviation of the dirty measurement from the clean measurement.

2.3 Assumptions

The following assumptions are made for the ultrasonic meter error prediction model:

- Base conditions are known, such as an initial meter tube roughness
- Flow is axi-symmetric , non swirling, steady state, Newtonian, and single phase
- Any effect of contamination of the ultrasonic meter transducers with oil, glycol, or other liquids is insignificant
- There is no pipe wall buildup in the clean meter
- If actual pipe wall roughness is not known for the baseline, an apparent roughness may be assumed to fit the calculated velocity profile to the initial log file profile
- Any assumed apparent roughness or buildup must be within a reasonable value as determined by experience (the actual boundary conditions may be assigned as more information is learned from field inspections)
- The initial baseline roughness, final factor, and value of the constant *a* as determined for the baseline case may not be changed for use in the dirty case
- Only the assumption for maximum velocity for the log file data may be changed in the clean meter flow rate calculation
- Because actual dirty condition pipe wall roughness is not known, it may be assigned from an empirical fit of the logged path velocity measurements

It is possible to have more than one solution that matches log file data. However, the calculated values must be rationalized against the facts that are known about the actual operating conditions. It is also good if there is some historical knowledge of what type of contaminant is most common for the meter installation being evaluated. Confidence in the calculation results is established by correlation of several parameters which include mean velocity and individual path velocities for both the clean and dirty condition.

2.4 Required Input

Information required from the "Clean" condition:

1) Logged data containing individual path velocities (both Axial & Swirl)
2) Logged Averaged Velocity after profile correction over same period
3) Measure of pipe wall roughness
4) Measure of pipe wall build up (predominantly zero on a clean meter!)
5) Temperature & Pressure at Flowing conditions
6) Calculated profile factor derived using values from (1) above
7) Calculated nCorrection "Alpha"
8) Measured Pipe Internal Diameter
9) USM Final Factor (if applicable)

Information required from the “Dirty” condition

1) Logged data containing individual path velocities (both Axial & Swirl)
2) Logged Averaged Velocity after profile correction over same period
3) Determination of apparent pipe wall roughness
4) Determination of apparent pipe wall build up
5) Determination of maximum centerline axial velocity under dirty conditions
6) Calculated profile factor derived using values from (1) above

Calculation of Velocity Profile and It's Change with Pipe Roughness and Buildup

Worksheet by J.N. Witte

Location:

	Clean	Dirty
Flowing Pressure, psig	843.0000	
Temperature degrees, F	81.0000	
Maximum Velocity, ft/sec	26.4200	26.7959
Average Roughness ra, microinches	85	861
Pipe Inside Diameter, inches	11.933	11.849
USM Final Factor	1.0060	
Pipe contaminant buildup, mils		42.000
n Correction		1.353

Flow Rate Error
0.76%

	Clean	Dirty
Average Velocity, ft/sec	25.6196	25.8144
Axial, ft/sec	26.4200	26.7959
Swirl, ft/sec	25.2986	25.4600
Profile Factor	1.04433	1.05247
Reynolds Number =	1.0041E+07	1.0112E+07

	Avg	1 - Axial	2 - Swirl	3 - Axial	4 - Swirl	5 - Axial	Avg Axial	Avg Swirl	PF
Clean	26.9565	27.9060	26.6635	27.9060	26.7715	27.9060	27.9060	26.7175	1.04448
Dirty	25.8121	26.8943	25.5120	26.8943	25.5952	26.8943	26.8943	25.5536	1.05247

Note: for three path meters enter axial path velocity for Paths 1, 3, & 5 enter swirl path velocities for paths 2 & 4.

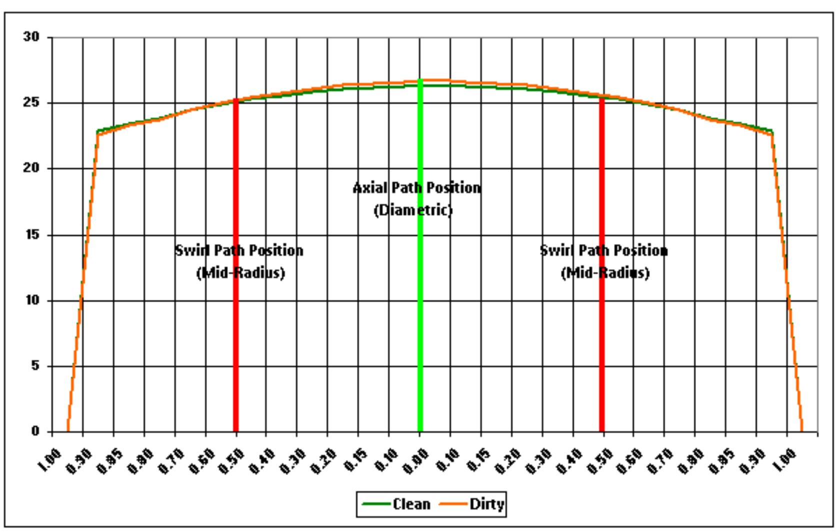


Fig. 4 – The figure above is a screen snap shot of an error calculation in an Excel Worksheet.

3.0 Driving factors for Development of a Condition Based Monitoring (CBM) system

Since the publication of AGA Report No.9 in 1998[3] multipath ultrasonic flow meters have become the dominant method used for measuring flow in large pipelines, particularly for the purpose of custody transfer of natural gas. The reasons for this surge are many – excellent accuracy, high turn-down, good resistance to installation effects, and economical when compared to multiple runs of other kinds of meters, such as orifice.

Additionally, the basic ultrasonic technology used to measure flow in these transit-time devices lends itself to extensive analysis for the purpose of understanding the performance of the meter and the environment in which it performs. One is not only able to observe the meter's behavior with time, but also characteristics of its performance on a near-instantaneous basis (pulses traverse the pipe in milliseconds) as well as a function of pipe geometry.

When compared to traditional meters that use only one or two measurements to infer flow, the multipath ultrasonic technology clearly offers a huge increase in diagnostic capability, albeit at the expense of increased device complexity.

While the meters were rich in potential, until recently the manifestation of this had not been revealed. This was possibly due to a combination of underdeveloped technology and users who were uncertain of what was being offered. However, it is now mandatory that any serious vendor who is introducing a new device brings diagnostic tools as well as flow measurement to the party.

As good as these meters can be, like all meters they can be affected by the conditions in which they are placed. In particular, the upstream pipe work conditions determine the velocity profile of the fluid as it passes through the meter. The meter's flow velocity readings, properly analyzed, can suggest whether there is a problem with the meter, or if perhaps the profile contains irregularities, for whatever reason.

Historically, due to the importance of these meters and the level of revenue passing through them, regular calibration was deemed critical. Depending on the country or nature of the agreement between trading parties, the initial calibration and subsequent recalibrations is either a legal or contractual obligation. The frequency of the recalibration is often time, calendar or volume based, and in the absence of an onsite meter proving facility often requires the removal of the meter to return it to a traceable high pressure calibration facility[4] [5].

As a result of recalibration, many end users have developed an audit trail that has highlighted the stability of the ultrasonic meter. Meters that have been in operation for many years may have been recalibrated 20, 30 40+ times, and although they demonstrate this long term stability may currently still require relatively frequent recalibration in order to comply with legal or contractual obligation.

The concept of Condition Based Monitoring in itself is not new**.** However, the application to ultrasonic metering has only been adopted relatively recently; indeed it was covered at the NSFMW 2008 by Peterson et-al[6]. The ability to monitor the health and operation of the flow meter 24/7 can enable the end used to detect any significant change either in the flow meter itself, or the process and environment in which it is operating. Any changes that are detected may or may not impact on the performance of the meter, but either way they will be detected early, enabling the operator to take appropriate action.

Additional factors behind developing a condition based monitoring system was to deliver a 24/7 monitoring and reporting capability of the flow measurement system that required minimal personnel intervention. The continuous monitoring system also aspires to identify any potential issues before they turn into critical events and force an unpredicted outage of either the ultrasonic flow meter or any of the associated secondary equipment that make up the measurement system. (Pressure, temperature of gas quality measurement devices).

Any such system would also be required to simultaneously handle a vast array of diagnostics, from multiple measurement streams, containing multiple measurement devices. These may include ultrasonic meters, turbine meters, gas chromatographs, pressure & temperature transmitters as well as other measurement technologies. Even though there have been some instances where end users configured their RTUs to collect additional information, these were not numerous and often increased the level of complexity for the customer.

During the specification stage, it was also identified that the Enhanced CBM system should also be designed so that it could incorporate advanced modeling and predictive schemes into the real time calculations. In turn this dedicated system would assist technical groups & managers who are responsible for the health & reliable operation of the metering system without cluttering the already busy data stream of SCADA.

3.1 Upfront considerations and goals

The ultimate objective of the monitoring system is to ensure that the USM diagnostics are continually monitored, and by doing so, determine if the meter is in a healthy condition. If the meter remains in a healthy condition and the diagnostics do not change, the meter is deemed to be performing well and the calibration remains valid.

If the diagnostics do change, the system will notify the operator and advise what action may need to be taken. Ideally, the system will also assist in determining the nature of the problem, and advise if it is USM related, process related, or system related, depending on what diagnostics have changed.

In addition to monitoring the health of the system the captured information will ultimately be used to also provide live information required by the predictive models

Having the above mentioned in mind, the benefits from using condition based monitoring are:

A) The operator will have an increased level of confidence in the meter.
B) The lost and unaccounted for (LAUF) gas would be reduced which in turn would reduce cost.
C) Historical diagnostic information can be used to support extended periods between calibrations to the regulatory authorities. This in turn may result in a move away from a regime of 'calendar based' off site calibration to an 'as required based' off site calibration. [7]
D) Significantly reduce / potentially eliminate service engineer site visit.
E) Improved response time to diagnose & rectify any potential meter or process issues
F) Develop a meter audit trail that supports third party audits or metrology approvals.
G) Can feed directly into preventative maintenance schedule.
H) Improves & promotes close working relationship between manufacturer & end user.
I) Enables manufacturers to offer an increased level of response should issues arise.
J) Ensures manufactures are 'In touch with reality' In terms of metering conditions in the field.
K) Provides 'real data' that can inspire product enhancements & new product development (NPD).
L) Advocates the benefits of USM's both inside and outside the industry.

3.2 Development

One of the most fundamental functions of the continuous based monitoring system is real time data collection which is then sorted and becomes historical artifacts for operational analysis. The system should provide a clear overview of the entire system and the ability to determine the current status of any one of the monitored measurement systems. The CBM system excels at collating and simplifying vast quantities of data that is captured every second from the ultrasonic flow meter & its associated secondary devices. This is subsequently processed into meaningful, unambiguous operational data that can be clearly understood.

Further more, any potential issues should be clearly visible so that it is simple to drill down and identify the reason for the warning or alarm. It is becoming almost customary in the industry to accept the “traffic light” concept for the initial graphical user interfaces (GUI) such that anything green in color denotes healthy or within operational limits. Amber is a warning stage when normal boundaries have been exceeded but have not yet reached critical levels. Lastly, red indicates that a diagnostic parameter, calculation or a status exceeded the predefined maximum allowable limits and the device is now operating outside the agreed tolerances as defined by the manufacturer or end user.
The screen below in figure 5 was designed such that it provided a clear overview of all the meters associated with plant A at the El Paso facility. The operational day is broken up in to four 6-hour periods. In addition to the 6-hour periods, current & previous day, current month and current 6 month periods have also been selected as desirable reporting periods. All data is archived for future interrogation should it be necessary.

Fig. 5 – The Overview screen for the El-Paso CBM system.

By selecting the relevant ‘traffic light’ the user is able to drill down further in to the system. The GUI begins to reveal more detailed information on a particular measurement device whilst still maintaining the specified operating periods.

The user can continue to request more detailed information until raw instantaneous or historical values are displayed.

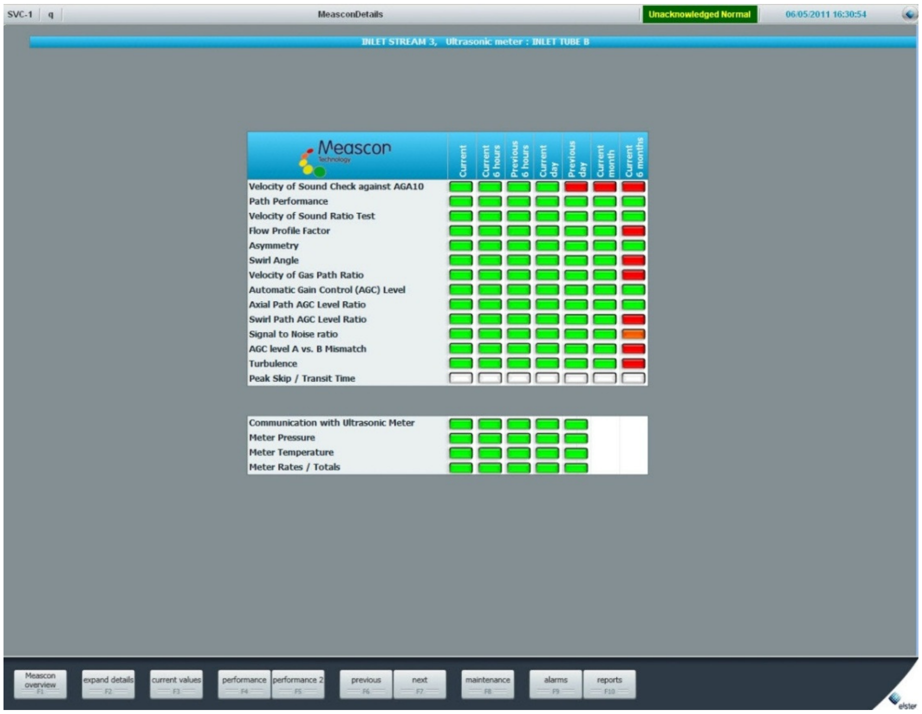


Fig. 6 – Drilling down through the system to reveal more information.

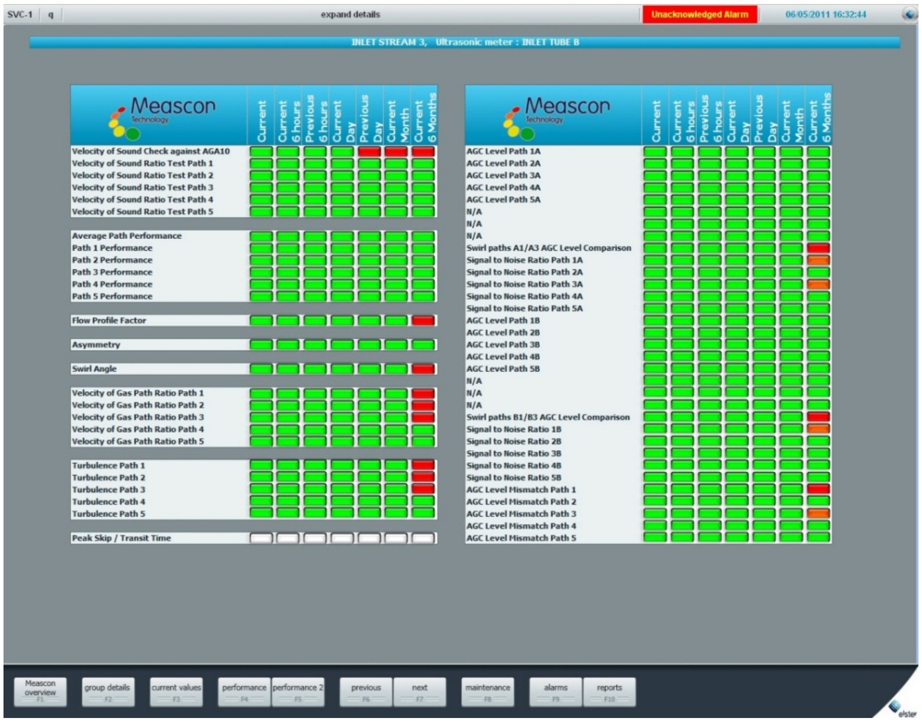


Fig. 7 – Individual diagnostics still displayed in selected time formats.

In addition to capturing & analyzing operational data, the CBM specification also identified the requirement to be able to compare any data (current or historical) against reference data. Historically, USM's in high accuracy applications have an initial factory setup which is an integral part of the production process (often called the 'dry calibration'), and a dynamic calibration against a known reference in a certified calibration facility (often called the 'wet calibration'). The combined information generated during these tests (often called baseline conditions) is extremely valuable as it acts as a starting point for the meter upon which many future comparisons can be made. These reference files begin to form the backbone of the Continuous based monitoring system. The more comparison references that are available, the better the CBM becomes at ultimate predictability.

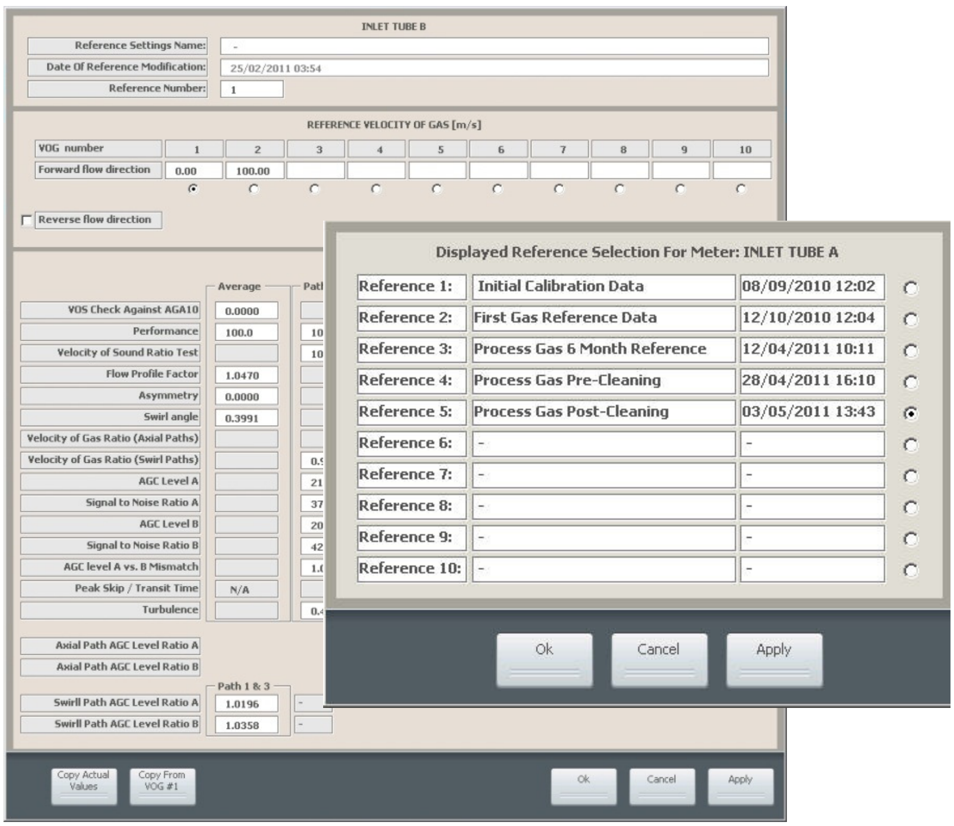


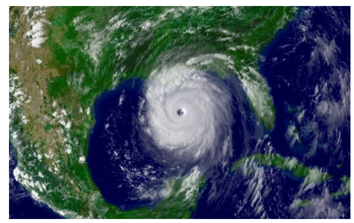
Fig. 8 – The Detailed reference input screens.

3.3 Testing

For the purposes of the El-Paso system, the CBM system was designed & manufactured as a stand alone system. Although it would be installed on a live plant for Bata testing, it could not interfere or influence the normal day to day operation of the site in any way. Therefore, it was possible to conduct a full factory acceptance test (FAT) on the system and check all the functionality of the inputs, outputs and calculations prior to it been delivered to site. Many of the warning & alarm limits had been left at default values as some of these would be site specific and could only be set once the operating regime of the site was fully known & understood. It was always envisaged that there would be a period of observation once the system had been installed & commissioned. In addition, the development of such a system is dependant on a close working relationship with both the manufacturer & operator.

4.0 The Beta Test Site

4.1 The El-Paso Metering Station



El-Paso identified a potential test & development site for the enhanced CBM in Louisiana in the southern United States. The principle function of this station is to accept natural gas from production platforms in the Gulf of Mexico, process out the heavy hydrocarbon components and then return the gas to the transmission network. The plant is organized into two process trains A and B. Following the trail of devastation left by Hurricane Katrina on August 28th, 2005, the site underwent a major overhaul.

4.2 Plant A Inlet / Outlet

Plant A consists of 4 inlet meters runs in parallel that are brought on line by a cascading run switching control method as flow demands. As the Gulf of Mexico production gas enters the plant for processing it then passes through a lean oil absorption process which removes most of the components greater than ethane. Once processed the residue gas exits the plant via 4 outlet meters. All 8 meters are 12 inch ANSI 600, Q.Sonic-3 type USM’s. The meter runs are engineered with inspection Tees at either end of the meter run section. An anti-swirl element is placed at the exit of the inlet inspection Tee, followed by an AGA configuration of 10 diameters of honed meter run with a pipe roughness of about 85 micro inch. El-Paso has selected a Gallagher type flow conditioning plate that is also installed as per AGA recommendations. This is then followed by another 10 diameters honed inlet section. The gas flow then passes through the ultrasonic flow meter and out into a 10 diameter discharge section with taps for temperature. The final element in the meter run is the final inspection Tee.

Fig. 9
The Outlet Meter Run

Fig. 10
The Anti-swirl element

Fig. 11
The Gallagher Plate

The purpose of the meter station is to determine the total plant shrinkage which requires precise measurement of the gas. In order to ensure the best possible accuracy, a master meter is installed and applied monthly in transfer proof of each run meter. Each inlet and residue station is proven by one master meter.

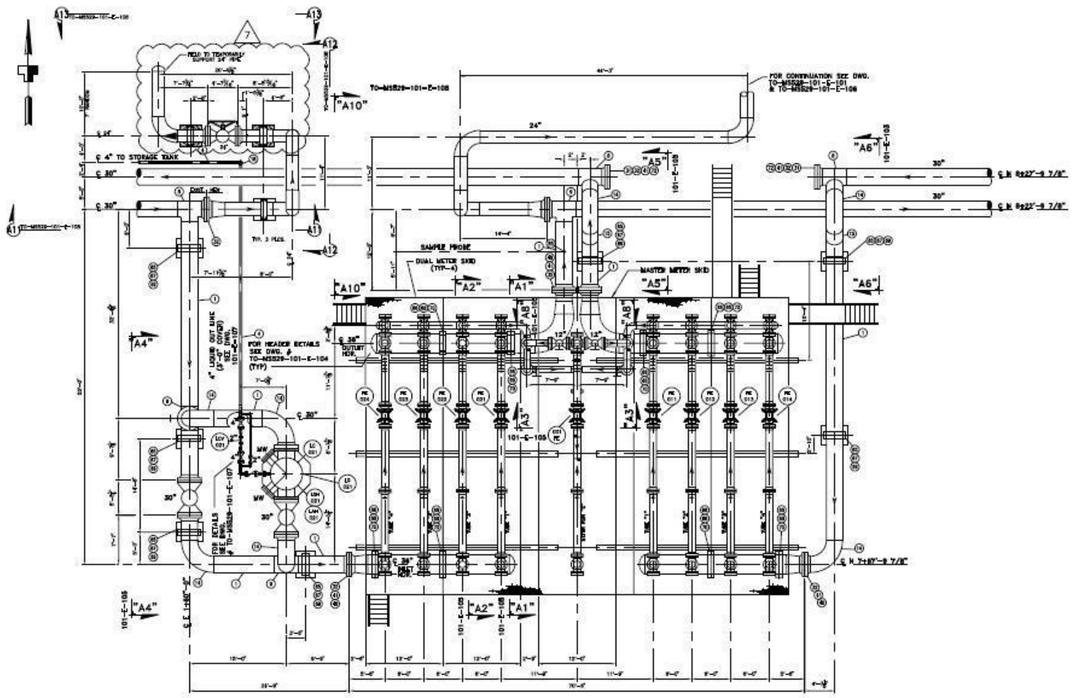


Fig. 12 Plant 'A' Outline

4.3 The Master Meter

A unique design feature of the El Paso facility is a permanently installed master meter on the inlets & outlets of each plant train. As the incoming Gulf of Mexico gas is not yet of "pipe line gas quality", this station sees differing degrees of foreign material that frequently foul the measurement sections. The level of contamination is significantly more than would normally be associated with typical pipeline gas applications. Operation and observations of this station have proven that as the flow meters become contaminated it can have a direct impact on the accuracy of the measurement. Rather than annually removing all the meter runs and calibrating them at great effort and expense, a master meter was installed with appropriate valve automation to allow a proof of an individual meter against the master. The master meter is only exposed to gas during the verification period, all other times the master meter is blocked in. The master meter is

the only meter that is calibrated annually on a time based schedule at an accredited calibration facility. Due to the level of contamination and the potential shift in the observed flow measurement the inlet and outlet meters are verified against the master every month +/- one week.

4.4 The Proof Process

Every month a technician responsible for the station performs a proof of all meters against the relevant master. The proof process is an automated process that sequentially valves the master meter in series with each run meter, or meter under test (MUT). Flow is established at the given flow throughput that day and the total flow measurement system (Master & MUT) are allowed to come to a thermal equilibrium. The initial temperature differential between the idle master meter and the meter under test could be as much as 10° C. Therefore, to eliminate as many errors as possible from the verification process, temperature is monitored on both the meter under test and the master. One key indication of equilibrium stability is the convergence of measured speed of sound of the gas in the master meter as well as the meter under test. Once they are within 0.5°C and 0.1% speed of sound the test can commence. During the proof, diagnostics are collected via a local computer and archived. Gas composition and process conditions are also noted and archived such that an error can be calculated between the two devices. Measured flow error between the master & MUT is then calculated and a corresponding proving factor is produced. Following the test, this value is entered into the stream flow computer for real time volumetric flow correction. The proving data is saved and a meter control chart is updated.

5.0 Installation / Commissioning

5.1 Plant and Control room preparation

Following an upfront review of the site, all power & I/O terminations had been identified before installing the enhanced CBM system. This revealed that the inlet & outlet meters on the ‘A’ Plant were equipped with the older Instromet Series III version electronics. Prior to installation of the CBM it was decided to upgrade them to Series IV electronics to allow for multiple independent communication ports. This would enable the Station engineers and technicians to proceed as normal with their monthly verifications, and simultaneously allow the CBM system to interrogate the same meters 24/7 without any conflicts and potential data crashes. The Series IV electronics would also allow for digitized acoustic signals to be gathered and transmitted as needed for deeper functional flow meter review. The master meter installed at Plant A was already equipped with Series IV electronics so no further upgrade was required.

As part of the upgrade from Series III to IV the Inlet and Outlet meters were compared "as found" Series III and "as left" Series IV to the master meter to identify any potential shift in accuracy or error in configuration during the upgrade process. This shift was found to be less than 0.1% relative to the master on all upgraded meters.

During the upgrade process it was verified that there were spare cable runs from the measurement shelter to each individual flow meter. This simplified the installation since no new cable and conduit had to be installed to facilitate the additional RS485 communication to the conditioned based monitoring system. Power requirements were more than adequate and the system was connected to a 120 VAC supply on the plant UPS system to maintain data integrity. Once the CBM system was in place, connection to the 9 via RS485 was completed & communication was established.

5.2 Communication with the Outside World.

Although the site identified by El-Paso is manned, external communication capability was still required both for general performance monitoring and any potential enhancements & upgrades. Therefore, the CBM system was configured to communicate with Elster and El Paso via Verizon 3G wireless telephone network.

6.0 Analysis and Data

6.1 Monthly Verifications & Proof

The master meter verification allows this project to test the functionality of both the predictive model and the continuous based monitoring system on almost a real time basis. As indicated in figure 13, the monthly proof provides meter shift corrections as well as trends in accuracy. It is clear to see that due to the line contamination, Plant A outlet 0 meter has continued to exhibit a unidirectional shift relative to the master meter. Due to the timing of the installation of the CBM & subsequent connection to the gas chromatograph, data has only been captured since March 2011. At this point, the meter had been in service for 3 months since its previous maintenance and cleaning cycle in November 2010.

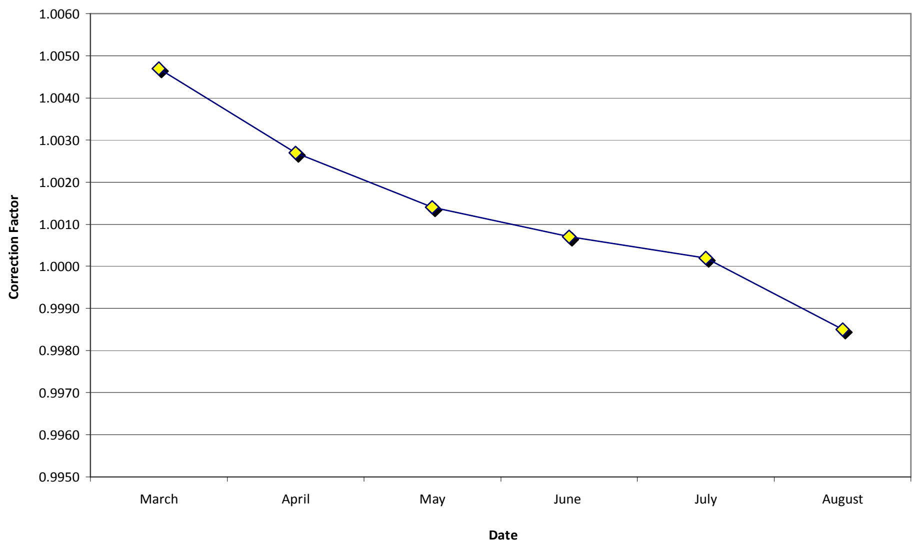


Fig. 13 A-Outlet, Tube 0 Proving correction factors.

6.2 Exercising the predictive model & CBM system.

In order to utilize the prediction model, detailed diagnostic information must be available from the ultrasonic flow meter during the time of each verification, as well as on a continuous basis thereafter. These diagnostics include average flow velocity, individual path velocities, calculated flow profile factor, pressure, temperature, gas composition to name a few. This data is then processed in the prediction model by inputting the Average flow velocity as seen by the ultrasonic meter under real, time dirty conditions. The next step of the prediction model is to input values of apparent roughness of the flow meter body and associated inlet spools.
At the same time a second value of 'apparent build-up' needs to be entered into the predictive model. This is an educated estimation backed up by experience of historical measurements and observations when these meter runs were taken out of service. These two values must fall into a range of realistic values that have either been observed or measured in the past. By adjusting the average flow velocity, the apparent roughness and apparent buildup in the model, the user attempts to match the diagnostic values in the model with those obtained from the ultrasonic meter.

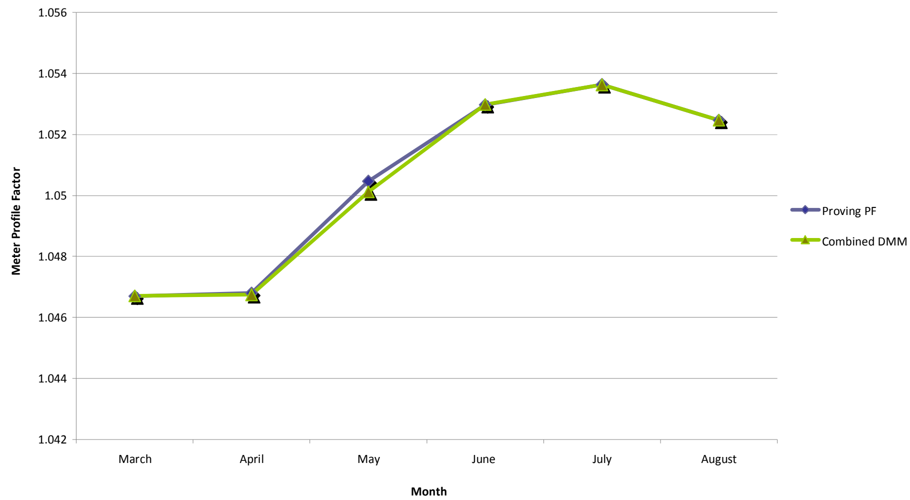


Fig. 14 Progressive Shift in meter profile factor.

The velocity, roughness and buildup values are iterated until convergence occurs between the predicted individual path velocities and the measured path velocities. The result is further tested by verifying that the calculated profile factor from the predictive model agrees with the calculated flow profile factor calculated by the Continuous Based monitoring system. The result of this prediction can be seen in figure 14 above.

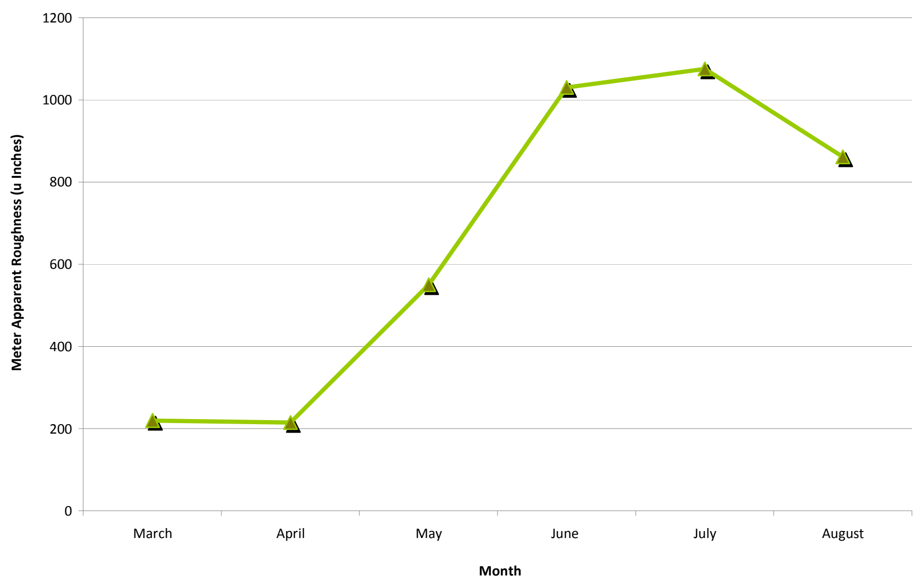


Fig. 15 Progressive shift in meter's apparent roughness from dirty meter model.

Figure 15 demonstrates the predicted change in apparent roughness in the meter body and inlet tube section. The apparent roughness is iterated in the predictive model to yield a calculated flow profile factor as close as possible to that reported from the flow meter. It is important that the roughness value remains in an acceptable "reasonable" range as pertinent to that particular installation, and should be cautiously verified.

As summer approached the apparent roughness began to increase and appeared to peak in July. It would appear that the continuous increase in roughness could not be sustained, possibly due to the changing nature of the type of contamination. The roughness change may not always continue in a liner, unidirectional fashion but may exhibit a sinusoidal behavior depending on the type of contamination. All these effects are related to the variability of the process conditions and operating styles. Particulate type contaminants may increase apparent roughness where as liquid type contaminates may ultimately reduce it.

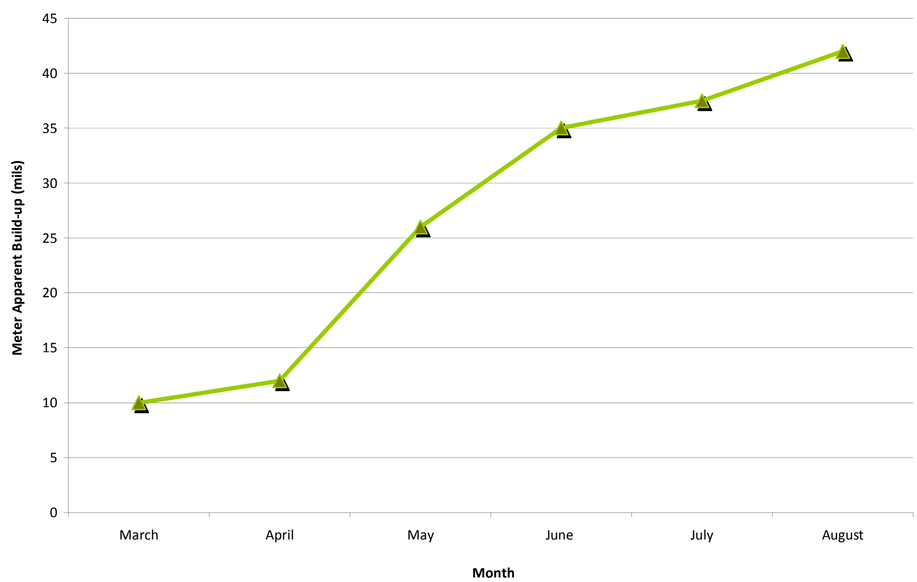


Fig. 16 Progressive shift in meter apparent build-up from dirty meter model.

In figure 16 it can be seen that the predictive model calculates the apparent buildup to be increasing from March through to August with a strong positive trend. This type of behavior correlates with previously gathered historical maintenance data.

It is important to note that the buildup values entered into the model need to be carefully reviewed to see that they fall into reasonable and probable ranges that are either expected for that particular application or that have been measured in the past. If either the apparent roughness or buildup exceeds typical values it may be necessary to visually inspect the meter to verify the model.

There may be more than one combination of apparent roughness & buildup that results in convergence of the predicted individual path velocities, the profile factor and the average flow velocity to those measured by the meter. However, as the predictive model evolves along with the sophistication of ultrasonic flow meter diagnostics, it is believed that the level of confidence and accuracy will increase in the calculations of flow measurement error.

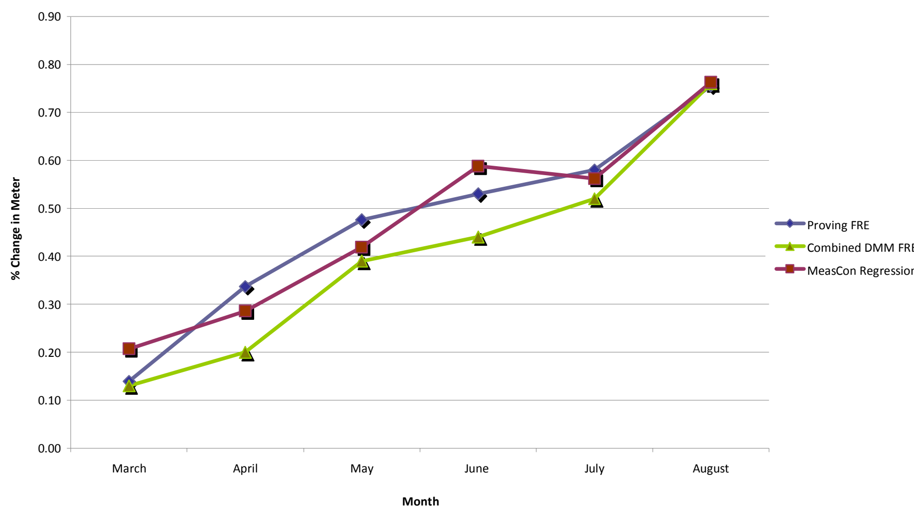


Fig. 17 Progressive shift in meter flow rate error due to build-up & roughness

Figure 17 indicates the measured error on Outlet Tube 0 as compared to the master meter, the predicted error by the predictive model and the CBM regression analysis. It can be clearly seen that both the predictive model and CBM regression correlate well with the master meter verification. They have comparable trend & slope and the resulting difference tends to agree within approximately +/- 0.1

Progressive Shift In Meter Over Time

	Proving FRE	DMM Calculated FRE	Difference in FRE	CBM Regression Analysis FRE	Difference in FRE
March	0.14	0.13	0.01	0.21	0.07
April	0.34	0.2	0.14	0.29	-0.05
May	0.48	0.39	0.09	0.42	-0.06
June	0.53	0.44	0.09	0.59	0.06
July	0.58	0.52	0.06	0.56	-0.02
August	0.76	0.76	-0.01	0.76	0.01

Fig. 18 Comparison table of flow rate error using data from proving, predictive model and CBM multi-variable regression analysis.

7.0 Summary and Conclusions

The initial intention of the beta test was to focus on the plant inlet meters as it was understood that these meters would be exposed to a greater degree of fouling material than the outlet meters. This was further substantiated by the historic data that had been collected since the installation was initially commissioned. At the point of the initial installation it became apparent that the incoming gas was changing. This had two effects. Firstly the level and nature of contamination was different, and secondly the plant's ability to process it was also different. This in itself was an interesting phenomenon and one that is not yet fully understood.

The CBM system had been designed with sufficient capacity to collect information from all nine meters on the specified plant, so all diagnostic data from both inlet & outlet meters was been collected.

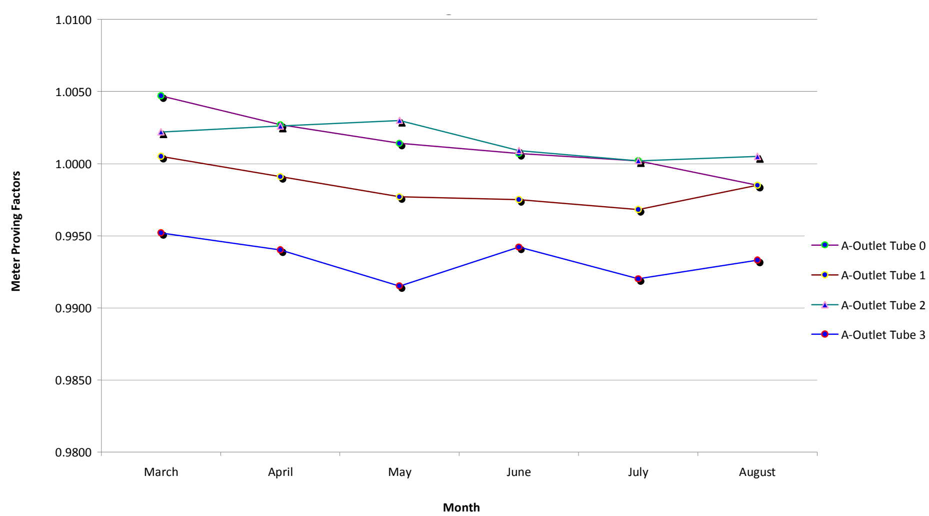


Fig. 19 A-Outlet Proving Correction Factors (All Meters)

Early analysis of the Outlet meters indicated that the meters were generally demonstrating a consistent shift in relation to the master meter. Tube 0 & Tube 1 which had spent the greatest amount of time in service showed very similar characteristics, both in terms of slope direction & magnitude of change. The typical movement in proving factors for both meters as a result of the contamination was in the order of 0.3% with reference to the master, over a 3 month period.

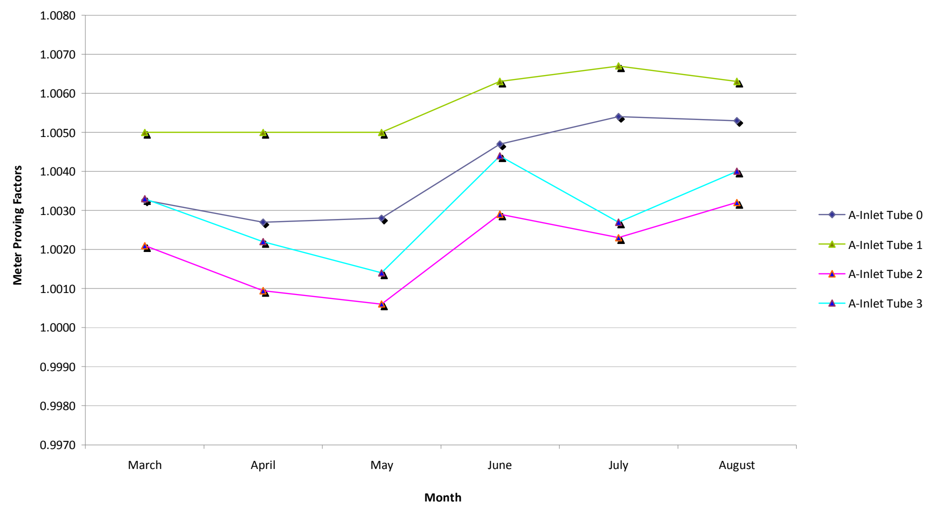


Fig. 20 A-Inlet Proving Correction Factors (All Meters)

Early analysis of the Inlet meters indicated that the meters were generally demonstrating a consistent shift in relation to the master meter, all be it to a much lesser degree than the outlet meters. Tube 0 & Tube 1 which had spent the greatest amount of time in service showed very similar characteristics, both in terms of slope direction & magnitude of change. However, the movement in proving factors for these meters was 0.05% and 0% respectively, with reference to the master over the same 3 month period.

Therefore, for the purposes of this paper the focus of attention became the outlet meters. These meters appeared to be changing by a greater degree due to the change in the incoming pre processed gas, and the way in which the processing plant was now operating.

Based on the above reasoning, the following observations have been made:

i) Although it is still a relatively new field of exploration, early indications suggest that the predictive model and CBM system are extremely useful tools when applied properly, and within the bounds of the assumptions for which they are designed.

ii) It should be noted that the predictive model & CBM System are not yet intended as devices to automatically correct for a shift in measurement accuracy, but rather to predict if a large enough shift has occurred (as defined by the end user or regulating body) and if maintenance or other intervention needs to be carried out on the measurement system.

iii) It is important to understand to some extent the nature of build-up and grime that occur in a specific station or meter run. This can be based on historical data when meters are taken out of service for cleaning and calibration. For the predictive model to function, values of typical thickness of buildup need to be entered as well as the apparent roughness of the build up. At present no practical technology exists that can measure these parameters in real time, and thus the reliance on experience and historical observations and measurements is important.

iv) The predictive model attempts to match specific characteristics of the ultrasonic flow meter that are captured by the CBM system, such as individual path velocities, path velocity distribution and profile factor. Values are attributed to mean pipe velocity, apparent pipe wall roughness and apparent build-up until data convergence is achieved.

v) The CBM system allows us a real time window into the continuous operation of the ultrasonic meter and the environment in which it operates. Since installing the system at the El Paso facility, observations on even the most common of diagnostics have revealed just how quickly the measurement environment can change as different equilibriums are reached.

8.0 Future Goals

Understand effects on short term accuracy of measurement on a minute or faster basis.

Continue to test & develop the predictive & regression models further on both the inlet & outlet plants.

Evaluate the level of roughness & build-up during the next cleaning cycle in November 2011 and compare to the apparent values of the model.

Start building up database of typical buildup over time and apparent roughness change.

Understand the measurement at a 24/7 level as opposed fixed period calibrations/validations.

Develop an understanding of how process conditions change due to changes in the pre processed source gas form different locations and sources such as Shale.

9.0 References

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