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Operational Measurement Experiences in North Sea Applications

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1 INTRODUCTION

CNR International (U.K.) Ltd (CNRI) currently operates in six North Sea Asset locations (Tiffany, Murchison and Ninian North, South and Central platforms together with the Petrojarl Banff FPSO). All these assets have been operating for a significant number of years, ranging from the Ninian platforms, which commenced production in 1978, to the Banff FPSO, being the most recent having started production in 1996.

Providing accurate flow measurement on such mature North Sea assets therefore provides operators, CNRI being no exception, with a continuing number of challenges to solve with the back-drop of declining production, difficult flow regimes, aging facilities, and equipment designed at a different time for a different production scenario. In addition, the improving knowledge base within the offshore measurement community can have certain knock-on effects that bring their own issues to solve.

This paper describes some key offshore measurement issues experienced by CNRI in recent years and the steps taken to meet these challenges. The areas covered in this paper will be:

a) Use of orifice plates with drain holes:

   i) Results of testing 2”nb orifice plates with drain holes; current perception being that drain holes cannot be used in pipe sizes smaller than 4”nb (100mm).

   ii) Experience of installing an 18”nb (438mm) orifice plate with a drain hole in the field.

b) Further experiences with small bore (4”nb) ultrasonic flowmeters, building on the paper by Coull, Spearman and Laidlaw presented at the North Sea Flow Measurement Workshop (NSFMW) in 2008 [1]:

   i) Test results showing the effect of a chord failure.

   ii) Test results showing the effect of liquid contamination.

c) Results of calibrating two densitometers at high pressure and temperature with the new UK offshore DECC preferred verification methodology utilising NEL’s dedicated primary density standard system.

2 ORIFICE PLATES WITH DRAIN HOLES

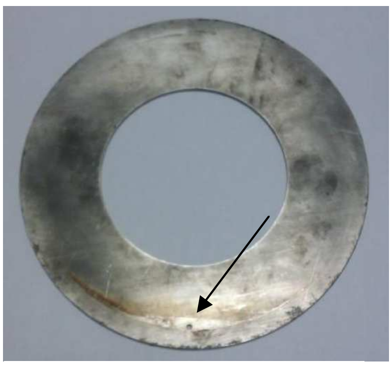


Figure 1:- Orifice Plate with Drain Hole Indicated

Whilst the performance of orifice plates in single phase applications is well understood over a wide range of Reynolds numbers and flow parameters [2] & [3], the performance of plates with modifications for specific applications is less so. Of specific interest to CNRI is the use of orifice plates with drain holes in produced natural gas applications where there is a possibility of liquid presence within the gas itself; mainly on separator gas off-takes where either there is risk of some liquid carry-over from slugging production or where the off-take gas has cooled sufficiently to cause heavier gaseous hydrocarbons to drop out in liquid form.

In these applications, experience has shown that over time the liquid can build-up sufficiently in front of a standard orifice plate flowmeter to cause it to over-measure significantly, with additional problems of plate contamination and, in some extreme circumstances, even the impulse lines to fill with liquid. Despite the CNRI requirement for overall mass and/or standard volume measurement uncertainty in these particular applications to be a reasonably relaxed ±5%, measured flowrates of 2 or 3 times the correct value have been caused by this issue and hence it has become a key concern.

The international document covering this application is ISO/TR 15377:2007 [4] but it is becoming increasingly apparent that this document has its limitations. An important contribution was made to the understanding of this area of flow measurement by Reader-Harris et al at the NSFMW in 2008 [5]. That paper accurately summarised much of the industry by stating:

"While drain hole plates are a cost-effective way of measuring gas with a low liquid content, they are not as accurate as the standard design. As the extent of this inaccuracy is not well documented and as industry is sceptical of the existing formula (in ISO/TR 15377:2007), drain hole plates are not as widely used as they might be: new data are therefore needed to give confidence in their use."

The work by Reader-Harris et al demonstrated a range of new test data in 4" and 8"nb pipe diameter (D) sizes, with various β sizes and drain hole diameter (dh) to orifice diameter (d) ratios, and concluded that:

- Increasing the drain hole diameter in relation to the orifice diameter (dh/d) increased the discharge coefficient of the orifice plate.

- Increasing β for the same value of dh/d generally increased the discharge coefficient of the orifice plate.

- The discharge coefficient is also sensitive to the positioning of the tappings with respect to the drain hole.

- The effects of Reynolds number and plate thickness were found to be relatively minor.

It was demonstrated that increases in discharge coefficient of over 3%, compared to the standard case without a drain hole, were readily achievable and some combinations even achieved an increase of over 5%.

In the light of this information, the author reviewed CNRI's application of drain holes in orifice plates on the basis that in a worst case scenario, the shift in discharge coefficient witnessed could be the actual error in measurement in the field and therefore significant errors could be occurring causing the CNRI measurement requirement of ±5% to be exceeded. This could come about from the 'correction' in ISO/TR 15377:2007 being incorrect or even if it is valid not having actually been applied. This is because some of the plates concerned were installed many years ago and it is unclear whether a correction was applied at the time or not.

Fortunately this review identified that the combinations of β and dh/d were such that the largest shifts in discharge coefficient expected, compared to the non-drain hole case, would be circa 1% maximum, which is sufficiently low (assuming a worst case scenario of discharge coefficient shift = error in the field) to allow the overall target of ±5% uncertainty budget to be met. However, the review did identify a case where a plate had been inserted on Ninian Central which was non-standard even for ISO/TR 15377:2007. An installation of only 2"nb (50mm nb) was utilising an orifice plate with β = 0.5 and a drain hole of 1.01mm.

ISO/TR 15377:2007 Section 5.1.2 a) states:

"D should be larger than 100mm"

and therefore this installation was outside the bounds of the ISO technical report.

2.1 Testing of D = 2”nb Orifice Plates with Drain Holes

CNRI therefore commissioned NEL to perform some new tests on orifice plates with drain holes, in the same manner that NEL’s tests had been performed previously, but with the pipe and plate dimensions of the installation on Ninian Central. As the previous NEL test results had shown that Reynolds number effects were small in magnitude, water was used to simplify the testing process. A schematic of the test system is shown below.

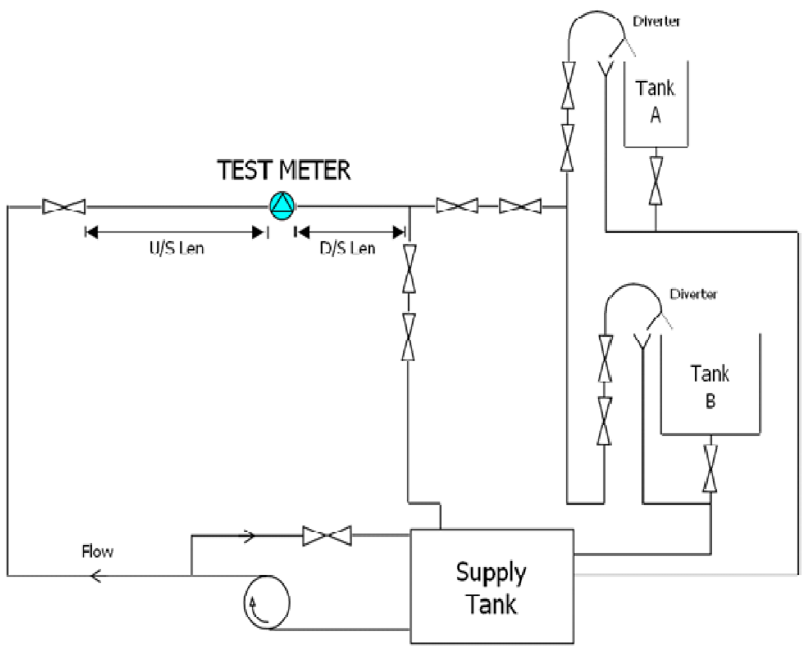


Figure 2:- Schematic Diagram of Gravimetric Test Circuit

The tests involved two sizes of β and the details were as follows:

- D = 52.5mm (nominally 2”)
- d = 25.66mm (β = 0.49) with dh = 1.01mm and 2.66mm (dh/d = 0.039 and 0.104)
- d = 31.5mm (β = 0.60) with dh = 1.01mm and 3.15mm (dh/d = 0.032 and 0.100)
- The orifice plate thickness for the tests was 3mm therefore E/D =0.0571

Tests with no drain hole were also performed to provide a baseline for comparison.

The tappings were ‘Flange’ type in all cases. The β = 0.49 set were at 90^o to the drain hole while the β = 0.6 set were at 180^o. The β = 0.49 tests closely resembled the installation on Ninian Central while the β = 0.6 tests were an extra collaboration with NEL to provide additional information which may be used in future to determine a calculated discharge coefficient equation similar to that in ISO 5167-2:2003 for standard orifice plates.

The tests were performed at nominal volumetric flow rates of:

- 1 to 6.5 litres/sec for the β = 0.49 plates
- 2 to 10 litres/sec for the β = 0.60 plates

The discharge coefficient (Cd) for the various tests was derived using the standard orifice plate flowrate equation and configured accordingly for non-compressible flow, therefore:

$$Cd = \frac{Qm}{\left(\frac{\pi d^2}{4}\right)} \frac{\sqrt{1-\beta^4}}{\sqrt{2\Delta P \rho}} \qquad (1)$$

The water density and differential pressure outputs across the orifice plates were recorded and compared with the values of mass derived in a period of time from the reference gravimetric system. The nominal pressure and temperature for the tests were 1.5 barg and 20°C respectively.

Figures 3 and 4 below show the results for the two sizes of β.

Figure 3:- Effect of drain hole size on discharge coefficient for a 2"nb orifice plate with β = 0.49

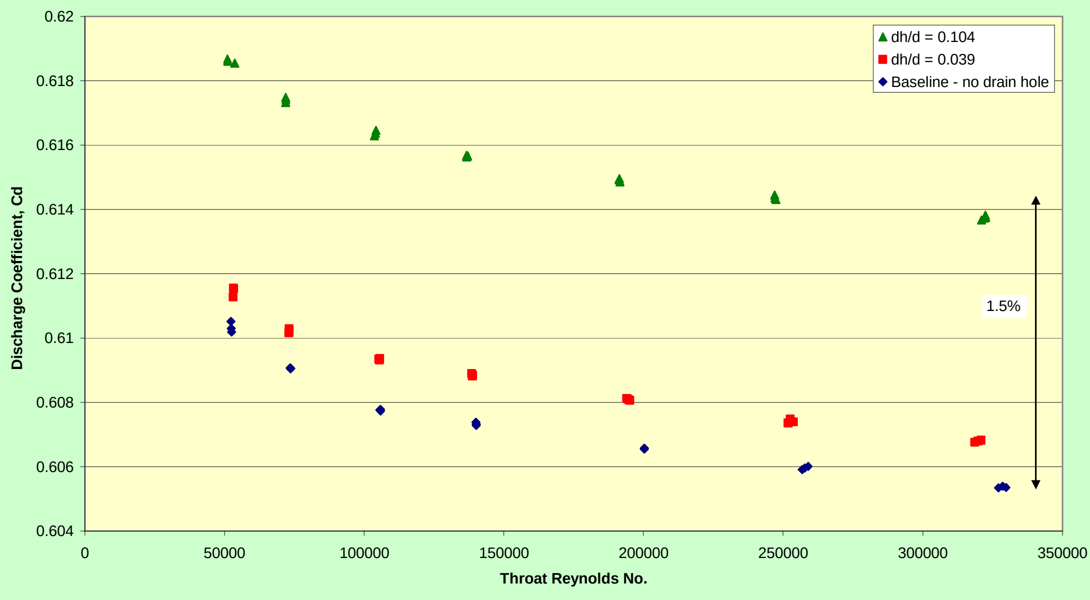
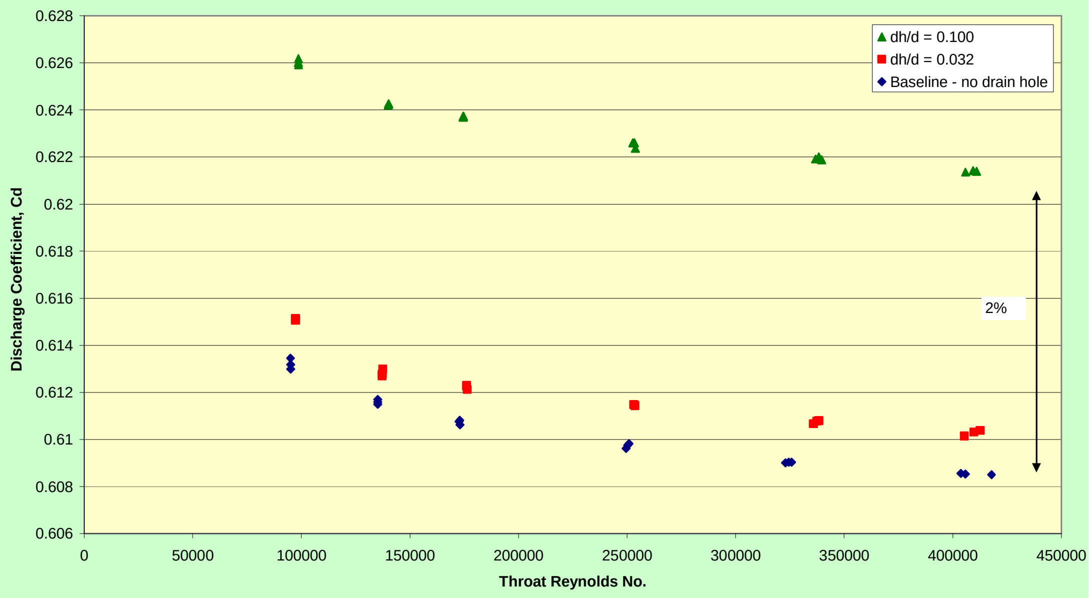


Figure 4:- Effect of drain hole size on discharge coefficient for a 2"nb orifice plate with β = 0.6



There are some clear similarities between the two sets of data namely:

- The graphs show very repeatable data for each set of Throat Reynolds Numbers indicating, at least in this application, that the orifice plates are behaving in a repeatable and stable manner. NEL reported an instance of instability in their tests with β = 0.4 and dh/d =0.2 but this instability is clearly not occurring on this occasion.

- Both sets of data show very similar trending of the baseline and drain hole data, with very consistent increases in Cd for each drain hole compared with the baseline.

- The smaller drain hole data for both sizes of β produce very similar shifts in Cd of circa 0.002, which is approximately 0.3%.

- The larger drain hole data show a more tangible difference between the two β sizes; β = 0.49, with dh/d = 0.104, produced an increase of approximately 1.5% throughout the test range while the β = 0.6 plate with dh/d = 0.100 produced an increase exceeding 2%.

A summary of some of the data reported by NEL at the NSFMW in 2008 is shown below:

Table 1 – Summary of NEL data reported at the NSFMW in 2008

TUVNEL DATA - NSFMW 2008				% increase in Cd	
D (mm)	**E/D**	**β**	**dh/d**	**Tapping pair A**	**Tapping pair B**
102	0.03	0.4	0.07	0.751	0.913
102	0.03	0.4	0.1	1.249	1.612
102	0.03	0.6	0.07	0.84	1.528
102	0.03	0.6	0.1	1.456	2.578
102	0.03	0.6	0.167	3.487	5.163
102	0.05	0.6	0.07	0.892	1.583
102	0.05	0.6	0.1	1.575	2.778
102	0.05	0.6	0.167	3.662	5.429
102	0.03	0.75	0.07	1.59	2.33
102	0.03	0.75	0.1	2.266	3.508
203	0.03	0.42	0.1	1.512	1.258
203	0.03	0.6	0.1	2.234	1.306

In this instance the two sets of tappings were different:

- Tapping pair A were flange tappings at 115° to the drain hole.

- Tapping pair B were corner tappings at 155° to the drain hole.

Table 1 clearly shows that the results of these new CNRI tests are broadly in keeping with those obtained by NEL. For example, D = 102mm, E/D = 0.03, β = 0.4, dh/d = 0.1, with Flange tappings at 115° to the drain hole produced an increase in Cd of 1.249%, while D = 203mm and β = 0.42 produced an increase in Cd of 1.512% with the same tappings. Both were of similar magnitude to the 1.5% obtained in these new CNRI tests with β = 0.49.

ISO/TR 15377:2007 Section 5.1.2 e) states a ‘correction’ to apply to the plate bore diameter to allow for the additional orifice area caused by the inclusion of the drain hole:

$$dc = d\left[1 + 0.55\left(\frac{dh}{d}\right)^2\right] \tag{2}$$

In the field, this correction is applied routinely but just how effective is it?

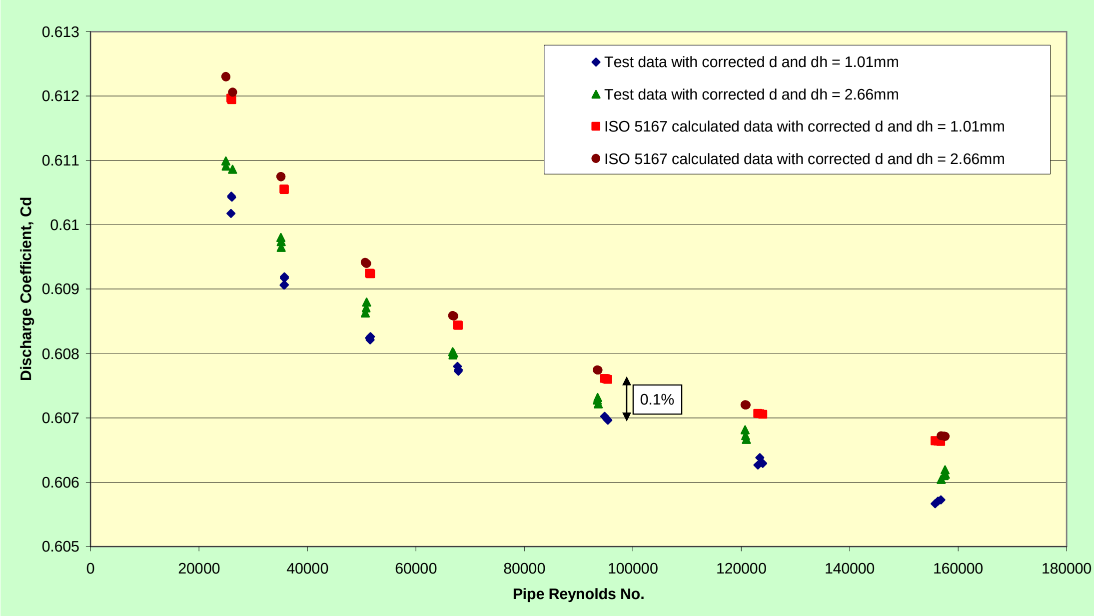
The effectiveness of this correction can be investigated with the results of these tests by comparing the following:

i) Re-calculating the discharge coefficients derived in the tests by using Equation (1) and the corrected orifice plate diameters from Equation (2).

ii) Calculating predicted discharge coefficients from ISO 5167-2:2003 [3] Section 5.3.2.1, also using Equation (2).

Figure 5 shows the comparative data for β = 0.49 with respect to Pipe Reynolds Number.

Figure 5:- Effect of correction from ISO/TR 15377:2007 for β = 0.49



Overall there is a good agreement between the 4 sets of data with discrepancies, between the corrected Cd test data and the calculated Cd data, ranging from 0.1% at Pipe Reynolds Numbers of approximately 95000 to 0.3% at 25000. The calculated values are consistently greater than the test derived data. Interestingly the dh = 2.66mm data shows better agreement that the smaller dh = 1.01mm data. For the application on Ninian Central aiming for ±5% as an overall uncertainty target, this is a welcome result as it demonstrates that, with the application of the corrected bore diameter, the additional uncertainty in the discharge coefficient from the 'correction' of Equation (2) is just a few tenths of a percent. However for systems where the highest accuracy is required (typically ±1%), the additional discrepancy between actual and calculated discharge coefficients is significant and could cause a system to exceed its uncertainty target. With the 4 sets of data showing distinct and predictable trends, there is an opportunity with further work to derive an equation similar to that in ISO 5167-2:2003 to improve the uncertainty with a calculated discharge coefficient for an orifice plate with a drain hole.

Therefore to conclude this part of the discussion, since the results quoted in this paper were obtained in a 2"nb (52.5mm) pipe diameter, showing stable and repeatable data broadly in keeping with the NEL test results obtained in larger pipes, the statement in ISO/TR 15377:2007 regarding orifice plates with drain holes:

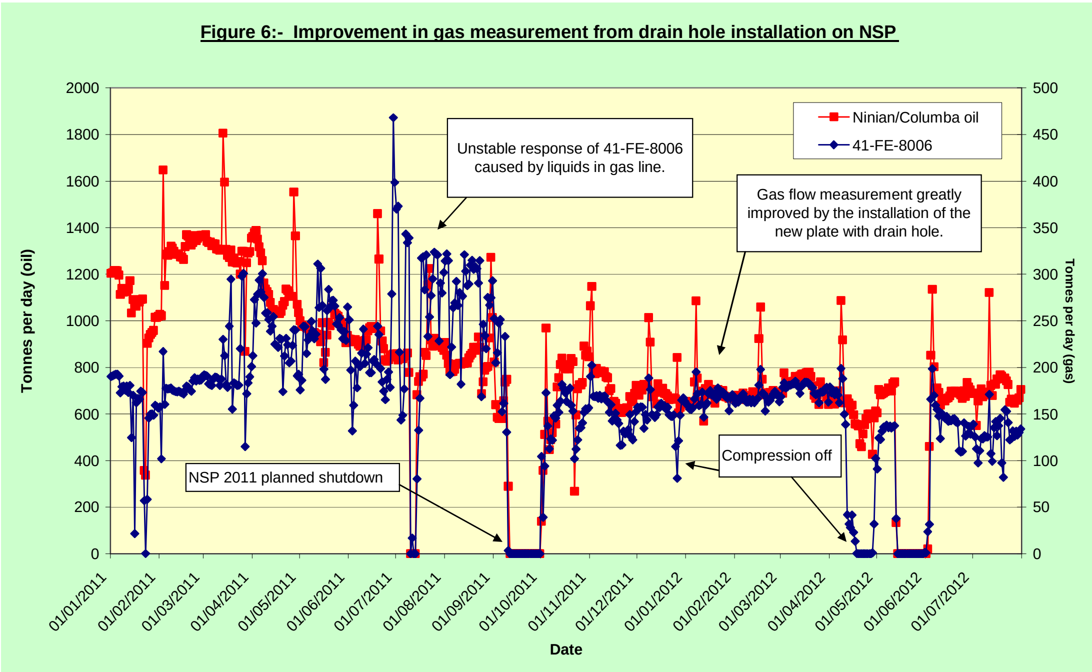
"D should be larger than 100mm"

is incorrect and, at least under the conditions of these new tests, it is valid to apply drain holes to orifice plates of D < 100mm. It has also been shown that the 'correction' in ISO/TR 15377:2007 is a good first order improvement to the discharge coefficient calculation for a plate with a drain hole but there are limitations for high accuracy applications.

2.2 Experience of Installing an 18”nb Orifice Plate with a Drain Hole in the Field

The one issue to take account of in the field is how small a drain hole can be before it becomes ineffective through blockage. To some extent this is discovered through practice but in this section an application of a relatively small drain hole in an 18”nb pipe diameter meter run is discussed.

On Ninian South Platform (NSP), one of our gas meters (Tag no. 41-FE-8006) started to behave unexpectedly from March 2011. The orifice plate meter is of 18”nb (438mm) and had at that time an orifice diameter of d = 208.75 and β = 0.477. As well as the gas generally increasing, the day to day totals were fluctuating markedly. This can be seen in Figure 6 prior to the NSP planned shutdown in 2011.



The oil associated with this gas (measured using a high accuracy turbine meter / prover system) from our Ninian and Columba fields declined steadily over this period as a successful new well brought on-line at the end of Dec 2010 (SP87) declined from significant early production to a more constant flow. Therefore we would expect a similar trend to the gas measurement over the same amount of time. Instead the gas flow rates achieved were twice and in some extreme examples three times, the flow rate expected.

The platform was asked to investigate and drain down the impulse line system to ascertain if liquids were present and this was indeed confirmed. Each time the impulse line system was drained down, the flowrate decreased and became more stable but it wasn’t long before the rates increased again and became more erratic. The source of the liquids in this case was most likely to be fall-out of heavy gaseous components which leave the upstream production separators at approximately 90^{o}C but cool to around 75^{o}C at the meter causing them to coalesce and form liquid traces. These can build up over time in front of the orifice plate dam and even find their way into the impulse lines. Figure 7 demonstrates a worst case scenario from another metering point on the Ninian Central Platform.

To overcome this issue, a new orifice plate with a drain hole was installed during the 2011 planned shutdown. The drain hole applied was 3.2mm in diameter. The opportunity was also taken to reduce the main orifice diameter and optimise it for the expected flowrates. The new orifice plate bore diameter was 138.1mm resulting in a new β = 0.315. The value of dh/d was 0.023.

Figure 7:- The challenges of liquid build-up in gas metering streams – worst case scenario!

The impact of the new plate was dramatic as shown in Figure 6. Straight away the gas measurement was stable and tracked the oil production trend very closely. Oil spikes when the SP56 well was brought on-line after pressure build-up coincide with sudden increases in measured gas as expected. In fact the only periods when the gas doesn't follow the oil trend so well is when gas is flared from a point upstream of the meter, which can happen for example if the compression system is off-line.

So to conclude this section, applying a drain hole to an orifice plate, even of relatively small size at 3.2mm and dh/d = 0.023, can be very effective at removing the impact of liquid presence within a metered gas stream and provides for a far more accurate measurement.

3 FURTHER EXPERIENCES SMALL BORE (4"NB) ULTRASONIC FLOWMETERS

At the North Sea Flow Measurement Workshop in 2008, Craig Coull presented a paper regarding experiences with small bore ultrasonic flowmeters on the Petrojarl Banff FPSO operated by our colleagues at Teekay Petrojarl [1]. This section builds on that paper and provides details of some further experiences that have been encountered since. The gas ultrasonic measurement system on the Petrojarl Banff FPSO is shown in Figure 8.

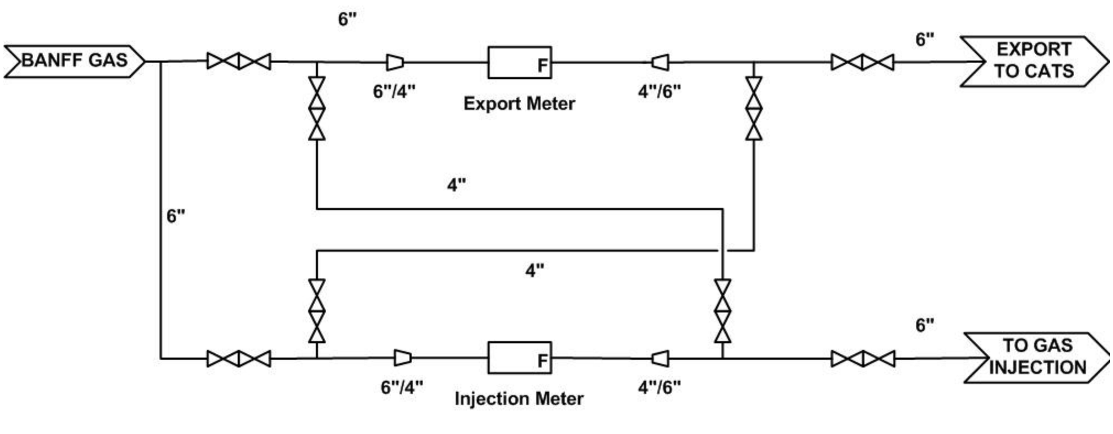


Figure 8:- Banff FPSO export / injection metering schematic diagram

The system was commissioned in 2004, replacing the previous orifice plate based system, to account for the additional gas quantities from the introduction of the Kyle field to the FPSO. The system features two Instromet 4"nb Q-Sonic 3S flowmeters installed in parallel; one essentially dedicated to 'gas injection' (which comprises Banff field re-injection gas and the total gas lift quantity) while the other meter is for gas export measurement to the BP operated CATS pipeline. There has also been cross-over pipework installed to allow the meters to be routed 'in series' to allow a periodic 'series line check' to validate that both meters are operating effectively and within tolerance.

The normal mode of operation is to re-inject all surplus gas into the Banff field to aid oil recovery but since October 2009, gas has been exported on a small number of occasions for just a few days to the CATS pipeline. So in fact the export flowmeter is not on-line anywhere near the amount of time that the injection meter is on-line. Apart from the rare gas export events, the export meter is on-line once a week for a few hours to perform the series line checks.

As reported in 2008, the meters have been very reliable in the field and while some standard calibration parameters were very difficult to achieve, because they are small bore meters with increased relative uncertainties on dimensional measurements (the original standard peak-to-peak maximum tolerance of 0.7% from AGA9 [6] was difficult to achieve in all cases and the most linear meter serial number (S/N) 2901 had uncorrected errors from initial calibrations exceeding 1%), they have continued to provide good service. In fact any major issues that have been experienced previously with the meters have tended to occur during transit to and from onshore flow calibrations, and were not due to any shortcomings with the meters. Since 2008, further experience has been gained with the use of these meters and this is reported in the following sections.

3.1 The Effect of a Chord Failure

On 2nd February 2010, S/N 2902 suffered the failure of two chord paths during the weekly series line check. The meter was returned to Elster-Instromet for repair and was returned to the FPSO following re-calibration. On 5th March 2011, the same meter commenced a further single chord failure (chord 1) which started in a minor way but became terminal by 11th March 2011. In fact, this was the third time this particular meter had failed since March 2009. On investigation, it was difficult to understand why S/N 2902 was failing so often because neither S/N 2901 or 2903 had failed at all during this period and they had experienced more operational usage; in other words they had been installed for longer periods. After the first two failures S/N 2902 received new transducers (original Type P13 DX replacements) but had only been installed a few months before the meter had failed again. With the new transducers being installed and the rest of the meter being similar to the other reliable meters it was difficult to understand why S/N 2902 failed so often and the other meters didn't.

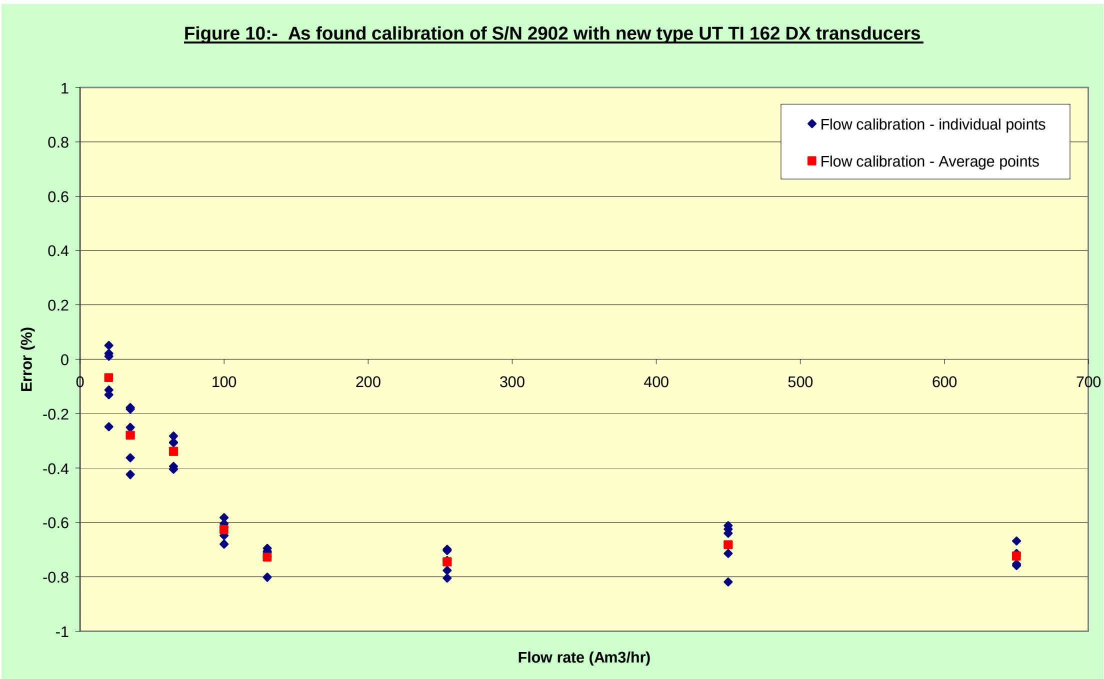
One point was apparent however and that was that in all three cases the meter was installed in the export meter slot. Apart from the weekly series line checks the meter hadn't seen much duty at all as very little export had taken place. It was therefore deduced that the process itself couldn't have been the cause of this issue because no failures had occurred to the meters installed in the injection meter slot, which has been in operation throughout the whole period.

In trying to identify the source of these failures, the only logical cause that could be envisaged was pressurisation and depressurisation of the export line at a more rapid rate than the transducers could cope with. Possibly some liquid contamination may have added to the sensitivity of the transducers to rapid pressure changes (see section 3.2). With the export meter being on and off-line more than the injection meter this idea does have some merit.

To address the issue two changes were made to the measurement process. Firstly, the operating procedures were reviewed and enhanced to ensure that the meter stream is pressurised and de-pressurised at the rate stated within BS 7965 [7], that is 5 bar/min. Secondly, S/N 2902 was upgraded to incorporate the new type UT TI 162 DX transducers (designed to be more robust in the field) and subsequently re-calibrated at the GL Noble-Denton facilities in County Durham, England. However, to obtain some indication of the magnitude of error from the previous meter failure chord 1, which is a swirl measuring path, was deliberately failed in a controlled manner and another calibration performed. The magnitude of any shift in meter response would enable a correction to be accurately applied to the hydrocarbon accounts for this issue. Since the first paper in 2008, CNRI & Teekay had decided to re-calibrate the Banff FPSO flowmeters at the GL Noble-Denton facility, instead of the original PIGSAR facility, purely because the transportation requirements are greatly reduced thus minimizing the risk of damage in transit to the flowmeters. This reduction in transit time has paid dividends with no further damage occurring to date.

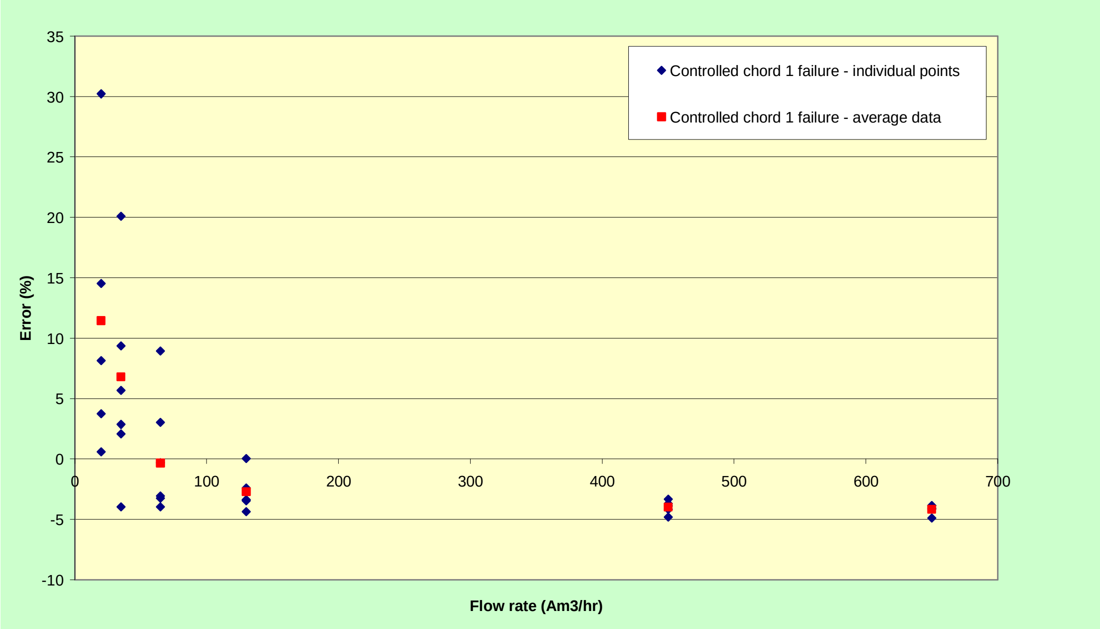
Figure 9 shows the ultrasonic flowmeter calibration line in the foreground at GL Noble-Denton with a CNRI Coriolis flowmeter used for fuel gas measurement installed in the background.

Figure 9:- Banff FPSO Export / Injection Meter Calibration Set-Up



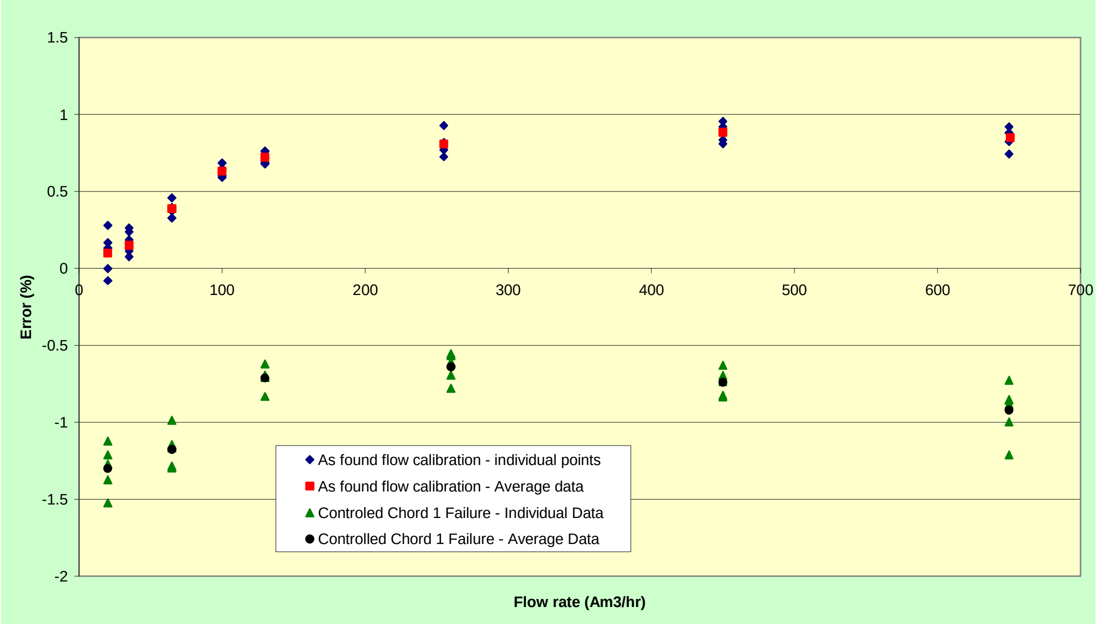
The standard flow calibration of the meter with the new transducers was very impressive. Figure 10 shows that a classic ultrasonic meter calibration response curve was achieved but what was striking for this meter was that 100% 'performance' was achieved throughout the complete flow range. This has never been witnessed before on any of the flowmeter calibrations under-lining the improved ability of the new transducers. Figure 10 also shows excellent repeatability at each flow point.

Figure 11:- Re-calibration of S/N 2902 with controlled failure of chord 1



However, Figure 11 shows the results of a controlled failure of chord 1, which are quite surprising. While the top half of the flow range is still relatively linear and displays reasonable repeatability, with a consistent offset of approximately -4%, the results at the lower flowrates show a high degree of unpredictability.

Figure 12:- As found calibration of S/N 2903 with original type P13 DX transducers



Since the results at the lower flowrates were so variable it was decided to perform a controlled failure of chord 1 during the next scheduled flow calibration as the other meters still had the original Type P13 DX transducers which S/N 2902 had when it last failed in the field. Figure 12 shows the results from the subsequent calibration of S/N 2903. It shows that for S/N 2903 with the original transducers the offset caused by the failure of chord 1 is relatively consistent across the full flow range at approximately -1.5%.

This type of ultrasonic meter is designed to automatically turn off a ‘good’ swirl path if the other swirl path fails. So in this case when chord 1 is ‘failed’, chord 3 automatically turns off (both being swirl type paths) resulting in a single bounce-path meter with only chord 2 functioning. Figure 12 shows that in good flow conditions S/N 2903 with the older type transducers will still operate in a predictable manner across the full flow range with a relatively constant negative offset. However S/N 2902 with the new transducers, and with the associated software changes, is clearly not as effective at measuring at the lower flow rates in the event of a swirl path failure.

The conclusion from these tests is that following a chord 1 failure, the original Type P13 DX transducers provided a more consistent performance at the lower flowrates which, at least in the short term, could allow continued operation and a relatively accurate correction to be calculated and applied to the hydrocarbon accounts. In contrast, once the flow for S/N 2902 with the new type UT TI 162 DX transducers is below approximately 120Am^3/hr, the meter is not usable following a chord 1 failure owing to the huge variation in measurement. In practice, this would require a change of operation on the FPSO to ensure that the meter wasn’t operating in this flow range as there is no possibility that a correction could be calculated with any degree of certainty. This change of operation could be performed by swapping from export to injection mode (or vice versa), going to an in-series operation or, if possible, increasing the flow rate for a short term period until one of the other options is implemented. Ultimately the meter would require to be removed and sent for repair and re-calibration.

However, it is important to re-iterate that the new UT TI 162 DX transducers were selected for their robustness in the field – and the meter has subsequently operated without any of the issues plaguing it previously with the older transducers. It is also important to note that the original Type P13 DX transducers for S/N 2903 did not produce the same ‘100% performance’ as the as-found S/N 2902 calibration and could only manage typically 96% at 450Am^3/hr and 84% at 650Am^3/hr. This indicates that S/N 2902 is likely to be usable at higher flowrates should that be required in the future.

So to conclude, by upgrading the transducers for S/N 2902 to a more effective and robust type of transducer, an unexpected response of the meter has been identified through these tests following a controlled failure of chord 1. However, the expected improvement in transducer reliability plus the proven improvement in performance far out-weighs this feature and the understanding of the operation of these meters on the Banff FPSO, with swirl-path failure on both types of transducer, has been greatly enhanced.

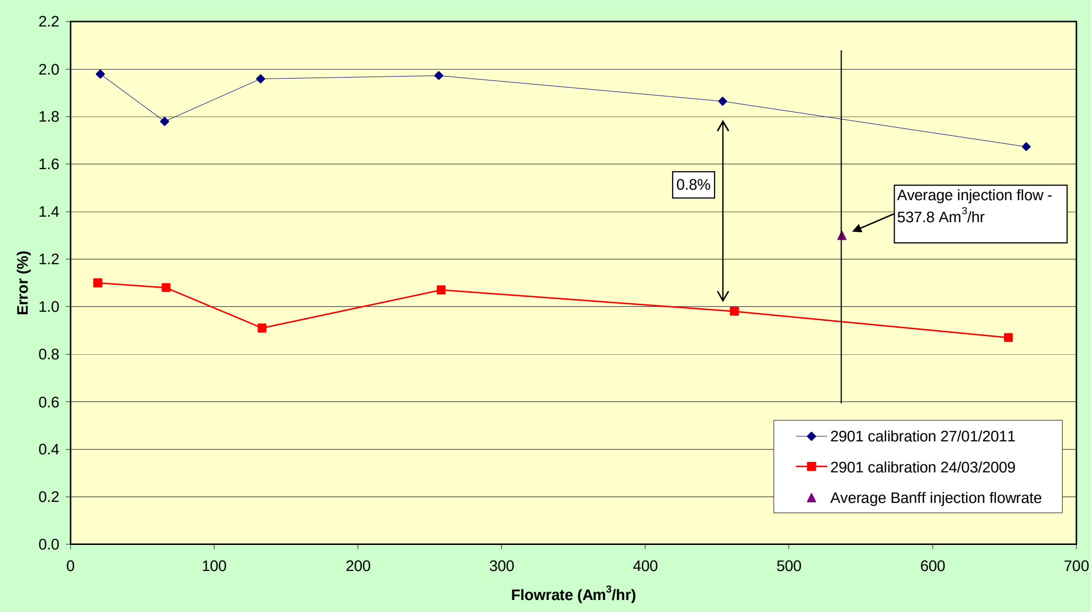
3.2 The Effect of Liquid Contamination

On 27th January 2011, one of the ultrasonic flowmeters (S/N 2901) was calibrated at the GL Noble-Denton facility. Figure 13 shows the results from that calibration compared with the previous calibration performed in 2009.

The response of the meter had shifted significantly by approximately +0.8% across most of the flowrange. This gave cause for concern as the checks in place offshore hadn’t identified this shift, which is of a magnitude that would have been expected to be identified by the series line checks and the diagnostics checks regularly performed on the Banff FPSO.

Since the shift was so significant, the meter was re-calibrated 2 months later in the same line. This re-calibration provided the same results and confirmed that the shift was reproducible. On further investigation of the inside of the meter, a possible cause of this shift was identified as liquid contamination. However, this was not immediately obvious. Figure 14 demonstrates that an oily substance was discovered in the pressure transmitter manifold located on the side of the meter. However, Figure 15 shows that the meter and adjacent spools were relatively clean with no significant build-up of debris and no obvious indication of any contamination at all. In fact, the only indication that there might have been some contamination within the meter stream was a slightly 'sticky' feel to the internal pipe walls.

Figure 13:- Calibration of Banff flowmeter S/N 2901



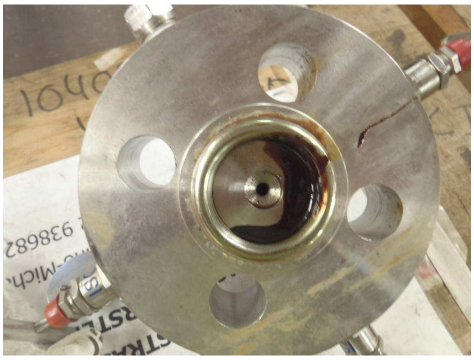


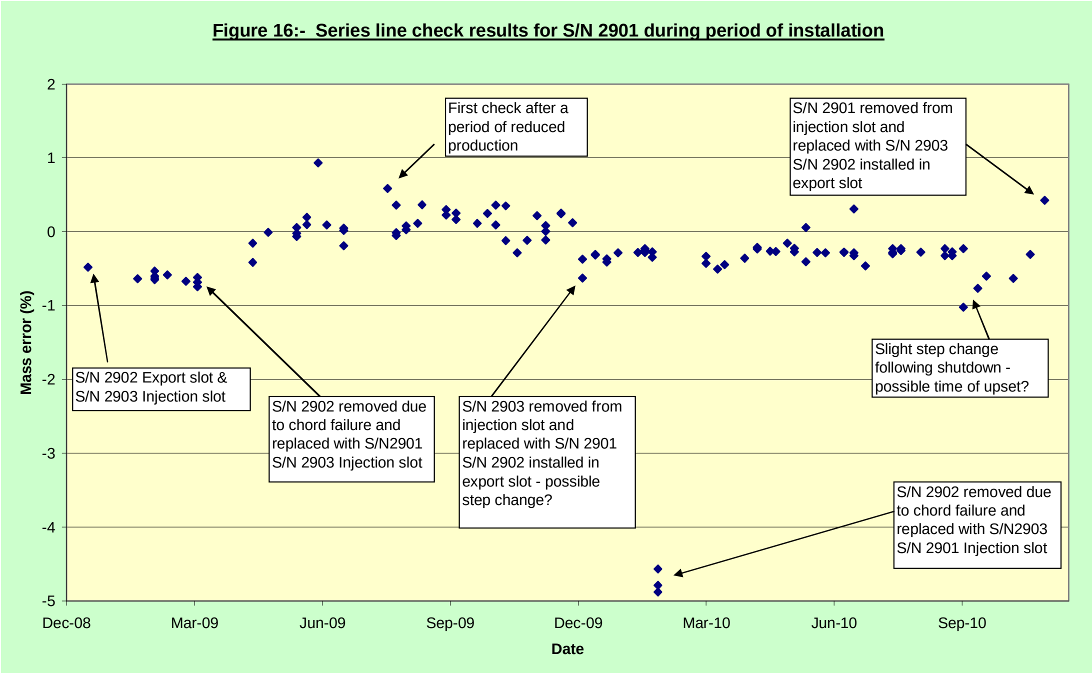
Figure 14:- Oil residue in pressure transmitter manifold

Figure 15:- Meter spool relatively clean

This contamination had not been witnessed before on any of the Banff FPSO meters and posed the following questions:

- What had caused the liquid to appear in these locations and
- Had something been missed in the checks offshore that could have identified this effect much earlier.

In terms of the liquid, it was confirmed from sample analysis that it was of a produced hydrocarbon liquid nature rather than, for example, a lubricating type oil or similarly refined product. However whatever had caused this issue, it did not appear to be an ongoing problem offshore; much rather it appeared to be caused by an isolated event, for example an unplanned system trip or an un-optimised process occurring at start-up. Subsequent to this S/N 2901 calibration, S/N 2903 did show similar oily content in the pressure transmitter manifold during the tests referred to in Section 3.1. However, the 'as found' calibration was in keeping with historical trends. Figure 16 shows the results of the series line checks during the period of installation of S/N 2901 prior to the onshore calibration at GL Noble-Denton.



Overall the series line checks in this period are well within expectations. The tolerance for the checks is ±0.75% as the checks give an overall evaluation of most of the uncertainty sources in the field. The meters have separate pressure and temperature measurement inputs, flow computers, and actually have quite different upstream pipe work configurations, so the checks are a very good indication of performance in the field. The only common source of measurement uncertainty in the field is the chromatograph composition, plus the onshore flow laboratory calibration uncertainty also has to be accounted for. However, some 'common mode errors' potentially affecting both meters at the same time, for example contamination, could theoretically be 'missed' by this series line check.

When S/N 2901 was installed in March 2009, after the failure of S/N 2902 in the export slot (see Section 3.1) an improvement was witnessed. Initially the overall difference in checks between S/N's 2901 and 2903 was very small. This indicates that S/N 2902 may have had an additional issue prior to its failure but the series line checks were still within field tolerance.

In fact it isn't obvious at all where an 'event' could have happened that caused the shift in the response of S/N 2901. There was a period of reduced production in July 2009 so was there some liquid entrainment when the additional wells came back on-line? Subsequent series line checks were very consistent and produced very good agreement up until S/N 2903 was removed in December 2009 so it doesn't appear likely. There was a step change following the subsequent installation of S/N 2902 but the errors before and after are still well within tolerance. When S/N 2902 failed again soon after there was virtually no change following the introduction of the newly calibrated S/N 2903 meter. The only other likely point at which the series line checks may have indicated a contamination 'event' is after the shutdown in September 2010. There was an initial shift in the mass error (%) consistent with the shift by S/N 2901 in Figure 13. However, just prior to the removal of S/N 2901 the mass error (%) value was almost back to where it was before the shutdown. This may indicate an issue immediately following a shutdown which had worked itself out soon after.

So to conclude, the series line checks even with the benefit of hindsight knowledge do not clearly identify the point at which the S/N 2901 meter shifted in its response by +0.8%. In fact, if anything the checks imply that the meter was working well within its expected performance envelope during the entire period of installation.

So what about meter diagnostics?

The meter diagnostics for the three Banff FPSO meters are taken and recorded periodically as part of the maintenance regime – So do any of these meter diagnostics identify a potential shift in the response of S/N 2901? The Banff FPSO doesn't have permanent on-line diagnostic monitoring. Rather the diagnostics are captured on a routine basis every 2 weeks typically. Figures 17 - 22 comprise the diagnostic checks performed over this period on S/N 2901. Once again, far from identifying a change in performance, the diagnostic checks imply that the meter was operating very consistently and at a very high level throughout the installation period. All the data are well within tolerance and the only significant step changes, small as they are, can be seen in swirl angle and path velocity ratio where the meter had been removed from the export meter slot and re-installed in the injection meter slot. Generally all meters are initially installed in the export meter slot for CATS requirements and following a period of 6 to 12 months they are removed and re-installed into the injection meter slot. The different orientation of upstream pipe work accounts for the slight change in swirl angle and velocity ratio seen in these figures.

Figure 17:- VOS footprints

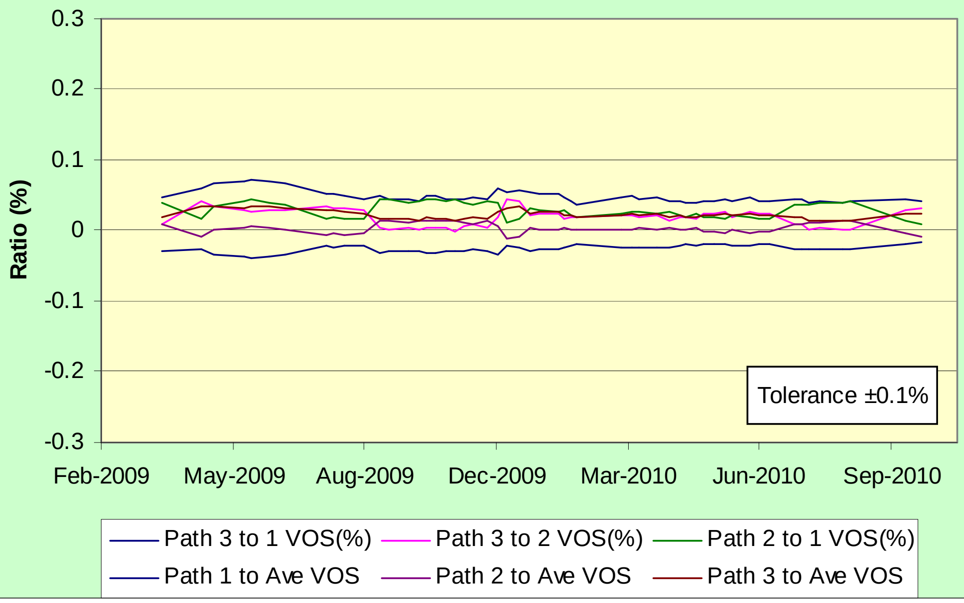
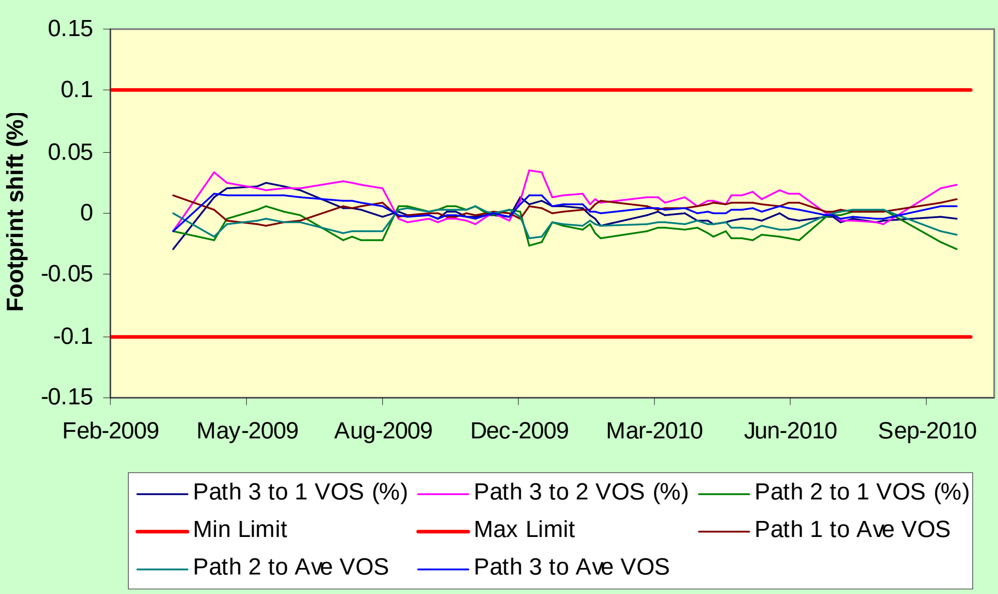
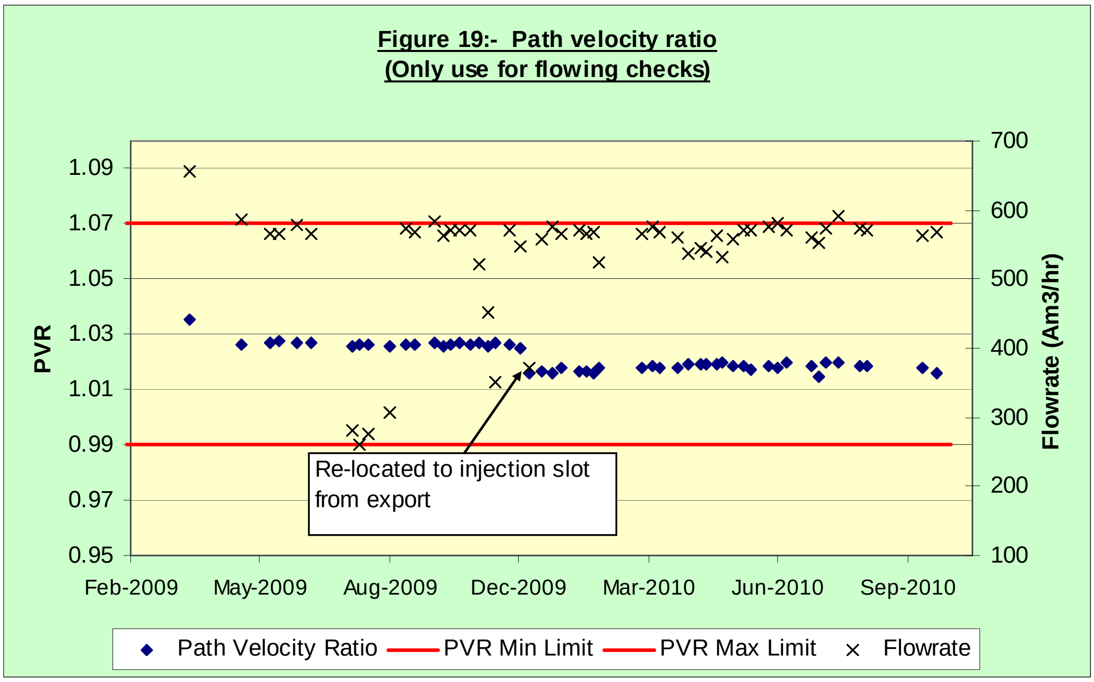
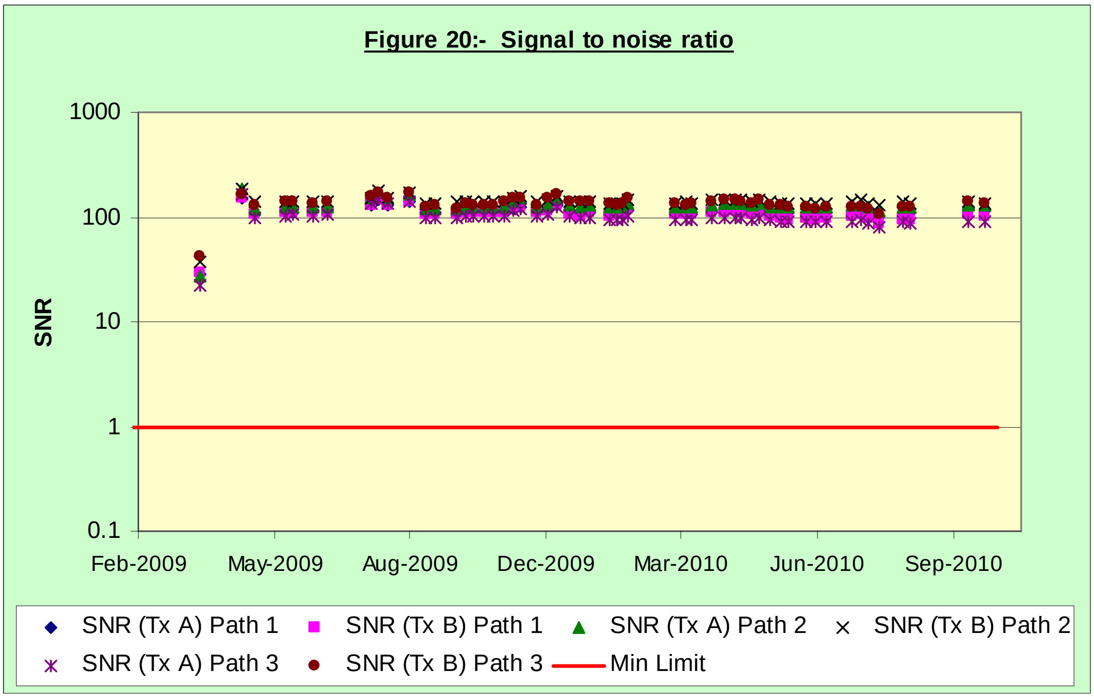


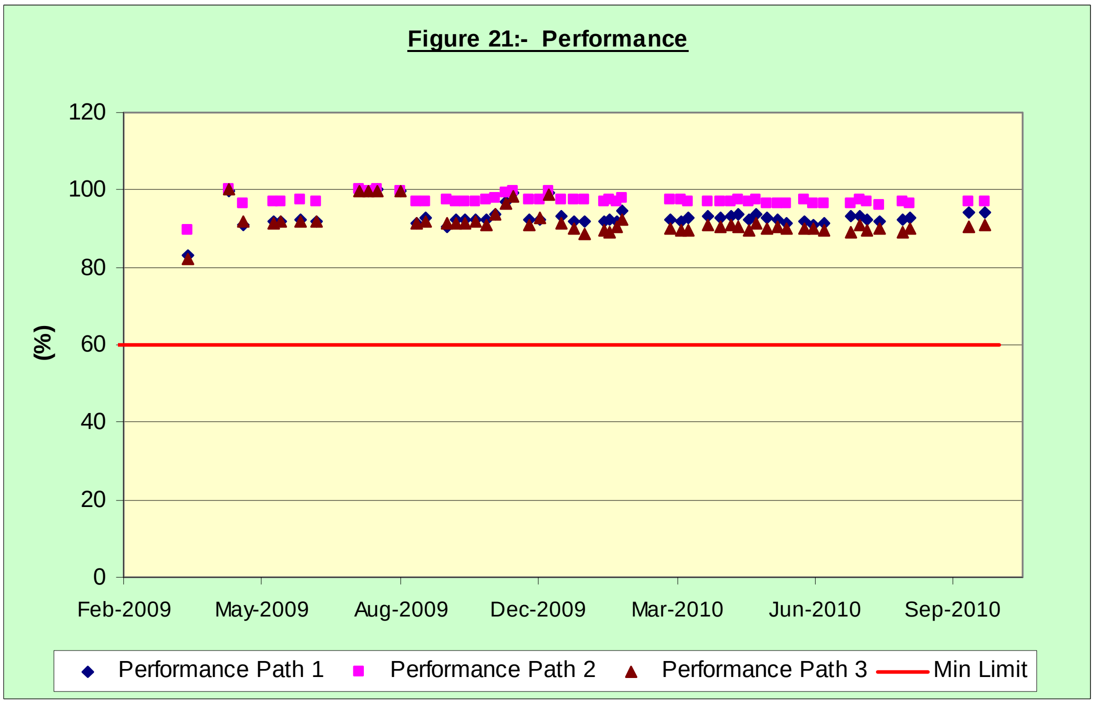
Figure 18:- VOS footprint shift from calibration

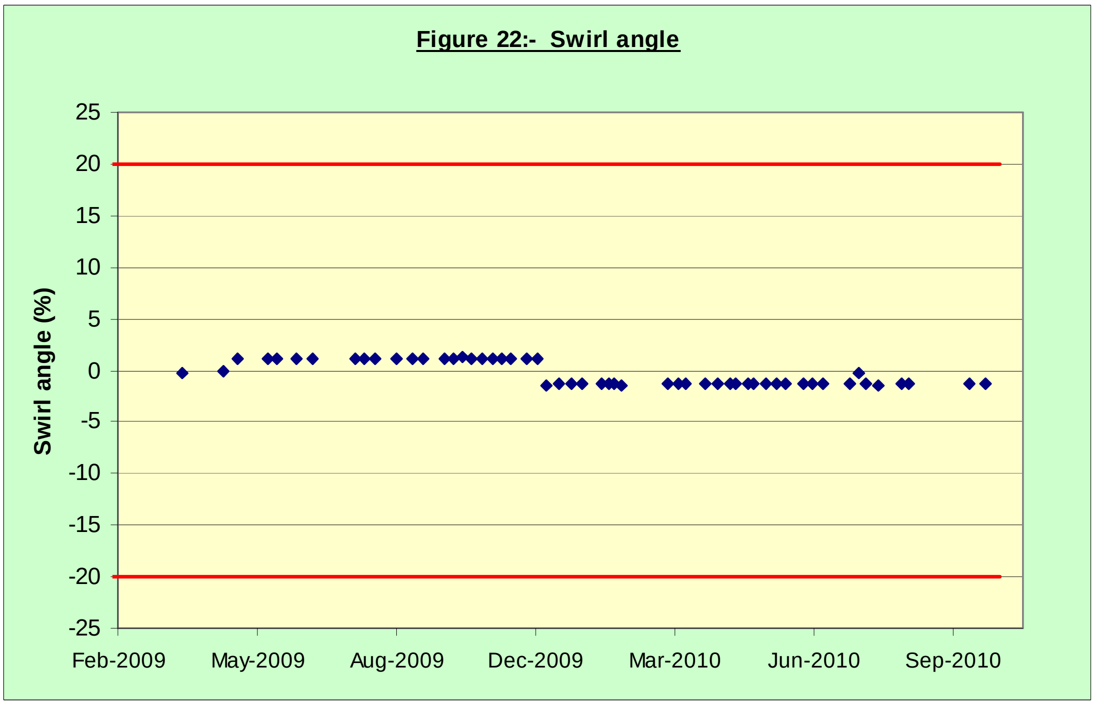






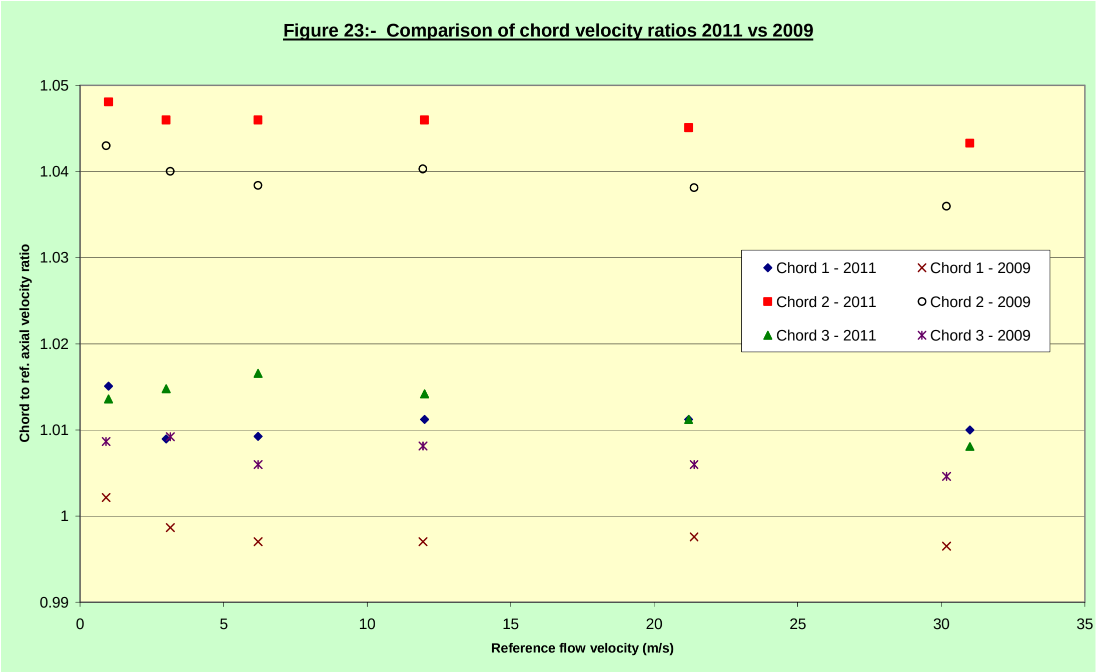
Therefore, the meter diagnostic checks for S/N 2901 during the period of installation do not identify a point at which the meter could have shifted in its response. On the contrary, the checks once again imply that the meter was working well within its expected performance envelope during the installation period.





So is there any information available that would indicate a potential shift in meter response?

Following the calibration in 2011, our colleagues from Elster-Instromet analysed the log file data and noted that while the various meter diagnostics were broadly similar in both this calibration in 2011, and the previous one in 2009, there was a slight increase in the relative velocities defined as the chord velocity divided by the average pipe velocity from the reference meter. The Elster-Instromet data has been reproduced in Figure 23.



This data indicates that the chord to reference gas velocity ratios are slightly higher in the 2011 calibration compared with the 2009 calibration at the same volumetric flowrate. This may indicate contamination as the source of the meter response shift but this could only be true if the meter diameter has reduced, which is theoretically possible if there is a coating of contamination on the internal wall of the meter as shown in Figure 24:

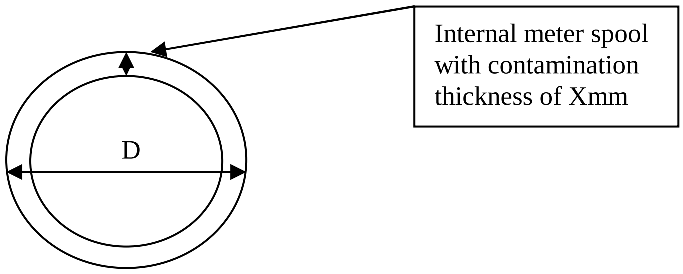


Figure 24:- Build-up of contamination within pipe spool

If a coating of contamination is present, the theoretical effect is to make the flowmeter over-measure. This is because the ultrasonic flowmeter continues to measure the velocity accurately (being primarily a flow velocity measuring device) but uses the same fixed diameter, and therefore area, to calculate the volumetric flowrate. The general equation is:

$$Q_{vol} = V\pi\left(\frac{D^2}{4}\right) \tag{2}$$

Assuming the axial mean velocity is determined accurately, an error of approximately +0.8% in Q_{vol} is equal to an error of only 0.4% in the diameter. The meter in question has a diameter of only 87.1mm therefore indicating a potential error in diameter of approximately 0.348mm. Assuming an equal layer of contamination within the meter spool, this equates to a contamination thickness (X) of only 0.174mm. So with liquid contamination witnessed to be present, and with this theoretical sensitivity to changes in meter diameter, a shift in meter response of 0.8% is quite possible. However, this effect has not been witnessed in other calibrations, even those where liquid presence was also identified, leaving some uncertainty.

In 2011, the United Kingdom's Department of Energy and Climate Change Measurement Group (DECC, formerly DTI) organised a seminar at the Aberdeen Exhibition and Conference Centre (AECC) focussing on Condition Based Monitoring (CBM) for ultrasonic flowmeters [8]. During this seminar a presentation was made regarding the success that Shell had experienced using meter diagnostic information to verify the performance of 20" nb meters, building on the work reported by Peterson et al at the NSFMW in 2008 [9]. There has been a lot of discussion regarding the effectiveness of CBM and its application in recent years, especially with the potential for reducing or even eliminating the need for meter calibrations at flow laboratories. Indeed the work published by Shell to date shows that some movement towards this goal is possible.

However, this experience with S/N 2901 has identified a significant shift of circa +0.8%, likely to have been caused by liquid contamination, that the offshore series line checks and meter diagnostic checks failed to identify. Even with the advantage of hindsight it is not clear when S/N 2901 shifted in its response. Comparison of calibration diagnostics in the controlled flow laboratories hinted at a change in chord velocity ratios but this would have been difficult to identify in the field. The clear difference between this application and Shell's is in meter size. While a small build-up of contamination on a meter spool of fractions of a mm can theoretically affect the performance of a 4"nb (87.1mm) diameter ultrasonic flowmeter significantly, this build-up depth would be insignificant in a meter of 20"nb diameter. So while series line and diagnostic checks in the field continue to be vital as part of the meter verification philosophy on the Banff FPSO, this experience demonstrates that periodic onshore flow calibration at an accredited laboratory remains ultimately important in the meter validation life cycle for these small bore flowmeters.

4 CALIBRATION OF TWO DENSITOMETERS WITH THE NEW UK OFFSHORE DECC PREFERRED VERIFICATION METHODOLOGY

In 2004, DECC issued a note relating to a small but systematic 'offset error' when a Solartron Type densitometer was operated at a temperature other than that at the calibration reference temperature (typically 20^{o}C) [10]. The inference was that the further away from the calibration reference temperature the device was operated at, the more this error was likely to be. This issue was a major concern as this type of densitometer has become the device of choice within the offshore oil industry as they are generally good and reliable devices.

To investigate this effect, and other potential effects like elevated pressure, a Joint Industry Project (JIP) was established by NEL in conjunction with DECC, Solartron and almost all of the UK oil operators. The background and subsequent findings of this JIP are discussed in more depth at the Poster Session by Norman Glenn at this NSFMW [11]. The JIP involved developing the NEL primary density standard to be able to perform densitometer calibrations at elevated temperatures and pressures, and with different liquids representing various densities and viscosities, to provide an actual reference density at operating conditions as opposed to the standard calibration of these units performed at a reference temperature of 20^{o}C and 1 bar absolute. This new methodology allows for a significant reduction in the uncertainty of the derived calibration constants from the following typical equations:

$$\rho_{raw} = K_0 + K_1 T + K_2 T^2 \tag{3}$$

$$\rho_{temp} = \rho_{raw}\,(1 + K_{18}(t - 20)) + K_{19}(t - 20) \tag{4}$$

$$\rho_{press} = \rho_{temp}\,(1 + K_{20}(P - 1)) + K_{21}(P - 1) \tag{5}$$

$$K_{20} = K_{20A} + K_{20B}(P - 1) \tag{6}$$

$$K_{21} = K_{21A} + K_{21B}(P - 1) \tag{6}$$

Figure 25:- The NEL Primary Density Calibration System with S/N 352825 installed

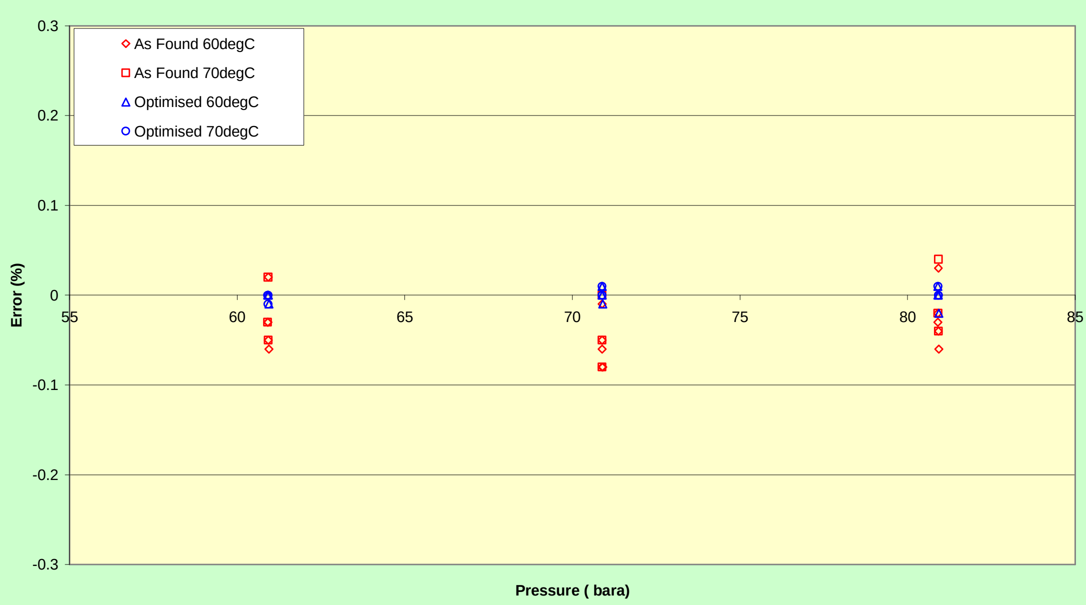
CNRI have commenced performing routine calibrations in keeping with the new methodology, and the final section of this paper focuses on the results from calibrating two Solartron Type 7835 units in the NEL primary density standard in April/May 2012. The two units are of particular interest as their normal operational installation was the Murchison platform operating at typically 70barg and 65°C, a far distance from the standard calibration reference conditions of 1 bar absolute and 20°C. The tests were performed by installing each unit in the primary calibration system and performing an 'as found' calibration utilising the densitometer constants from the previous standard calibration certificates. A new set of densitometer constants were then produced optimised around the unit's performance at its operating conditions. Figure 25 shows one of the units installed in the primary density facility.

The tests were performed using different liquids with varying densities and viscosities to ensure that there are no significant systematic biases with respect to density or viscosity. The 3 liquids with nominal viscosities and densities at 60°C and 71 bara are:

- Iso-Octane 0.356cP and 667kg/m^3
- Toluene 0.404cP and 835kg/m^3
- Di(2-ethylhexyl) sebacate 7.27cP and 890kg/m^3

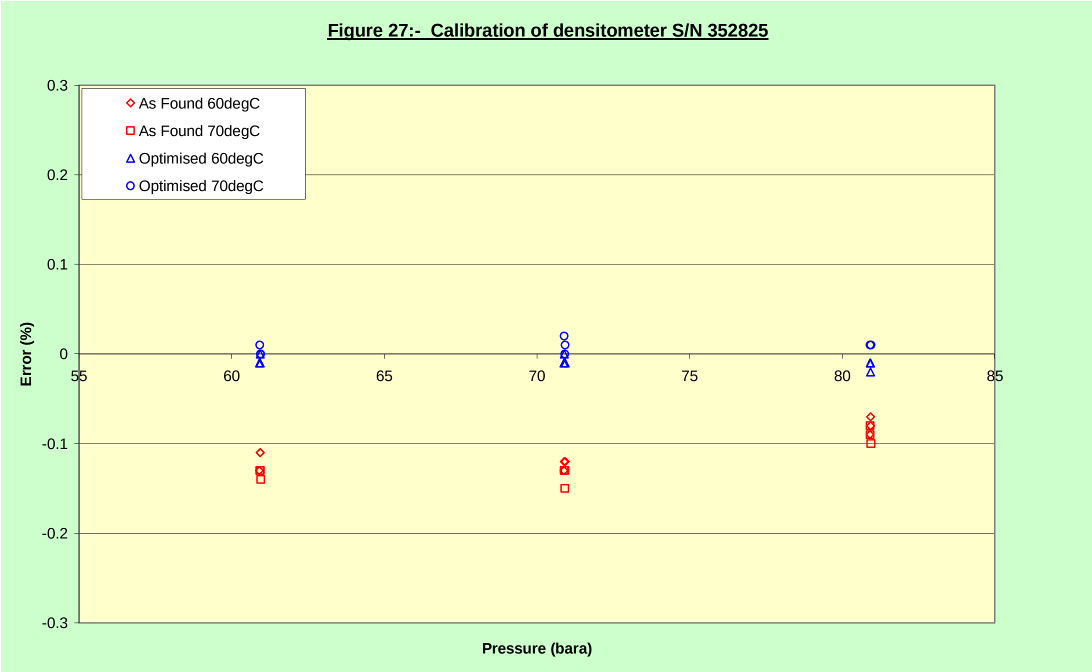
Figure 26 shows the results for densitometer S/N 350943. Tests were performed at nominally 61, 71 and 81 bar absolute, with temperatures of 60 and 70°C, utilising the 3 fluids. The test uncertainty in the determined density was ±0.05%. The obvious message from the 'as found' calibration is how appropriate the previous calibration constants were in hindsight. The spread of data is circa 0.1% at each of the test pressures, and the errors are reasonably well spread about zero apart from at 71 bara where the densitometer mostly under-measured.

Fig 26:- Densitometer calibration for S/N 350943



With all the errors within -0.08%, this was a very welcome result. Considering the concerns over the potential errors at this high pressure and temperature application, the results obtained were well within the duty/standby tolerance for the two densitometer system in the field of 1.5kg/m^3 (approximately 0.19%). The advantage of optimising the constants for the working range is clear with the improvements in repeatability and measurement uncertainty.

Contrast this result with Figure 27, which shows the results for the unit S/N 352825. This time the results obtained are more consistent compared to S/N 350943 with a total spread of approximately 0.03%. The optimised data do not improve significantly on this initial result. However, this unit produces clear 'as found' under-measurement across the pressure range between -0.07% (achieved at 81 bara) and the worst result of -0.15% achieved at 71 bara. This is a significant quantity and justified the calibration (and will pay for them) on its own. However, this result was still not as large as pre-test concerns.



Incidentally, the air check results from the two units were compared with those obtained at the previous standard calibrations. It is interesting to note that both units produced periodic times within a nano-second of their previous value.

So to conclude this section, the results of these two densitometer calibrations at relatively high operating pressure and temperature have demonstrated that significantly improved measurement uncertainty can be achieved at operating conditions by utilising the new methodology, which has been implemented by NEL in their primary density calibration system. However, in this particular high pressure/temperature application the 'as found' results were not as large as were originally feared prior to the tests taking place and S/N 350943 showed very little systematic bias compared with the uncertainty allowance in the field. The result for S/N 352825 showed a small but significant systematic under-measurement of density and demonstrates the importance of calibrating densitometers with the new methodology. The tests also demonstrated that identical models of densitometer can produce different performance characteristics at the same operating temperature and pressure.

5 CONCLUSIONS

This paper has demonstrated some of the recent in-field measurement experiences that have occurred on CNRI North Sea mature assets, and the methodologies that have been used in over-coming or compensating for them. This paper has demonstrated the following:

i) Orifice plates with drain holes are an effective way of measuring gas with small amounts of liquid present. This has been demonstrated with the case study of an 18”nb meter on Ninian South platform. In addition, it has been demonstrated that the statement in ISO/TR 15377:2007 regarding drain holes only being valid in pipe sizes greater than D = 100mm (4”nb) is too restrictive. Test results showing 2”nb orifice plate meters performing effectively have been demonstrated.

ii) Test results have been shown to demonstrate the different responses of the Banff FPSO 4”nb ultrasonic flowmeter transducer types in the event of a chord 1 (swirl path) failure.

iii) Test results have been shown to demonstrate the apparent impact of a liquid contamination event on the response of the Banff FPSO 4”nb ultrasonic flowmeters. While this effect was identified during routine re-calibration at a flow laboratory, series line checks and diagnostic checks performed offshore did not appear to indicate any change in meter response. This under-lines the importance of the three elements of verification, including flow laboratory re-calibration for these flowmeters.

iv) Test results of calibrating two Solartron model 7835 densitometers in the new primary density facility at NEL have been demonstrated. While pre-test concerns regarding the potential of large errors did not materialise, when comparing ‘as found’ results with the primary reference, the results did indicate that significant improvements in both repeatability and uncertainty can be achieved with the improved verification methodology.

The results described in this paper have been useful in improving and optimising the measurement effectiveness of a number of flowmeter systems within CNRI.

6 NOTATION

The notation used in this paper is as follows:

D	Internal pipe diameter*
d	Orifice plate bore diameter*
dh	Drain hole diameter (mm)
dc	Corrected plate bore diameter (mm)
E	Orifice plate thickness (mm)
β	Orifice bore to pipe diameter ratio
Q_m	Mass flowrate (kg/sec)
Q_{vol}	Actual volumetric flowrate (Am^3/hr)
ΔP	Differential Pressure (Pascals)
t	Temperature (^oC)
P	Pressure (bara)
T	Periodic time (µsecs)
ρ	Line density (kg/m^3)
V	Mean axial pipe velocity (m/sec)
X	Contamination thickness (mm)
K_0, K_1, K_2, K_{18}, K_{19}, K_{20}, K_{20A}, K_{20B}, K_{21}, K_{21A}, K_{21B}	Standard densitometer constants
ρ_{raw}	Uncorrected density reading (kg/m^3)
ρ_{temp}	Density reading corrected for temperature (kg/m^3)
ρ_{press}	Density reading corrected for pressure (kg/m^3)

*Note that pipe and bore diameters in this paper are provided in inches and mm throughout the document. In Equation (1), d is required to be applied in metres.

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