Testing of an Orifice Plate Meter Diagnostic System
at the ATMOS Energy Corp. Training Center

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1. Introduction

DP Diagnostics and their partners Swinton Technology have developed an orifice meter diagnostic system which has been tested and used in the field throughout the world. This DP meter diagnostic system, called 'Prognosis', has had its theory, test data and field trials well documented.

In 2011 ATMOS Energy Corp. opened a large, $12.9 million, hydrocarbon production equipment training center in Plano, Texas, called the Charles K. Vaughan Center (See Fig. 1). This state of the art training center includes a replica of a neighborhood with natural gas meters, pipelines and furnaces for employees to practice working on. It also includes a lecture theatre and a large flow lab. The flow lab has long rows of natural gas pipes hung with every bit of equipment that ATMOS employees might encounter in the field. The gas used by the training center is compressed air. Employees use the flow lab to practice working on the equipment in relative safety. No other U.S. company has such a lab.

Fig. 1 The ATMOS Energy Corp. Training Center in Plan, Texas.

In 2012 after the proposal by Quorum Business Solutions, ATMOS installed the DP Diagnostics / Swinton Technology orifice meter diagnostic system 'Prognosis' on the ATMOS training center flow labs 2" senior fitting orifice meter. Several ATMOS staff and several different Gas Transmission Company personnel attended with DP Dignostics, Swinton Technology and Quorum Business Solution staff to witness the system under test. This paper documents the results of this test, i.e. the results of the first orifice meter diagnostic system tests by a US Mid-Stream Natural Gas Company.

The diagnostic system was first tested with a correctly operating orifice meter to show the diagnostics result for when the meter is fully serviceable. Then a series of orifice meter malfunctions were deliberately induced on the meter. This paper describes the diagnostic systems theory before showing the systems reaction to a correctly operating orifice meter and then various meter malfunction tests. The flexibility of the ATMOS Energy Training Center and the reliability of the orifice meter diagnostic system "Prognosis" are clearly shown.

2. The Operating Principles of the DP Diagnostics Orifice Meter Diagnostic System

In this discussion the orifice meter will be used as an example, but the DP Diagnostics patented Differential Pressure (DP) meter diagnostic system operates with 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 the DP meter on which the diagnostics are applied.
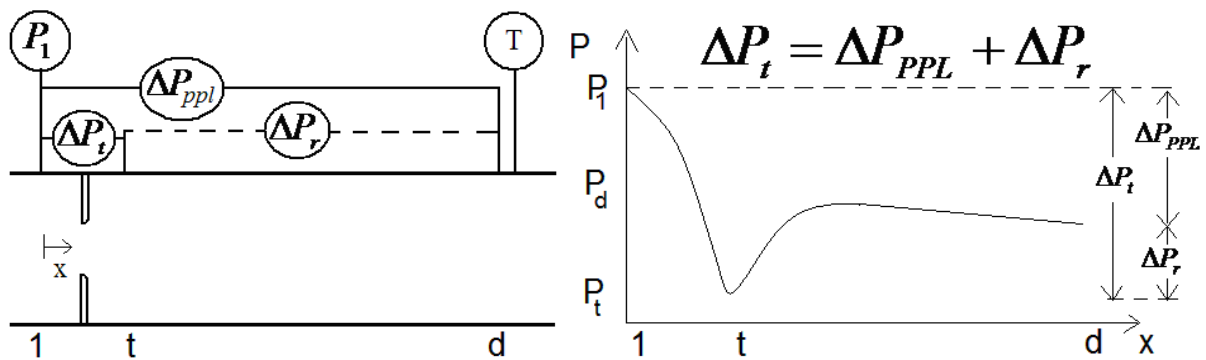

Fig 2. Orifice meter with instrumentation sketch and pressure fluctuation graph.

Traditional DP meters read the inlet pressure (P_1), the downstream temperature (T) and the differential pressure (ΔP_t) between the inlet pressure tap (P1) and a pressure tap positioned in the vicinity of the point of low pressure (P2), 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 (P3) further downstream of the primary element. This allows the measurement of two extra DPs. That is, it allows extra pressure field

information to be read. The two extra DPs are the differential pressure between the downstream (P3) and the low (P2) pressure taps (or "recovered" DP, ΔP_r) and the differential pressure between the inlet (P1) and the downstream (P3) 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: $\quad \dot{m}_t = EA_t Y C_d \sqrt{2\rho\Delta P_t}$, $\qquad$ uncertainty $\pm$ x% $\qquad$ --- (2)

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

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

For an orifice meter, these three flow coefficients can be derived from information supplied in the International Standards Organisation (ISO) orifice meter standard, ISO 5167 part 2 [1]. Alternatively, for any generic DP meter these three flow coefficients can be found by the same calibration procedure that is used to find the discharge coefficient, with the addition of extra DP's being read. Each flow coefficient 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 [2].

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

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:

Traditional & PPL Meters allowable difference ($\phi\%$): $\qquad \phi\% = x\% + z\%$ -- (6a)

Traditional & Expansion Meters allowable difference ($\xi\%$): $\qquad \xi\% = x\% + y\%$ -- (6b)

Expansion & PPL Meters allowable difference ($\upsilon\%$): $\qquad \upsilon\% = y\% + z\%$ -- (6c)

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

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

PPL to Expansion Meter Comparison: $\qquad \chi\% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \middle/ \dot{m}_{PPL} \right\} * 100\%$ -- (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. 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 associated 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.

For any DP meter, once the PLR value is known, the PRR and RPR value can be directly calculated. For an orifice meter, these three DP ratios can be derived from the PLR prediction supplied in ISO 5167 part 2 [1]. However, ISO does not give an uncertainty rating to the PLR equation it quotes. DP Diagnostics has noted that the accuracy of the ISO PLR prediction is beta ratio (β) dependent. For β ≤ 0.55 the ISO PLR prediction is impressively accurate. Therefore, for β ≤ 0.55 DP Diagnostics derives the three DP ratios from ISO 5167 Part 2 [1]. However, DP

Diagnostics has noted that the ISO orifice meter PLR equation has a slight bias that develops as the beta ratio increases above 0.55β. DP Diagnostics has massed orifice meter data sets from different size orifice meters, different beta ratios and different labs with different fluids. DP Diagnostics has therefore assigned realistic uncertainties to the ISO orifice meter PLR prediction and the associated PRR & RPR predictions, for $\beta \leq 0.55$. DP Diagnostics has developed an in-house PLR calculation for $\beta > 0.55$ orifice plates, which allows associated PRR & RPR values to also be predicted, all with an assigned uncertainties. Alternatively, for any generic DP meter these three DP ratios can be found by the same calibration procedure that is used to find the discharge coefficient, with the addition of extra DP's being read. Thus we also have:

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

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

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

Here then is another method of using the three DP's 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.

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

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

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

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 DPs 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 <u>absolute statement by the diagnostic system that there is an erroneous DP reading coming from the instrumentation</u> (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 will be *slightly* different. The percentage difference ($\delta\%$) can be calculated as seen in equation 9.

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

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 threshold, i.e. >1. For convenience we use the following naming convention for the normalized data:

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

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

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

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

Table 1. The DP meter possible diagnostic results.

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[1] DP's are not typically read simultaneously. The three DP readings for a single diagnostic check will typically be read from a data logging sweep and therefore they 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 effects of natural DP fluctuations around their mean is smoothed out.
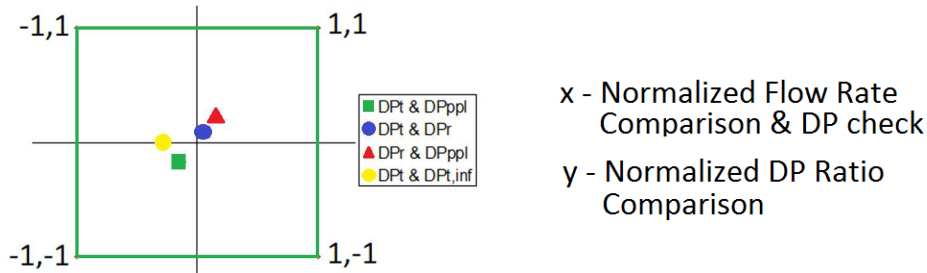
Fig 3. Normalized diagnostic box (NDB) with diagnostic results, DP check included

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 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) & $(x_4,0)$.

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. Each DP pair therefore produces an x & y co-ordinate. That is, for the three DP pairs we get diagnostic results (x_1,y_1), (x_2,y_2) & (x_3,y_3). If the six diagnostic results all fall within +1/-1 then all three points are inside the NDB and no meter system malfunction is noted. If one or more of these six diagnostic results fall 0ut with +1/-1 then one or more of the three points are outside the NDB and a meter system malfunction is noted.

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 four 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 four points falls outside the NDB the meter operator has an indication that the meter system 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 not 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 also 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. ATMOS Energy Corp. Orifice Meter Diagnostic Tests

A 2", sch 40, senior orifice meter fitting was installed in at the at the ATMOS Energy Charles K. Vaughan Center training flow lab (see Figure 4). For the flow conditions ATMOS planned to run, a plate with an orifice of 1.125" was chosen, i.e. a beta ratio of 0.5443 (see Figure 7). The downstream pipe work was typical of a standard orifice meter run. The downstream spool had a series of generic ports between 5D and 10D downstream of the orifice plate to allow sampling, temperature and pressure measurement, if and when required by the operator (see Figure 4). The existence of these downstream pressure ports means that often existing orifice meter installations already have an appropriate downstream pressure port for which to apply the diagnostic system 'Prognosis'. This fact, along with the fact that the orifice meter does not need to be calibrated for the diagnostic system, means that many orifice meters can easily be retrofitted with Prognosis. Here, a thermowell at 6D downstream of the orifice plate was used successfully as the downstream pressure port. Figure 4 shows a photograph of the 2" orifice meter Prognosis set up with the ATMOS training flow lab in the background. The traditional DP transmitter is inside the flow computer. The downstream pressure tap (flow right to left) is clearly seen as are the additional recovered and PPL DP transmitters.

During the two days of flow tests ATMOS kindly allowed DP Diagnostics, the air flow pressure was held nominally held at 150psig. The flow rates were varied. Figure 5 shows a baseline (correctly operating orifice meter) result when the flow rate was 410 MSCFD.

Figure 5 is a screenshot from the actual Prognosis output that would be displayed on a control room screen. Prognosis runs live on a DP meter, updating the screen up to once a second. The actual frequency of the updated screen can be chosen by the operator. Each screen shows the average diagnostic result of a set of previous DP measurements points. The operator of Prognosis sets the number of DP's / data sweeps averaged, down to a minimum of 1 data sweep, i.e. no averaging. Prognosis will average and record to file data at a frequency chosen by the operator. The operator can later choose historical mode and review the data when they see fit, going directly to highlighted warning events, or running through historical data on various fast forward speeds (exactly analogous to fast forwarding through recorded television programs!) looking for adverse events.

Figure 5 shows in the top right of the screen that the screen sheet comes from a historical play back after the live test. In this case of a correctly operating meter, at 147.5 psig and 410 MSCFD,
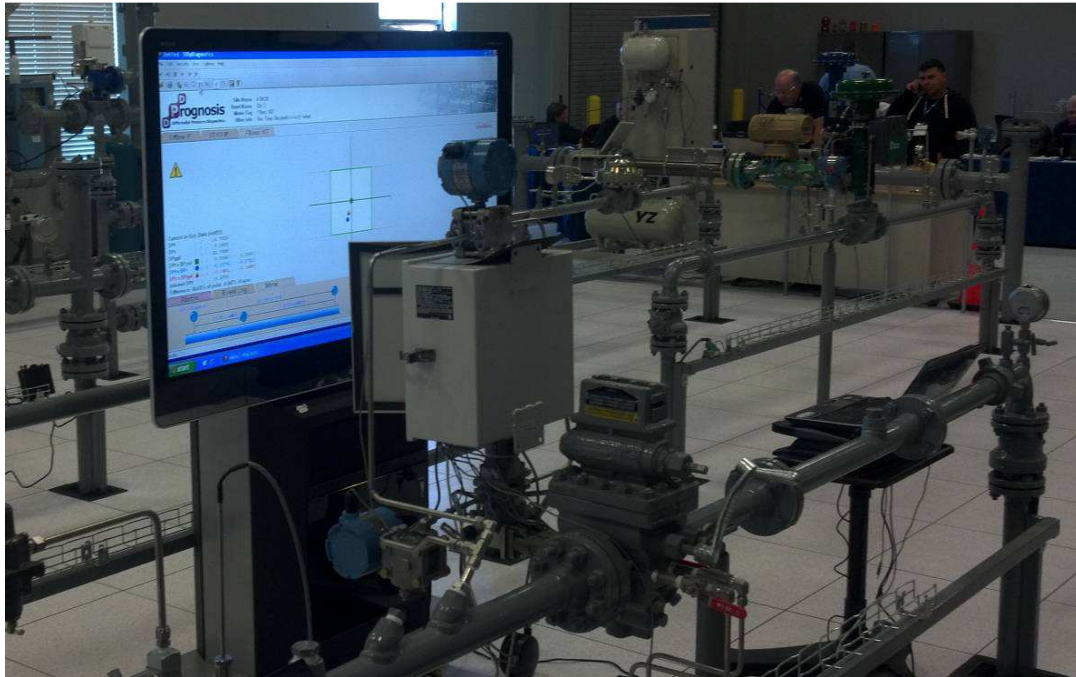
Fig 4. ATMOS Training Flow Lab with 2" orifice meter with Prognosis Installed.
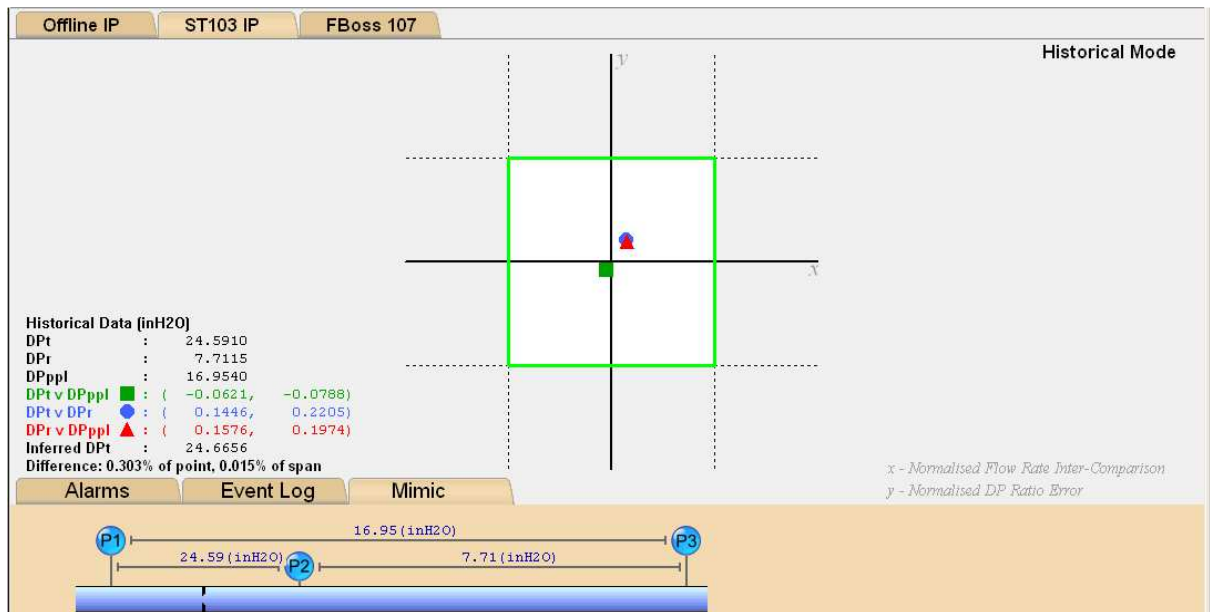

Fig 5. Correct Meter Operation at 410 MSCFD.

the traditional DP is shown as 24.59"WC, the recovered DP is shown as 7.71"WC, and the PPL DP is shown as 16.95"WC. These values are seen in the column of information in the bottom left of the screen. Below this are the three co-ordinates (x_1,y_1), (x_2,y_2) & (x_3,y_3). All three points are in the center of the NDB indicating (correctly) that the meter is fully serviceable. As such, Prognosis colors the box green, meaning 'no warning'.

The screenshots from Prognosis running in ATMOS do not include the fourth diagnostic point $(x_4,0)$ diagnosing the health of the DP readings. This is because the screenshots are from the

first edition of Prognosis created in 2011 and the fourth point is only on the second edition released in 2012. However, Prognosis edition 1 still has the DP reading diagnostic, it just doesn't plot an associated point on the NDB graph. Notice in the bottom left of the screenshot, below the three co-ordinates, the inferred traditional DP is shown along with the percentage difference of this value with the directly read traditional DP. In Figure 5 the directly read traditional DP is 24.591"WC, the inferred traditional DP is recorded as 24.6656"WC (i.e. more decimal places than are significant), while the percentage difference is recorded as 0.303%. This percentage difference is in effect the fourth point, i.e. for a chosen traditional DP reading uncertainty of say 1%, the fourth point $(x_4, 0)$ is $(0.303\%/1\%, 0)$, i.e. (0.303,0).

Notice in Figure 5 that at the top left of the screen are tabs to select the flow computer operating Prognosis, e.g. a remote computer analyzing historical data, a dedicated diagnostic standard computer (which requires an analog to digital convertor, i.e. ST103), or an integrated flow computer. In this case the flow computer happened to be a FBoss 107, but Prognosis can be introduced to any generic flow computer.

Notice in Figure 5 that at the bottom left of the screen are three tabs. The first gives a list of the historical 'alarms' the system has registered. The 'event log' shows details of each 'event', i.e. alarm / warning. The third tab, 'mimic', is selected in Figure 5. This shows a diagram of the meter with the three DP's shown.

4. Orifice Meter Malfunctions and Prognosis Response

Once the 2" orifice meter was installed, and the reference meter and Prognosis both showed independently that the meter system was fully serviceable, deliberate malfunctions were induced to show the diagnostic systems response. ATMOS were able to test several common orifice meter malfunctions[2], including a reversed / backwards installed orifice plate, a partially blocked orifice, a DP reading error, a worn plate, an incorrect keypad entered inlet diameter, an incorrect keypad entered orifice diameter and an incorrectly seated orifice plate in a dual chamber orifice meter system. The various tests conducted at ATMOS are now discussed.

4a. A Reversed / Backwards Orifice Plate

A common mistake in the field is for the technician to install an orifice meter backwards / in reverse. For orifice plates with a bevel in the downstream side of the orifice (i.e. most orifice plates) this produces a change in DP meter primary element geometry and an associated change in performance. A backwards installed orifice plate produces a negative bias on the flow rate prediction. The scale of the negative bias is beta ratio dependent. The 2", sch 40, 0.5443 beta ratio plate was installed backwards at ATMOS, while the air flow conditions remained as shown for the initial base line / correctly operating meter test discussed in Section 3, i.e. 147.5 psig with

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[2] Due to the nature of the test facility being a closed clean re-circulation loop it was not possible in this project to test wet gas flow, contaminated flow or asymmetric flow. Due to the fact the orifice meter was a dual chamber device it was not possible to test a buckled orifice plate. However, these four orifice meter malfunction tests not included here have been tested by DP Diagnostics at CEESI and have been discussed in detail (see Steven [3]).
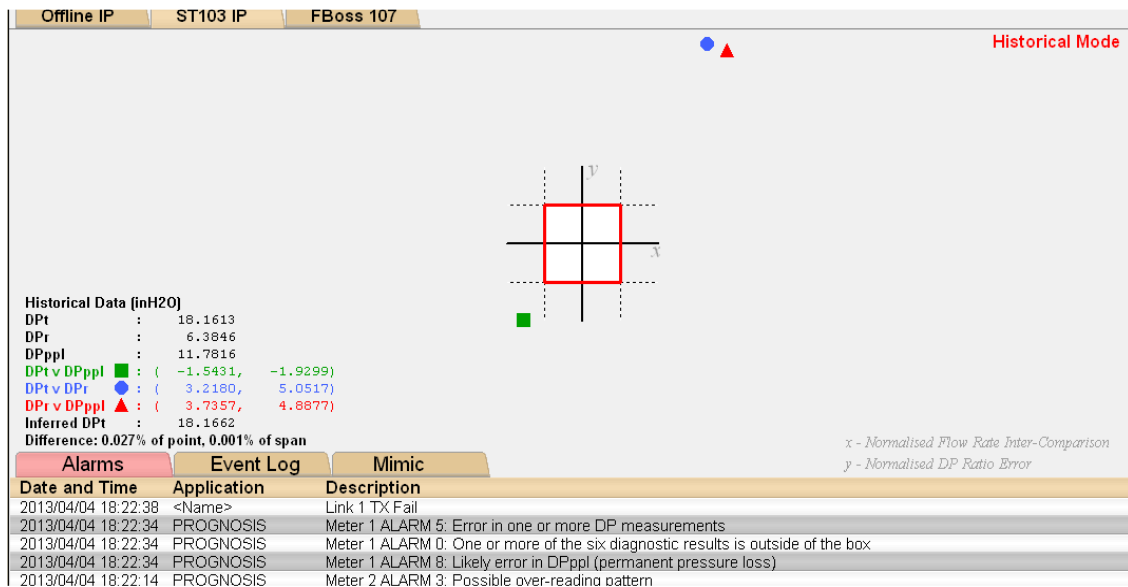
Fig 6. Reversed / Backwards Plate Orifice Plate, -14% error

410 MSCFD. The associated error was -14%. Traditionally there is no orifice meter internal diagnostic system that can identify this error. Figure 6 shows a screenshot of the actual Prognosis result. Prognosis clearly shows that the meter has a malfunction. The DP check shows that the inferred and directly read traditional DP agree within 0.027% indicating that the DP's are correct. The malfunction must therefore be a meter body / flow condition problem. A reversed orifice plate has a very particular geometry. Hence, a reversed orifice plate induces a very particular performance change on an orifice meter and an associated very particular diagnostic result. The pattern shown in Figure 6 is the precise pattern of a reversed orifice meter with a 0.544 beta ratio. A short list of orifice meter malfunctions that could cause this diagnostic pattern is produced (although in this case the short list is narrowed to one malfunction). Hence, Prognosis is telling the operator:

- There is a meter system malfunction.
- The DP readings are correct.
- The malfunction is meter body based.
- The pattern looks like a reversed plate (where the error can be estimated from published information on the flow rate prediction bias induced by a reversed plate of various beta ratios).

The Prognosis software screenshot shown in Figure 6 had the 'Alarms' tab selected. This shows all historical warnings the software has noted with a time stamp. As the operators had been 'playing' with the system giving it various malfunctions before recording the reversed plate test, we see here alarm tabs for previous malfunctions.

4b. A Partially Blocked Orifice

Debris from upstream can partially block the orifice. This causes the cross sectional area at the orifice to reduce and the traditional DP to increase. Partially blocked orifices cause the orifice meters flow rate prediction to have very significant positive biases. Figure 7 shows an upstream

Fig 7. A Serviceable Orifice Plate.   Fig 8. An Partially Blocked Orifice Plate.
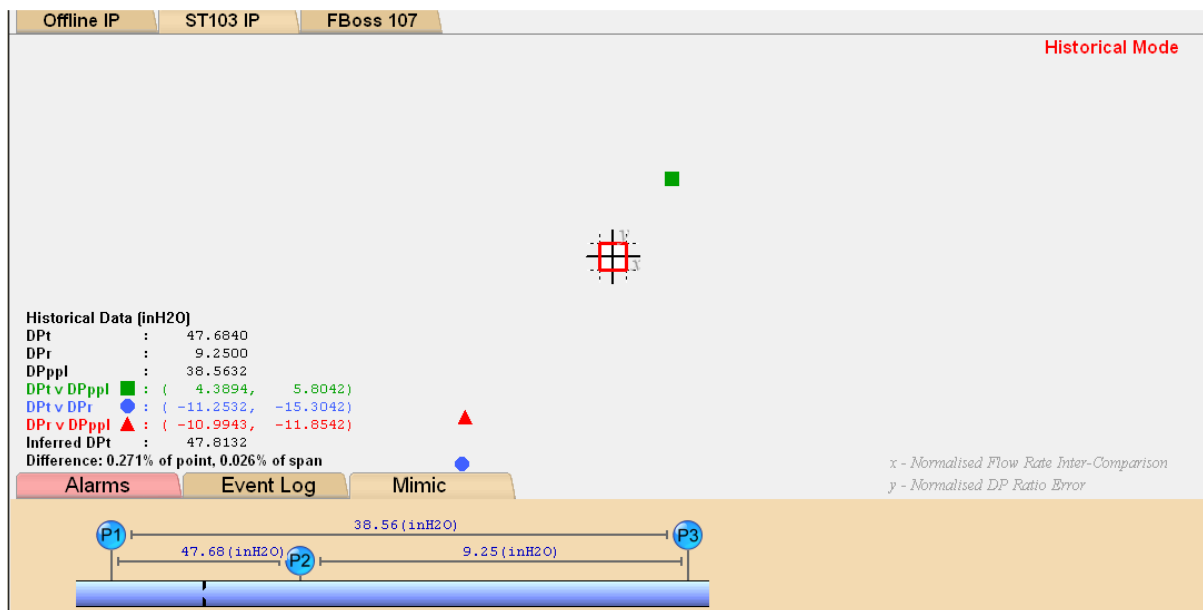

Fig 8. Partially Blocked Orifice, +40% error

view of a serviceable 2", sch 40, 0.5443 beta ratio plate. Figure 8 shows a downstream view of a 2", sch 40, 0.5443 beta ratio plate with a plate welded across part of the orifice area.

This partially blocked plate was installed when the flow conditions were the same as the initial baseline conditions discussed in Section 3, i.e. 147.5 psig with 410 MSCFD. The associated error was +40%. Traditionally there is no orifice meter internal diagnostic system that can identify this error. Figure 8 shows a screenshot of the Prognosis result. Prognosis clearly shows that the meter has a malfunction. The DP check shows that the inferred and directly read traditional DP agree within 0.271% indicating that the DP's are correct. The malfunction must therefore be a meter body / flow condition problem. A short list of orifice meter malfunctions that could cause this diagnostic pattern is produced. Hence, Prognosis is telling the operator:

- There is a meter system malfunction
- The DP readings are correct
- The malfunction is meter body based
- A short list of potential problems that could produce this particular diagnostic result that include a partial orifice blockage.

The Prognosis software screenshot shown in Figure 8 had the 'mimic' tab selected. This shows the three DP's of the last data average before the screenshot was taken.

4c. <u>DP Transmitter Malfunctions</u>

An orifice meter is wholly reliant on the DP transmitters reading the correct DP. Traditionally, an erroneous DP leads to an erroneous flow rate prediction. Traditionally, there are no internal orifice meter diagnostics that can identify an incorrect DP reading and associated flow rate prediction error.

Fig 9. A Saturated Traditional DP Transmitter

When flowing at approximately the same baseline flow conditions as discussed in section 3, i.e. 147.5 psig and 412 MSCFD, the correct traditional DP read by the transmitter (i.e. approximately 25.8"WC) was replaced in the flow computer by a set value of 23"WC. This simulates an over-ranged, or 'saturated', traditional DP transmitter. If the upper limit of the DP transmitter was 23"WC, then any actual DP > 23"WC would be read by the transmitter as it maximum range, i.e. 23"WC. A saturated DP transmitter therefore always produces a negative DP reading bias (in this case -10.8%) and by association the orifice meter would produce an associated negative flow rate prediction bias (in this case -4.1%). Although such an issue is potentially easily noted by meter operators in reality it seldom is. Saturated DP transmitter flow rate prediction errors are a relatively common occurrence in industry.

Figure 9 shows a screenshot from the Prognosis result. Prognosis clearly shows that the meter has a malfunction. The DP check shows that the inferred and directly read traditional DP differ

by approximately -12%. The error is therefore due to a DP reading problem. It is known from experience and theory that this type of pattern states a DP reading error.

The Prognosis pattern shown in Figure 9 gives further information. Once the DP check indicates a DP transmitter reading issue the pattern shows which DP transmitter has the problem. The recovered & PPL DP pair have their diagnostic point inside the NDB. Both the traditional & recovered DP pair and traditional & PPL DP pair have their diagnostic points outside the NDB. The communal DP transmitter reading to the two diagnostic points outside the NDB is the traditional DP. Furthermore, the only DP reading not used to create the diagnostic point inside the NDB is the traditional DP reading. The problem is therefore with the traditional DP transmitters reading.

Figure 9 shows that the directly read traditional DP reading should be dis-regarded. Traditionally, a traditional DP transmitter malfunction means the orifice meter is unserviceable. However, Prognosis not only states that the traditional DP transmitter has a problem, but that the other two DP transmitters do not have a problem. If either or both of these DP transmitters did have a problem the recovered & PPL DP pair's diagnostic point would not be inside the NDB. Therefore, the correct traditional DP can be inferred (i.e. it is inferred correctly as 25.76"WC in Figure 9). The correct flow rate can still be calculated by using the inferred traditional DP in equation 2, and / or by using the correctly read recovered & PPL DP's with flow rate prediction equations 3 & 4. Hence, Prognosis is telling the operator:

- There is a meter system malfunction.
- The malfunction is DP reading based.
- The traditional DP is the particular DP transmitter with the problem.
- The recovered & PPL DP readings are correct.
- The correct traditional DP is inferred.
- The correct flow rate can still be calculated in three ways, i.e. equation 2 with the inferred traditional DP, equation 3 with recovered DP or equation 4 with PPL DP.
- The size of the flow rate error due to the erroneous traditional DP reading can be easily calculated by comparing the correct and incorrect DP readings.

This example used a saturated DP transmitter as a generic example of a DP transmitter problem. However, any DP transmitter problem will produce the same result. That is, a drifting or incorrectly calibrated DP transmitter issue is identified in the same way. The diagnostics monitor the health of all three DP transmitters and can just as easily identify if it is the recovered or PL DP transmitter that has the problem. If the recovered or PL DP transmitter has a problem the main orifice meter flow rate prediction is correct, and the diagnostic system indicates so while showing which DP transmitter has malfunctioned. This limits the diagnostic system to inferring the faulty DP reading via the two serviceable DP transmitters and equation 1 until maintenance can fix the DP transmitters problem. Note here, that although there has been some reluctance to use three DP transmitters instead of one, as "this means three DP transmitters to regularly calibrate", with Prognosis for the first time there is a diagnostic system monitoring for DP transmitter drift. Therefore, in fact, the amount of DP transmitter maintenance required can actually reduce with Prognosis, as the operator now has the ability to switch to condition based maintenance instead of routine scheduled maintenance.

4d. Keypad Entry Geometry Errors

A common source of orifice meter flow rate prediction errors is incorrect geometries being keypad entered into the flow computer. Such flow rate prediction errors are traditionally very difficult to diagnose. Traditionally there are no diagnostics internal to the orifice meter system that can identify an incorrect geometry input.
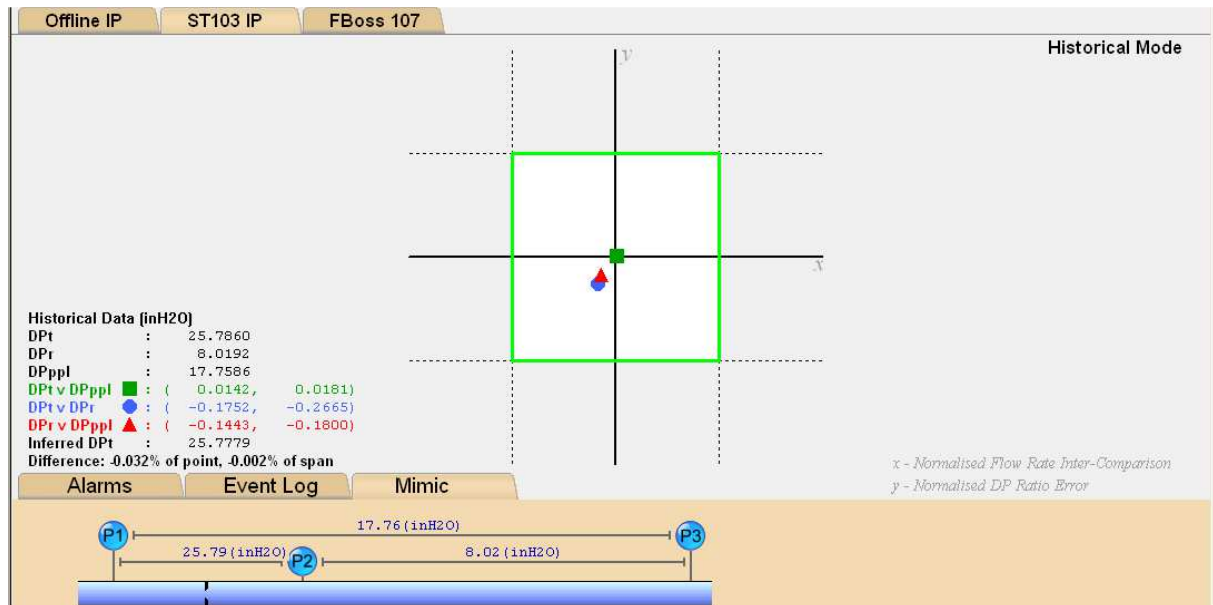

Fig 10. Correctly Operating 2", sch 40, 0.5443β Orifice Meter at 147.5 psig & 418 MSCFD.

Figure 10 shows a Prognosis screenshot for the 2", sch 40, 0.5443 beta ratio orifice meter operating correctly at a baseline of 147.5 psig and 418 MSCFD. The inlet and orifice diameters are correctly keypad entered as 2.067" & 1.125" respectively.

4d.1 Incorrect Inlet Diameter Keypad Entry

For the same flow conditions that created Figure 10, Figure 10a show a Prognosis screenshot for when the inlet diameter was changed from the correct 2", sch 40 (i.e. 2.067"), to the incorrect 2", sch 80 (i.e. 1.939"). The associated flow rate prediction error is + 0.75%.

Traditionally there is no orifice meter internal diagnostic system that can identify this error. Prognosis clearly shows that the meter has a malfunction. The DP check shows that the inferred and directly read traditional DP agree within 0.039% indicating that the DP's are correct. The malfunction must therefore be a meter body / flow condition problem (as it is, the actual physical meter is a different geometry to the flow computer calculation geometry). A short list of orifice meter malfunctions that could cause this diagnostic pattern is produced. Hence, Prognosis is telling the operator:

- There is a meter system malfunction.
- The DP readings are correct.
- The malfunction is meter body based.
- A short list of potential problems that could produce this particular diagnostic result that includes too small an inlet diameter keypad entry.
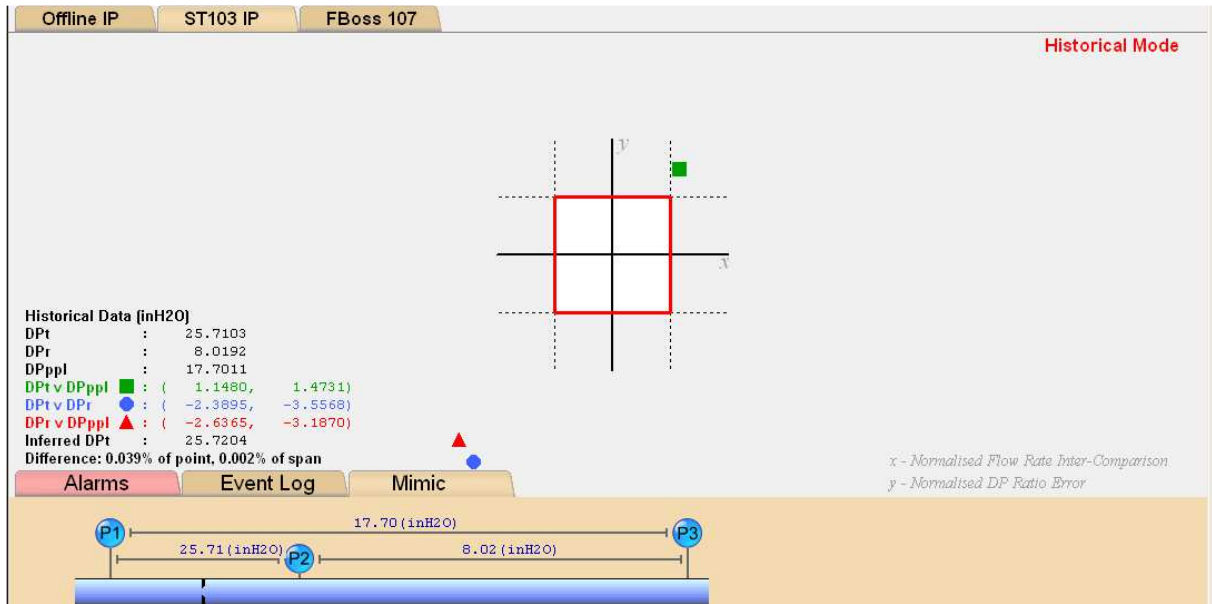
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Fig 10a. Prognosis Result for Inlet Diameter of 2.067" Being Entered Incorrectly as 1.939".

4d.2 Incorrect Orifice Diameter Keypad Entry

For the same flow conditions that created Figure 10, Figure 10b show a Prognosis screenshot for when the orifice diameter was changed from the correct 1.125" to 1.16". The associated flow rate prediction error is +5%.
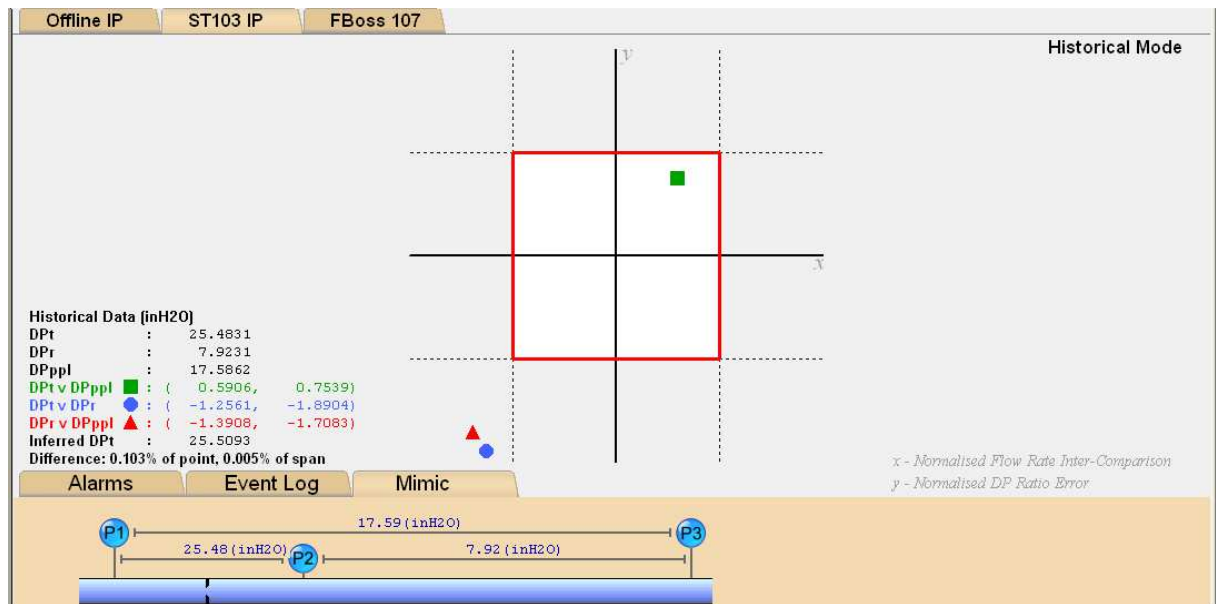

Fig 10b. Prognosis Result for Orifice Diameter of 1.125" Being Entered Incorrectly as 1.16".

Traditionally there is no orifice meter internal diagnostic system that can identify this error. Prognosis clearly shows that the meter has a malfunction. The DP check shows that the inferred and directly read traditional DP agree within 0.1% indicating that the DP's are correct. The malfunction must therefore be a meter body / flow condition problem (as it is, the actual physical

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meter is a different geometry to the flow computer calculation geometry). A short list of orifice meter malfunctions that could cause this diagnostic pattern is produced. Hence, Prognosis is telling the operator:

- There is a meter system malfunction.
- The DP readings are correct.
- The malfunction is meter body based.
- A short list of potential problems that could produce this particular diagnostic result that includes too large an orifice diameter keypad entry.

4e. Worn Orifice Edge

Fig 11. Worn Orifice Edge.

The performance of an orifice meter is dependent on the rifice plate's geometry. As was shown in the reversed plate example, if the orifice edge is not sharp, but beveled, the orifice meter performance is affected. Wear on the 'sharp' orifice edge causes the orifice meters performance to change. A worn orifice edge is effectively the same type of issue as the reversed plate, as the reversed pates bevel is an extreme example of a non-sharp orifice edge.

Figure 12 shows a Prognosis screenshot for the correctly operating 2", sch 40, 0.5443β

orifice meter at 147.5 psig and 383 MSCFD. For this flow condition a 2", sch 40, 0.5443 beta ratio orifice plate with a worn edge was then installed. Figure 11 shows a photograph of the severely worn edge plate. The 'rounding', or 'bevel', is obviously less than a reversed plate, however this level of wear is extreme to most metering applications. The resulting flow rate prediction error was -5.5%. It is noteworthy that such substantial damage to the plate still results in a flow rate prediction negative bias less than -6%.

Figure 13 shows a screenshot of the resulting Prognosis result. Traditionally there is no orifice meter internal diagnostic system that can identify this error. Prognosis clearly shows that the meter has a malfunction. The DP check shows that the inferred and directly read traditional DP agree within -0.057% indicating that the DP's are correct. The malfunction must therefore be a meter body / flow condition problem. A short list of orifice meter malfunctions that could cause this diagnostic pattern is produced. Hence, Prognosis is telling the operator:

- There is a meter system malfunction.
- The DP readings are correct.
- The malfunction is meter body based.
- A short list of potential problems that could produce this particular diagnostic result that includes a worn orifice edge.
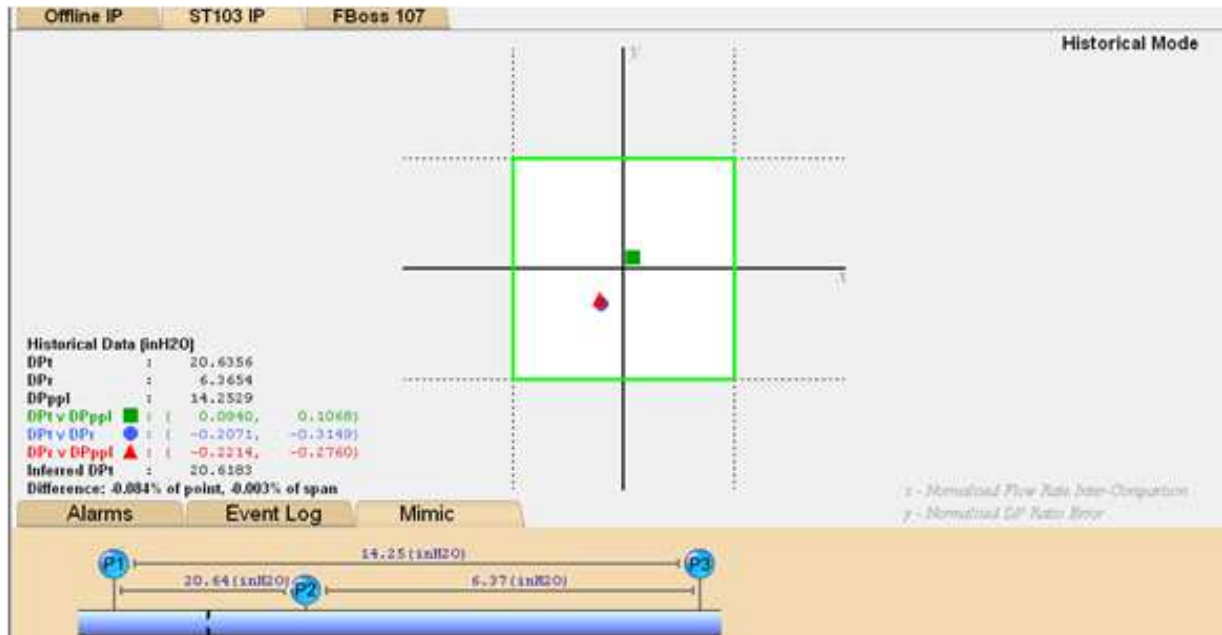
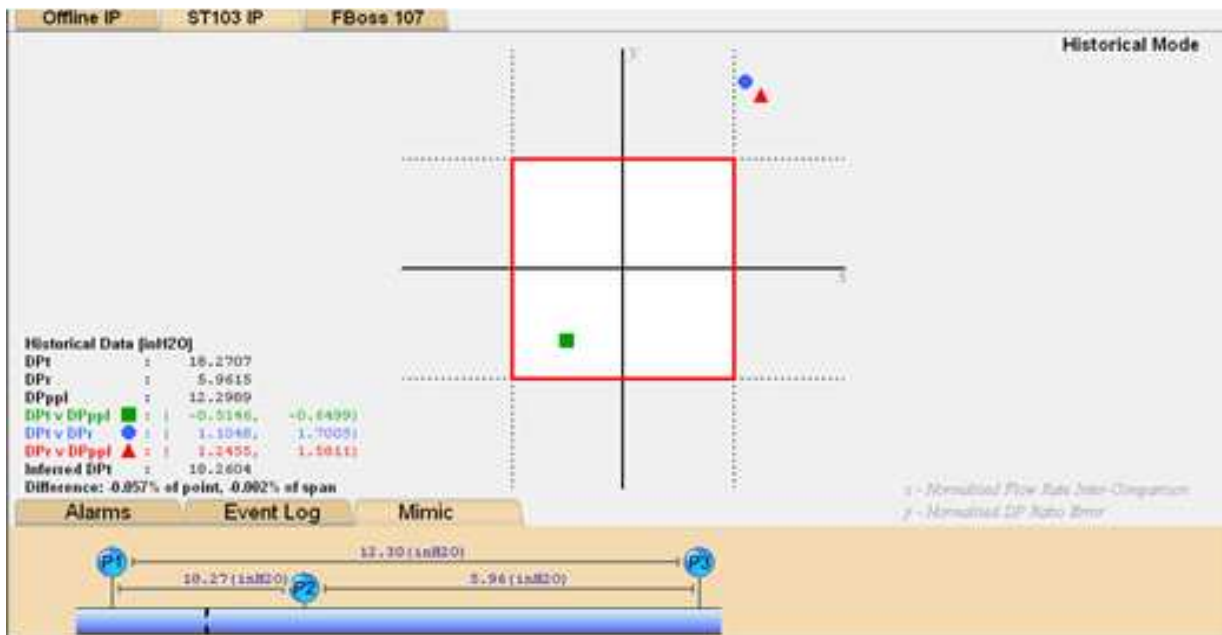Fig 12. Correct Meter Operation at 417.5 psig &383 MSCFD.

Fig 13. Extreme Worn Orifice Edge, Approximate Flow Rate Error is -5.5%.

Aside: Using the Diagnostic System to Trend developing Problems

Figure 6 and Figure 13 show the same 'type' of diagnostic pattern, i.e. the traditional & PPL DP pair diagnostic point in the third quadrant, with the other two diagnostic points in the first quadrant. This is not a coincidence, as the reversed plate showing a substantial bevel to the on-coming flow is effectively the same physical issue as a very badly worn plate. Notice then, that the reversed plate diagnostic result shown in Figure 6 has a more extreme diagnostic result than the worn edge diagnostic result shown in Figure 13. That is, the further from the correct sharp

edge geometry the plates edge gets, the further the diagnostic points are further from the NDB. This example shows how this diagnostic system can be used to not just show orifice meter malfunctions but to actually track developing problems. In the field Prognosis has been used to show erosion slowly wearing the orifice edge, wet gas flow conditions changing, contamination slowly building in a meter run, a DP transmitter slowly drifting away from its calibration etc.

<u>4f. Incorrectly Seated / Wound Down Orifice Plate in Dual Chamber Fitting</u>

Dual chamber orifice meters are popular as they allow the plate to be removed / inspected / replaced without the system requiring to be isolated and blown down. The 2" orifice meter at the ATMOS training center is a 2" dual chamber device. Figure 4 shows this meter. The winding handle for installing and removing the plate is clearly visible. If a technician does not fully wind down the plate such that the plate is not correctly seated a significant measurement error will occur. The source of this error is two-fold. The orifice is not centered in the meter body / pipeline center line and some fluid can potentially flow under the plate instead of through the orifice.

ATMOS simulated this scenario by deliberately running the otherwise serviceable orifice meter with an unseated orifice plate. The flow conditions were 147.5 psig and 471 MSCFD. No baseline (correct operation) diagnostic results were recorded for this flow, but Figure 14 shows the diagnostic result. The flow rate bias was -15%.
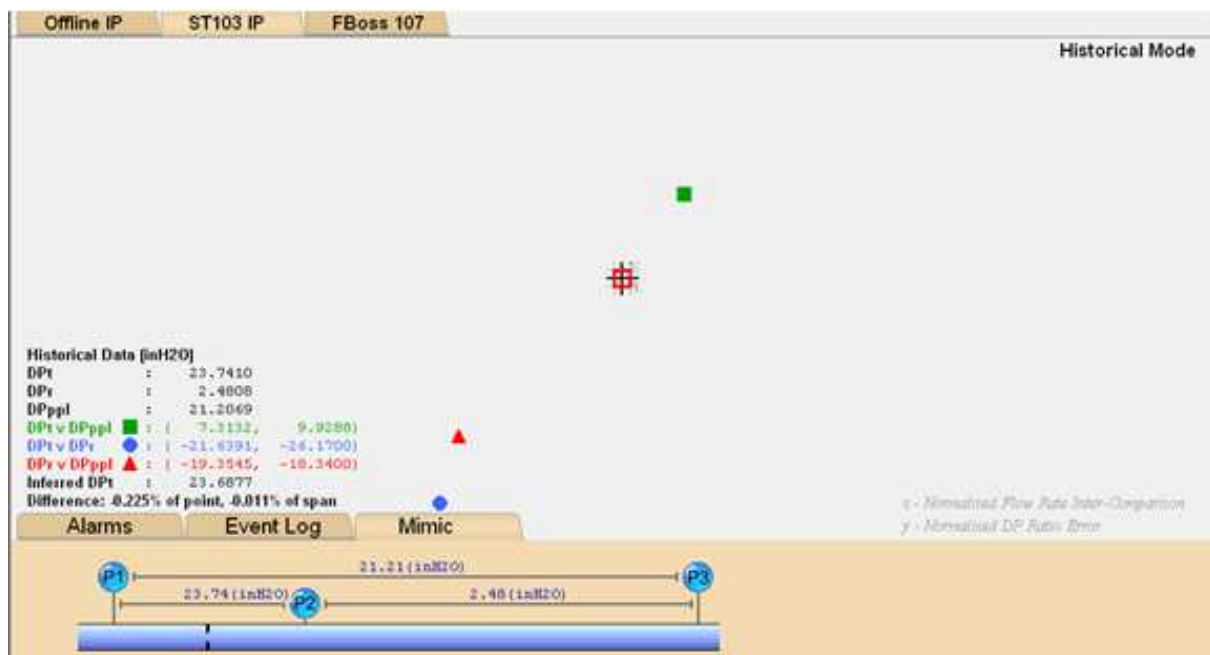

Fig 14. Unseated / Incorrectly Positioned Orifice Plate in the Carrier, Approximate Flow Rate Error is -15%.

Traditionally there is no orifice meter internal diagnostic system that can identify this error. Prognosis clearly shows that the meter has a malfunction. The DP check shows that the inferred and directly read traditional DP agree within -0.225% indicating that the DP's are correct. The malfunction must therefore be a meter body / flow condition problem. A short list of orifice meter malfunctions that could cause this diagnostic pattern is produced. Hence, Prognosis is telling the operator:

- There is a meter system malfunction.
- The DP readings are correct.
- The malfunction is meter body based.
- A short list of potential problems that could produce this particular diagnostic result that includes an unseated, misaligned plate in the orifice carrier.

5. Conclusions

The ATMOS Energy Corp. Charles K. Vaughan Center, a hydrocarbon production equipment training center in Plano, Texas, is fully open. This training center is a valuable asset to the natural gas industry.

ATMOS retrofitted the DP Diagnostics / Swinton Technology orifice meter diagnostic system to their resident 2", 0.5443β dual chamber orifice meter. The standard dual chamber orifice run had the appropriate downstream pressure tap available. No calibration of the orifice meter was required for the diagnostic system to be fully operational.

The orifice meter diagnostic system (called 'Prognosis') was found to work correctly and identified every common orifice meter malfunction that it was possible to give the meter at the ATMOS training center. Prognosis is the first, and only, comprehensive orifice meter diagnostic system to be developed. Due to multiple laboratory tests and field trials of Prognosis by independent companies, Prognosis is now procured by ten different international operators. However, these successful ATMOS tests of Prognosis are the first US mid-stream industry tests.

6. Acknowledgements

7 . References

1. ISO, "Measurement of Fluid Flow by Means of Pressure Differential Devices, Inserted in circular cross section conduits running full", no. 5167.
2. Steven, R. "Diagnostic Methodologies for Generic Differential Pressure Flow Meters", North Sea Flow Measurement Workshop October 2008, St Andrews, Scotland, UK.
3. Steven, R. "Orifice Plate Meter Diagnostics", American School Gas Measurement Technology, September 2012, Houston, Texas, USA.