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DP Meter Diagnostic Systems – Operator Experience

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1. INTRODUCTION

In 2008 [1] & 2009 [2] DP Diagnostics divulged the first comprehensive diagnostic concept for DP meters. In 2010 Swinton Technology partnered with DP Diagnostics and this diagnostic concept was developed into the industrial system called "Prognosis". The first field tests of Prognosis were carried out by BP CATS and ConocoPhillips TGT and reported to the NSFMW in 2010 by Skelton et al [3]. Since then Prognosis has been further developed and applied in the field to orifice and Venturi meters by several operators. This paper describes these developments and the field experience of these operators.

BP CATS (see Fig.1) initially field tested Prognosis on the 16", 0.6 beta ratio orifice meter on stream 5 of the EX1 metering skid in May 2010. After initial successful field tests, BP initiated a long term endurance test. Prognosis has run on this meter from May 2011 until the present time proving the long term reliability of the diagnostic system. This paper shows the results of this long term test. As a result of this test BP now has agreement with the UK's DECC to operate a Condition Based Maintenance, or "CBM" process (as described by DECC [4]). The traditional periods between the orifice meters inspection have been extended by monitoring of the Prognosis system.

Fig 1. BP Central Area Terminal Service.

In 2011 Centrica included Prognosis with one 8", 0.4 beta ratio Venturi meter and two nominally identical 6", 0.4 beta ratio Venturi meters bound for the York platform in the North Sea. ISO 5167-4 [5] states that Venturi meters for high pressure natural gas flow metering applications should be calibrated for optimum performance. Likewise, DP Diagnostics recommends a Prognosis system on a Venturi meter should be calibrated for optimum performance. The Prognosis and standard Venturi meter calibrations can be combined meaning that one calibration is required to set both the discharge coefficient and all the diagnostic parameters. That is, the calibration of the diagnostic system is not an extra cost to the operator. These three Centrica York Venturi meters were calibrated at the GL Flow Centre in the UK. Centrica's decision to add the "insurance policy" of Prognosis to the project was unexpectedly vindicated almost immediately when Factory Acceptance Testing of Prognosis using the calibration report led to Prognosis warning of a real abnormality in the calibration data that had been missed by all the normal quality control procedures of the multiple companies involved. This paper discusses this event and describes the real problem found before going on to give virtual examples of Prognosis alarms for various common problems.

Petronas Carigali Hess included Prognosis on one 6", 0.7 beta ratio Venturi meter bound for wet natural gas flow service on a satellite platform in SE Asia. The diagnostic calibration of this Venturi meter and subsequent wet gas flow testing was described in detail by Vijay et al [6,7] in 2011. This meter has now been installed and is operating correctly. However, the commissioning of the meter did not run smoothly. Initial Prognosis results showed a system malfunction. This was found to be due to the recovery and PPL DP's being mis-measured due to a communication

problem between the transmitters and flow computer. Wet gas Venturi meters use the PPL to monitor the liquid loading. Prognosis had correctly proved the wet gas Venturi meter was initially unserviceable. This paper discusses the details of this event.

Finally, a Prognosis system was temporarily operated during 2011 to aid the auditing of orifice meters. In this paper three real examples of Prognosis in use during these audits are discussed. One example shows the system response to a correctly operating meter. The two other examples each show Prognosis correctly diagnosing a meter malfunction and correctly short listing the probable cause, and the likely direction of bias, before the subsequent maintenance proved these predictions correct.

2. A TECHNICAL REVIEW OF THE 2012 DP METER DIAGNOSTIC SYSTEM –"PROGNOSIS"

In this discussion the orifice meter will be used as an example, but the same arguments hold for any generic DP meter. Fig. 2 shows an orifice plate meter with instrumentation sketch and the (simplified) pressure fluctuation (or "pressure field") through the meter body. This pressure field is **wholly** dependent on the combination of DP geometry and the flow conditions. Therefore, the pressure field inherently contains a large amount of information regarding both the DP meter geometry and the actual flow conditions. Since the initial conception of the DP meter design, the very purpose of the primary element (e.g. orifice plate) has been to create this pressure field so that a difference in pressure within the field can be read and related to the flow rate. Hence, the pressure field has **always** been an integral part of the DP meter operating principle. However, traditionally, DP meters have not fully utilized this easily accessible and substantial pressure field information for flow metering or diagnostics purposes. Traditional DP meters only compare the difference in pressure at two set points within this pressure field. Therefore, traditionally DP meters are *needlessly* restricted in their capability compared to the substantial extra flow rate and diagnostic information that the pressure field as a whole has always offered. The DP meter diagnostic methods discussed here open up the potential of more closely monitoring the pressure field as a whole, thereby significantly increasing the capabilities of DP meters on which the diagnostics are applied.

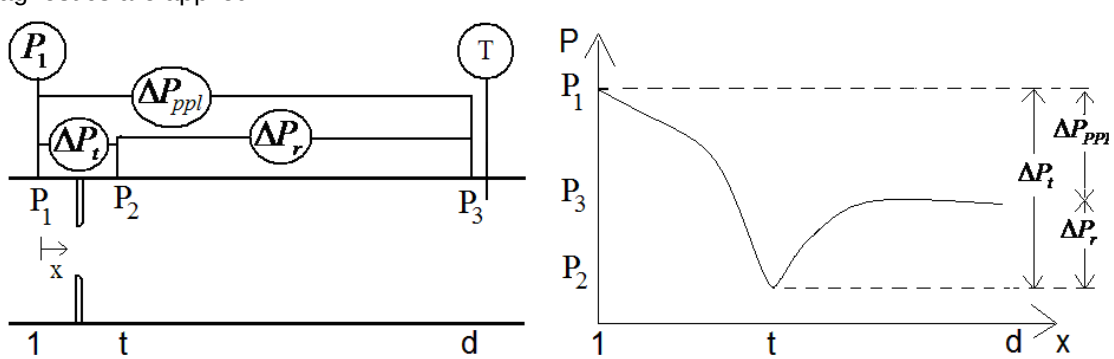

Fig 2. Orifice meter with instrumentation sketch and pressure fluctuation graph.

Traditional DP meters read the inlet pressure (P_1), the downstream temperature (T) and the differential pressure (ΔP_t) between the inlet pressure tap (P_1) and a pressure tap positioned in the vicinity of the point of low pressure (P_2), created by the primary element. That is, traditionally DP meter technology only takes a single DP measurement from the pressure field. However, note that the DP meter run in Figure 2 has a third pressure tap (P_3) further downstream of the primary element. This allows the measurement of two extra DP's. That is, it allows extra pressure field information to be read. The two extra DP's are the differential pressure between the downstream (P_3) and the low (P_2) pressure taps (or "recovered" DP, ΔP_r) and the differential pressure between the inlet (P_1) and the downstream (P_3) pressure taps (i.e. the permanent pressure loss, ΔP_{PPL}, sometimes called the "PPL" or "total head loss"). The sum of the recovered DP and the PPL **must** equal the traditional differential pressure (equation 1).

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad \text{--- (1)}$$

Traditional Flow Equation: $\dot{m}_t = EA_t YC_d \sqrt{2\rho\Delta P_t}$, uncertainty ± x% --- (2)

Expansion Flow Equation: $\dot{m}_r = EA_t K_r \sqrt{2\rho\Delta P_r}$, uncertainty ± y% --- (3)

PPL Flow Equation: $\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}}$, uncertainty ±z% --- (4)

The traditional orifice meter flow rate equation is shown here as equation 2. Traditionally, this is the only orifice meter flow rate calculation. However, with the additional downstream pressure tap three flow equations can be produced. That is, the recovered DP can be used to find the flow rate with an "expansion" flow equation (see equation 3) and the PPL can be used to find the flow rate with a "PPL" flow equation (see equation 4). Note $\dot{m}_t$, $\dot{m}_r$ and $\dot{m}_{PPL}$ represents the traditional, expansion and PPL mass flow rate equation predictions of the actual mass flow rate ($\dot{m}$) respectively. The symbol ρ represents the inlet fluid density. Symbols E , A and A_t represent the geometric constants of the velocity of approach, the inlet cross sectional area and the minimum (or "throat") cross sectional area through the meter respectively. The parameter Y is an expansion factor accounting for gas density fluctuation through the meter. (For liquids Y =1.) The terms C_d, K_r and K_{PPL} represent the discharge coefficient, the expansion coefficient and the PPL coefficient respectively.

These three flow coefficients can be found by calibrating the DP meter. Each can be set as constant values with set uncertainty ratings, or, may each be fitted to the Reynolds number, usually at a lower uncertainty rating. The Reynolds number is expressed as equation 5. Note that μ is the fluid viscosity and D is the inlet diameter. In the case of a flow coefficient being fitted to the Reynolds number, as the Reynolds number (Re) is flow rate dependent, each of the three flow rate predictions must be independently obtained by an iterative method. A detailed derivation of these three flow rate equations is given by Steven [1]. The orifice meter is a special case, as although it can be calibrated, an expression for the discharge coefficient can be found in ISO 5167-2 [8], and expressions for the expansion and PPL coefficients can be derived by other information contained within ISO 5167-2.

$$\mathrm{Re} = \frac{4\dot{m}}{\pi\mu D} \quad \text{--- (5)}$$

Every DP meter body is in effect three flow meters. As there are three flow rate equations predicting the same flow through the same meter body there is the potential to compare the flow rate predictions and hence have a diagnostic system. Naturally, all three flow rate equations have individual uncertainty ratings (say x%, y% & z% as shown in equations 2 through 4). Therefore, even if a DP meter is operating correctly, no two flow predictions would match *precisely*. However, a correctly operating DP meter should have no difference between any two flow rate predictions greater than the root mean square value of the two flow prediction uncertainties. Therefore, the maximum allowable difference between any two flow rate equations, i.e. $\phi\%$, $\xi\%$ & $\upsilon\%$ is shown in equation set 6a to 6c. If the percentage difference between any two flow rate predictions is less than the root mean square of those two flow rate prediction uncertainties, then no potential problem is found. If however, the percentage difference between any two flow rate equations is greater than the root mean square of those two flow rate prediction uncertainties, then this indicates a metering problem and the flow rate predictions should not be trusted. The three flow rate percentage differences are calculated by equations 7a to 7c.

This diagnostic methodology uses the three individual DP's to independently predict the flow rate and then compares these results. With three flow rate predictions, there are three flow rate predictions pairs and therefore three flow rate diagnostic checks. In effect, the individual DP's are therefore being directly compared. However, it is possible to take a different diagnostic approach.

Traditional & PPL Meters % allowable difference $\phi\% = \sqrt{(x\%)^2 + (z\%)^2}$ -- (6a)

Traditional & Expansion Meters % allowable difference: $\nu\% = \sqrt{(y\%)^2 + (z\%)^2}$ -- (6b)

Expansion & PPL Meters % allowable difference: $\xi\% = \sqrt{(x\%)^2 + (y\%)^2}$ -- (6c)

Traditional to PPL Meter Comparison : $\psi\% = \left\{ \left(\dot{m}_{PPL} - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\%$ -- (7a)

Traditional to Expansion Meter Comparison: $\lambda\% = \left\{ \left(\dot{m}_r - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\%$ -- (7b)

PPL to Expansion Meter Comparison: $\chi\% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \Big/ \dot{m}_{PPL} \right\} * 100\%$ -- (7c)

The **P**ressure **L**oss **R**atio (or "PLR") is the ratio of the PPL to the traditional DP. Like the DP meter flow coefficients the PLR is a meter characteristic for all DP meters operating with single phase homogenous flow. It can be expressed as a constant value or related to the Reynolds number. We can rewrite Equation 1:

$$\frac{\Delta P_r}{\Delta P_t} + \frac{\Delta P_{PPL}}{\Delta P_t} = 1 \quad \text{--- (1a)} \qquad \text{where} \qquad \frac{\Delta P_{PPL}}{\Delta P_t} \text{ is the PLR.}$$

From equation 1a, if PLR is a set value (for any given Reynolds number) then both the **P**ressure **R**ecovery **R**atio or "PRR", (i.e. the ratio of the recovered DP to traditional DP) and the **R**ecovered DP to **P**PL **R**atio, or "RPR" must then also be set values. That is, all DP ratios available from the three DP pairs are constant values for any given DP meter geometry and Reynolds number. These three DP ratios can be found by calibrating the DP meter. Alternatively, for the particular case of an orifice meter not to be calibrated before use, an expression for the PLR can be found in ISO 5167-2 [8], and expressions for PRR and RPR can be derived by the information contained in ISO 5167-2. Thus we also have:

PPL to Traditional DP ratio (PLR): $(\Delta P_{PPL} \ / \ \Delta P_t)_{calibration}$, uncertainty ± a%

Recovered to Traditional DP ratio (PRR): $(\Delta P_r \ / \ \Delta P_t)_{calibration}$, uncertainty ± b%

Recovered to PPL DP ratio (RPR): $(\Delta P_r \ / \ \Delta P_{PPL})_{calibration}$, uncertainty ± c%

Here then is another method of using the three DPs to check an orifice meters health. Actual DP ratios found in service can be compared to the fixed known correct values. Let us denote the percentage difference between the actual PLR and the known correct value as $\alpha\%$, the difference between the actual PRR and the known correct value as $\gamma\%$, and the difference between the actual RPR and the known correct value as $\eta\%$. These values are found by equations 8a to 8c.

$$\alpha\% = \{[PLR_{actual} - PLR_{calibration}] / PLR_{calibration}\} * 100\% \quad \text{--- (8a)}$$

$$\gamma\% = \{[PRR_{actual} - PRR_{calibration}] / PRR_{calibration}\} * 100\% \quad \text{--- (8b)}$$

$$\eta\% = \{[RPR_{actual} - RPR_{calibration}] / RPR_{calibration}\} * 100\% \quad \text{--- (8c)}$$

If the percentage difference between the in-service and the known correct DP ratio is less than the stated uncertainty of that known DP ratio value, then no potential problem is found. If the

percentage difference between the in-service and the known correct DP ratio is greater than the stated uncertainty of that known DP ratio value, then a potential problem is found and the flow rate predictions should not be trusted. With three DP ratios, there are three DP ratio diagnostic checks.

A seventh diagnostic method was added in 2012. Equation 1 holds true for all generic DP meters. Equation 1 is a consequence of the first law of thermodynamics and as such it cannot be violated, even if a DP meter has malfunctioned. Therefore, if all three DP's are directly read they can be checked against the infallibility of equation 1. As this equation must hold true, any result that suggests that it does not hold true is an absolute statement by the diagnostic system that there is an erroneous DP reading coming from the instrumentation (regardless of whether the meter body is serviceable or not). A DP meter reading all three DP's can infer the actual traditional DP (ΔP_t) by summing the read recovery DP (ΔP_r) and permanent pressure loss (ΔP_{PPL}). This gives an inferred traditional DP ($\Delta P_{t,\inf}$) that can be compared to the directly read traditional DP ($\Delta P_{t,read}$). Whereas theoretically these values are the same, due to the uncertainties of the three DP transmitters, even for correctly read DP's, they can be slightly different. The percentage difference ($\delta\%$) can be calculated as seen in equation 9.

$$\delta\% = \{(\ \Delta P_{t,\inf} - \Delta P_{t,read}\ )\ /\ \Delta P_{t,read}\ \}*100\% \quad \text{--- (9)}$$

The uncertainty rating of each DP reading will be known from the individual DP transmitter specifications. Therefore, it is possible to assign a maximum allowable percentage difference ($\theta\%$) between the directly read and inferred traditional DP values. However, it has been found in practice that as long as a reasonable population sample is taken (i.e. enough scans are averaged[1]) setting $\theta\% = 1\%$ is a reasonable practical value that covers a wide range of DP's measured. Therefore, if the percentage difference between the directly read and inferred traditional DP values ($\delta\%$) is less than the allowable percentage difference ($\theta\%$), then no potential problem is found. However, if the percentage difference between the directly read and inferred traditional DP values ($\delta\%$) is greater than the allowable percentage difference ($\theta\%$), then a problem with the DP measurements is confirmed and the flow rate predictions cannot be trusted.

Table 1 shows the seven possible situations that would signal a warning. Each of the seven diagnostic checks has ***normalized data***, i.e. each diagnostic parameter percentage difference output is divided by the allowable percentage difference for that parameter to produce the same warning criteria of out with: -1 ≤ diagnostic result ≤ 1. For convenience we use the following naming convention for the normalized data:

Normalized flow rate inter-comparisons: $x_1 = \psi\%/\phi\%$, $x_2 = \lambda\%/\xi\%$, $x_3 = \chi\%/\upsilon\%$

Normalized DP ratio comparisons: $y_1 = \alpha\%/a\%$, $y_2 = \gamma\%/b\%$, $y_3 = \eta\%/c\%$

Normalized DP sum comparison: $x_4 = \delta\%/\theta\%$

For practical real time (or historical auditing) use, a graphical representation of the diagnostics continually updated on a control room screen (while being archived) can be simple and effective. Any such graphical representation of diagnostic results should be immediately accessible and

[1] Most systems will read the DPs in sequence during a data sweep, i.e. the DP's are not typically read simultaneously and the three DP readings for a single diagnostic check will be out of synchronization. Even in "steady" flow each DP will have a finite standard deviation, i.e. it will fluctuate around its mean value. Therefore a representative population size has to be read to ensure that the three DP's used are the three average DP values and any DP fluctuation effects are smoothed out.

DP Pair	No Warning	WARNING	No Warning	WARNING
ΔP_t & ΔP_{ppl}	$x_1 \leq 1$	$x_1 > 1$	$y_1 \leq 1$	$y_1 > 1$
ΔP_t & ΔP_r	$x_2 \leq 1$	$x_2 > 1$	$y_2 \leq 1$	$y_2 > 1$
ΔP_r & ΔP_{ppl}	$x_3 \leq 1$	$x_3 > 1$	$y_3 \leq 1$	$y_3 > 1$
$\Delta P_{t,read}$ & $\Delta P_{t,\inf}$	$x_4 \leq 1$	$x_4 > 1$	N/A	N/A

Table 1. The DP meter possible diagnostic results.

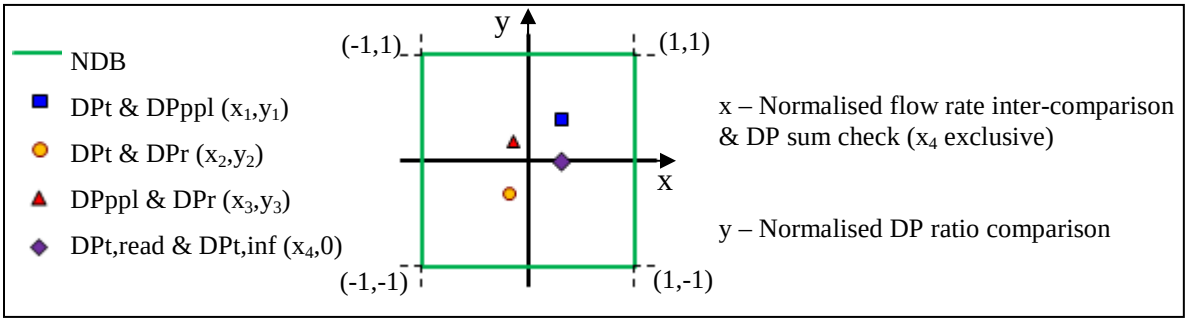

Fig 3. Normalized diagnostic box (NDB) with diagnostic results, DP measurement check included

understandable to the average operator. Therefore, four points are plotted on a normalized graph (as shown in Fig 3). This graph's abscissa and ordinate (i.e. x & y axis) are number lines only, i.e. the axis have no units. On this graph a normalized diagnostic box (or "NDB") can be superimposed with corner co-ordinates: (1,1), (1,-1), (-1,-1) & (-1,1). On such a graph four meter diagnostic points can be plotted, i.e. (x_1,y_1), (x_2,y_2), (x_3,y_3) & $(x_4,0)$. Therefore, first, the three DP's have been split into three DP pairs and for each pair both the difference in the flow rate predictions and the difference in the actual to set known DP ratio are being compared to the maximum allowable differences. Secondly, the difference between the directly read and inferred traditional DP and is being compared to the maximum allowable difference. The abscissa is being used as a number line when the value $\delta\%/\theta\%$ (x_4) is being plotted (and the ordinate value is therefore zero by default). If the resulting diagnostic value falls within the range $-1 \leq x_4 \leq +1$ then the point $(x_4, 0)$ falls inside the NDB and no DP reading problem is noted. If the resulting diagnostic value falls out with the range $-1 \leq x_4 \leq +1$ then the point $(x_4, 0)$ falls outside the NDB and a DP reading problem is noted. If all points are within the NDB the meter operator sees no metering problem and the traditional meters flow rate prediction should be trusted. However, if one or more of the points falls outside the NDB the meter operator has an indication that the meter is ***not*** operating correctly and that the meters traditional (or any) flow rate prediction cannot be trusted.

If the DP's are read correctly the diagnostics show $-1 \leq x_4 \leq +1$ regardless of whether there is any meter malfunction. A physical meter malfunction, where the DP's are still being correctly read, will be indicated by $-1 \leq x_4 \leq +1$ with one or more of the **other** diagnostic points outside the box. Such a plot indicates the problem is with the meter body and <u>not</u> the DP readings. However, if the DP readings are erroneous then the diagnostics will show that $-1 \leq x_4 \leq +1$ does not hold (i.e. this diagnostic point is outside the NDB) and therefore the DP readings **must** be erroneous, regardless of whether the meter has an additional physical meter malfunction or not. In this scenario the DP reading error/s could cause the other three diagnostic points to <u>also</u> be outside the NDB. However, from the fact that the $(x_4, 0)$ falls outside the NDB the operator categorically knows the DP readings are the source (or one of the sources) of the meter malfunction. Once, the DP reading problem is fixed, if one or more of the other points are still out the box then the operator knows the meter body had also malfunctioned. Therefore, such a plot as Figure 3 allows the meter operator to not only see a problem but be able to distinguish the problem between a secondary DP instrumentation problem and a primary meter body based physical problem.

The further from the NDB the points are, the more potential for significant meter error there is. Note that in this random theoretical example shown in Figure 3 all points are within the NDB indicating the meter is operating within the limits of normality, i.e. no metering problem is noted.

3. LONG TERM PROGNOSIS RESULTS FROM BP CATS

The initial field trails of Prognosis at BP CATS in May 2010 were followed by a long term trial starting in May 2011. This meter was subject to the same 4 monthly maintenance schedule as the other four meters on the skid and was therefore periodically in and out of service. However, between May 2011 and August 2012 substantial service time was logged and each period of operation had the Prognosis system operating correctly and showing the same results.

The diagnostic system received the process data and the meter geometry directly from the stream's main flow computer. During this test the diagnostic software was set to poll data once per second. Each second an average of the last ten data polls was taken and the diagnostic screen was updated. The software was set to archive every tenth update, i.e. a snapshot of every tenth update was recorded. There was therefore 8,640 archived points per day.

Fig 4. BP CATS EX1 stream 5 meter run.

Fig 5. BP CATS EX1 instrument enclosure.

Figures 4 & 5 show the BP CATS EX1 stream 5, 16", 0.6 beta ratio orifice meter run and the DP transmitters rack protected from the elements in an enclosure respectively. Figure 6 shows the three flow rate predictions from the three independent DP readings (i.e. the traditional meter using DPt, the expansion meter using DPr and the PPL meter using the DPppl) for twenty four

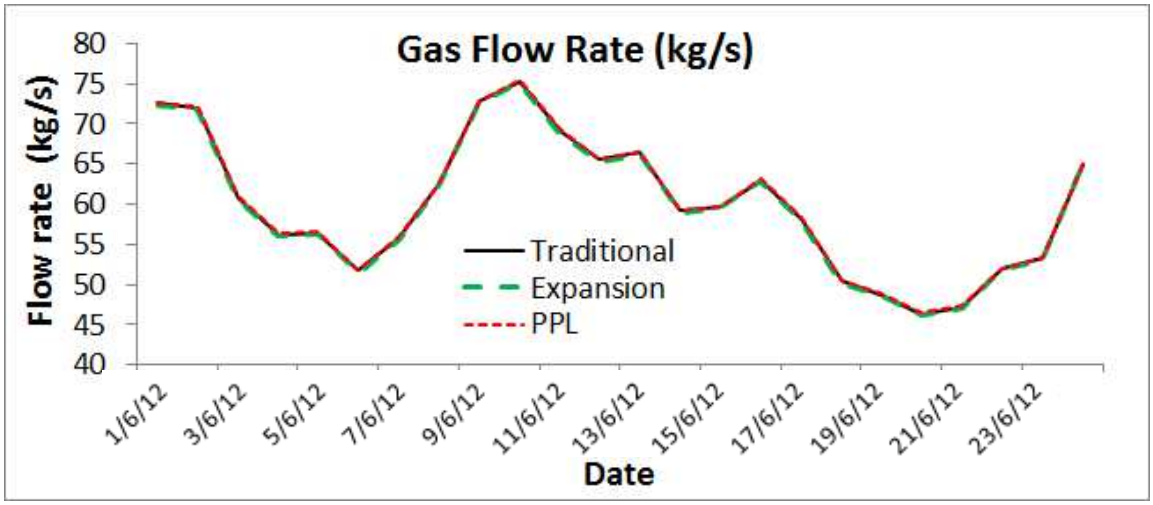

Fig 6. BP CATS EX1 stream 5 flow rates during June 2012.

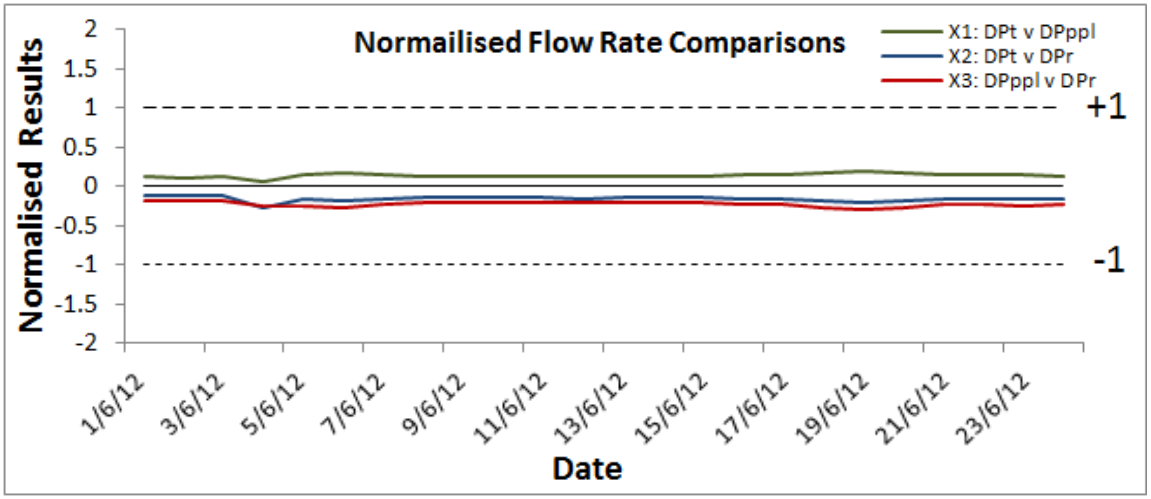

Fig 7. BP CATS EX1 stream 5, three flow rate pair comparison diagnostics during June 2012.

consecutive days in June 2012. Each of these lines link the *daily average* values for the respective flow rate predictions. All three flow rates generally agree (as they should for a correctly operating meter) and therefore the three predictions lie on top of each other giving the impression of one flow rate prediction in Figure 6. This was a consistent result throughout the long term trial.

Naturally, on close inspection (i.e. the diagnostic analysis) it is found that the three flow rates are not identical due to the natural uncertainties in the three flow rate prediction methods. Figure 7 shows the three pairs of flow rate predictions being compared by the diagnostics over the sample period in June 2012. That is, Figure 7 shows the plot $\psi\%/\phi\%$, $\lambda\%/\xi\%$ & $\chi\%/\upsilon\%$ (or x_1 ,x_2 & x_3) vs. time. Again, each of these three lines link the *daily average* values for the respective diagnostic results. The uncertainty settings for this normalization were x=1%, y=2.5% & z=2.5. Clearly from Figure 7: $x_1 \leq 1$, $x_2 \leq 1$ & $x_3 \leq 1$. In fact, for each of the three flow rate prediction pairs the two flow rate predictions are seen to have been very close, i.e. all three diagnostics have a result << 1, meaning there is *very* little difference between the flow rate predictions. Over the long term correct operation of the meter this Prognosis result remained constant.

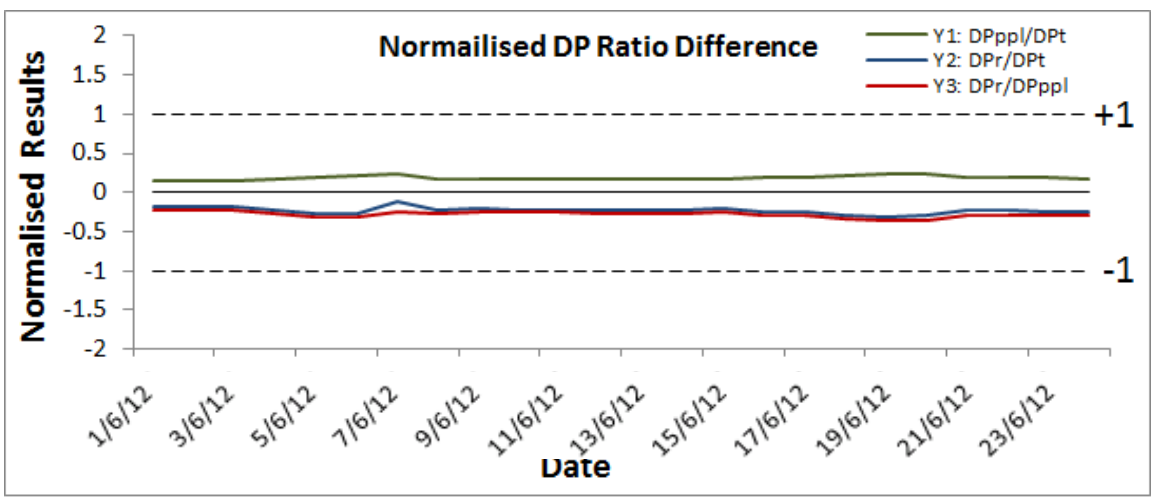

Fig 8. BP CATS EX1 stream 5, three DP Ratio diagnostics during June 2012.

Figure 8 shows the three DP ratio diagnostic results over the sample period. That is, Figure 8 shows the plot $\alpha\%/a\%$, $\gamma\%/b\%$ & $\eta\%/c\%$ (or y_1 ,y_2 & y_3) vs. time. Again, each of these three lines link the *daily average* values for the respective diagnostic results. The uncertainty

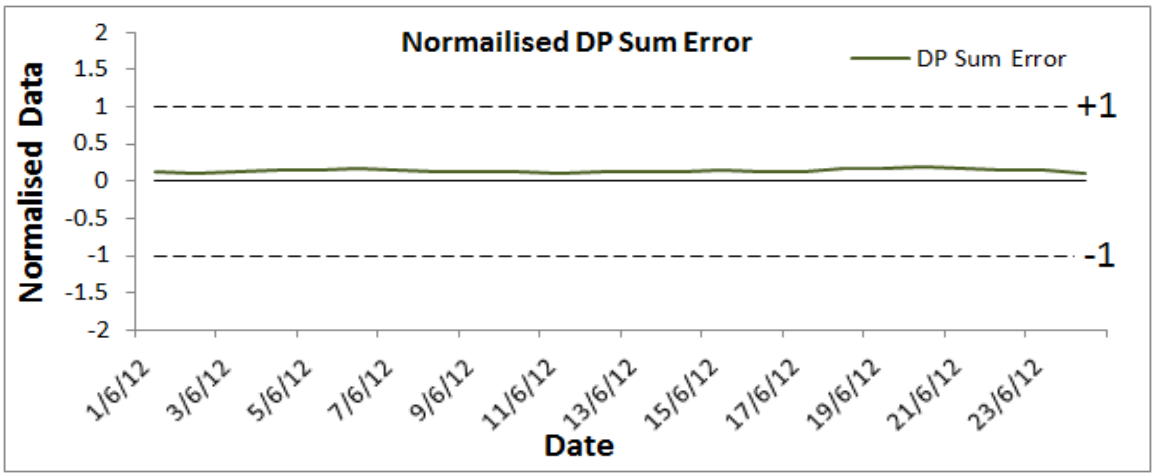

Fig 9. BP CATS EX1 stream 5, DP integrity diagnostic during June 2012.

settings for this normalization were a=3%, b=2.5% & c=4%. Clearly from Figure 8: $y_1 \leq 1$, $y_2 \leq 1$ & $y_3 \leq 1$. In fact for each of the three DP ratios the readings and predictions are seen to have been *very* close, i.e. all three diagnostics have a result << 1, meaning the meter behaved extremely closely to the predictions derived from ISO 5167.

Figure 9 shows the DP reading integrity diagnostic results over the sample period in June 2012. That is, Figure 9 shows the plot $\delta\%/\theta\%$ (or x_4) vs. time. The line links the *daily average* values of the diagnostic result for the 24 consecutive days. The uncertainty settings for this normalization were $\theta\%$=1%. Clearly from Figure 9: $x_4 \leq 1$, meaning that the DP readings were stable and read correctly to low uncertainty.

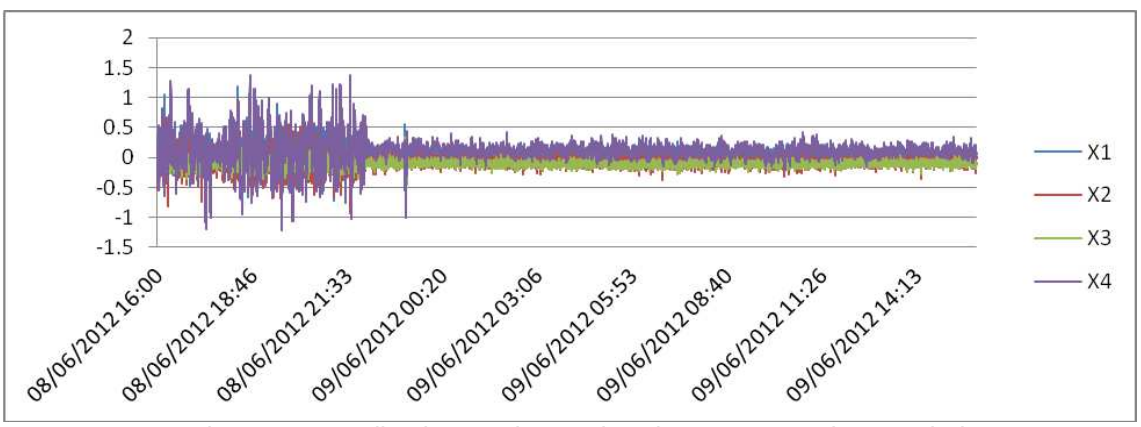

Fig 10 – Normalised NDB plot x-axis values over a 24 hour period

These average daily results shown in Figures 7, 8 & 9 were reproduced throughout the long term test. However, with 8,640 points averaged per day these daily average points smooth out any short term fluctuations. That is, a daily average is a macroscopic view of the meters performance. When significantly shorter periods of time are considered we get a microscopic view of the meters performance. From this perspective it becomes evident that the live diagnostic results are significantly more animated than a daily average would suggest. Figures 10 & 11 show every archived diagnostic result (i.e. all 8,640 results from averaging each 10 seconds) over a 24 hour period. Over the first 6 hours the system fluctuates significantly more than the remainder of the day. The daily average of all seven diagnostic checks is still clearly well within the acceptable [+1,-1] limits. However, fluctuations in the "live" short term results (due to small perturbations in typical industrial pseudo-steady flows) occasionally cause short term intermittent diagnostic results where one or more of the seven diagnostics may momentarily register a result > 1, i.e. a

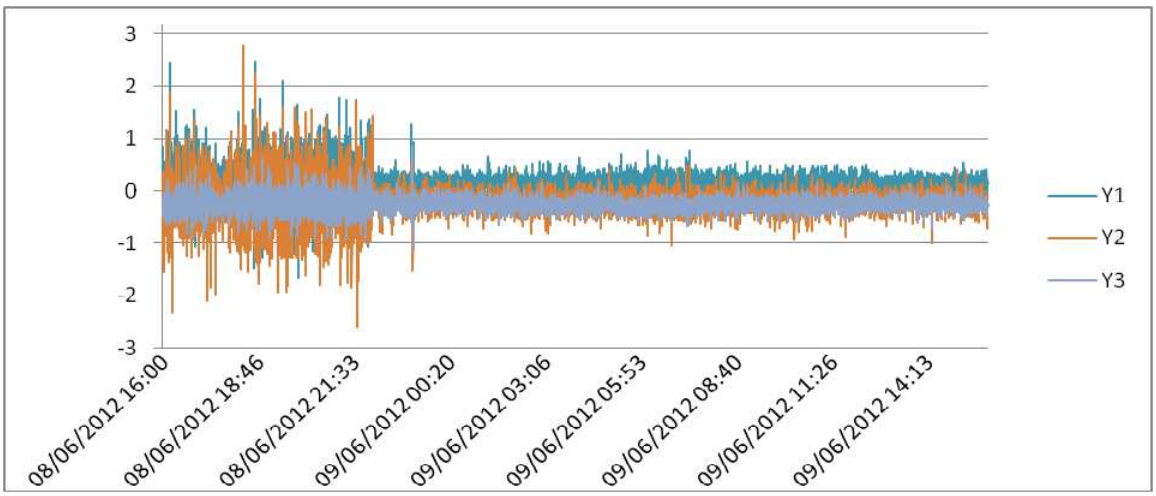

Fig 11 – Normalised NDB plot y-axis values over a 24 hour period

malfunction warning. Such perturbation in the flow is normal operation for any refinery and Figures 10 & 11 are the normal Prognosis response to these perturbations. Such short term variations are averaged out over time to give the correct flow rate and the correct diagnostic result (as seen in Figures 7, 8 & 9). Therefore, the macro view of the diagnostics shows the operator that the meter is operating correctly and the flow rate prediction for that day is trustworthy. The operator, then has the ability to review the archived data in more detail (as in Figures 10 & 11) to investigate any short term issues that occurred during production. Prognosis allows the operator to choose the amount of data / period of time to be averaged per diagnostic result, and to set the amount of time the diagnostics indicate a potential fault (i.e. >1) before they signal a malfunction warning. That is, the operators can increase or reduce the sensitivity of Prognosis to short term flow fluctuations as they see fit.

Reviewing the Prognosis data from BP CATS showed that the orifice meter had run without any significant problems throughout all periods that it was in service. The periods the meter was off-line during the long term Prognosis test were largely due to the routine BP CATS maintenance schedule of checking each orifice meter every four months. However, Prognosis had correctly showed prior to each maintenance procedure that no problem with the meter would be found. As such in 2011 BP submitted a request to the UK regulators (DECC) to extend the meter inspection period from four to eight months, and subsequently (given continued proof of the diagnostic system's integrity) to yearly inspections. DECC did not object to this proposal. That is, BP has instigated a Condition Based Maintenance scheme rather than the traditional scheduled maintenance scheme on the BP CATS EX1 stream 5 16", 0.6 beta ratio orifice meter. In the 2012 DECC "Guidance Notes for Petroleum Measurement Issue 8" [4], DECC make the following three statements in the Guidance Note's section 6.7.7:

"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 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."

4. CENTRICA YORK VENTURI METERS

One 8”, 0.4 beta ratio Venturi meter and two nominally identical six inch, 0.4 beta ratio Venturi meters for the York platform were calibrated to be diagnostic ready at the GL Flow Centre in the UK in February and March 2012. All the Venturi meters were ISO 5167-4 (2003) compliant.

4a. ONE 8”, VENTURI METER CALIBRATION (S/N 2009080-3)

The GL Flow Centre calibrated an 8”, 0.4 beta ratio Venturi meter (see Figure 12). Flow was from right to left. The straight pipe length requirements of ISO 5167-4 were met. The downstream tap was downstream of two thermo-wells. However, the diagnostic parameter calibration data includes the effect of the thermo-wells. The natural gas flowed at approximately 49 Bar(a). The minimum DP value used was set at 10 mBar / 4”WC.

Figure 13 shows that the discharge coefficient, expansion coefficient and PPL coefficient for this Venturi meter were fitted to 0.4%, 0.6% & 0.6% uncertainty respectively. More precise data fitting can produce lower uncertainties, but for the purpose of the diagnostic system this is deemed to be adequate performance. The uncertainties used for diagnostic analysis were set at 0.75%, 1.0% & 0.75% respectively[2]. Figure 14 shows that for this Venturi meter the DP ratios PLR, PRR & RPR were fitted to 0.7%, 0.4% & 0.9% uncertainty respectively. Again, to avoid false warnings the uncertainties used in the diagnostic system were raised to default values of 1.5%, 1.5% & 2% respectively. Throughout the calibration it was checked that the equation 1 held for each logged point. Figure 15 shows the resulting calibration data diagnostic points on the NDB plot.

Fig 12. 8”, 0.4 Beta Ratio Venturi meter (S/N 2009080-3) at GL Flow Centre

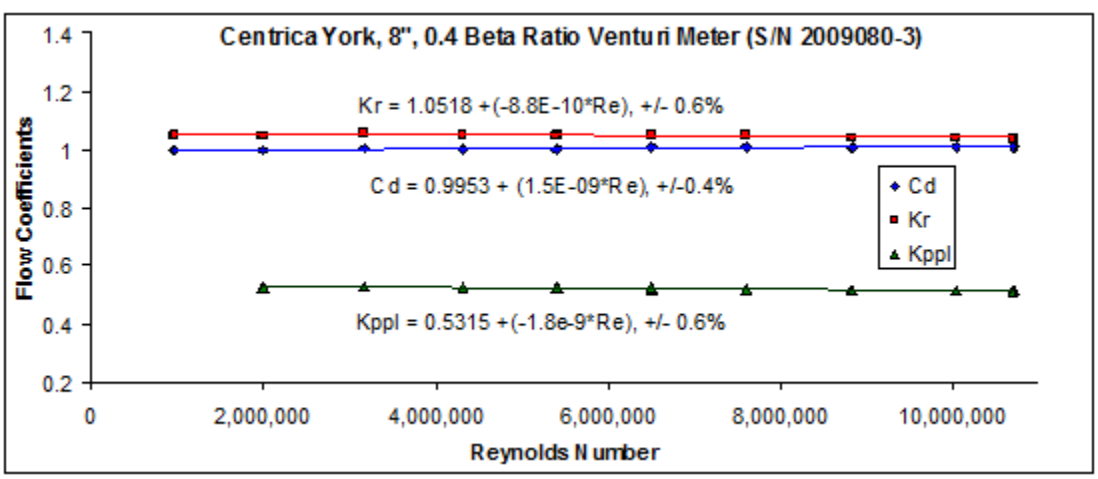

Fig 13. Venturi Meter (S/N 2009080-3) Flow Coefficient Calibration Results.

[2] These values are far less than typically used for orifice meter diagnostics. This is simply down to the fact that this meter has been calibrated, whereas the orifice meter relies on the ISO 5167 uncertainty statements.

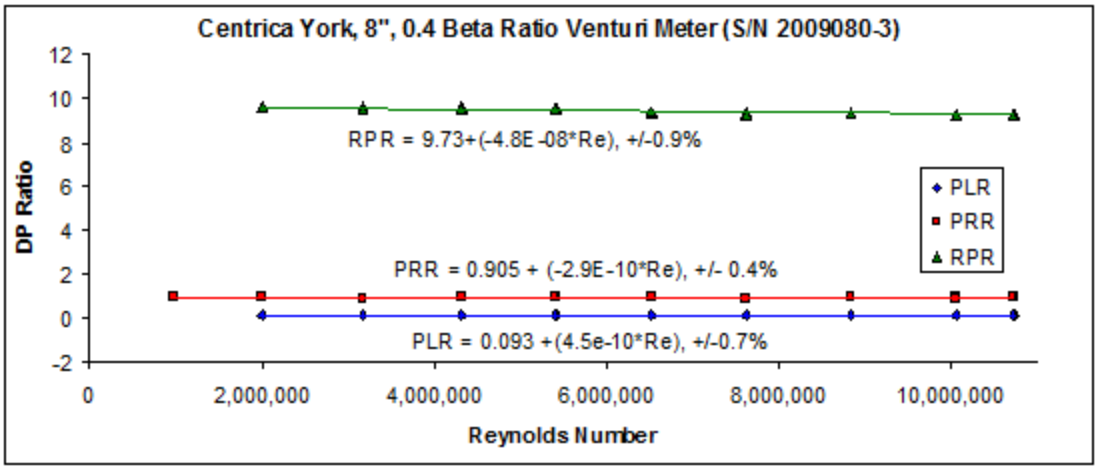

Fig 14. Venturi Meter (S/N 2009080-2) DP Ratio Calibration Results.

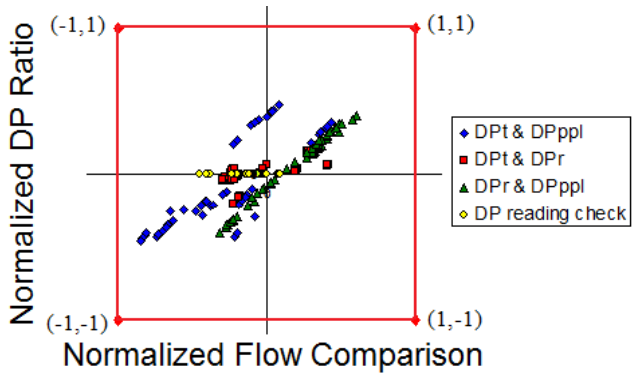

Fig 15. Baseline Calibration Data of S/N 2009808-3 on a Normalized Diagnostic Box.

4b. A PROBLEM WITH CENTRICA YORK 8", 0.4 BETA RATIO VENTURI METER

The Centrica York Venturi meter calibrations were witnessed by multiple observing engineers including staff from the flow laboratory, a Centrica employee, a Centrica contracted consultant, a York Platform contactor, a metering skid contactor and representatives from Swinton Technology and DP Diagnostics. During the test the data was scrutinized and double checked. DP Diagnostics confirmed the diagnostic calibrated parameters directly from the raw data in an independent report to Swinton Technology. These diagnostic results were subsequent used in the Prognosis Factory Acceptance Test (or "FAT").

After the calibration of this meter was complete and the multiple engineers on site 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. Swinton Technology duly initiated Prognosis pre-FAT procedures. The Prognosis software was configured with the meter geometry from this ***official*** calibration report. This act is the correct procedure. The meter's flow computer would almost certainly have the geometry inputted by an engineer reading it directly from the official calibration report. Swinton Technology then added the calibrated diagnostic parameters to the Prognosis software. Finally, in order to carry out the FAT, Swinton Technology then added sample flow data from the calibration, i.e. the raw DP's from one of the calibration flow points. The Prognosis software was then run on that data. As the meter had the calibration report's geometry values, diagnostic flow parameters derived from that calibration and actual DP's from that same calibration it was wholly expected that the diagnostics would show there was no problem with the meter. However, contrary to this expectation, **Prognosis immediately signaled a malfunction**. Figure 16 shows the resulting Prognosis diagnostic plot.

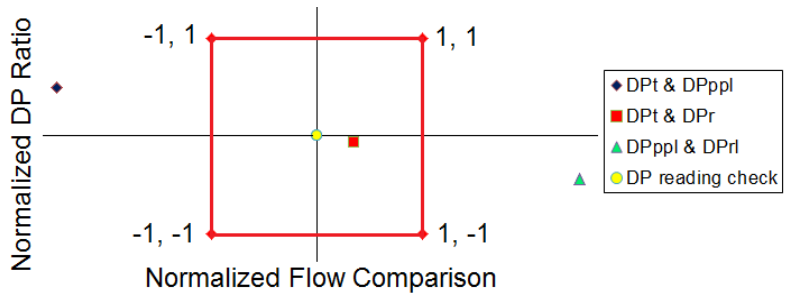

Fig 16. Prognosis Result at Centrica York 8", 0.4 Beta Ratio Venturi Meter FAT.

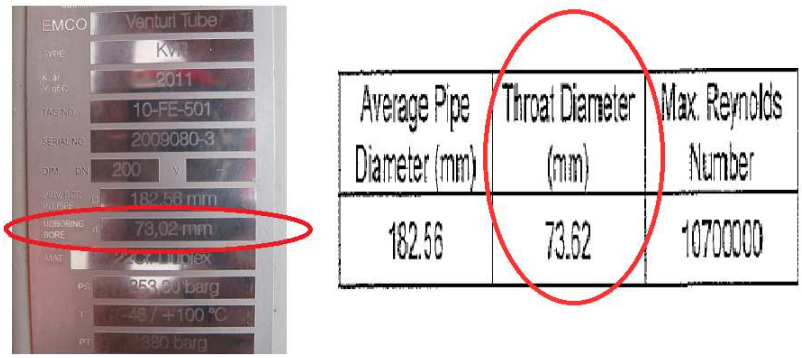

Fig 16a. Manufacturer and Calibration Report Stated Venturi Meter Throat Diameters.

There is a short list of possible malfunctions that cause such a diagnostic pattern on the NDB graph. The first possibility 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. Figure 16a shows on the left hand side a photograph of the manufacturer's meter label while on the right hand side a scan of the calibration report stated geometry. The 8", 0.4 beta ratio Venturi meter has a throat diameter of 73.**0**2mm. However, the calibration report lists the throat diameter erroneously as 73.**6**2mm. This then is the reason for the Prognosis system warning. After all the care of the calibration and all the multiple checks by multiple engineers a simple typographical error (most probably the result of the reading of a hand written "0" as a "6") had set the meter up to run with the wrong throat diameter. The difference in actual to reported throat diameter was approximately +0.8%. However, DP meters use the throat area to calculate the flow rate. Therefore, the associated throat area and flow rate error were double the throat diameter error at approximately +1.6%. None of the multiple engineers charged with monitoring the meter's calibration and in receipt of the calibration report spotted the typographical error. After Prognosis clearly indicated the problem the meter skid consultants were informed and the calibration report was re-issued with the correct Venturi meter geometry. If this meter was not diagnostic capable it would have in all likelihood ended up operating with a +1.6% bias. Such an error is financially significant but small enough to be hidden from a mass balance check. Such incidences of human error can never be totally eradicated from such procedures and only Centrica's prudent decision to include diagnostics with the meter saved the meter from running in the field with a bias.

4c. TWO CENTRICA YORK 6", 0.4 BETA RATIO VENTURI FLOW METER CALIBRATIONS

The two 6", 0.4 beta ratio Venturi meters were nominally identical, i.e. they were built to the same drawing with the same material specification, by the same manufacturing facility. The meter's serial numbers were S/N 2009080-1 and S/N 2009080-2. Both meters were tested at GL Flow Centre one after the other in the same calibration set up. The natural gas calibration system was run at approximately 50 Bar(a).

Figure 17 shows Venturi S/N 2009080-1 during calibration. The straight pipe length requirements of ISO 5167 are met. Flow is from right to left. Note the three pressure taps. The first two are the

Fig 17. 6", 0.4 Beta Ratio Venturi meter (S/N 2009080-1) at GL Flow Centre.

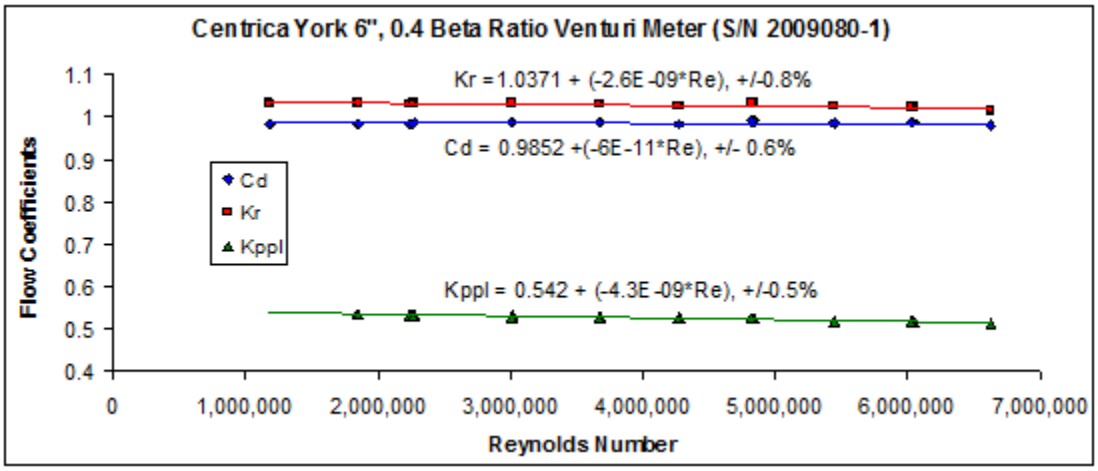

Fig 18. Venturi Meter (S/N 2009080-1) Flow coefficient Calibration Results.

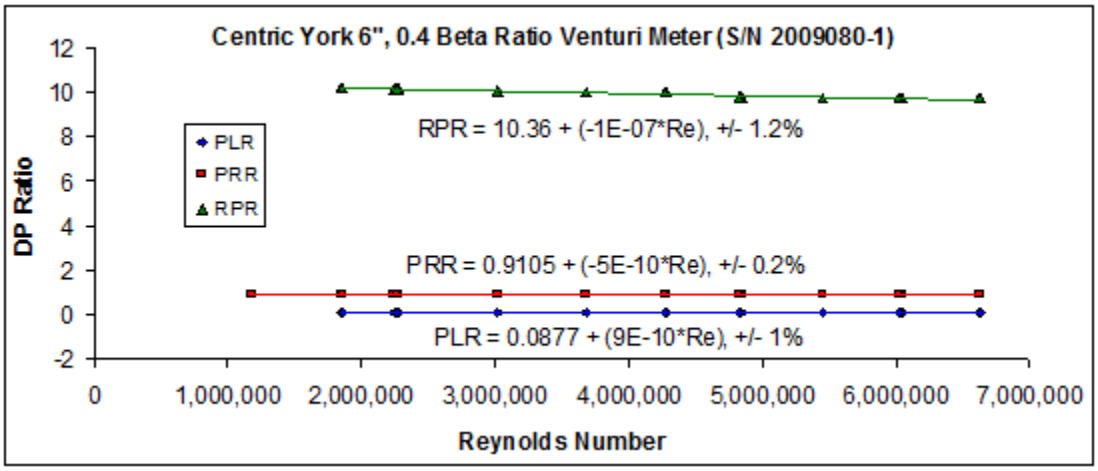

Fig 19. Venturi Meter (S/N 2009080-1) DP Ratio Calibration Results.

traditional pressure ports for the traditional meter. The third pressure tap downstream of the Venturi meter body is on the dedicated downstream spool supplied with the meter. Like with the Centrica 8" Venturi meter there are two thermo-wells between the Venturi diffuser exit and the pressure tap at 6D downstream of the diffuser exit. However, as the meter is being calibrated with these thermo-wells in place their affects are fully accounted for. Figures 18 & 19 show the diagnostic system calibration results for Venturi meter S/N2009080-1. Figure 20 shows this meters calibration diagnostic analysis on the NDB plot (for all DPs > 10 mBar). Figures 21 & 22

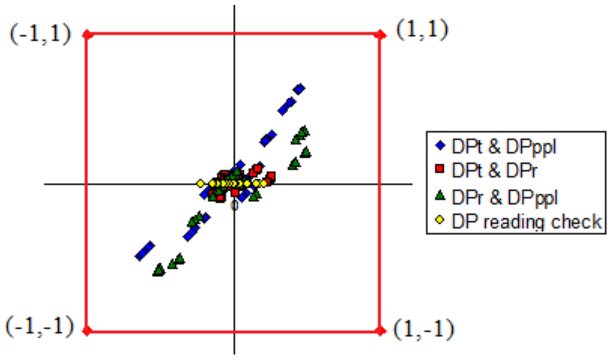

Fig 20. Venturi Meter (S/N 2009080-1) Calibration Data Plotted on the NDB.

show the diagnostic system calibration results for Venturi meter S/N2009080-2. Figure 23 shows all the S/N2009080-2 Venturi meter's calibration diagnostic analysis on the NDB plot (for all DPs > 10 mBar). During the calibration of both meters it was checked that equation 1 held at all times.

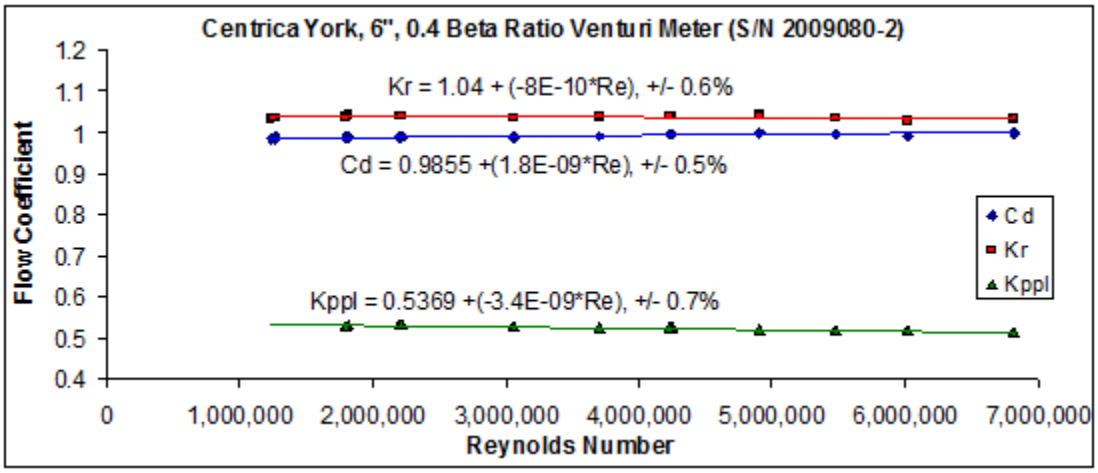

Fig 21. Venturi Meter (S/N 2009080-2) Flow coefficient Calibration Results.

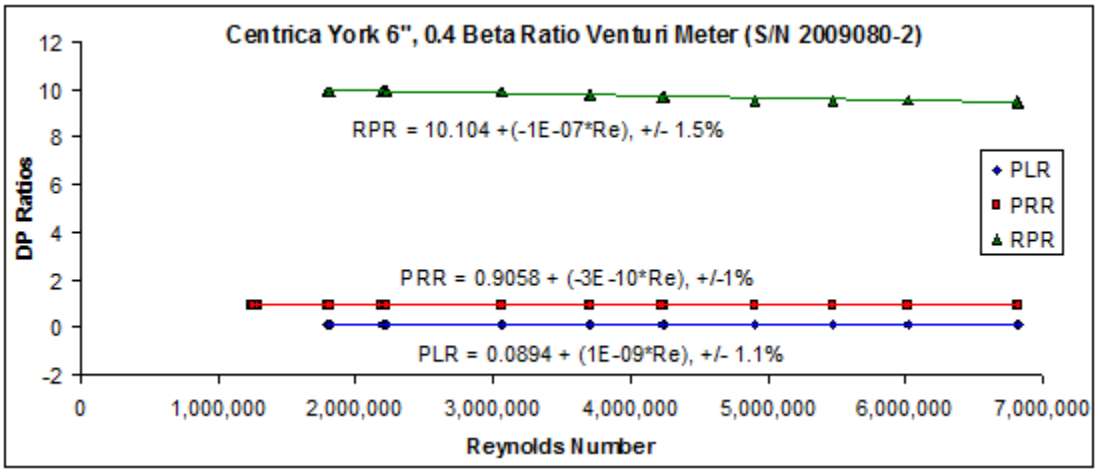

Fig 22. Venturi Meter (S/N 2009080-2) DP Ratio Calibration Results.

Figure 18 shows that the discharge coefficient, expansion coefficient and PPL coefficient for Venturi meter S/N 2009080-1 were fitted to 0.6%, 0.8% & 0.5% uncertainty respectively. As the diagnostic system is not metering the flow but checking the health of the meter slightly larger uncertainties are used to guard against false warnings. The uncertainties used for diagnostic

analysis were therefore set at 0.75%, 1.0% & 0.75% respectively. Figure 19 shows that the DP ratios PLR, PRR & RPR for Venturi meter S/N 2009080-1 were fitted to 1.0%, 0.2% 1.2% uncertainty respectively. Again, to avoid false warnings the uncertainties used in the diagnostic system were raised to default values of 1.5%, 1.5% & 2% respectively.

Figure 21 shows that the discharge coefficient, expansion coefficient and PPL coefficient for Venturi meter S/N 2009080-2 were fitted to 0.5%, 0.6% & 0.7% uncertainty respectively. To avoid any false warning the uncertainties used for diagnostic analysis were therefore again set slightly higher at 0.75%, 1.0% & 0.75% respectively. Figure 22 shows that for Venturi meter S/N 2009080-2 the DP ratios PLR, PRR & RPR were fitted to 1.1%, 1.0% & 1.5% uncertainty respectively. Again, to avoid false warnings the uncertainties used in the diagnostic system were raised to default values of 1.5%, 1.5% & 2% respectively.

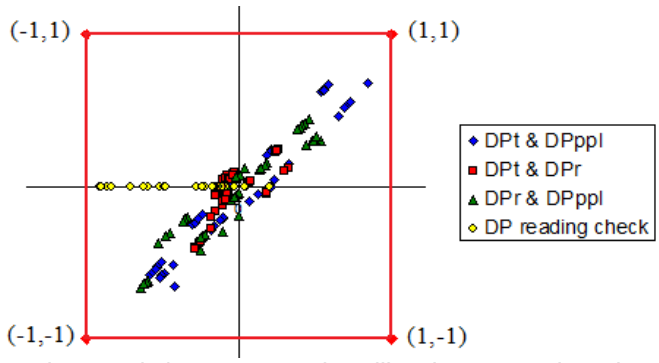

Fig 23. Venturi Meter (S/N 2009080-2) Calibration Data Plotted on the NDB.

4d. COMPARING TWO NOMINALLY IDENTICAL VENTURI METER CALIBRATIONS RESULTS

It is common for operators to order batches of nominally identical DP meters. Nominally identical DP meters built to the same drawing, from the same material, by the same manufacturer in the same fabrication shop by the same staff using the same fabrication equipment may look truly identical to the casual observer. They may even look identical after inspection. However, they are seldom truly identical. Manufacturing tolerances make each meter unique. Hence, batch meters are usually individually calibrated. Most meters so calibrated have the geometry values and calibration data / flow coefficient assigned to that meter's serial number (S/N) for future implementation in the meter's flow computer. Assigning the correct calibration information to each meter when a batch of "identical" meters have been individually calibrated is left to operator due diligence. If an error is made, and the wrong geometry values and calibration is assigned to a meter, then that meter's flow rate output will have a bias. As these meters are nominally identical, i.e. *almost* the same, these geometry differences and performance differences are relatively small and therefore any bias in the flow rate prediction is usually not obvious. Yet even a small unnoticed flow rate bias over time can lead to large monetary loss for the operators. However, if Prognosis is utilized with the DP meters such small biases can be seen. The nominally identical Centrica York 6", 0.4 beta ratio Venturi meter calibrations can be used to show this.

Table 2 shows the two Centrica 6", 0.4 beta ratio Venturi meter calibration results for the traditional discharge coefficient at various Reynolds numbers. It can be seen that meter S/N 2009080-1 has a discharge coefficient smaller than S/N 2009080-2. This is a typical result when multiple nominally identical Venturi meters are calibrated. The discharge coefficients are never identical which is why ISO 5167 states it is important to individually calibrate each gas Venturi meter. Therefore, if the calibration data of meters S/N 2009080-1 and S/N 2009808-2 get mixed up a bias is created on the respective meters. Traditionally there is no method available to indicate this.

Table 3 shows the same calibration results with respect to the PLR. The PLR difference between the meters is significantly larger than for the discharge coefficient. Such variance in nominally identical Venturi meter PLR values is typical, and this is why ISO 5167 Part 4 (2003) gives a

Re	2.E+06	4.E+06	6.E+06	8.E+06
Calibrated Cd S/N 2009080-1	0.9851	0.9850	0.9848	0.9847
Calibrated Cd S/N 2009090-2	0.9891	0.9927	0.9963	0.9999
% Difference	-0.40	-0.78	-1.2	-1.5

Table 2. Two Centrica York 6”, 0.4 beta ratio Venturi meter traditional calibration results..

Re	2.E+06	4.E+06	6.E+06	8.E+06
PLR S/N 2009080-1	0.0895	0.0913	0.0931	0.0949
PLR S/N2009080-2	0.0914	0.0934	0.0954	0.0974
% Difference	-2.08	-2.25	-2.41	-2.57

Table 3. The Centric York 6”, 0.4 beta ratio Venturi meter PLR calibration results

loose prediction of the PLR being somewhere between 0.05 and 0.2 (i.e. a PLR between 5% & 20%). Clearly, Table 3 shows the two PLR values are indeed in this range. However, clearly the two meter’s PLR values are different. The result of this PLR difference is that if Prognosis is employed this pair of diagnostic capable meters cannot be mistaken for one another. In fact this is just a single diagnostic example (i.e. point y_1 in a NDB plot). Other diagnostic checks can also indicate such an error. Figures 24 and 25 show the resulting NDB plots if the meter’s calibration results are accidentally swapped. Clearly Prognosis sees such a problem and therefore protects the operator against these potential biases. Furthermore, note that the diagnostic plots indicate the problem is not with the DP measurements. These results are not a coincidence. A similar but different example was given by Ayre [6] in 2011.

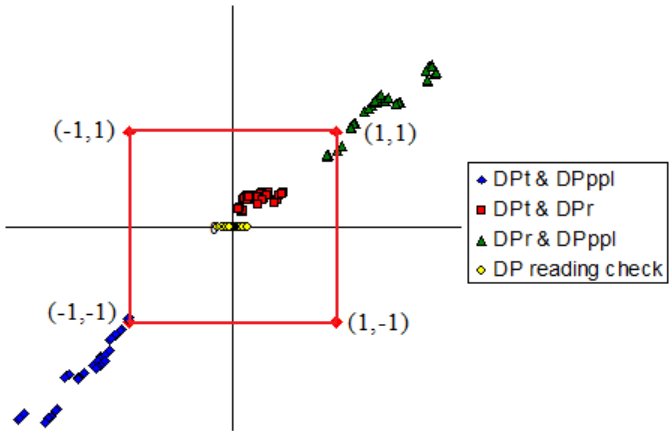

Fig 24. S/N 2009080-1 using S/N 2009080-2

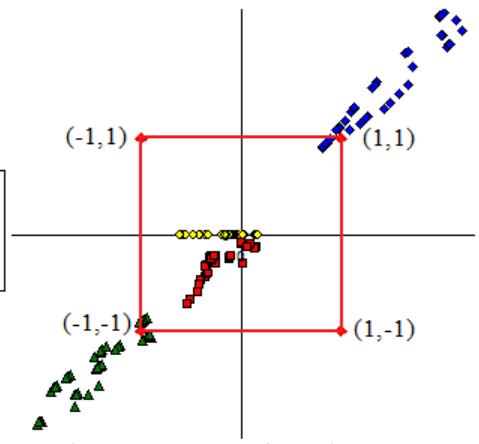

Fig 25. S/N 2009080-2 using S/N 2009080-1

4e. DIAGNOSTIC ALARMS FOR HYPOTHETICAL MALFUNCTIONS USING THE CENTRICA YORK 6”, 0.4 BETA RATIO VENTURI METER CALIBRATION DATA SETS

Like the above hypothetical example of the two 6” Venturi meters having their calibration data accidentally swapped, further hypothetical examples will now be shown to show the diagnostic system (Prognosis) in operation. These examples are hypothetical as the meters were correctly calibrated by GL Flow Centre. Examples that will be shown are an incorrect discharge coefficient keypad input (both high and low), a saturated traditional DP transmitter, a drifting DP transmitter (both high and low) and keypad entry errors for the inlet diameter (both high and low).

<u>Keypad Entry Error of Inlet Diameter Too High & Too Low</u>

The nominal 6”, sch 120 meter (S/N 2009080-1) has an inlet diameter of 5.501” / 139.73 mm. A nominal 6”, sch 80 meter has a listed inlet diameter of 5.76” / 146.3 mm. If, in way of an example, we input the diameter for a nominal sch 80 meter, the meter inlet diameter is entered as larger than it actually is. This causes a flow rate prediction negative bias. In fact, the Venturi meter is rather insensitive to such diameter errors. This incorrect diameter error of +4.7% corresponds to a negative bias of less than 1%, i.e. within the typical Venturi meter flow rate prediction

uncertainty of ±1%. However, although small, this is a bias and not an additional uncertainty. Hence, it is useful to be able to see and correct this error. The diagnostics are very sensitive to the issue. Figure 26 shows the result. Note that for the Venturi meter S/N 2009080-1 the correct diameter gave the diagnostic result shown in Figure 20.

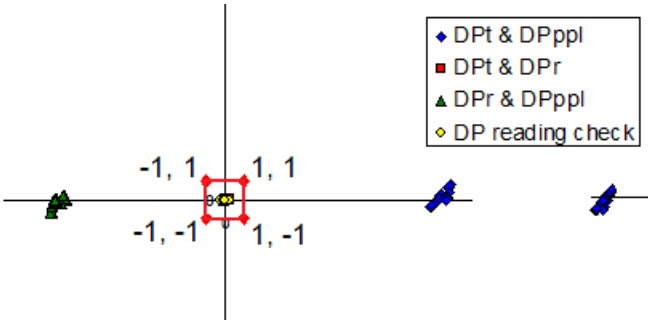

Fig 26. Inlet Diameter Entered Too High

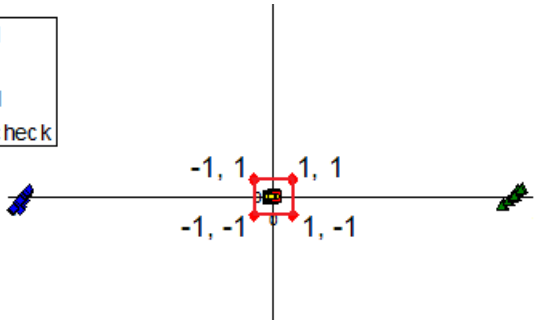

Fig 27. Inlet Diameter Entered Too Low

The nominal 6" sch 160 meter has a listed inlet diameter of 5.187" / 131.75 mm. If we input the diameter for a nominal sch 160 meter the meter inlet is entered as smaller than it actually is. This causes a positive flow rate prediction bias. Again, as the Venturi meter is rather insensitive to diameter errors this incorrect diameter error of -5.67% corresponds to a positive bias less than 1%. However, the diagnostics are very sensitive to the issue. Figure 27 shows the result. Note in both cases, the diagnostic results in Figures 26 & 27 indicate correctly that the DPs are reliable.

A Saturated DP Transmitter

All DP meters are wholly dependent on their secondary instrumentation working correctly. A common problem is the actual traditional DP being produced being of higher value than the maximum value the DP transmitter can measure. In such a situation the DP transmitter is said to be "saturated". A saturated DP transmitter does not always have any warning associated with it. When saturated most DP transmitter designs continue to send a DP value to the flow computer, but this value is the DP transmitter's upper DP limit, not the correct higher DP value. Hence, a saturated DP transmitter causes the DP to be under-read and therefore causes a DP meter to under-read the actual flow rate. An example is now given showing the diagnostics response to this scenario.

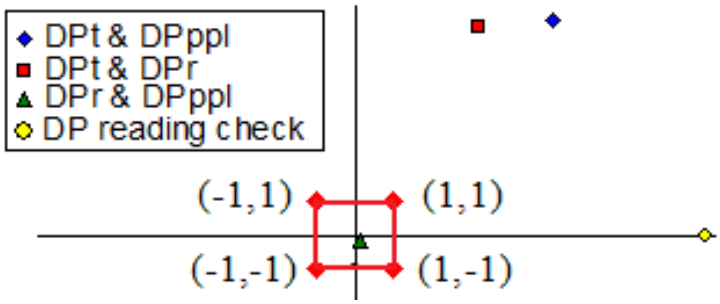

Fig 28. Saturated Traditional DP Transmitter.

Let us consider the GL Flow Centre's calibration data for meter S/N 2009080-1. During one calibration run the actual traditional DP was 1.091 Bar. In reality the GL Flow Centre of course read the correct value. However, let us imagine that scenario in the field where the DP transmitter was spanned to read 1.00 Bar at 20mA. If this was the case then the transmitter would have read 1.00 Bar when the actual DP was 1.091 Bar. Let us consider what the consequences would have been for the meter output if the traditional DP transmitter was saturated at 1.00 Bar. The error in the traditional flow rate prediction would have been approximately -4.3%. For this example, let us assume that this is the only DP transmitter that is saturated. (The diagnostics still indicate a meter system DP reading malfunction if there is more than one of the three DP transmitters saturated, but that is another scenario not discussed here due to lack of space.)

Figure 28 shows the diagnostic result. Prognosis correctly warns of a meter system malfunction. However, the pattern on the NDB gives more information. The DP reading check shows a very clear indication that there is a problem with the DP readings. Furthermore, both the traditional DP & PPL diagnostic pair and the traditional & recovered DP diagnostic pair have moved into the first quadrant, i.e. both the PLR and PRR have both become larger than their calibrated values. However, as equation 1a is a consequence of the first law of thermodynamics, it cannot be violated. This means that any physical problem with the meter body that causes the PLR to shift in one direction from the correct operating value ***must*** also cause the PRR to shift in the opposite direction. That is, no physical problem with the meter body can cause DPs to behave in the way shown in Figure 28. Hence, such a diagnostic pattern reinforces the DP reading check warning by showing that at least one of the DPs cannot be correct. In Figure 28, the recovered DP and PPL diagnostic pair show no problem with either the DP ratio or flow meter comparison checks. The two points showing a problem have one common DP, the traditional DP. Hence, Prognosis has shown the meter has problem, it is a problem with the DP readings, and in particular it is a problem with the traditional DP reading. Once, it is established that the recovered DP and PPL are correct then the flow rate prediction from the expansion meter or the PPL meter can be trusted. Alternatively, equation 1 may be utilized to correctly infer the traditional DP and therefore the correct flow rate. Therefore, for DP reading error scenarios, by comparing the correct flow rate prediction to the erroneous flow rate prediction Prognosis can even indicate the size of the flow rate error due to the identified malfunctioning DP transmitter.

Incorrect Keypad Entry of Flow Coefficients

A Venturi meter is traditionally calibrated to find the discharge coefficient. Hence, just like the real example of the wrong throat diameter being used above, there is the risk of human error when keypad entering the DP meters calibrated discharge coefficient into the flow computer.

At GL Flow Centre is was found that the 6”, 0.4 beta ratio Venturi meter S/N 2009080-1 had Cd= 0.9852+(-6E-11*Re) ±0.6% (as shown in Figure 18.) A more precise fit as done for the primary measurement flow computer reduces the uncertainty of this meters discharge coefficient to <0.5% for the primary flow rate prediction. However, again note that this level of calibration is all that is required to offer detailed DP meter diagnostics. Let us consider hypothetical examples of wrong discharge coefficient values being keypad entered to the flow computer.

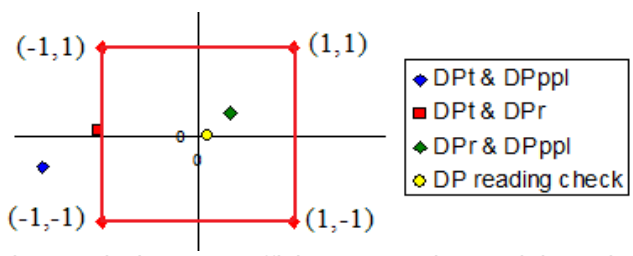

Fig 29. Discharge Coefficient Entered Too High

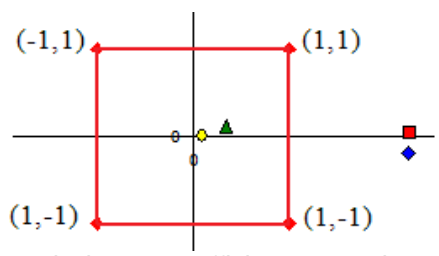

Fig 30. Discharge Coefficient Entered Too Low

For the first discharge coefficient example, consider the scenario of the discharge coefficient being set at unity (i.e. a random high discharge coefficient example) while the other diagnostic parameters are correctly used. This produces a +1.95% flow rate prediction bias. The resulting diagnostic plot is shown in Figure 29. For the second example, let us consider flow computer entry for the discharge coefficient that gives an approximately equal and opposite bias to the first discharge coefficient example, i.e. a discharge coefficient constant value of 0.96. In this case a -2.1% flow rate prediction bias is produced. The resulting diagnostic plot is shown in Figure 30.

Both scenarios produce diagnostic results that indicate a problem. In both cases the DP reading check correctly indicates that there are no problems with the DPs being read, thereby suggesting the problem is related to the meter body. Also, no DP ratio pair indicates any problem exists (thereby re-enforcing the suggestion DP readings are correct). Furthermore, in both cases comparisons of the expansion and PPL flow rate predictions do not indicate a problem while the

other two flow rate comparison pairs do indicate there is a problem. The communal flow rate prediction for the two flow rate comparison pairs is the traditional flow rate prediction. We therefore know the traditional flow rate prediction has a problem. However, from the diagnostic pattern it is known that the meter geometry is correct (as the expansion and PPL flow rate predictions are unaffected) and the DP's are being read correctly. Hence, the problem must be with the discharge coefficient entry. Once, the discharge coefficient keypad entry error is found, the other two flow rate predictions are known to be trustworthy, although correcting the discharge coefficient in the flow computer will immediately fix this problem.

A Drifting (or Incorrectly Calibrated) DP Transmitter

A DP transmitter has a raw output scaled between a nominal range of 4 & 20mA. The exact current that represents no DP or maximum DP is not always *exactly* 4mA or 20mA respectively. Hence, each DP transmitter is calibrated to link the precise maximum and minimum current to maximum and minimum read DP. DP transmitters can drift away from these calibration values over time, or the DP transmitter calibration can be incorrect from the outset. The diagnostic system monitors for such DP reading issues.

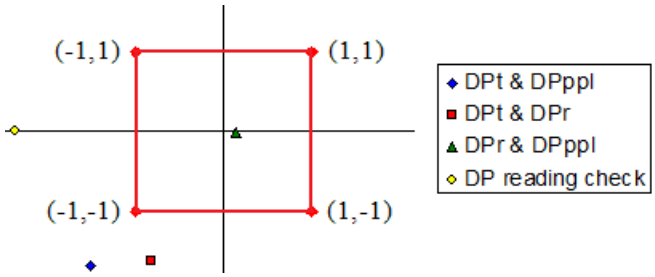

Fig 31. DP Transmitter reading high.

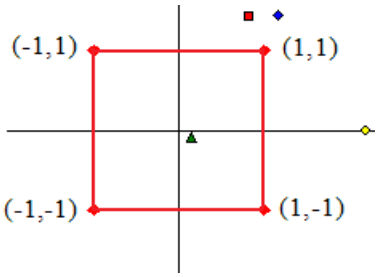

Fig 32. DP Transmitter reading low.

As an example, we again shall consider a point from the 6", 0.4 beta ratio Venturi meter S/N 2009080-1 calibration. The actual (correctly read) DPs were DPt =1.091 Bar, DPr = 0.992 Bar & DPppl = 0.102 Bar. However, let us consider the scenario where the traditional DP transmitter has drifted from its calibration values. Let us say, the traditional DP transmitter incorrectly reads 1.12 bar instead of 1.091 bar. This will create a traditional flow meter flow rate prediction error of +1.2%. The diagnostic result is shown in Fig 31. However, DP transmitters can drift in either direction. Therefore consider the scenario when the traditional DP transmitter incorrectly reads 1.070 bar instead of 1.091 bar. This will create a traditional flow meter flow rate prediction error of -1.1%. The diagnostic result is shown in Figure 32.

The traditional DP being low due to transmitter drift gives a similar diagnostic pattern as the saturated DP transmitter scenario. The DP transmitter drifting low is effectively the same scenario to Prognosis as the saturated DP transmitter. The traditional DP reading is low. It is therefore not a coincidence that Figure 28 (for a saturated DP transmitter) and Figure 32 (for a DP transmitter reading a low DP due to drift or incorrect DP transmitter calibration) are the same pattern that can be analyzed to give the same conclusion – i.e. the metering system has malfunction, the problem is with the DP readings and in particular with the traditional DP reading which is reading low. Note that Figure 31 represents the scenario of the traditional DP transmitter reading high. It is almost a mirror image of Figure 32.

It should be noted that these examples pick the traditional DP transmitter to have the problem (e.g. saturated, drifting or incorrectly calibrated). In reality a DP meter with three DP transmitters can have any (or more than one) of the three DP transmitters malfunctioning. The traditional DP transmitter is chosen here as an example as it directly effects the traditional flow rate prediction. However, if the recovery or PPL DP transmitters malfunctioned the diagnostics would indicate a system malfunction and which DP transmitter had malfunctioned. Therefore, in these scenarios the diagnostics self-diagnose that there is a problem with the diagnostic system. A real example of this is now discussed in section 5.

5. A PETRONAS DIAGNOSTIC READY WET GAS FLOW", 0.7 BETA RATIO VENTURI METER

In 2010 Petronas dry gas flow calibrated and wet gas flow tested a DP Diagnostics built 6", 0.7 beta ratio Venturi meter at CEESI. This Venturi was to meter a wet natural gas production flow on an unmanned offshore platform in SE Asia. This meter was therefore labeled "a wet gas Venturi meter" from the outset.

Petronas planned to carry out normal wet gas Venturi meter procedures. That is, they would read the traditional DP and predict the gas flow rate. However, as the gas is known to be wet the traditional DP, and hence the gas flow rate prediction, would have a positive bias induced by the liquid phase (see Vijay et al [6,7]). In order to meter the gas flow rate Petronas would therefore apply "a wet gas correlation", i.e. a correction factor, to remove the bias induced by the liquid. Such correlations require that the liquid flow rate is an input to the correction factor. The liquid flow rate is typically found by a tracer dilution technique. This technique is a spot check that estimates the liquid flow rate at the point in time in which the tracer dilution technique is carried out. The operator then applies this spot liquid flow rate estimate to the correction factor continuously as the meter operates. The assumption here is that the liquid flow rate estimate remains constant over time. However, it is known that this may not be the case. The liquid flow rate therefore requires monitoring. The common "liquid loading" monitoring technique internal to the Venturi meter system is the monitoring of the PLR. The PLR is known to be sensitive to wet gas flow. A significant change in the average PLR over time would signal a change in liquid loading and another tracer dilution test would find the new liquid flow rate. This practice was first suggested by Shell in the 1990's (e.g. de Leeuw in 1997 [9]) and is now relatively common practice in the natural gas production industry. However, the whole procedure inherently relies on the PLR measurement being trustworthy. Unfortunately wet gas flow is a very adverse flow condition for DP transmitters compared to dry gas flow service. Problems include:

- Severe slugging which causes DP spikes, which can cause premature DP transmitter drift,
- Higher standard deviations in DPs than with single phase gas flows causing premature drift,
- Significantly higher DP's for the same gas flow without the liquid present, meaning saturated DP transmitter/s is a significant possibility
- Water based wet gas flow can deposit hydrates, scale, salts & wax that can plug impulse lines.

Hence, wet gas Venturi meters have a higher possibility of DP transmitter problems than dry gas DP meters. If the DP readings on the Petronas wet gas Venturi meter were not trustworthy then the system could give traditional gas flow rate prediction errors in addition to those imposed by the liquid's presence thereby rendering the wet gas correction factor ineffective. Furthermore, such a wet gas meter also relies on the traditional and PPL DP transmitters measuring correctly in order to predict the correct PLR. If one (or both) of the DP transmitters is / are in error, then the liquid loading monitoring sub-system of the wet gas meter has malfunctioned. However, Prognosis is effective at monitoring the health of the DP measurements with wet gas Venturi meters. Petronas therefore specified that this meter was to include Prognosis.

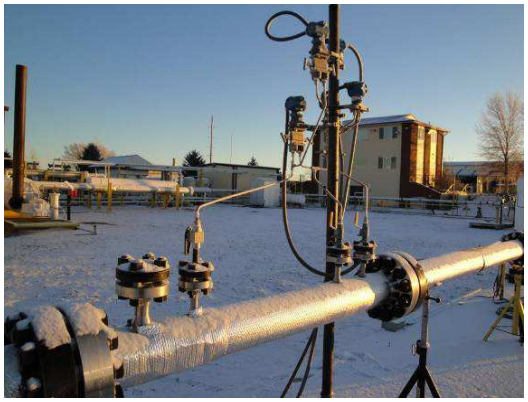

Fig 33. Venturi meter wet gas tests, CEESI.

Fig 34.Venturi Meter Off-Shore in Malaysia.

The initial CEESI calibration (see Figure 33) and wet gas test results, including the Prognosis results, were described in detail by Vijay et al [6,7]. Table 4 shows the CEESI dry gas flow constant value calibration results. In January 2012 Petronas started the commissioning of this wet gas Venturi meter. Figure 34 shows the meter installed off-shore. Prognosis is currently monitoring the fully serviceable meter. On the initial commissioning Prognosis signaled that the metering system was fully serviceable. A screenshot of the diagnostic result was sent to Swinton Technology from the platform in February 2012 (see Figure 35). The meter geometry and the temperature and pressure (of 65°C and 85 Bara) were taken from the main flow computer. The gas density of 59.5 kg/m^3 was keypad entered into the Prognosis software.

Parameter	Value	Uncertainty	Parameter	Value	Uncertainty
Cd	1.014	+/- 1%	PLR	0.067	+/- 5%
Kr	1.047	+/- 2%	PRR	0.934	+/- 2%
Kppl	2.205	+/- 2%	PRR	14.03	+/- 4%

Table 4. Venturi Meter Constant Value Calibration Results.

The Prognosis software used on this flow meter is the first generation software where the fourth diagnostic point, i.e. the DP reading check, is not included. However, the diagnostic method is included in a numerical check in the bottom left hand side of the Prognosis screen. Note that below the three diagnostic co-ordinates the traditional DP is inferred by summing the read recovered & PPL DP readings. This then allows a comparison between the inferred and read traditional DP. (That is, equation 9 is effectively being checked.) Here we see the read DP was 200.29 mBar and the inferred DP is 201.21 mBar, i.e. a difference of +0.46%, which is well within the nominal 1% threshold for a DP reading warning set by Prognosis. Hence, on initial commissioning Prognosis showed the DP's were all read correctly.

Prognosis also indicated a very significant meter malfunction warning. Note that in Figure 35 all three points are far from the NDB. However, this is the pattern Prognosis creates when the meter is exposed to wet gas flow. Wet gas flow was expected so this was the correct Prognosis response. The particular liquid loading caused that particular diagnostic pattern. The diagnostics could then be "zeroed" to that liquid loading. (For details on how the zeroing technique works see Skelton et al [3]). Figure 36 shows the same data as Figure 35 after the system has been zeroed with $Z = PLR_{actual} – PLR_{calibrated} = 0.085$ to that particular wet gas liquid loading.

No further data was fed back to Swinton Technology or DP Diagnostics for several months. The unmanned platform has no external communications with which the computer running Prognosis could relay information. In July 2012 after personnel visited the platform Swinton Technology were given two days of archived files from Prognosis. However, Prognosis now showed a meter system malfunction. In particular the DP reading check was indicating a very significant DP reading problem. Figure 37 shows a screen shot. The recovered DP was read as significantly higher than the traditional DP (which is impossible), with the PPL being approximately the same as the traditional DP (which is highly unlikely). The percentage difference between the read and inferred traditional DP can be seen to be 251%. Clearly there was a serious issue with the DP transmitters. Petronas was informed. An investigation discovered that modifications to the Flow Computer (S600) after the initial commissioning had led to incorrect scaling being applied in the flow computer to the recovered and PPL DP's. Hence the recovered and PPL DPs were incorrect while the traditional DP was correct. (It was noted that the displays on the three DP transmitter heads still showed the correct values thereby suggesting to the maintenance crew that the DP readings were correct.) The main meter was therefore operating correctly, but the PLR liquid loading monitoring sub-system had malfunctioned. The scaling problem was rectified and the Prognosis DP reading check immediately switched to indicating no problem. A screenshot of the resulting Prognosis result (with no zeroing) is given as Figure 38. Note that the DP check shows a difference between the read and inferred traditional DP of 0.595%, i.e. less than the nominal DP reading warning threshold of 1%. The diagnostic plot has returned to the typical pattern seen with wet gas flow. This was again zeroed, this time with Z = 0.099. The resulting Prognosis screenshot is shown as Figure 39.

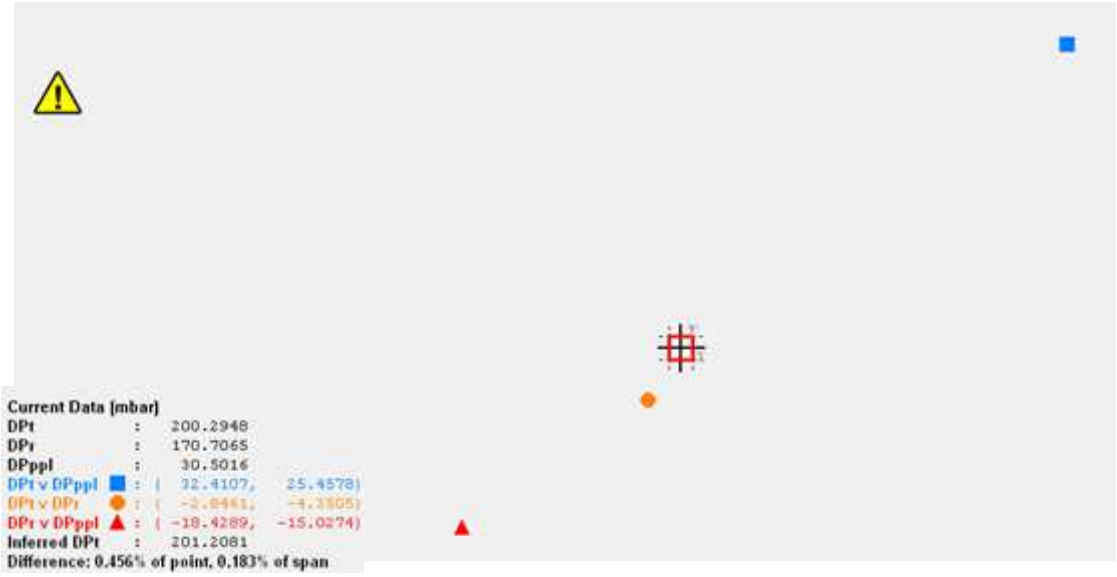

Fig 35. Correct Results for Prognosis on Initial Venturi Meter Commissioning Off-Shore Malaysia.

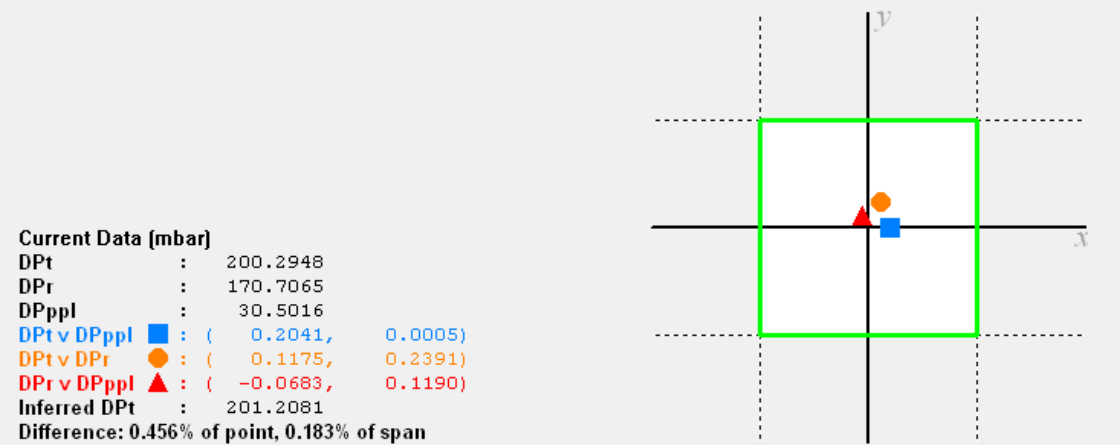

Fig 36. The Initial Venturi Meter Commissioning Data Zeroed to the Particular Liquid Loading.

Fig 37. Prognosis Screenshot from July 2012 Showing DP Reading Anomalies.

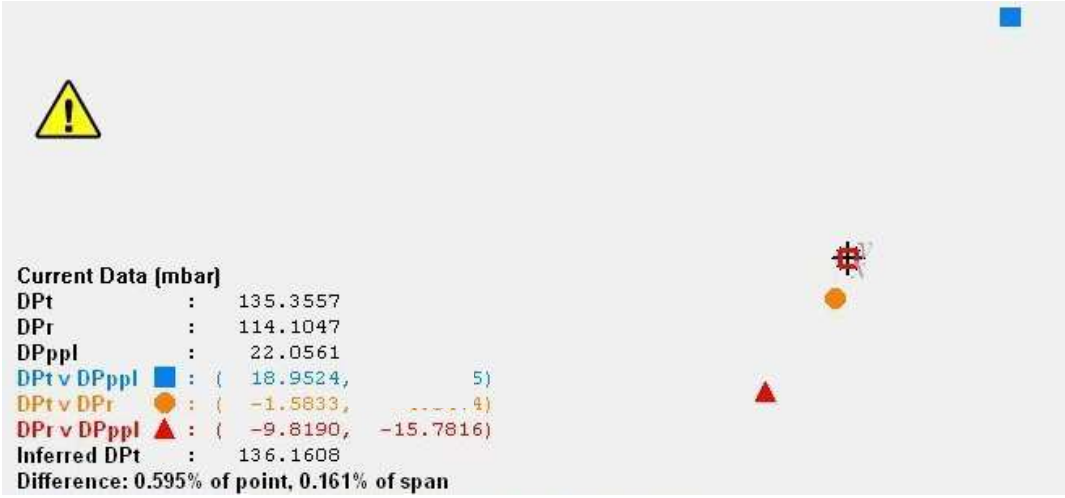

Fig 38. Prognosis Screenshot from July 2012 After DP Readings Corrected, No Zeroing Applied.

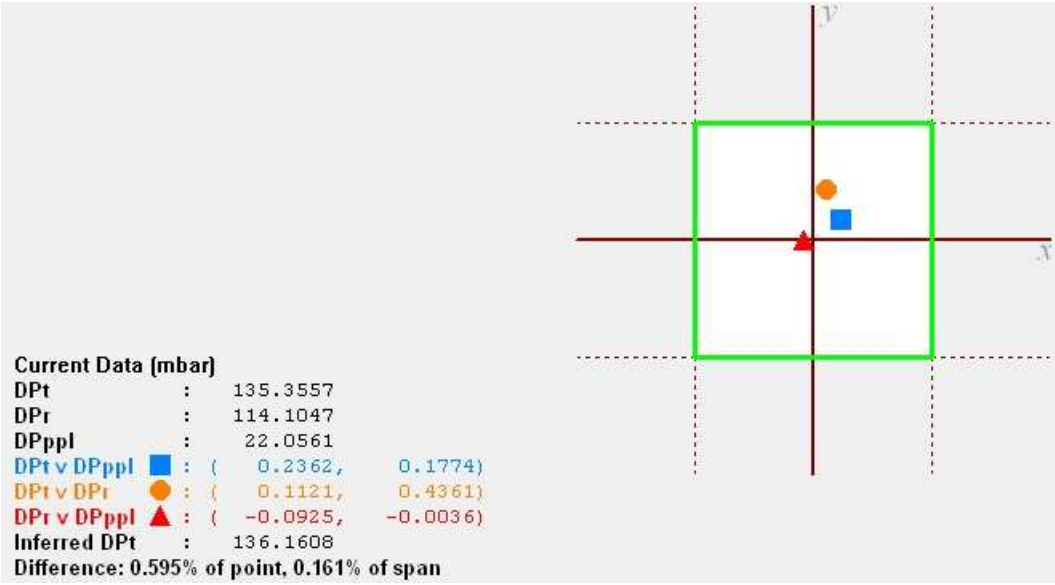

Fig 39. Prognosis Screenshot from July 2012 After DP Readings Corrected and Zeroed.

Table 4 shows the correctly operating Venturi meter with dry gas has a PLR of 0.067. Between February and July the zeroing factor changed from 0.085 to 0.099, meaning the actual PLR was 0.152 and 0.166 respectively. Therefore, between these months the actual PLR had increased by approximately 9%. The uncertainty in the base PLR value was 5%. As an increasing PLR indicates an increasing liquid loading, the liquid loading of the wet gas flow has evidently increased in this period. (Note however, that the PLR value for a given Venturi meter with wet gas flow is dependent not just on the liquid loading, but also the gas to liquid density ratio and gas flow rate. A discussion on this relationship is beyond the scope of this paper.)

Prognosis on this meter is set to poll data every second, average the last ten seconds data every second and update the Prognosis screen every second with the result of that averaging. Every tenth update (i.e. every tenth second) Prognosis archives the update. After the DP readings were corrected the subsequent logged data showed that the zeroing factor Z = 0.099 held the three points in the NDB for 99.7% of all the logged time. That is, the points only occasionally exited the NDB and when they did it was momentarily before returning to within the NDB with no intervention from an operator. Likewise, the DP reading check showed similar behaviour. Equation 1 was seen to hold 99.7% of the same logging time to 1.3% (instead of the nominal

1%). This is typical for wet natural gas production flows. Such flows are by their nature only pseudo-steady. The liquid loading can change slightly in a random manner from moment to moment, even if the average liquid loading over time is relatively steady. If the average of these diagnostic results are taken over a few minutes, rather than a few seconds the diagnostic result averages out to show a pseudo-steady wet gas result. Averages of PLR values read over long periods are advised (whether using Prognosis or not) before making decisions on liquid loading shifts and tracer dilution requirements.

The Prognosis monitoring of the Petronas wet gas Venturi meter performance installed on an unmanned platform was precise and correct. The initial data received was correct and the Prognosis system confirmed the DP's were being measured correctly and that the gas flow was wet. A zeroing factor was then set. Subsequently, due to a real operator error associated with flow computer inputs (rather than a staged error to check the diagnostic system), the recovered and PPL DP readings became false and Prognosis immediately noted a DP reading anomaly. In this case the traditional meter continued to work but the two extra DP readings were incorrect and the wet gas Venturi meter's liquid loading monitor sub-system had a genuine malfunction. Prognosis showed a malfunction had occurred and the source of that problem was with the reading of the DPs. Once this problem was fixed Prognosis correctly monitored the liquid loading. In fairness, the scale of this DP reading / PLR system malfunction was such that it could have been noticed without Prognosis the first time Petronas checked the PLR value. However, crucially, Prognosis could have seen a similar problem *far* smaller than the real one it was presented with and indeed far smaller than any operator could be reasonably expected to see with standard procedures. If even one of the three DP transmitters was incorrect by say 2% over a period just a few minutes the diagnostic system would have set a warning. That is Prognosis, is *very* sensitive to DP reading problems with single phase and wet gas flow Venturi meters and is therefore a valuable addition to any dry or wet gas flow Venturi meter application.

6. ORIFICE METER AUDITING EXPERIENCES WITH PROGNOSIS

Since the introduction of DP meter diagnostics in 2010 there have been some claims that unlike other meter diagnostic systems which are integral to the meter, such as the Ultrasonic meter (or "USM") diagnostics, these DP meter diagnostics are an external add on to the DP meter. However, what constitutes integral diagnostic systems and what constitutes external diagnostic systems is simply down to perception. There are no rules to govern such labeling. Furthermore, there is a strong argument for refuting such claims.

The DP meter diagnostics monitor the health of a DP meter by monitoring the health of the DP meter's pressure field. This pressure field is integral to each and every DP meter regardless of whether the diagnostics are applied or not. The pressure field is at the core of the DP meter's basic operation. With no pressure field there is no DP meter. In order to monitor the pressure field an extra downstream pressure tap is required (if it does not exist anyway) along with two extra DP transmitters. Are these external sub-systems? The answer is wholly dependent on your perception.

In way of an analogy let us consider the Ultrasonic meter (USM). Almost everybody would say USM diagnostics are integral to the meter. The USM uses pairs of transducers to send and receive pulses between these transducers. From the difference in time to send the pulse with and against the flow, and a known distance between the transducers, the USM can find the average flow velocity across that transducer pair's path. For a fully developed (or distorted but known) velocity profile a USM could therefore predict the flow rate from one pair of transducers, i.e. one path. In fact, there are one path USMs. Each pair of transducers has diagnostic capabilities. They can monitor the standard deviation of repeat readings (i.e. the USM "turbulence" diagnostic). They can predict the speed of sound (as a by-product of the average flow velocity measurement) and compare it to the reference value. They can monitor the noise of the signal and monitor whether they need to boost the signal and by how much. In short, a one path USM can meter the flow rate and have some diagnostic capability. So why then do most custody transfer USMs have multiple transducers, i.e. multiple paths? The answer is to improve the meters accuracy and to

improve the meter's diagnostic system. Multiple transducers produce a better picture of the velocity profile as well as multiple diagnostic results. More diagnostics can be created by cross referencing the different path information, such as the USM "profile" diagnostics. By adding extra ports with extra transducers to make extra paths the USM manufacturer improves the meters ability to monitor the velocity profile and strengthens the quality of the meters diagnostics. Such multiple path USMs are indeed excellent meters. However, in order to:

a) better monitor the velocity profile and improve the meters diagnostics, the manufacturer must
b) physically add extra transducer ports and fill them with extra transducers (i.e. extra instrumentation) and then add the extra diagnostic software to the Flow Computer.

Nevertheless, industry still says the multiple path USM diagnostics are fully integral to the USM meter as they perceive the extra ports, transducers and software as critical to the meter and hence not an add on. Let us now look at the DP meter diagnostics. In order to:

a) better monitor the pressure field and improve the meters diagnostics, the manufacturer must
b) physically add an extra pressure port and add extra DP transmitters (i.e. extra instrumentation) and then add the extra diagnostic software to the Flow Computer.

So what's the difference!? Both meters have physical port additions, extra instrumentation and extra software to better monitor the flow and improve diagnostics. The only difference is ***perception***. Industry is used to the multipath USM design and therefore sees it as an integral unit. Industry is used to the basic DP meter configuration and is not used to the change in configuration to make it diagnostic capable. Hence, they ***perceive*** the change to the DP meter as external to the basic unit. However, the DP meter diagnostic system is really not an add on, it is just as integral to the DP meter as the USM diagnostic systems.

There are few operators that would be comfortable running a custody transfer USM without its diagnostics fully serviceable. The same operators are comfortable running a custody transfer DP meter without diagnostics. The sole reason is they are used to USMs having diagnostics and they are just as used to DP meters not having diagnostics – on the grounds that until 2008 it was a widely accepted false axiom that DP meters could have no diagnostics. DP Diagnostics therefore promotes the idea that DP meters should have this integral diagnostic system permanently operational just as USMs all have their diagnostic system permanently operational. As such, the concept of a portable DP meter diagnostic system is not promoted. However, in 2011 a US meter station audit company (CMSI) requested such a portable system. With the view of obtaining further field data special allowance was made and a one off portable system was supplied. The following are examples of this system being applied on live natural gas flow orifice meters during station audits. The diagnostic parameter uncertainties used were as stated in x=1%, y=2.5%, z=2.5 a=3%, b=2.5% & c=4%. The ownership and location of the metering stations is blinded.

6a) AUDIT 1: A 10", 0.6383 BETA RATIO ORIFICE METER

Fig 40. Audit 1 Meter Run

A 6", 0.4947 beta ratio flanged tapped orifice meter was audited. The client had no particular concerns about the meter and the audit was only part of the routine maintenance schedule. The natural gas flow meter was operating at 858 psia / 59 bara at 95^0 F. The flow rate was approximately 490 MSCFD (2.8 kg/s). The auditors installed both a clamp-on USM and Prognosis on the meter run. Figure 40 shows the meter run prior to the installation of Prognosis (and a clamp-on USM). Note that the downstream spool already had a suitable downstream pressure tap. This is a common trait amongst existing orifice meter runs.

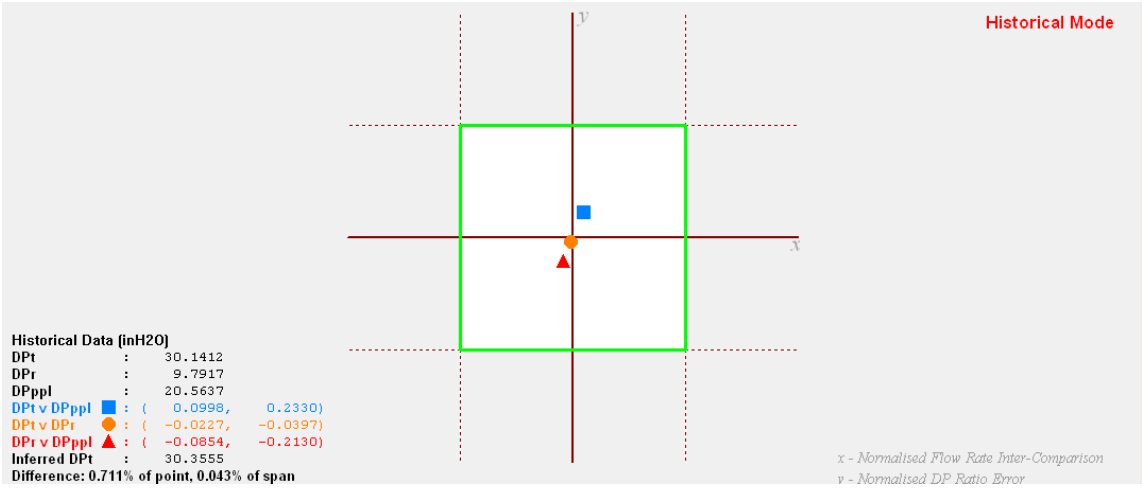

Figure 41. Audit 1's sample representative Prognosis screenshot.

Figure 41 shows an actual screenshot from Prognosis running on the meter. The DP reading diagnostic check indicates that the DP's are being read correctly, with a 0.71% difference being noted between the inferred traditional DP of 30.356 "WC and the read traditional DP of 30.14 "WC. This is lower than the nominal 1% DP reading warning threshold. The three diagnostic points are well inside the diagnostic box, and scattered around the origin. Prognosis was applying *internal* diagnostics to this orifice meter to show that the meter was fully serviceable, measuring the correct flow rate and did not need any maintenance.

Due to contractual obligations and the fact that Prognosis was seen as 'on trial' the auditors continued with the audit procedure. A clamp on USM was installed to allow comparison between the orifice meter and USM flow rate predictions. The over-all uncertainty of a correctly operating orifice meter system is considered to between 0.7% & 1%. The uncertainty stated for the clamp-on USM was 3%. Therefore, when comparing the two meters the difference between them should not be more than the root mean square of these uncertainties, i.e. approximately 3%. The actual difference was < 3%. Figure 42 shows the two meter's flow rate prediction comparison. The error bands for each meter per point are given. They overlap thereby indicating that there is no significance difference found between the meters. This gave confidence that the orifice meter was operating correctly. However, compelling as this result is, it does **not** guarantee that the orifice meter has no issues.

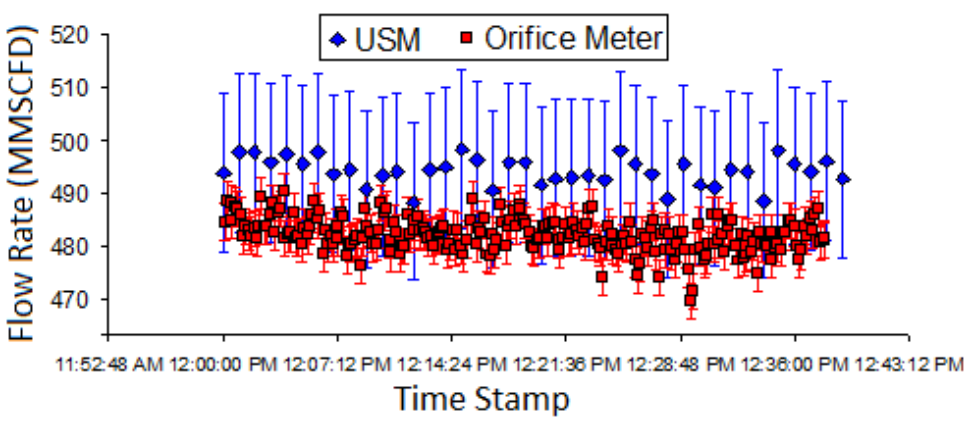

Figure 42. Audit 1's comparison between the orifice meter and the USM.

The comparison of a clamp-on USM with an orifice meter is not sensitive enough to guarantee that the orifice meter does not have a problem. For example, say the clamp-on USM produces a flow rate prediction that is +1.5% from the actual flow rate. With a rated uncertainty of 3% this is a reasonable example. Now let us say that the orifice meter has a problem and produces a flow

rate prediction that is +4% from the actual flow rate. Comparing the two flow rate outputs we would see that the difference between the two flow rate predictions is +2.5%. However, the comparison allows 3% difference before deciding something is wrong. Therefore, in this case no problem would be noticed even though the meter has a +4% bias! Hence, from comparing the clamp on USM and orifice meter alone cannot guarantee the orifice meter is operating correctly.

The auditors took the meter off-line (i.e. interrupted operations) to remove the orifice plate for inspection and to borescope the meter run and flow conditioner. Figure 43 shows a photograph of the plate. The plate was confirmed to have the correct orifice diameter, was found to be clean with a sharp orifice edge. Figures 44 thru 46 show the borescope images of the pressure taps, orifice carrier and the flow conditioner. The orifice meter system was seen to be uncontaminated with no blockage of the pressure ports or flow conditioner holes. No problem with the orifice carrier was noted. The DP transmitter was correctly sized and in calibration with no drift. Therefore, after comparing the orifice meter to a clamp-on USM, then checking the integrity of the DP transmitter and then removing the plate, checking the plate and borescoping the meter system, it was finally concluded that the orifice meter was fully serviceable just as Prognosis had initially said before the audit was initiated.

Fig 43. Audit 1 Plate Inspection.

Fig 44. Audit 1 borescope pressure tap.

Fig 45. Audit 1 Borescope orifice carrier.

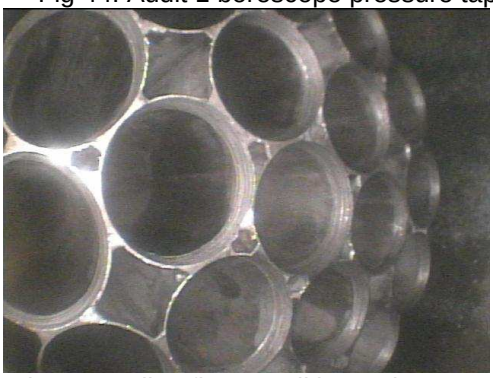

Fig 46. Audit 1 flow conditioner downstream

This orifice meter is back in service. It will be due scheduled maintenance in due time. Without Prognosis, if any future maintenance service finds any problem the operator may not be able to tell when the malfunction occurred. All that would be known is that there was a malfunction sometime between the two scheduled maintenance events. If Prognosis was permanently installed, if a malfunction was to occur the operators could examine archived results to pin-point when the malfunction occurred and therefore better address the mis-measurement issue.

Finally note that the alternative live diagnostic of putting a second check meter in series with the orifice meter is a lower quality diagnostic methodology. First, it is a high capital expense to add a second metering system. Once two meters are in series, they can only indicate an error if the root mean square of the two meter uncertainties is exceeded (which is not a particularly sensitive diagnostic method). Also, there is no guarantee that the meters will not suffer some common

mode error thereby making their flow rate predictions equally incorrect with the inter-comparison diagnostic showing no error. (This is in contrast to the multiple diagnostic methods within Prognosis which are very resistant to most common mode error issues.) Furthermore, even if the second / check meter does show a different flow rate to the primary meter this does not tell you which meter has malfunctioned. Prognosis will state if the DP meter it is monitoring has malfunctioned and what possible malfunctions could cause the diagnostic result. Hence Prognosis is advisable for permanent installation on financially important DP meters and is substantially better than the alternative method of using a second check meter.

6b) AUDIT 2: A 6”, 0.3503 BETA RATIO ORIFICE METER

A 6”, 0.350 beta ratio flanged tapped orifice meter was audited. The natural gas flow meter was operating at 1356 psia / 93.5 bara at 73^{0}F. The flow rate was approximately 220 MSCFD (1.68kg/s). Prognosis and a clamp-on USM were installed. Figure 47 shows the meter run prior to the installation of Prognosis and the clamp-on USM. Figure 49 shows an actual screenshot from Prognosis running on this meter.

Fig 47. Audit 2 Orifice Meter Run

Fig 48. Audit 2 plate inspection

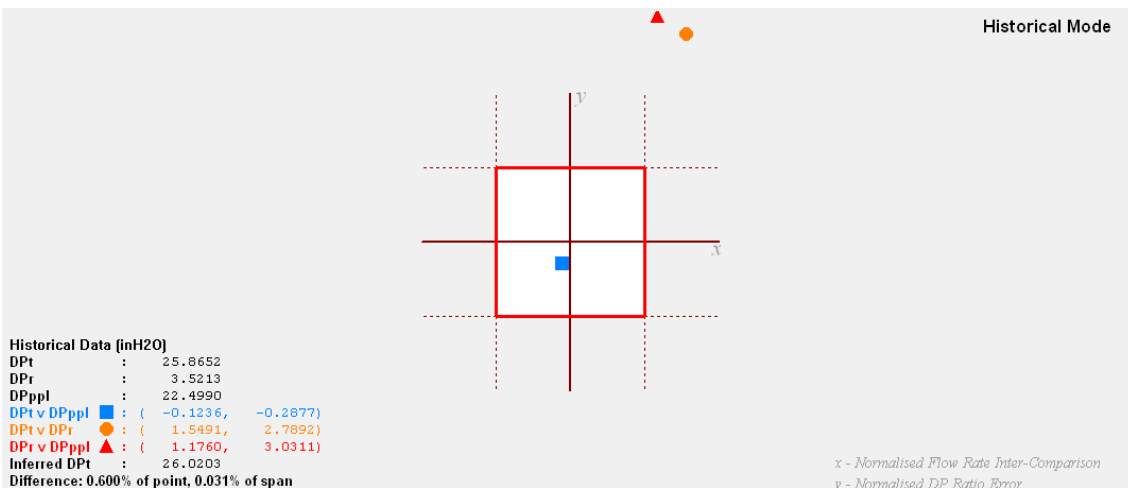

Figure 49. Audit 1’s sample representative Prognosis screenshot.

The DP reading diagnostic check indicates that the DP’s are being read correctly, with a 0.60 % difference being noted between the inferred and the read traditional DP. This is lower than the nominal 1% DP reading warning threshold. However, Prognosis is also showing that two out of the three diagnostic points are outside the NDB. Hence, Prognosis is stating that the meter has a problem with the meter body. Furthermore, as always, the particular pattern of the diagnostic plot gives more information. From experience, this pattern suggests the bias is probably a negative error. The source of such errors can be short listed. This list was incorrect inlet or orifice

diameter, distorted flow pattern, backwards installed plate, worn plate, buckled plate or contaminated metering run. A simple check of the meter geometry discounted any geometry error. The plot was not the correct co-ordinates for a reversed plate. The Prognosis result was therefore that the meter was in error, probably due to a distorted flow pattern, a damaged plate or contaminated meter run.

Again, due to contractual obligations and the fact that Prognosis was seen as 'on trial' the auditors continued with the audit procedure. Figure 50 shows the comparison of the clamp-on USM and orifice meter flow rate predictions. The orifice meter flow rate reading is approximately 10% lower than the clamp-on USM flow rate reading. The average difference between the flow rate predictions significantly exceeds the root mean square of the two meter uncertainties and it can be seen that the error bands of the two meters do not over-lap. On its own this result states that one (or both) of these meters has malfunctioned but nothing more. This is not therefore a declaration that the orifice meter is necessarily under-reading the actual flow rate by 10%. This simply says the two meters disagree by that amount. The problem is as yet unknown so the effect on each meter is as yet unknown. It was not reported if the USM diagnostics indicated any problem.

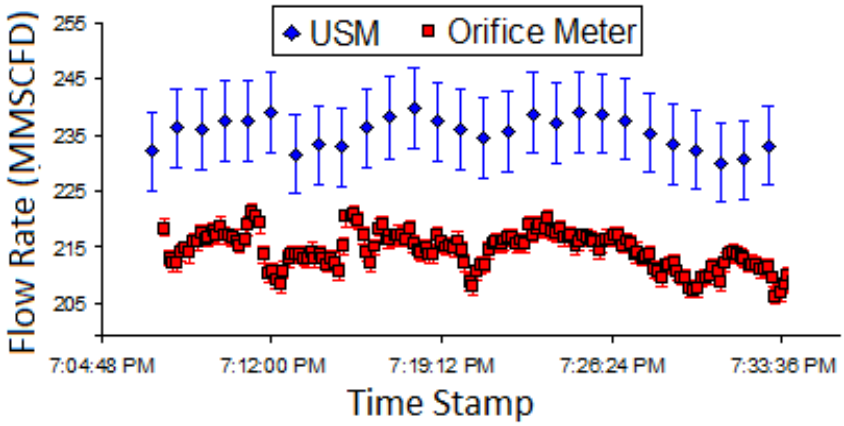

Figure 50. Audit 2's comparison between the orifice meter and the USM.

The meter was taken off-line (i.e. interrupted operations) to remove the plate for inspection and to borescope the meter run and flow conditioner. The DP transmitter was also checked. Figure 48 shows a photograph of the plate. The plate was contaminated. A subsequent borescope investigation of the meter run showed meter run contamination. Contaminated orifice meter runs produce negative errors on the meters flow rate output. Therefore, again Prognosis had correctly diagnosed that the meter had a problem and the problem was not with the DP readings but the meter body itself. Furthermore, the contamination and a negative bias error had been correctly shortlisted. The follow on auditor procedures of checking the DP transmitter and installing a clamp-on USM check meter were superfluous time consuming and costly additions procedures. If the operator had had Prognosis permanently installed on this meter the build-up of contamination would have been visible as it caused the diagnostic points to drift away from the centre of the NDB over time. This again, is evidence to why Prognosis should be thought of as a permanent installation with a DP meter.

6c) AUDIT 3: A 12", 0.476 BETA RATIO ORIFICE METER

A 12", 0.476 beta ratio orifice meter was in operation with natural gas flow at low pressure (of 20 psig / 0.4 barg). The operator suspected from plant mass balance checks that this orifice meter was giving an erroneous gas flow rate prediction. Figure 51 shows a photograph of this orifice meter prior to Prognosis being installed. Note Figure 51 also shows that the auditors installed a clamp-on USM. However, due to the low pressure, the USM results were unreliable and not used in the audit. Prognosis was installed using the available downstream pressure taps.

Fig 51. 12", 0.476 β orifice meter prior to Prognosis system installation.

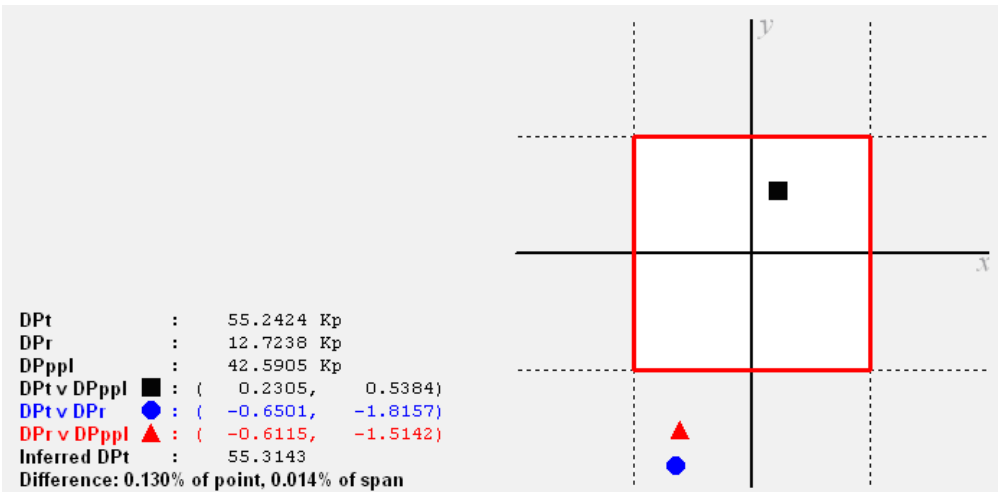

Fig 52. Prognosis screenshot from the 12", 0.476 β orifice meter with unsteady wet gas flow.

Figure 52 shows a screenshot from Prognosis installed on this meter. This screenshot is representative of the results. The averaged DP readings conformed to equation 1 thereby indicating that the DP transmitters were reading the correct DP's. Note that Figure 52 shows a difference of only 0.13%. From experience, this diagnostic pattern suggests the bias is probably a positive error. The source of such errors can be short listed. This list was incorrect inlet or orifice diameter, distorted flow pattern, a partially blockage in the orifice, pulsation or wet gas flow. A check of the geometry confirmed it was correct. The meter run was long (i.e. ISO 5167-2 compliant) with no flow conditioner so distorted flow was unlikely. The Prognosis result was therefore immediately narrowed to a partially blocked orifice meter, pulsating flow or wet gas flow.

Again, due to contractual obligations and the fact that Prognosis was seen as 'on trial' the auditors continued with the audit procedure. It was noted on pressing one's ear to the pipe a liquid "sloshing" sound was audible. The plate was removed and was found to be coated in fresh water. It was concluded that this pipe run with the orifice meter had significant water hold up. Again, before any further auditing was initiated Prognosis had correctly stated the orifice meter had a problem, the problem was with the meter body and not the DP readings, the problem was probably a positive bias and one of a short list that included the actual problem found. The remaining auditing procedure merely confirmed the initial Prognosis prediction.

7. CONCLUSIONS

Over the last four years the generic DP meter diagnostic concept first disclosed by Steven [1] in 2008 has been substantially developed by DP Diagnostics and Swinton Technology. The

methodology has been fully disclosed at several major conferences and has been proven to be technically sound. The DP meter diagnostic concept has been developed into a practical system for industry called “Prognosis”. Since 2009 multiple laboratory tests, operator field tests, DP meter calibrations and operator field usage have unfailingly proven Prognosis as a practical and powerful DP meter diagnostic tool.

BP has field tested Prognosis at BP CATS with deliberate induced meter malfunctions and then a long term endurance testing. DECC have reviewed the concept and deem it suitable for DP meter Condition Based Maintenance strategies [4]. Centrica has applied Prognosis to several Venturi meters. In one such case Prognosis alone alerted the engineers to a calibration error that would almost certainly have gone unnoticed causing a +1.6% bias in flow rate prediction. Petronas applied Prognosis to a wet gas Venturi meter. Again the worth of Prognosis was seen when the system correctly indicated the meter had a sub-system failure before any of the operator engineers were aware of it. The experience of orifice meter auditors using Prognosis as an aid to the auditing procedure was that Prognosis correctly stated if the meter was serviceable or not before any other auditing was required. Furthermore, when an orifice meter malfunction was discovered by Prognosis, the system subsequently produced a shortlist of potential reasons for the malfunction that always included the actual problem. The diagnostic system also correctly predicted whether the malfunction was producing positive or negative bias on the flow rate prediction.

The DP meter diagnostic system “Prognosis” has been proven over the last three years to do all that it was claimed to do and more. As a result the use of Prognosis is growing and it is expected that it will become ever more wide spread and popular.

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