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Aberdeen SMER SC006

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Previous issues of this document shall be destroyed or marked SUPERSEDED

Project Code: 1/18274

Distribution

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Executive Summary

Site name	Aberdeen Offtake
DNO	Scotland Gas Networks
LDZ	Scotland
Error start date	21 st July 2009
Error corrected date	10 th August 2010
Size of error (over or under read)	1,617 GWh under-registration
Error description	Following an orifice plate change the new plate was not lowered fully into the pipe. This resulted in a reduction in differential pressure and hence an under-registration of flow.
Meter type	Orifice Plate
SMER Unique Reference No	SC006
Compiled by	Ben Kirkman (GL Noble Denton)

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1 Error Description

Aberdeen Offtake metering consists of one 10" orifice plate metering system with a gas chromatograph for PTZ correction. The orifice plate is operated within a Heeco Ltd type E dual-chamber carrier (serial number 7603758). This allows for removal of the plate while the pipeline is still under pressure by raising the orifice plate into a top chamber which is then sealed off using a valve between the top and bottom chambers. Under normal operation the orifice plate is lowered through the valve into the bottom chamber and the valve remains open. The seal is then made by the o-ring seal around the rim of the orifice plate.

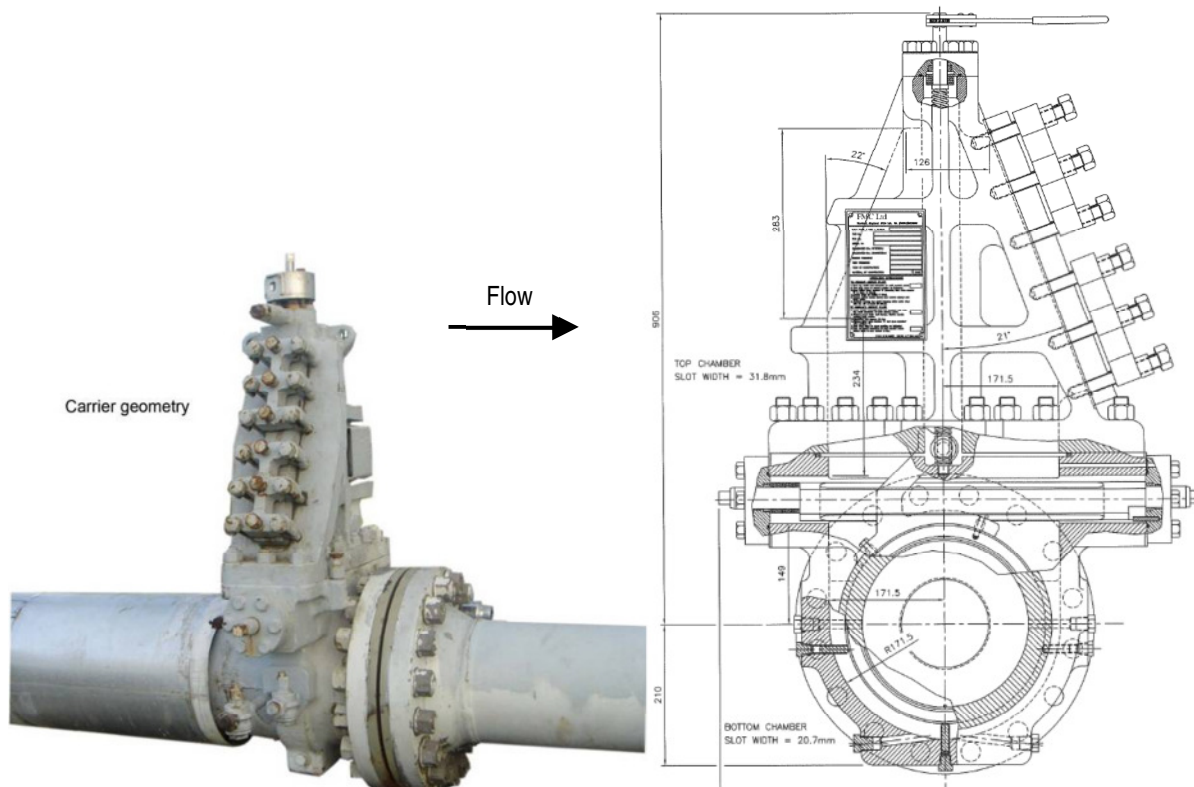


Figure 1 – [left] Heeco Dual-chamber Orifice Plate Carrier;

Figure 2 – [right] Orifice Plate Carrier Dimensional Drawing

On 7th August 2010 a fault was logged relating to 'possible metering issues' at Aberdeen Offtake following line pack calculations. The line pack or amount of gas stored at standard conditions in the downstream network is calculated knowing the dimensions of the pipe and the pressure and temperature at various points in the downstream network. The change in line pack should be equal to the difference between the amount going into and the amount going out of the network. If the demand is zero the line pack will increase by the amount going into the network through the offtake. On this occasion calculations showed the line pack increased by 32,000 scm in one hour when the flow rate through the site was 21,000 scm/h as was recorded in the Fault Log 112402:

'Ongoing investigations overnight have made us look at the reasons as to why Aberdeen is being shutdown so often, looking at the same time last year the flows are dramatically lower. There could be many causes for this which are being looked at. Since the meter validation on 27/7 the flows seem to have dropped even more. The meter validation post checks were checked with zero flow. Aberdeen has been shutdown this morning and when bringing the flow back on to 0.5 Mscm/d (21 kscm/h) at 09:00 the linepack in the system has gone up by 32 kscm. This is over 50% more than the actual flow going through the site. I have discussed with the SPOC that this is impossible, the linepack shouldn't go up any more than the flow that is going through the site even with the small amounts of

demand that are going through the system. He is discuss with E&I engineer and possibly get checked today.'

Following an on-site investigation, a mechanical team was requested.

On 10th August 2010 it was advised that the orifice plate was not set correctly. The differential pressure (DP) and flow were reading significantly lower before the plate was taken out and aligned properly. The log reads:

'Discussed problem with [operative] whilst doing post validation checks. He advises orifice plate was not set correctly. Where as orifice plate had a pressure differential of 6 mbar it was showing 54mbar. Also when 0.5Mscm/d was put on as a flow it was actually showing 1.42 Mscm/d. Orifice plate has been taken out and aligned properly and now flow is showing correctly. Errors in meter validation are down to the issue that the flow on GTMS was showing virtually 1/3rd of its actual flow.'

Subsequent interviews were held with the mechanical operatives who undertook the orifice plate changes on 21st July 2009 and 27th July 2010. The operatives were not able to confirm the counter reading on the orifice plate carrier at the end of the operations on 21st July 2009 or at the start of the operations on 27th July 2010. However, there is some confidence that the orifice plate was left at a counter reading of 99950 on 27th July 2010.

2 Methodology

2.1 Flow Profile Analysis

During normal operation Aberdeen Offtake is controlled using a combination of flow rate setpoint and low and high pressure overrides. The flow control valve will operate to supply a flow rate equal to the setpoint. If the downstream pressure gets too low or too high (based on pressure overrides), then the flow control valve will operate to maintain the pressure above the low override or below the high override.

When maintenance is carried out affecting the flow rate readings, the flow control valve can be put into direct valve control to maintain a constant flow rate while the readings are erroneous. A fixed flow override value is entered into the flow computer to maintain the signal to the Local Gas Treatment (LGT) system which controls the injection of odorant. This is normal procedure for an orifice plate change and occurred on 21st July 2009 and 10th August 2010.

From the data recorded while in direct valve control a step change in flow rate can be seen on both occasions in Figure 3 and Figure 4.

On 21st July 2009 the recorded flow rate changed from a mean value of 30,111 scm/h before the orifice plate change to a mean value of 20,788 scm/h in the initial period after the orifice plate change. This indicates an under-registration of 31 % following the plate change.

On 10th August 2010 the recorded flow rate changed from a mean value 20,914 scm/h before the orifice plate change to a mean value 68,075 scm/h in the initial period after the orifice plate change. This indicates an under-registration of 69 % prior to the plate change.

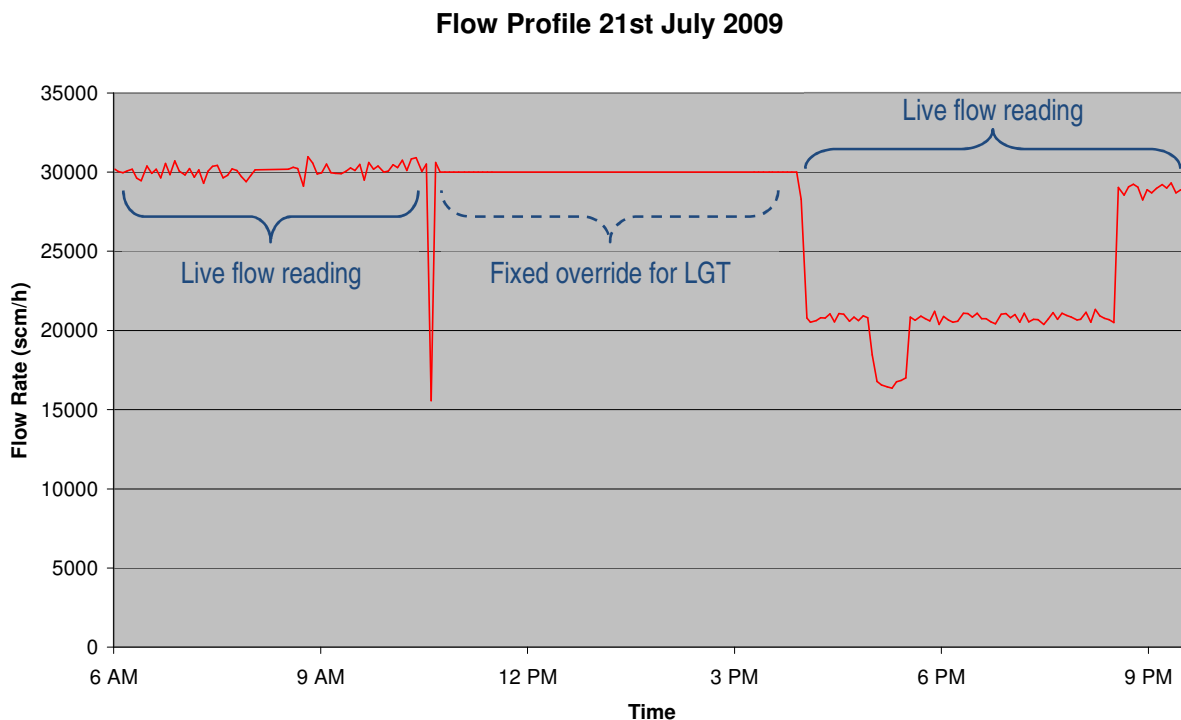


Figure 3 - Graph of flow rate on 21st July 2009

Flow Profile 10th August 2010

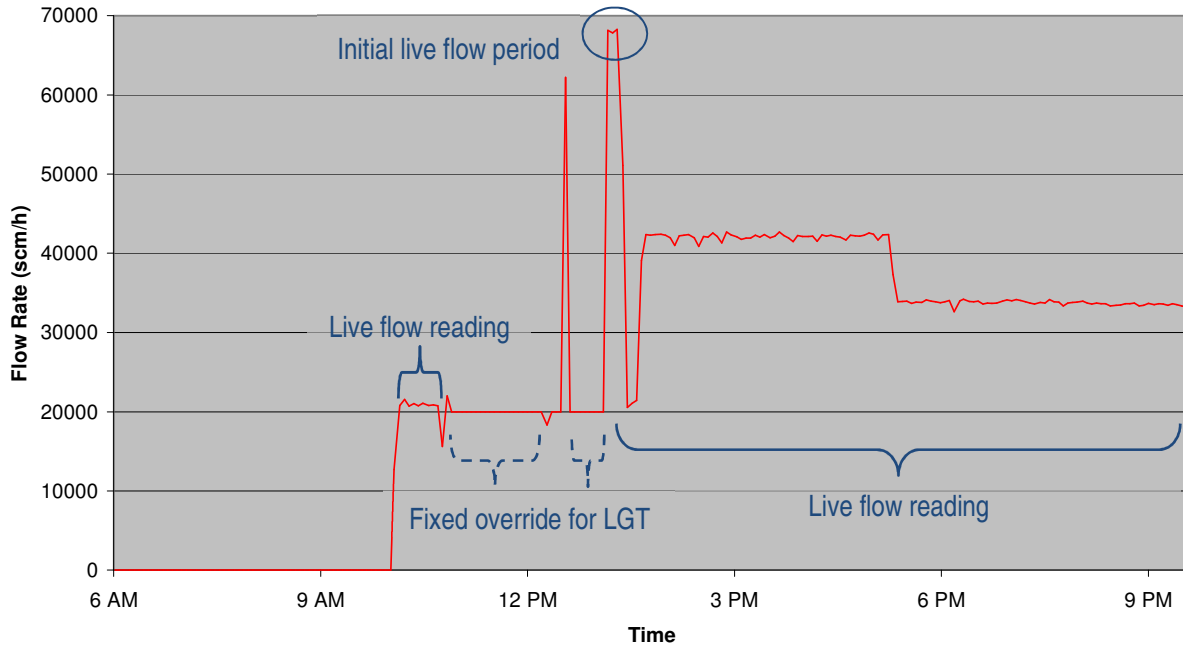


Figure 4 - Graph of flow rate on 10th August 2010

Flow Profile 27th July 2010

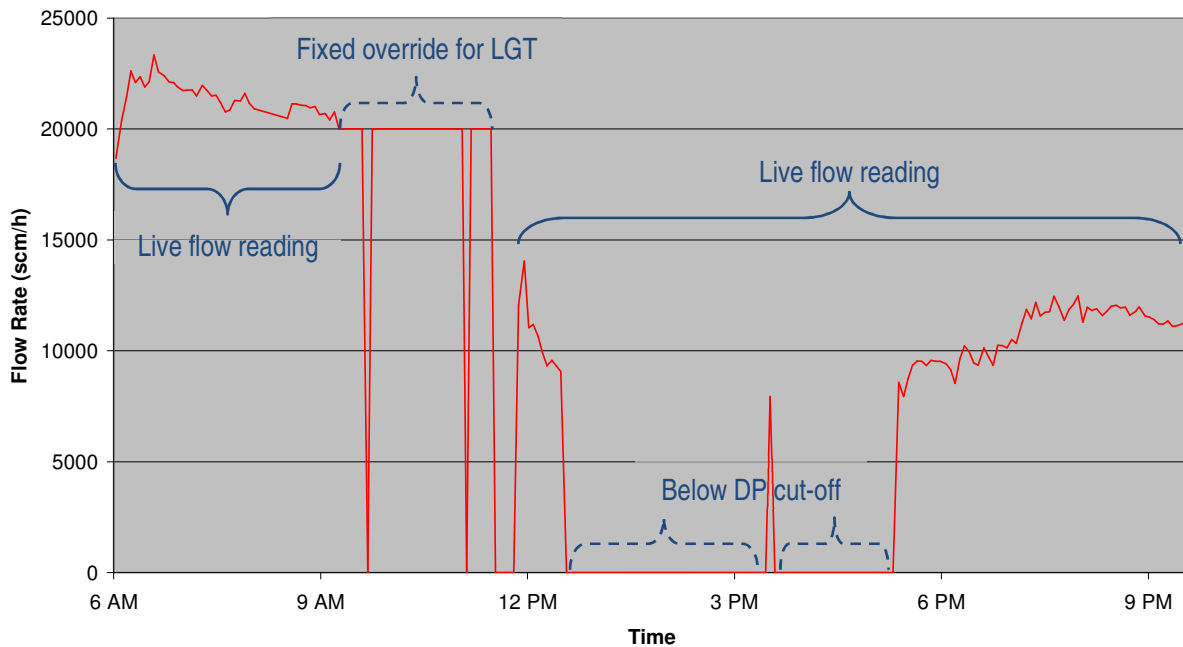


Figure 5 - Graph of flow rate on 27th July 2010

Figure 5 shows that on 27th July 2010 the flow rate was transient. The flow rate could not be maintained because the pressure differential across the site was minimal. Following the orifice plate change the differential pressure was close to the low DP cut-off (0.9 mbar) and some zero flow rates were recorded.

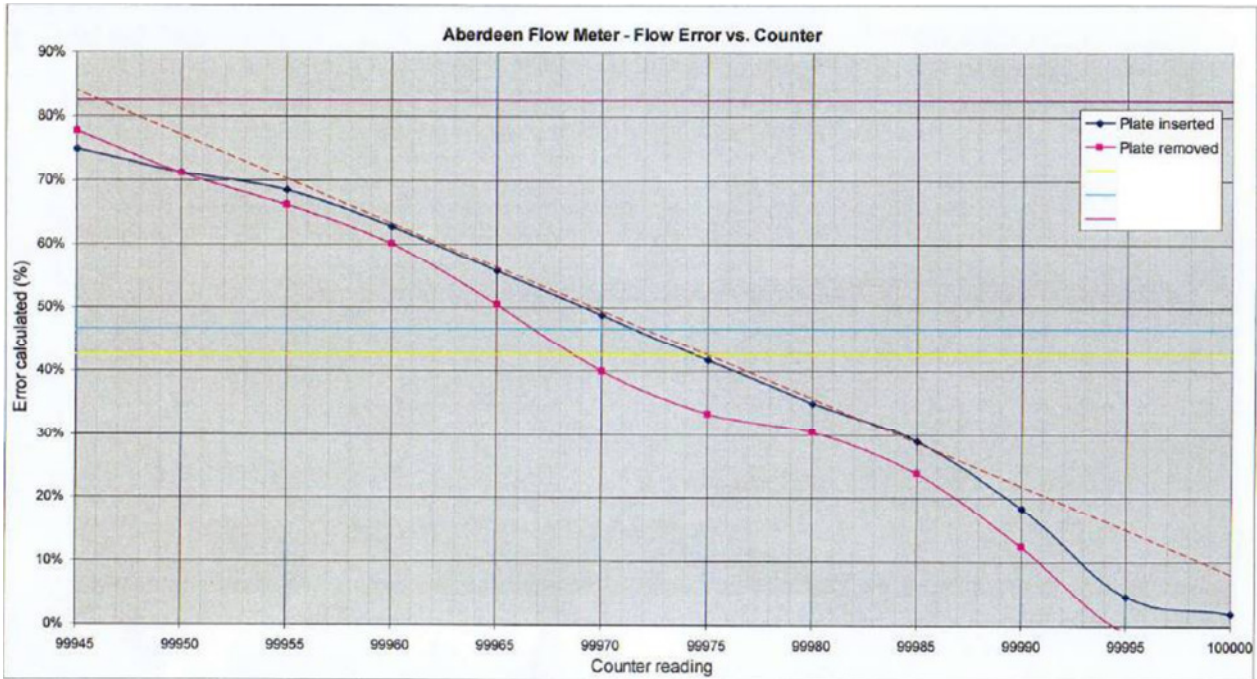


Figure 6 - Downstream party initial site tests

Initial site tests were carried out by the downstream party to estimate the magnitude of the error, the results of which are shown in Figure 6. These were carried out prior to the appointment of Independent Technical Experts and provided as background to the error. While these were not suitable for quantification of the error, they did give an indication of the potential relationship between counter readings and flow error.

The error found on the 10th August 2010, was estimated from flow rate data (Figure 4) to be 69 %. When compared to Figure 6, the suggested counter reading of 99950 would produce a similar error at 71 %.

The error on the 21st July 2009, was estimated from flow rate data (Figure 3) to be 31 %. Based on this the unknown counter reading between 21st July 2009 and 27th July 2010 was estimated to be around 99984.

2.2 Carrier Checks

The initial investigation aimed to determine the relationship between the counter reading and the physical location of the plate within the pipe.

The downstream spool was removed to provide access to the orifice plate inside the pipe. Figure 7 shows the measurements taken looking upstream. The vertical offset (A) and horizontal offset (B) of the orifice plate relative to the pipe were measured at various counter locations on both removal and insertion of orifice plate using slip gauges. The measurements were taken between the bottom centre of the pipe and the bottom of the orifice bore. The horizontal offset was measured because the orifice plate mechanism doesn't remove the plate in a vertical line, but draws it out against the far wall (B is positive and to the right when looking upstream). Conversely the plate follows the near wall on insertion.

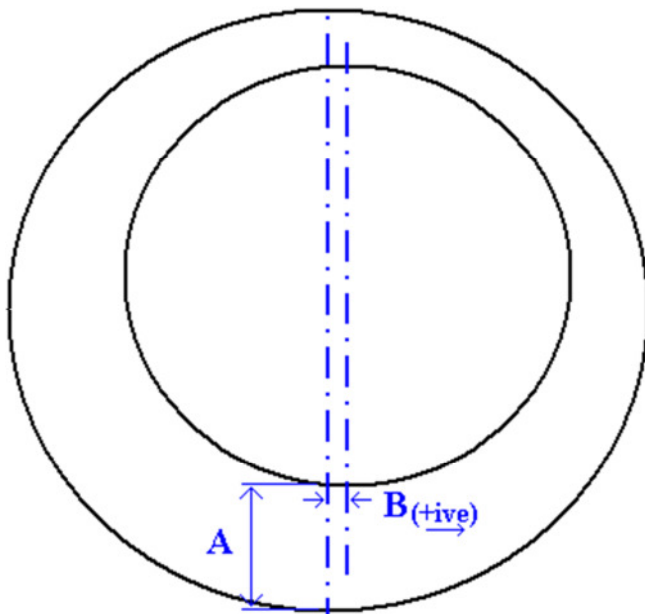


Figure 7 – Diagram of measurement parameters (looking upstream)

Figure 8 shows a similar orifice plate carrier (not geometrically identical to that used at Aberdeen) to illustrate how the orifice plate is removed from normal operation. It is raised through the valve into the upper chamber. The valve is then closed (and plugged with grease). Finally the retaining bar is removed and the orifice is fully removed from the upper chamber.

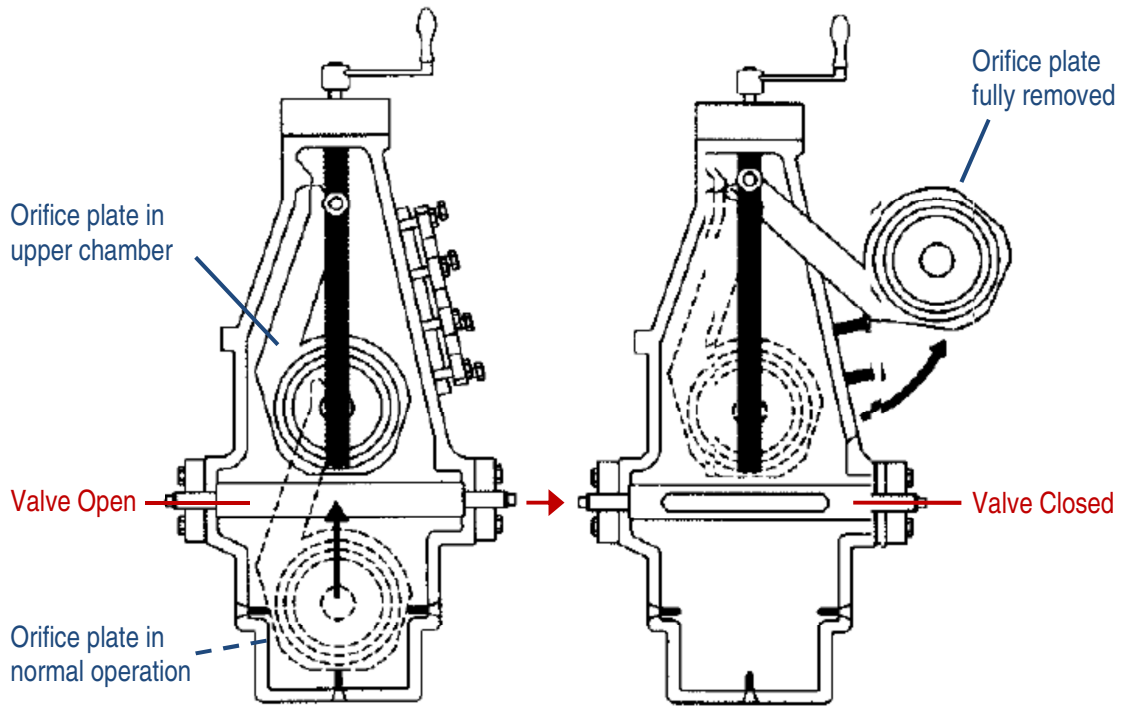


Figure 8 - Orifice Plate Carrier Diagram (looking downstream)

The following photographic sequence in Figure 9 to Figure 15 shows the plate being removed from the normal operating position and re-inserted (looking upstream).

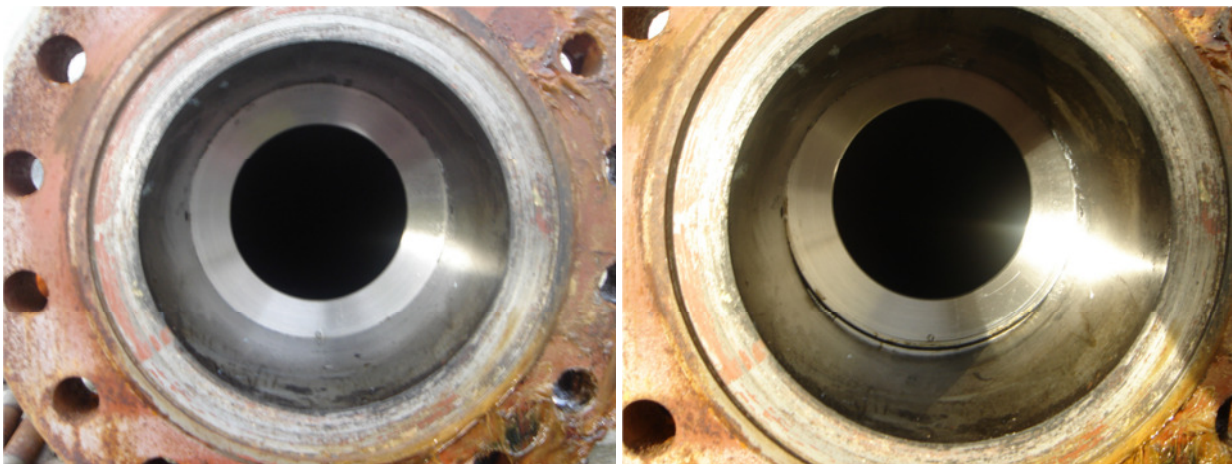


Figure 9 – (left) Orifice plate normal operating position; Figure 10 – (right) Orifice plate removal at 99995 counter reading

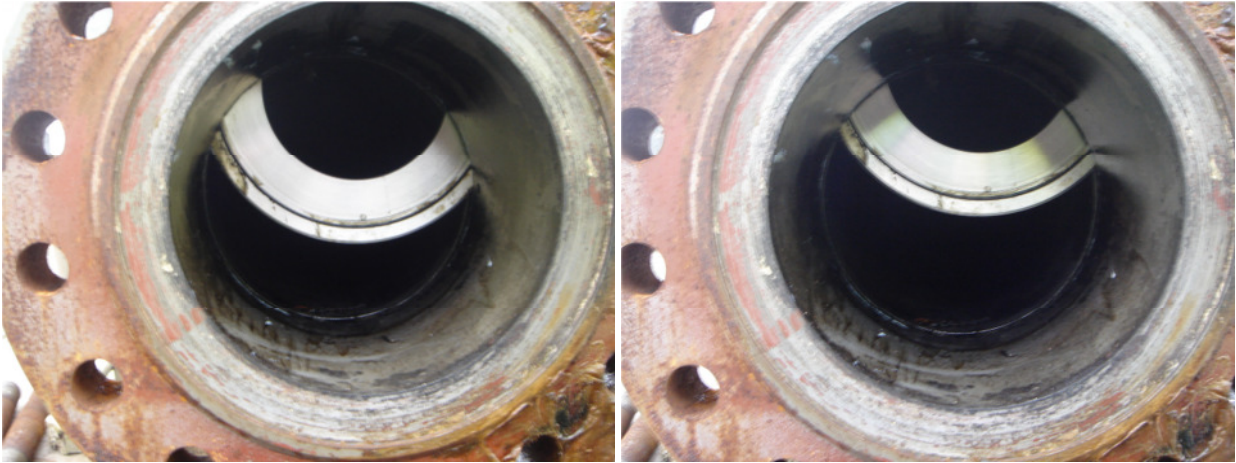


Figure 11 – (left) Orifice plate removal at 99970 counter reading; Figure 12 – (right) Orifice plate removal at 99960 counter reading

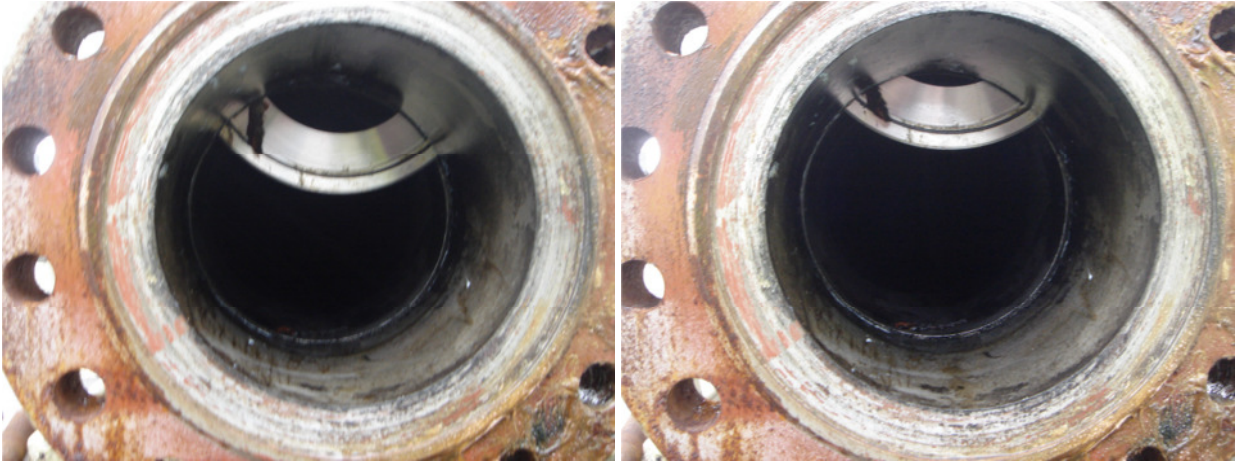


Figure 13 – (left) Orifice plate removal at 99950 counter reading; Figure 14 – (right) Orifice plate removal at 99940 counter reading

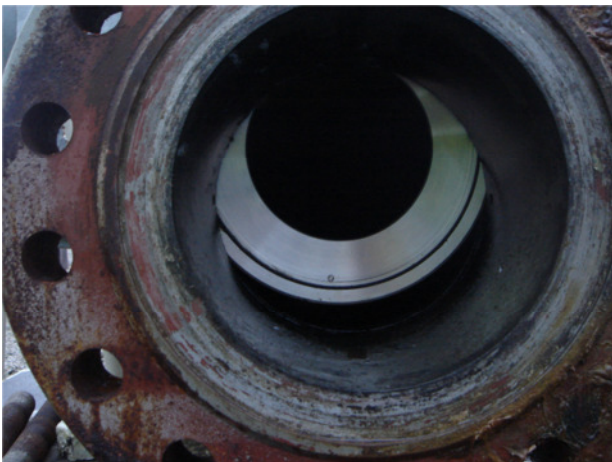


Figure 15 - Orifice plate insertion at 99984 counter reading

2.2.1 Results – Orifice Plate Removal

Starting from the fully inserted position measurements were taken at counter readings of 99995, 99984, 99970, 99960, 99950 and 99940. The results are shown in Table 1.

Counter Reading	Counter Offset	A (± 0.5 mm)	B (± 2 mm)
00001	-1	39.0	+0.0
99995	5	50.4	+0.0
99984	16	88.7	+11.5
99970	30	137.9	+17.5
99960	40	174.0	+24.5
99950	50	209.8	+22.5
99940	60	244.0	+14.5

Table 1 - Carrier check results - orifice plate removal

The uncertainty of measurement of the vertical offset (A) was ±0.5 mm. The uncertainty of measurement of the horizontal offset (B) was ±2 mm.

2.2.2 Results – Orifice Plate Insertion

The orifice plate was then removed and cleaned before being re-inserted to represent a typical orifice plate change. Measurements were then taken at the same counter readings (in reverse order) as the plate was lowered into the fully inserted position. The results in Table 2 show that the relationship between the vertical position and the counter reading is linear.

Counter Reading	Counter Offset	A (± 0.5 mm)	B (± 2 mm)
99940	60	245.5	-22.5
99950	50	210.5	-22.5
99960	40	175.0	-26.5
99970	30	139.1	-25.5
99984	16	90.8	-19.5
99995	5	52.5	-0.0
00000	0	39.0	-0.0

Table 2 - Carrier check results - orifice plate insertion

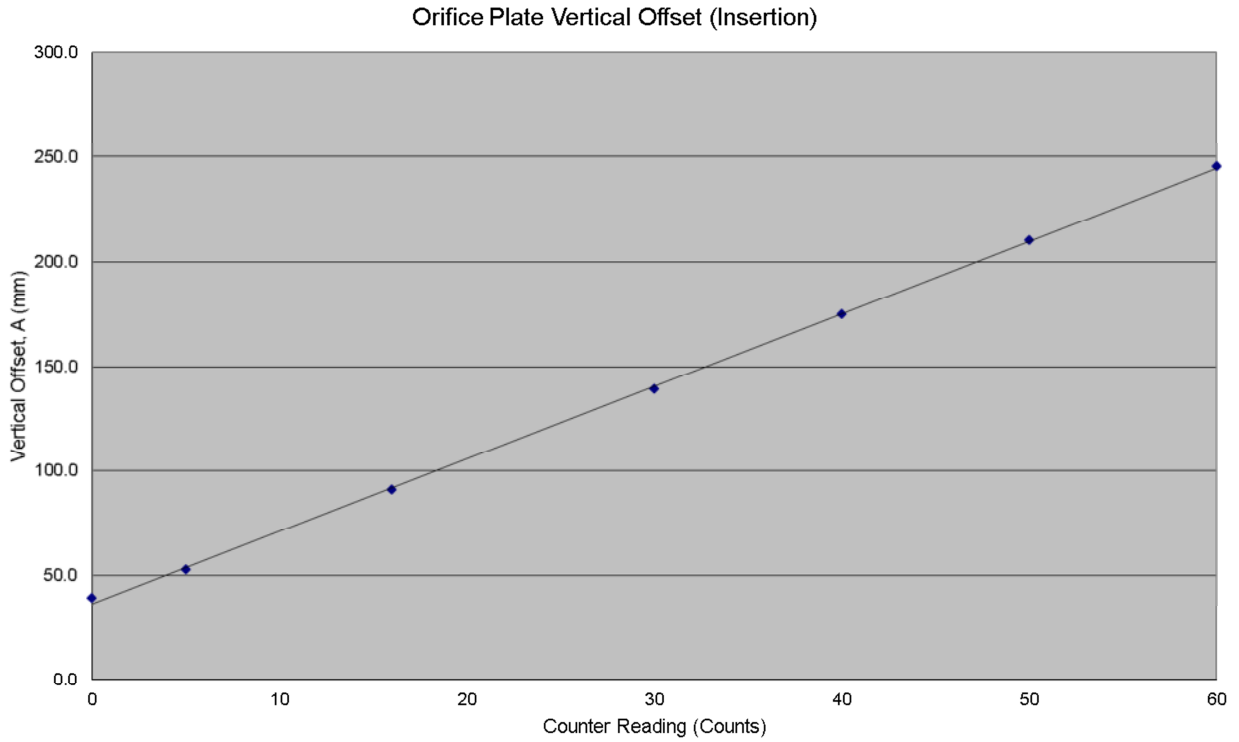


Figure 16 - Relationship between counter and vertical offset

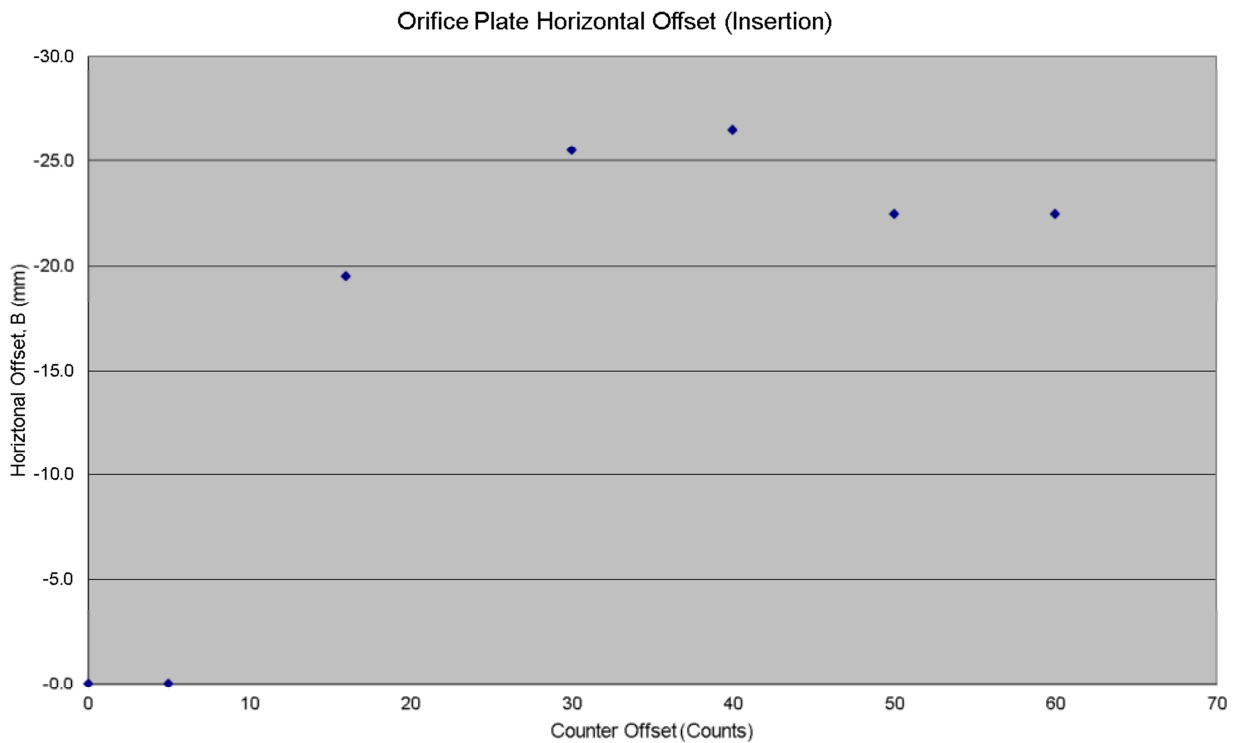


Figure 17 - Relationship between counter and horizontal offset

2.2.3 Results – Repeatability

Measurements were repeated twice more at counter readings of 99950 and 99984 on insertion in order to quantify the repeatability, as shown in Table 3.

Counter Reading	Reading 1 (mm)		Reading 2 (mm)		Reading 3 (mm)		Average (mm)		Standard Deviation (mm)	
	A	B	A	B	A	B	A	B	A	B
99950	210.5	-22.5	210.5	-22.5	210.5	-22.5	210.5	-22.5	0.0	0.0
99984	90.8	-19.5	90.5	-18.6	90.8	-19.5	90.7	-19.2	0.2	0.5

Table 3 - Carrier check results - repeatability

There was no difference in the results at the 99950 counter reading. The standard deviation of results at the 99984 counter reading was within (less than half of) the measurement uncertainty for vertical (A) and horizontal (B) measurements.

2.3 Carrier Data Plates

During the site visit the carrier data plates were provided for examination having been removed from the carrier and stored in the adjacent transmitter kiosk for preservation. Photographs of the plates are shown in Figure 18 and Figure 19. The text on the carrier information plate gives instructions for removal and replacement of the orifice plate but is not easily readable. The text from each data plate is reproduced in Appendix B.

Following this examination an explanation for the incorrect counter readings was sought. The data plate suggests that the fully inserted position should be at a counter reading of between 9995 and 0005 however the counter has five digits and the fully inserted position is exactly 00000. From this it can be seen that the four digit 9995 counter reading was likely to have been misinterpreted as a five digit reading of 99950.

There was no evidence to support a counter reading of 99984 as estimated from the initial tests and flow profile analysis. However it was thought that the 99885 which is stamped in two locations on the carrier information plate could have been misread as 99985.



Figure 18 - Carrier Identification Plate



Figure 19 - Carrier Information Plate

2.4 Orifice Plate Change Photographs

2.4.1 21st July 2009

The orifice plate with serial number 050/4 was removed on 21st July 2009 and replaced by the orifice plate with serial number 050/2.

2.4.1.1 Upstream Face



Figure 20 - Orifice Plate 050/4 Removed on 21st July 2009 (Upstream)

The upstream face can be seen to be clean and in good condition. The smears of grease on the rim are produced on removal of the plate through the plug valve.

2.4.1.2 Downstream Face



Figure 21 - Orifice Plate 050/4 Removed on 21st July 2009 (Downstream)

The downstream face can be seen to be clean and in good condition.

2.4.2 27th July 2010

The orifice plate with serial number 050/2 was removed on 27th July 2010 and replaced by the orifice plate with serial number 050/4.

2.4.2.1 Upstream Face

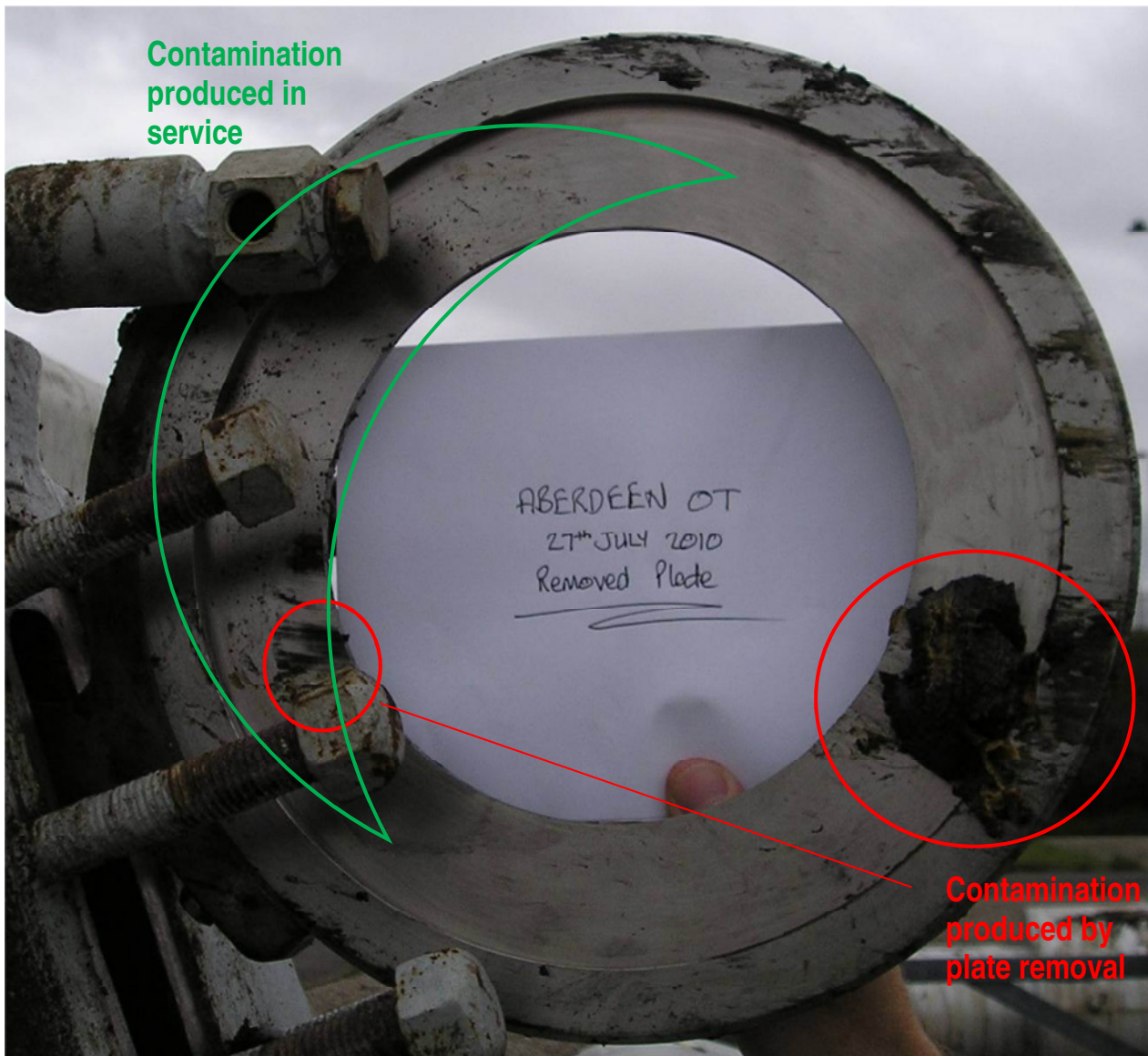


Figure 22 - Orifice Plate 050/2 Removed on 27th July 2010 (Upstream)

The photograph shows the plate in the orientation of removal. In normal operation the clamp seen here on the left hand side is at the top of the plate. Some spots of grease can be seen around the top right part of the upstream face. The splatter pattern suggests small amounts of grease being picked up and deposited by a flow of gas. However contamination of this kind would be removed by the flow of gas under normal operating conditions (higher flow rates), particularly around the bore edge. This is an indication that normal gas flows were not experienced by this part of the orifice plate. The large smears of grease on the rim are produced on removal of the plate through the plug valve.

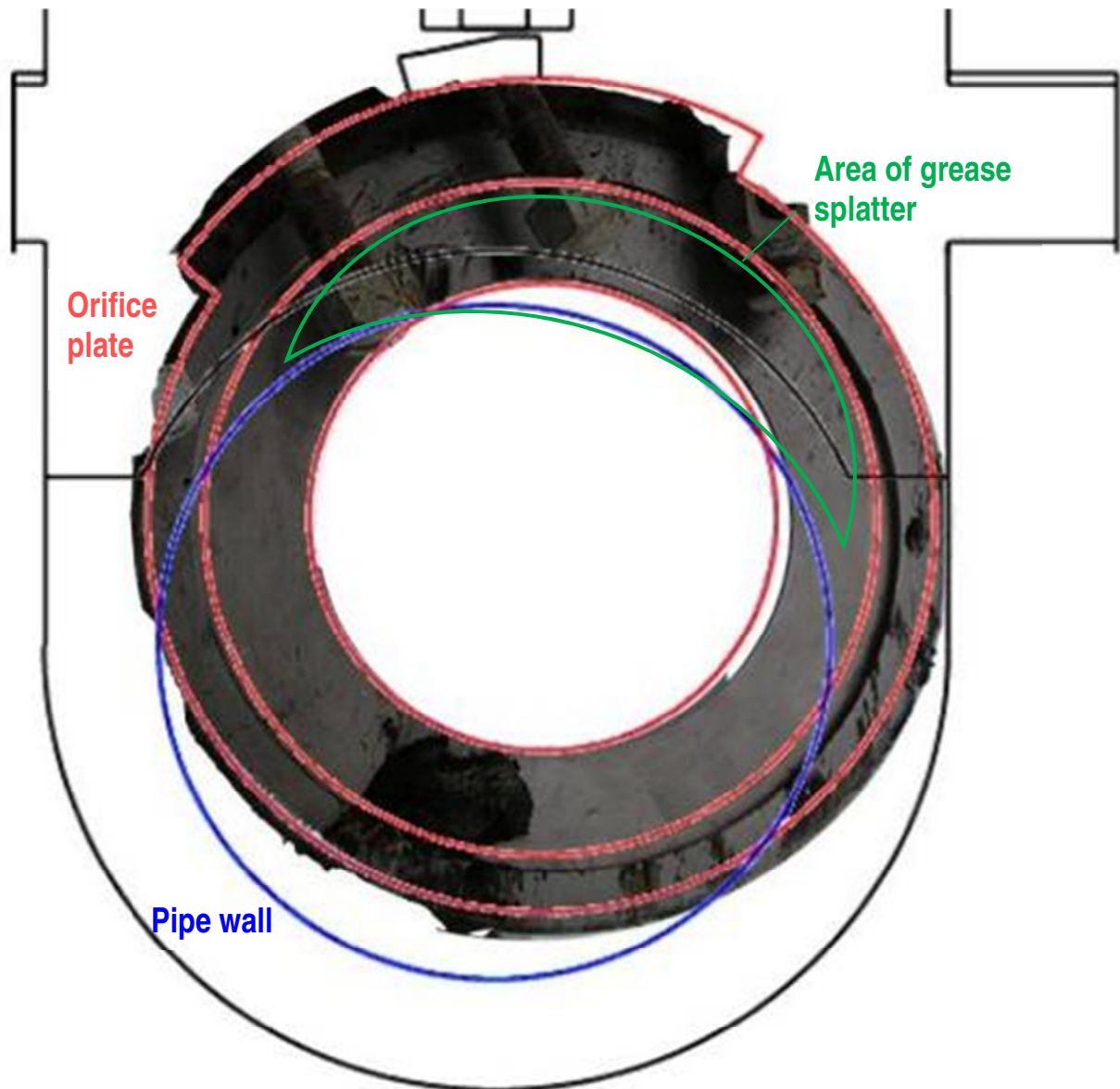


Figure 23 - Orifice Plate Contamination Orientation (Upstream)

A dimensional model was created for the CFD analysis with the orifice plate incorrectly positioned within the carrier at a counter reading of 99985. When compared to the photograph of the upstream face the spots of grease can be seen to be in the area of the plate outside of the gas stream. This is evidence that the plate was located at a counter reading of approximately 99985.

2.4.2.2 Downstream Face

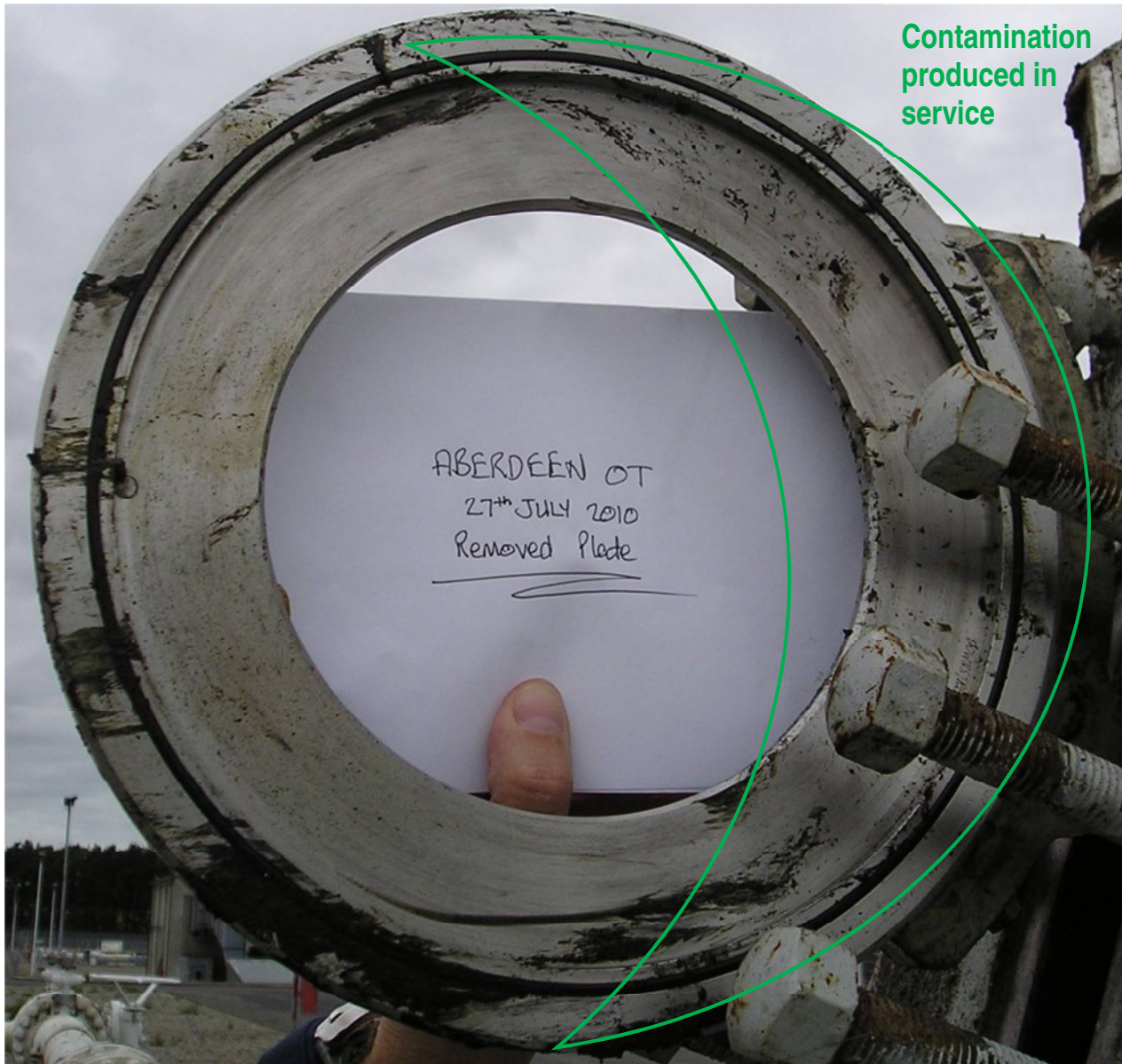


Figure 24 - Orifice Plate 050/2 Removed on 27th July 2010 (Downstream)

The photograph shows the plate in the orientation of removal. In normal operation the clamp seen here on the right hand side is at the top of the plate. Some spots of grease can be seen around the top of the downstream face. The splatter pattern suggests small amounts of grease being picked up and deposited by a flow of gas. However contamination of this kind would be removed by the flow of gas under normal operating conditions (higher flow rates), particularly around the bore edge. This is an indication that normal gas flows were not experienced by this part of the orifice plate. The large smears of grease on the rim are produced on removal of the plate through the plug valve.

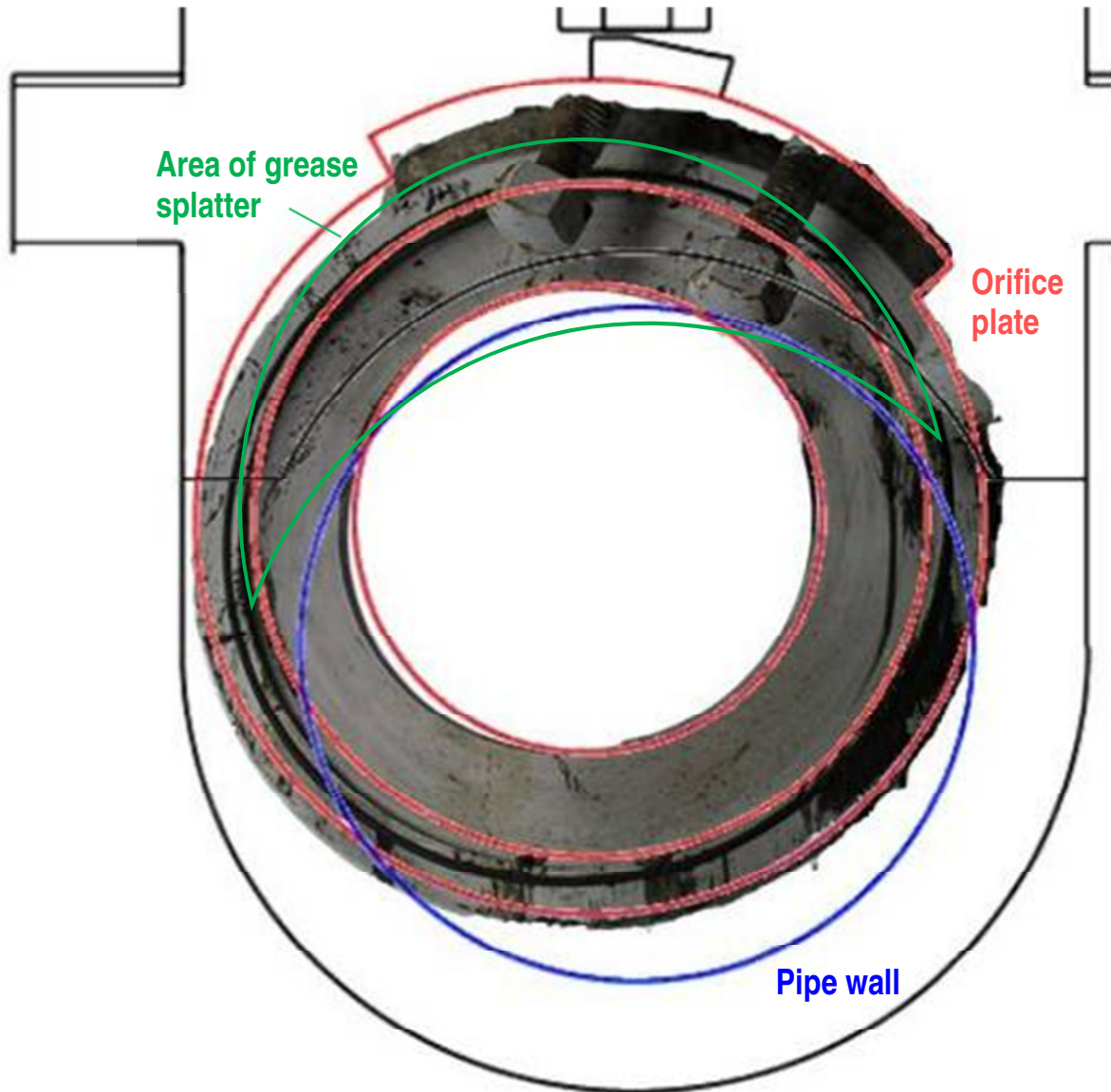


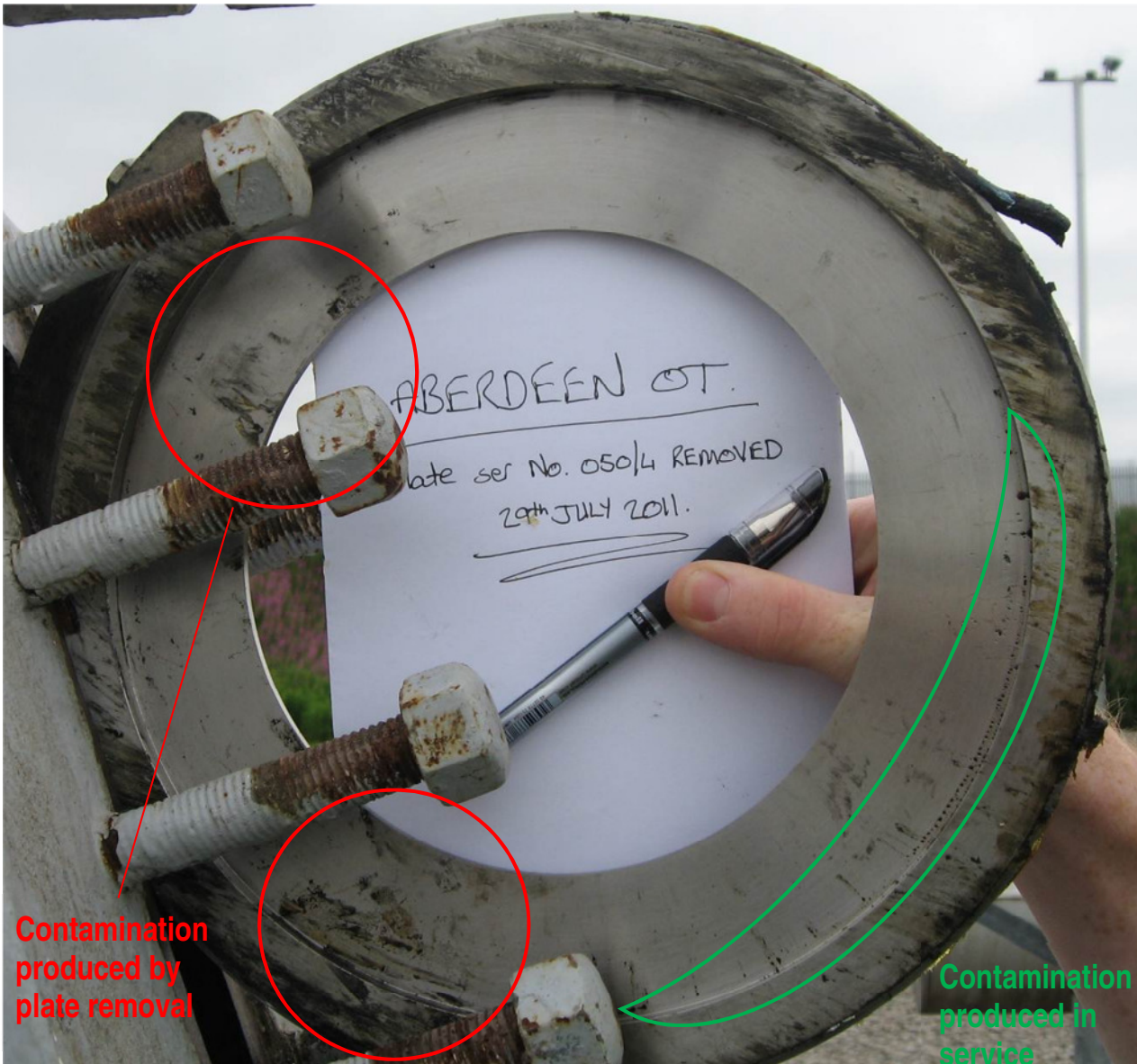
Figure 25 - Orifice Plate Contamination Orientation (Downstream)

When the CFD dimensional model is compared to the photograph of the upstream face the spots of grease can be seen to be in the area of the plate outside of the gas stream. This is evidence that the plate was located at a counter reading of approximately 99985.

2.4.3 29th July 2011

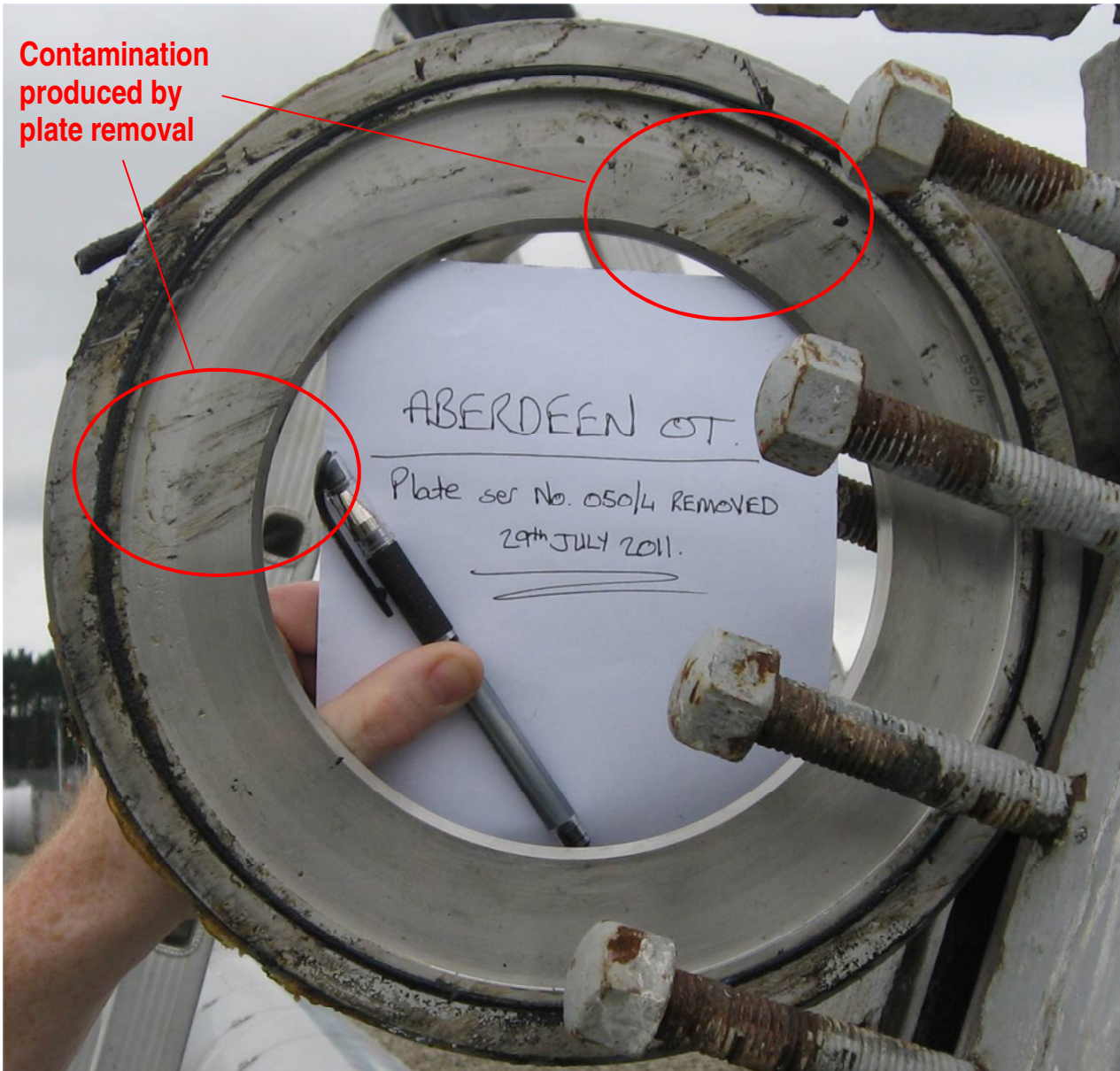
The orifice plate with serial number 050/4 was removed on 29th July 2011 and replaced by the orifice plate with serial number 050/2.

2.4.3.1 Upstream Face



The photograph shows the plate in the orientation of removal. In normal operation the clamp seen here on the left hand side is at the top of the plate. Some spots of grease can be seen around the bottom left part of the upstream face but these are confined to the region near the rim. The pattern of contamination being confined to the outer annulus and showing streaking from the centre of the plate is typical of a plate flowing under normal operating conditions. ISO TR 12767^[1] provides guidance on the effect of deposits on the discharge coefficient. The amount and location of contamination in this case would not have a significant effect (<0.1%) on the discharge coefficient. The precise effect could only be quantified through testing or further research. The smears of grease on the rim are produced on removal of the plate through the plug valve.

2.4.3.2 Downstream Face



The smears of grease on the rim are produced on removal of the plate through the plug valve. There is no evidence of contamination on the downstream face as would be expected under normal operating conditions.

2.5 On-Site Flow Testing

The next stage was to establish the relationship between the differential pressure and the counter reading at various flow rates and pressures. The experiments were designed to cover the true range of flow rates and pressures experienced at Aberdeen Offtake during the error period. The minimum and maximum pressures experienced were 54.8 barg and 66.5 barg respectively. Based on initial estimates of the error the site flowed above the site maximum flow rate¹ on a small number of occasions. Therefore the tests were designed to cover up to the site maximum flow rate (4.5 Mscm/d). The minimum flow rate chosen for testing was 1.0 Mscm/d because of higher uncertainties at lower flow rates.

The on-site testing was carried out on three days (two separate visits) due to problems achieving the desired pressures in the upstream National Transmission System (NTS). On 15th February 2012 the pressure was between 61.4 barg and 62.1 barg. This was taken as the medium pressure point based on the pressures experienced during the error period. The aim at this point was to test up to 66 barg and down to 55 barg, however it was suggested that 57 barg may be a more achievable target.

The pressure range that was tested was further restricted due to the difficulties achieving the desired pressures in the upstream NTS. On 18th April 2012 the pressure was between 63.6 barg and 64.0 barg which was taken as the high pressure point. On 19th April 2012 the pressure was between 58.1 barg and 58.7 barg which was taken as the low pressure point.

This pressure range was deemed to be acceptable as it covered the vast majority of the data (>85 %) as indicated in Table 4 (and on later analysis the error was shown to be insensitive to pressure).

	Error Period Pressures (barg)	Site Test Pressures (barg)	Percentage of Readings Outside Test Pressures (%)
Minimum	54.8	58.1	2.6 % below minimum
Maximum	66.5	64.0	9.6 % above maximum

Table 4 - Test Pressure Coverage

On each of the three days, the pressure was maintained at a fixed level (as far as practicable) by the upstream party for the duration of the testing and the metering pressure was continuously monitored. With the orifice plate in the correct location and the site in setpoint control the flow rate setpoint was fixed at the desired value (1.0 Mscm/d, 3.0 Mscm/d or 4.5 Mscm/d). Once the flow control valve had settled it was locked in position with the site put into direct valve control. This maintained a fixed flow rate (as far as practicable, see section 2.5.1) into the downstream network.

A validation of the metering equipment was carried out in accordance with T/PR/ME/2¹² prior to each test. A logger was set up to capture the process data, including differential pressures, flow rate (calculated not real), pressure and temperature. Gas composition data was continuously recorded by the chromatograph.

The logger was started with the orifice plate in the normal correct operating position. The orifice plate was removed in stages, waiting at each counter reading for the flow to become steady and data to be captured over a stable period. The counter readings used were 00000, 99985, 99984, 99970 and 99950. After the 99950 position the orifice plate was wound to the fully removed position and then inserted back into the

¹ The recorded flow rate would have been below the site maximum. Normally the site is limited by the scaling of the flow computer outputs and the range of the DP transmitters, designed for worst case site maximum flow rate conditions. In this case the flow computer outputs and DP transmitters were significantly under-reading and therefore it would have been possible to flow beyond the site maximum without these limitations.

99950 position. The same counter readings were used (in reverse order) as the plate was lowered into the fully inserted position.

2.5.1 Flow Rate Drift

Over the duration of each test the flow rate was seen to drift slightly due to changes in downstream pressure. The downstream demand was around 2 Mscm/d, therefore the changes in downstream pressure were brought about by a mis-match between the supplied flow rate and the demand. This was most prevalent at the highest flow rates (i.e. where the difference between supply and demand was at it's the greatest).

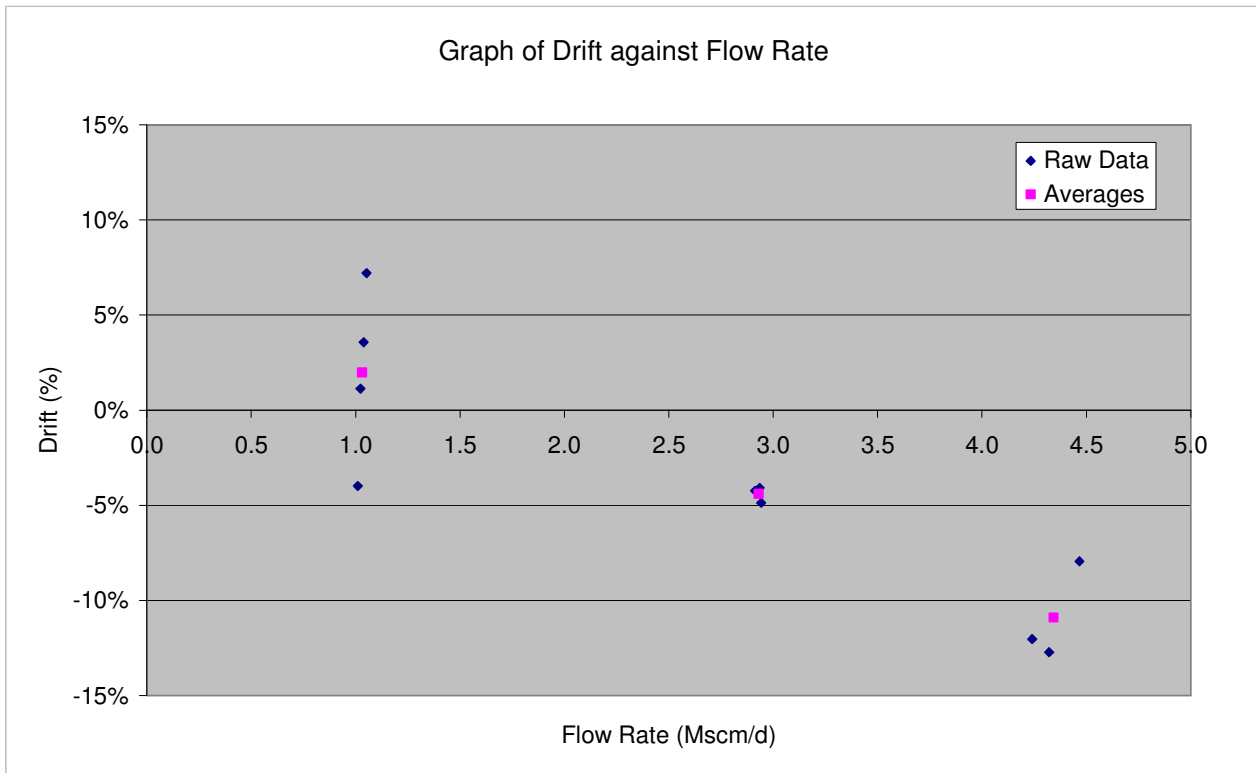


Figure 26 - Graph of Drift against Flow Rate

The flow rate drift was assumed to be linear over the duration of each test. The recorded flow rates (F1_Day) were corrected for this linear drift (expressed as a percentage) producing the corrected flow rate (F1_Day_COR) shown in the test flow rate results.

2.5.2 Summary of Tests

This section summarises the conditions and results of each test in Table 5 to Table 14 and Figure 27 to Figure 46.

Note: Test 5 was abandoned because the low pressure override was activated, affecting the flow rate. Therefore the results have not been included in the analysis.

2.5.2.1 Test 1 Summary

Date	15 th February 2012
Time	13:10
Pressure (Average)	61.5 barg
Flow Rate (Average)	1.04 Mscm/d
Flow Rate Drift	+3.6 % (+0.04 Mscm/d)

Table 5 - Test 1 Conditions

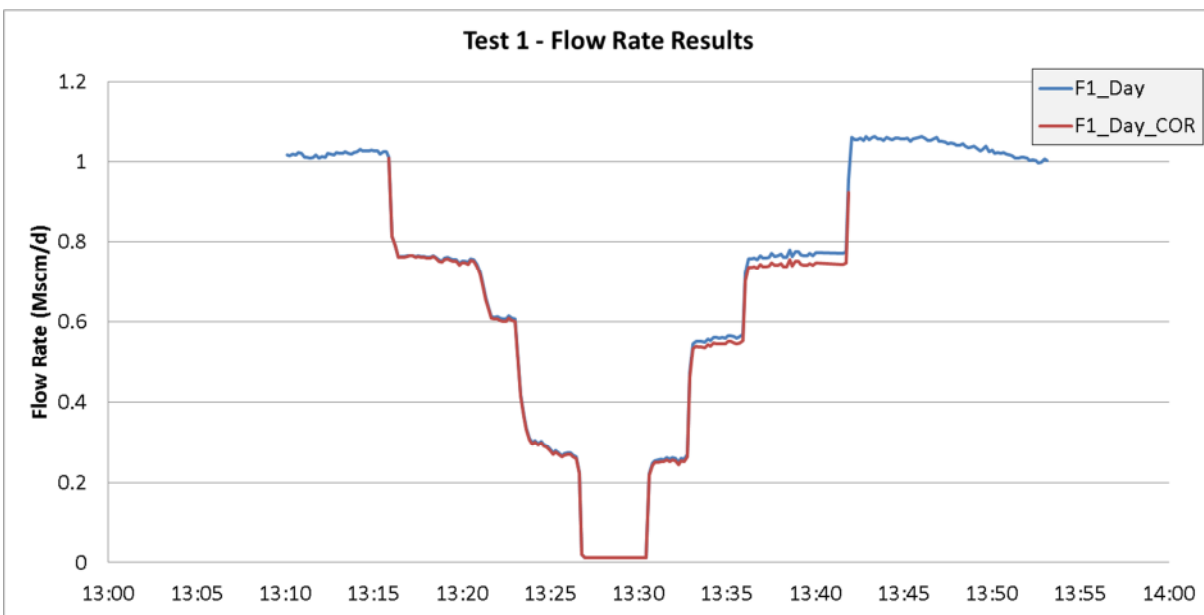


Figure 27 - Test 1 Flow Rate Results

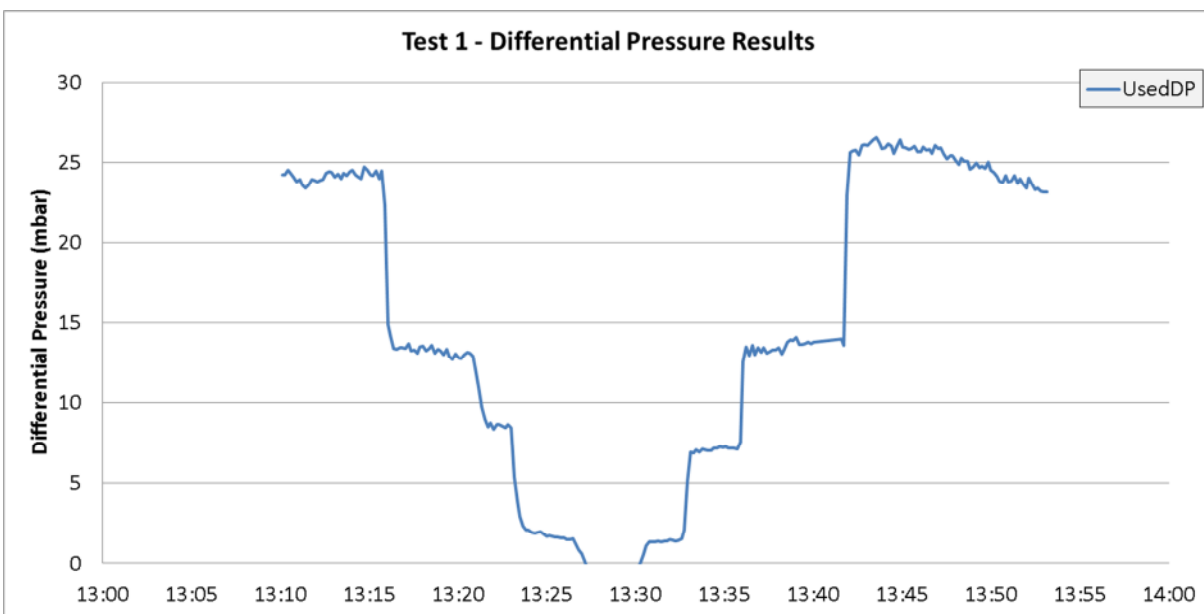


Figure 28 - Test 1 Differential Pressure Results

2.5.2.2 Test 2 Summary

Date	15 th February 2012
Time	14:03
Pressure (Average)	61.5 barg
Flow Rate (Average)	2.91 Mscm/d
Flow Rate Drift	-4.2 % (-0.12 Mscm/d)

Table 6 - Test 2 Conditions

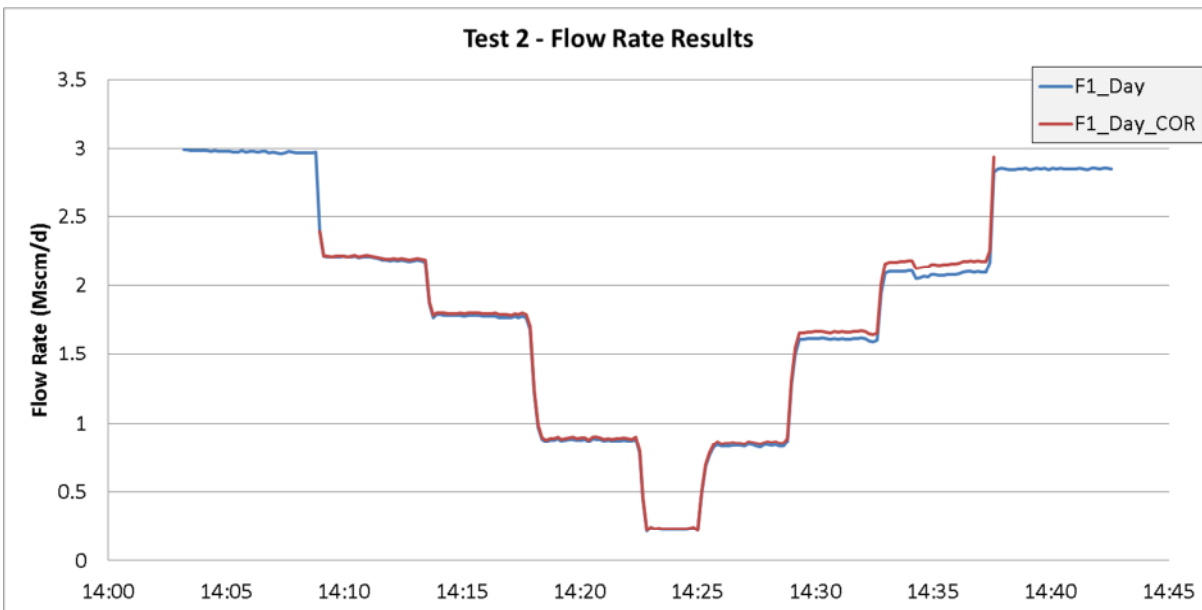


Figure 29 - Test 2 Flow Rate Results

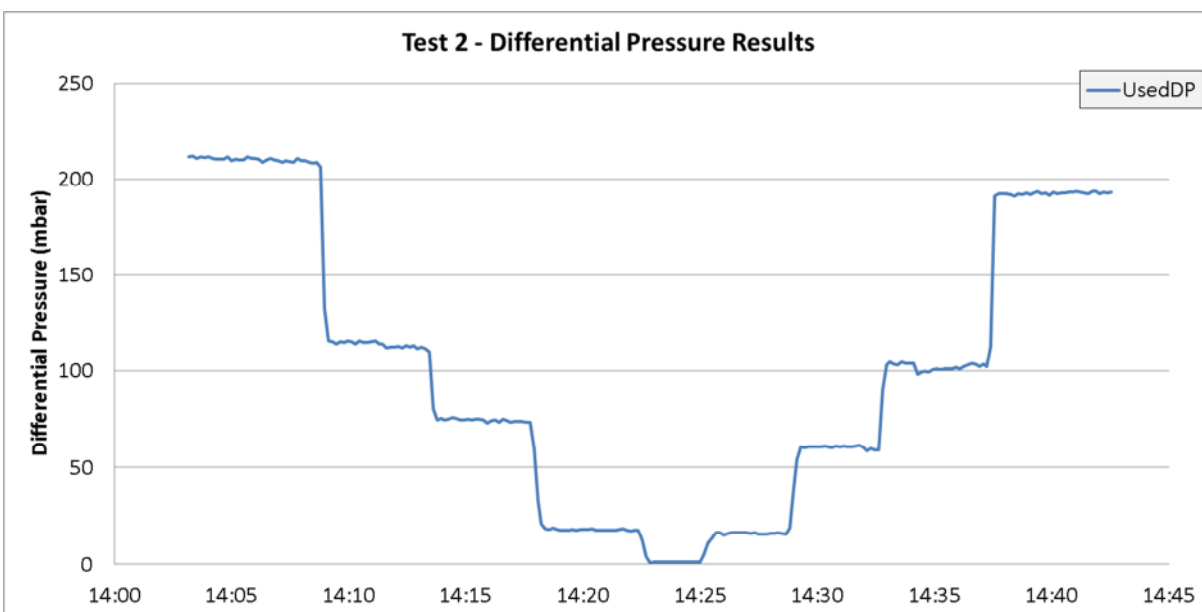


Figure 30 - Test 2 Differential Pressure Results

2.5.2.3 Test 3 Summary

Date	15 th February 2012
Time	15:53
Pressure (Average)	62.1 barg
Flow Rate (Average)	4.47 Mscm/d
Flow Rate Drift	-7.9 % (-0.35 Mscm/d)

Table 7 - Test 3 Conditions

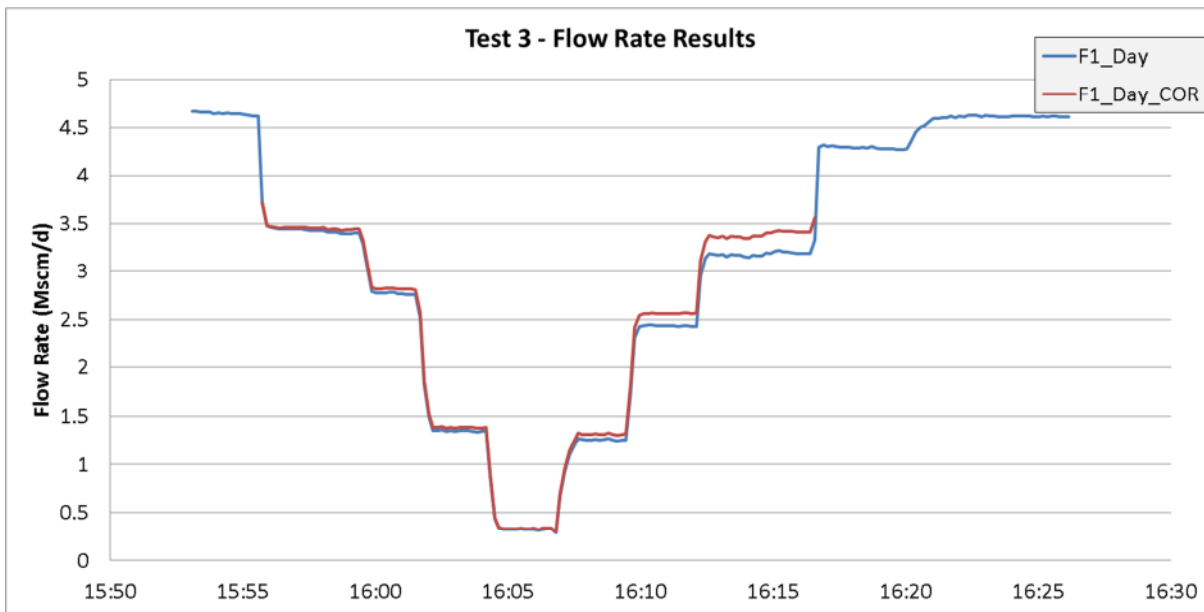


Figure 31 - Test 3 Flow Rate Results

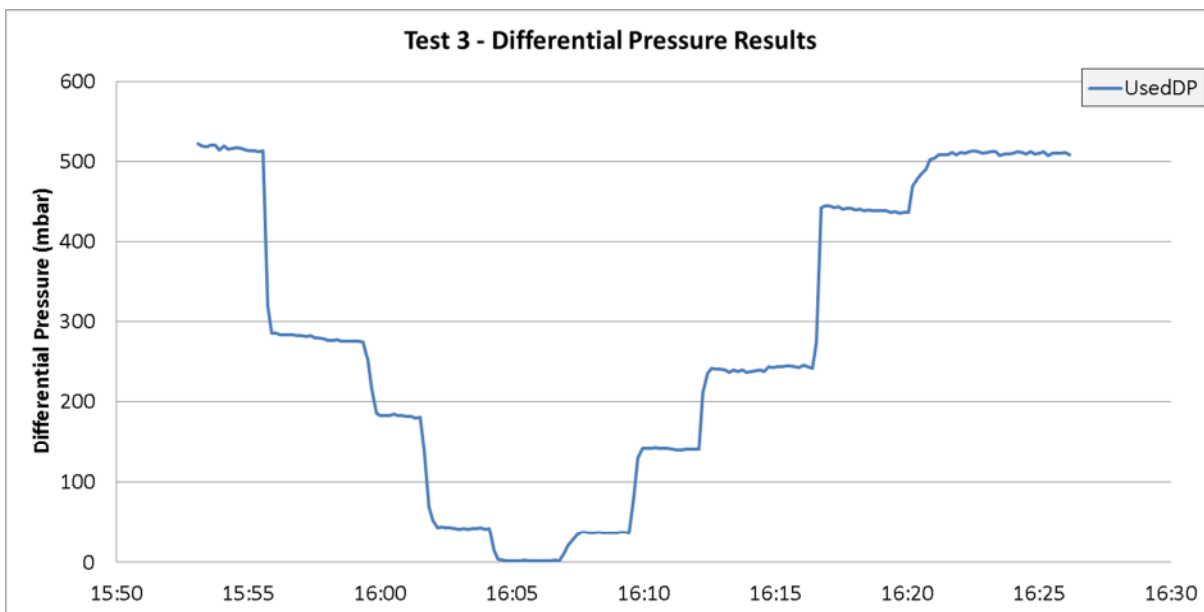


Figure 32 - Test 3 Differential Pressure Results

2.5.2.4 Test 4 Summary

Date	18 th April 2012
Time	11:19
Pressure (Average)	63.9 barg
Flow Rate (Average)	2.94 Mscm/d
Flow Rate Drift	-4.9 % (-0.14 Mscm/d)

Table 8 - Test 4 Conditions

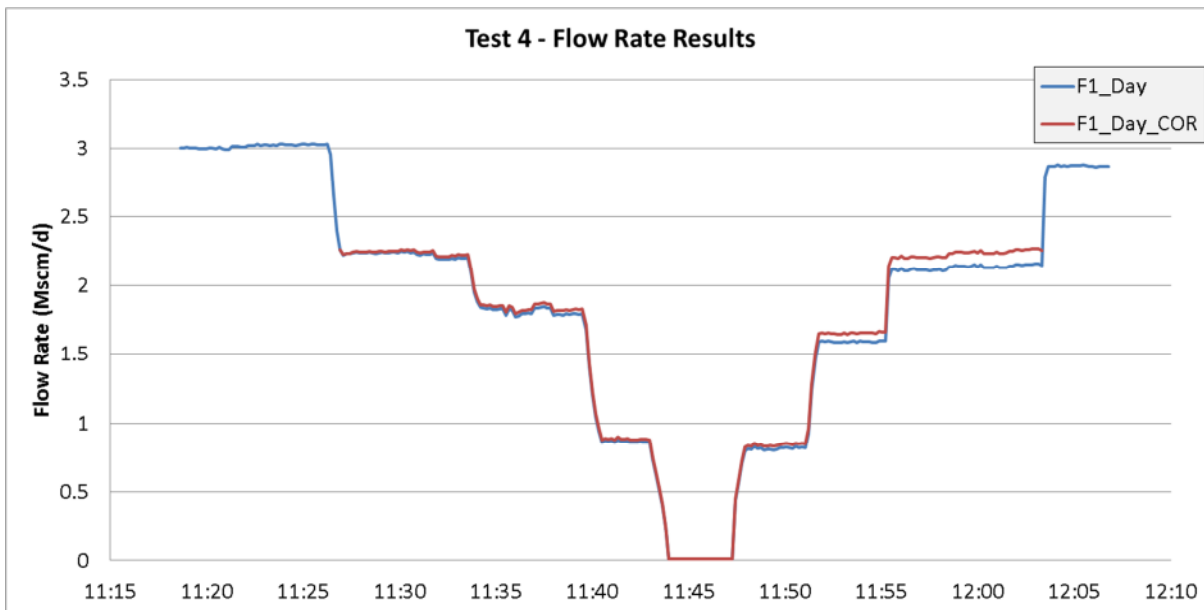


Figure 33 - Test 4 Flow Rate Results

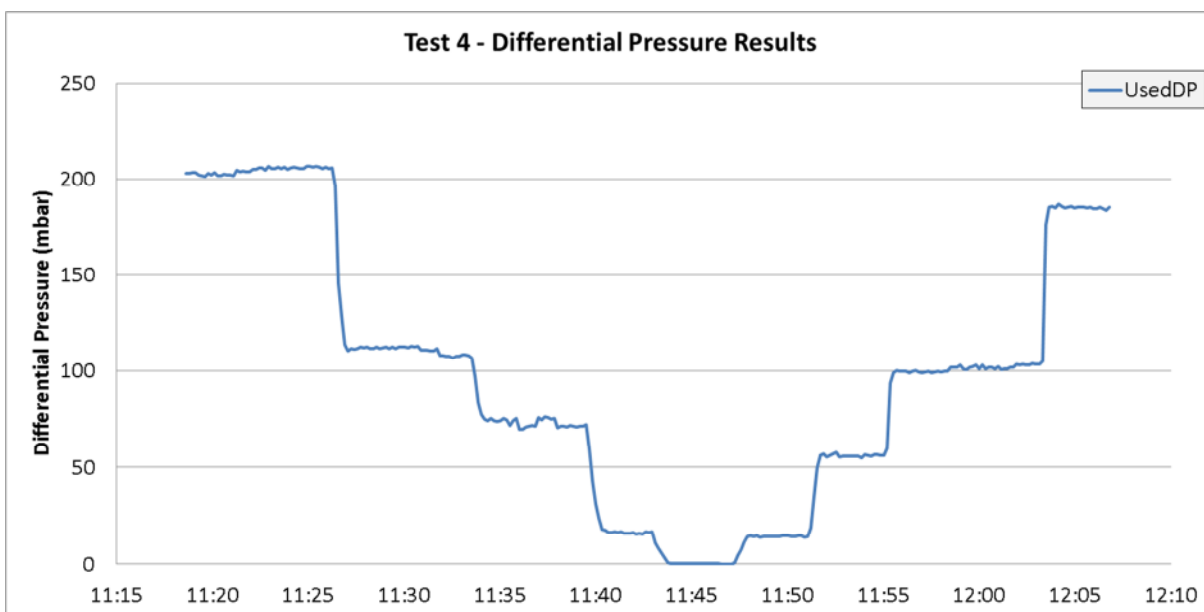


Figure 34 - Test 4 Differential Pressure Results

2.5.2.5 Test 6 Summary

Date	18 th April 2012
Time	13:24
Pressure (Average)	63.9 barg
Flow Rate (Average)	1.01 Mscm/d
Flow Rate Drift	-4.0 % (-0.04 Mscm/d)

Table 9 - Test 6 Conditions

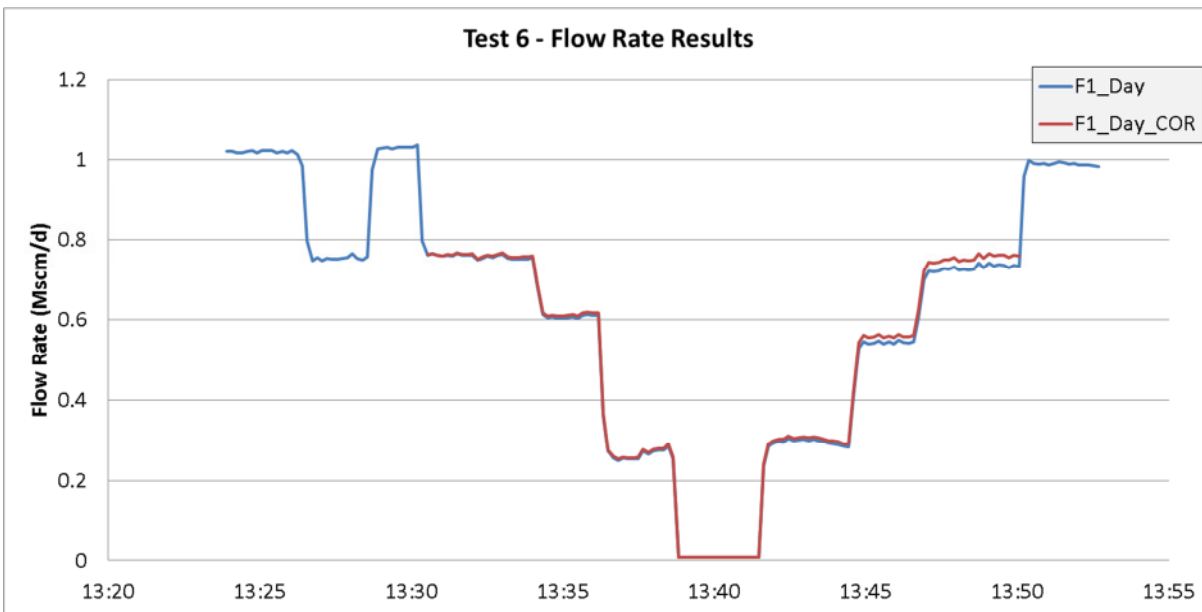


Figure 35 - Test 6 Flow Rate Results

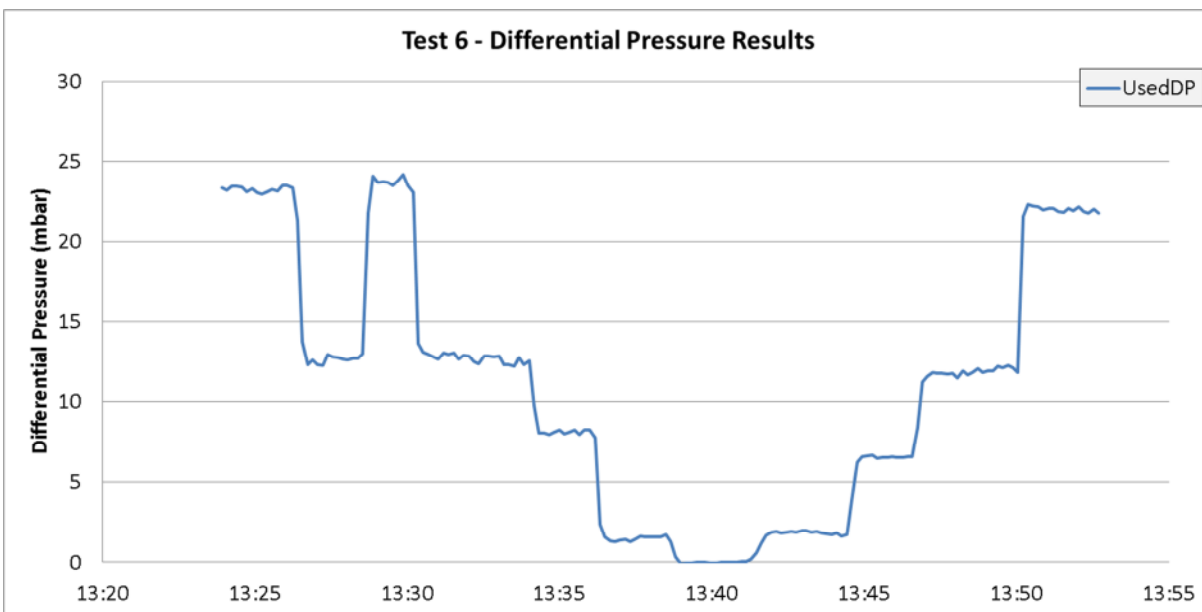


Figure 36 - Test 6 Differential Pressure Results

2.5.2.6 Test 7 Summary

Date	18 th April 2012
Time	15:31
Pressure (Average)	63.6 barg
Flow Rate (Average)	4.32 Mscm/d
Flow Rate Drift	-12.7 % (-0.55 Mscm/d)

Table 10 - Test 7 Conditions

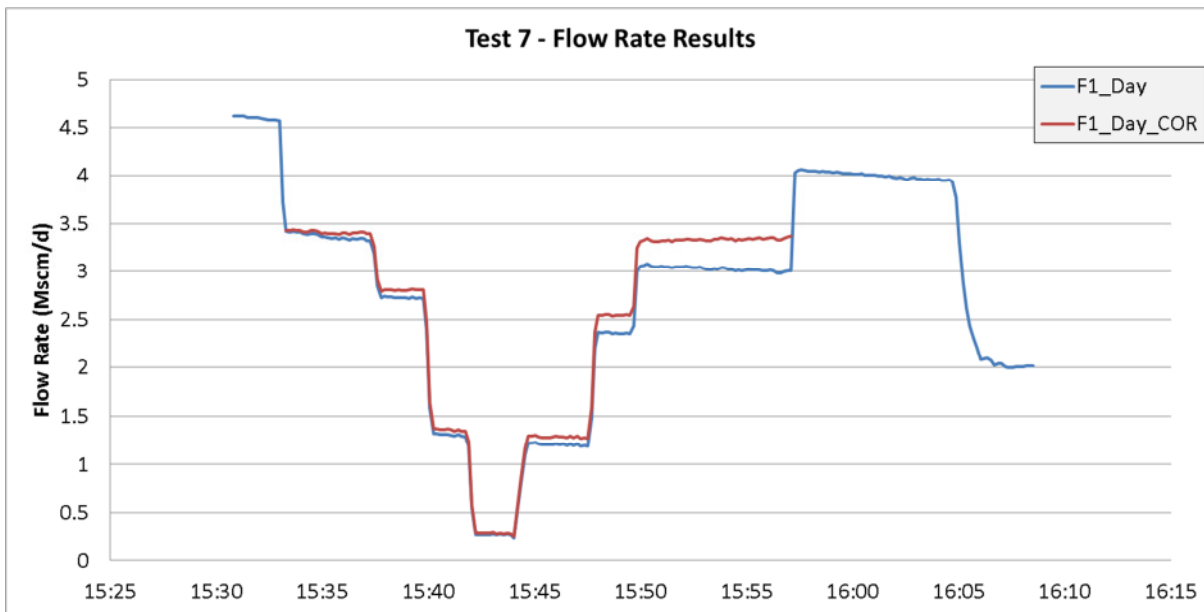


Figure 37 - Test 7 Flow Rate Results

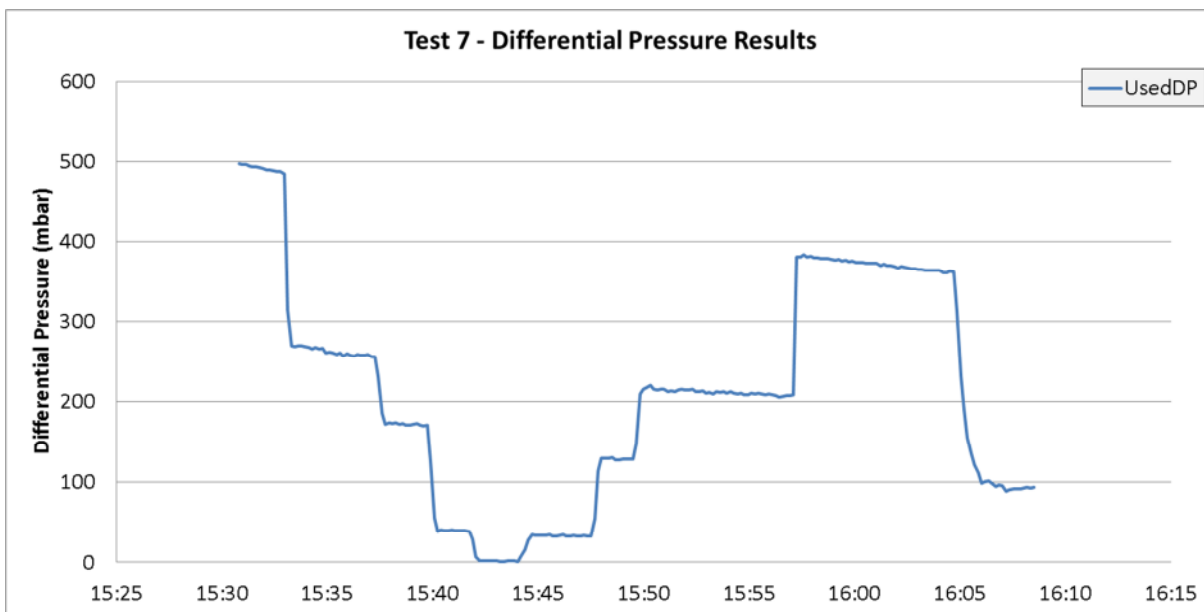


Figure 38 - Test 7 Differential Pressure Results

2.5.2.7 Test 8 Summary

Date	19 th April 2012
Time	12:54
Pressure (Average)	58.2 barg
Flow Rate (Average)	2.94 Mscm/d
Flow Rate Drift	-4.1 % (-0.12 Mscm/d)

Table 11 - Test 8 Conditions

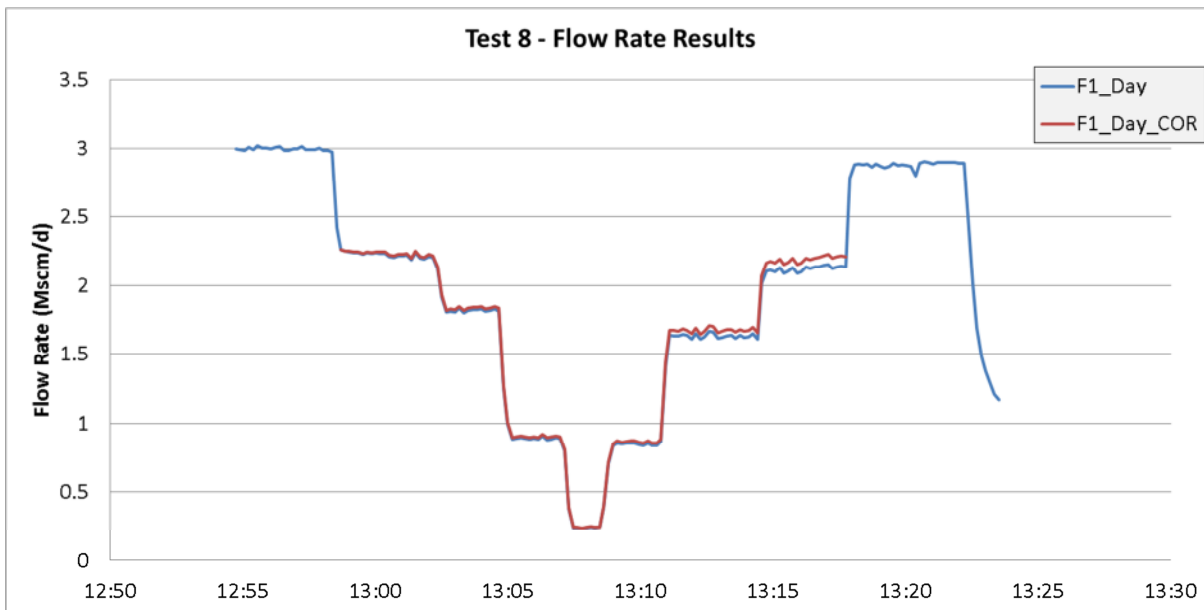


Figure 39 - Test 8 Flow Rate Results

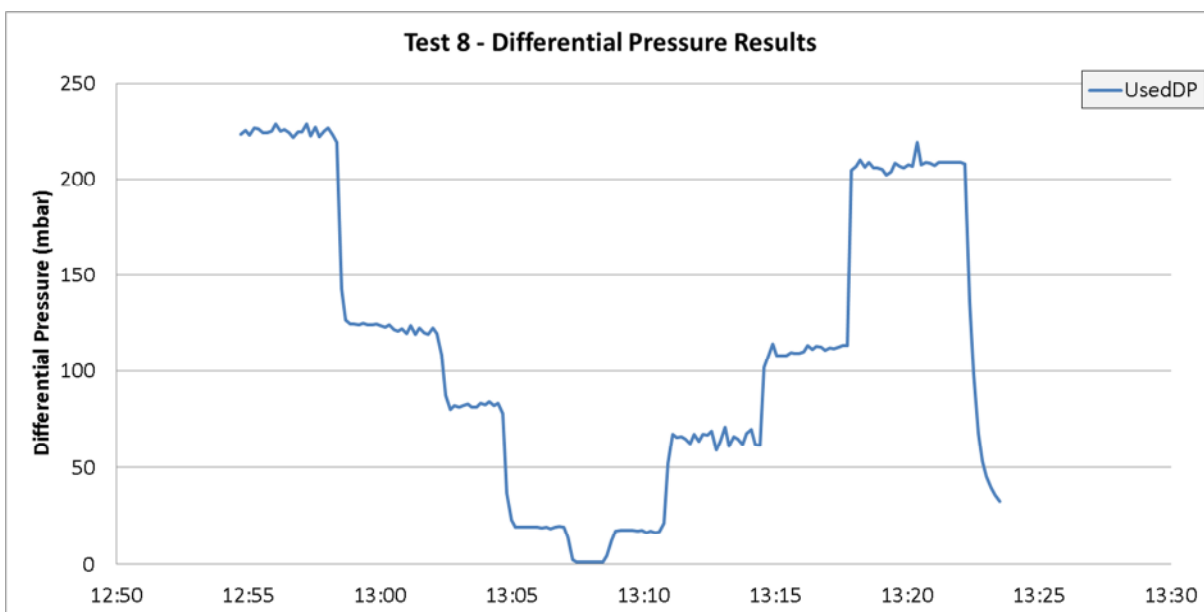


Figure 40 - Test 8 Differential Pressure Results

2.5.2.8 Test 9 Summary

Date	19 th April 2012
Time	13:28
Pressure (Average)	58.7 barg
Flow Rate (Average)	1.02 Mscm/d
Flow Rate Drift	+1.1 % (+0.01 Mscm/d)

Table 12 - Test 9 Conditions

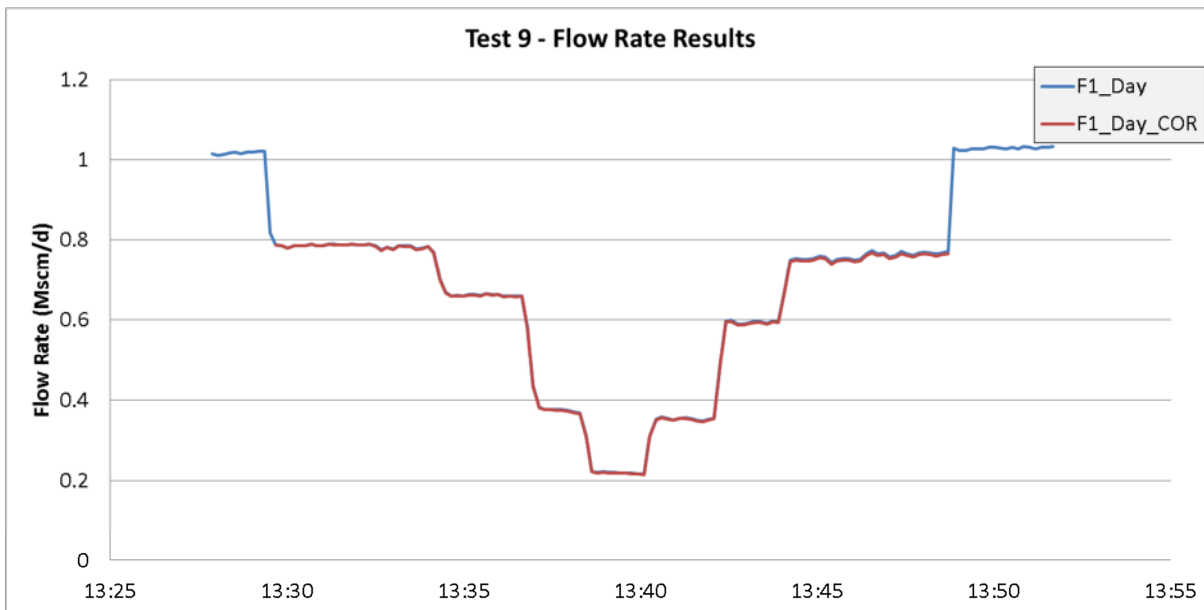


Figure 41 - Test 9 Flow Rate Results

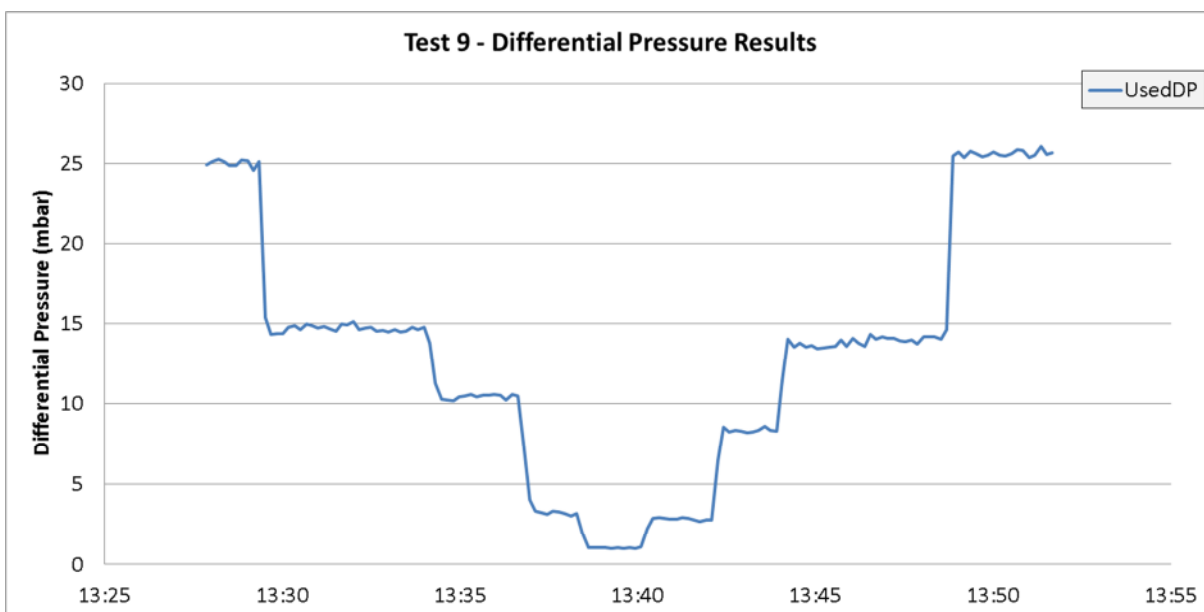


Figure 42 - Test 9 Differential Pressure Results

2.5.2.9 Test 10 Summary

Date	19 th April 2012
Time	14:03
Pressure (Average)	58.2 barg
Flow Rate (Average)	4.24 Mscm/d
Flow Rate Drift	-12.0 % (-0.51 Mscm/d)

Table 13 - Test 10 Conditions

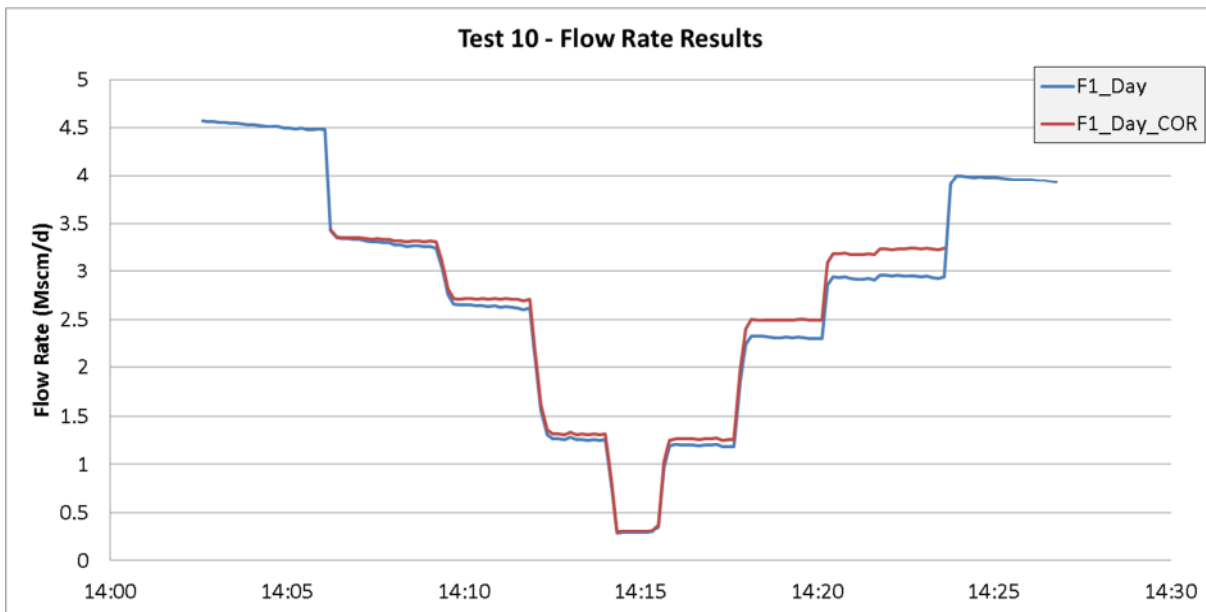


Figure 43 - Test 10 Flow Rate Results

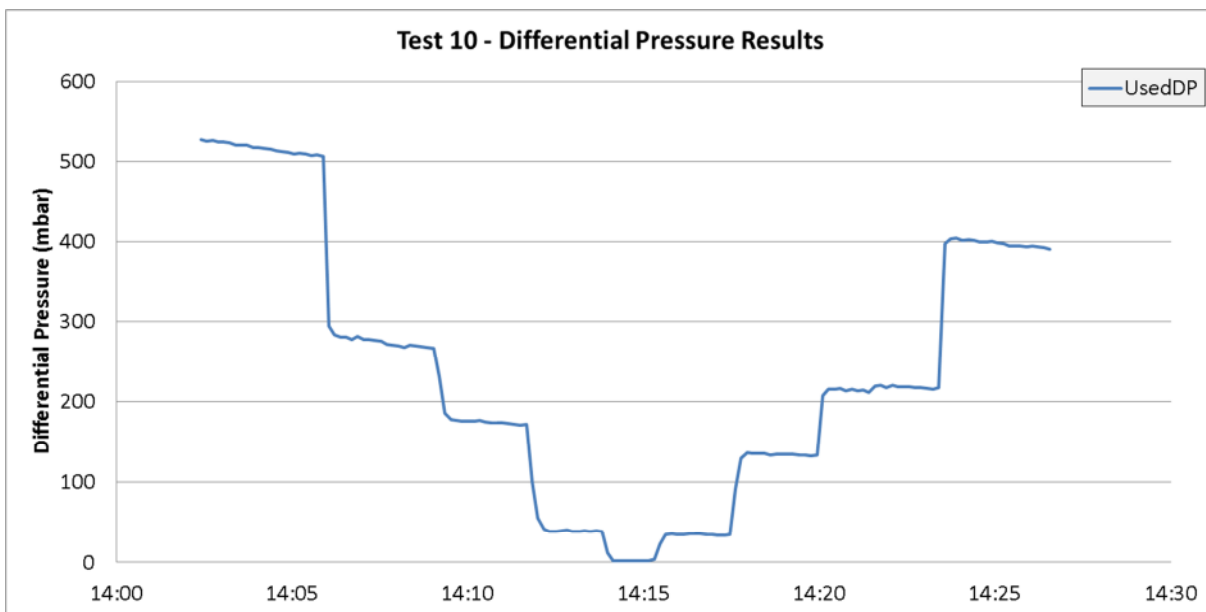


Figure 44 - Test 10 Differential Pressure Results

2.5.2.10 Test 11 Summary

Date	19 th April 2012
Time	14:35
Pressure (Average)	58.6 barg
Flow Rate (Average)	1.05 Mscm/d
Flow Rate Drift	+7.2 % (+0.08 Mscm/d)

Table 14 - Test 11 Conditions

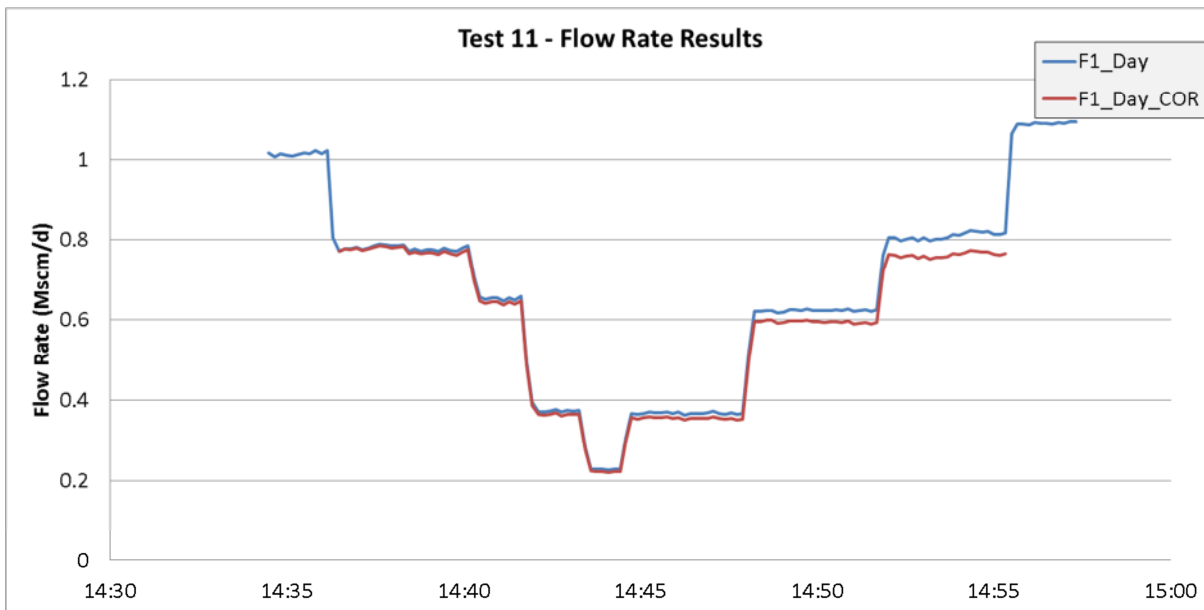


Figure 45 - Test 11 Flow Rate Results

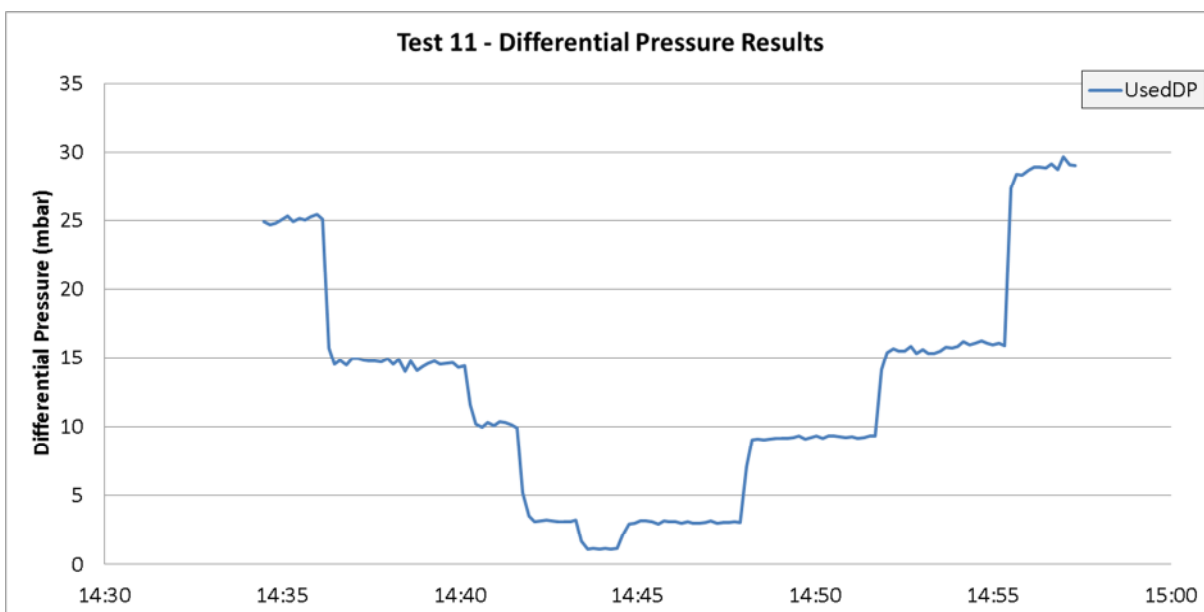


Figure 46 - Test 11 Differential Pressure Results

2.5.3 Processing of Results

The recorded flow rate was corrected for the drift over the duration of each test by applying a linear interpolation (as outlined in section 2.5.1). At each point there was a slight difference in results between removal and insertion of the orifice plate. This is due to the difference in direction of the horizontal offset which means that the plate moves towards the differential pressure tapping points on removal and away from them on insertion. This results in slightly higher (corrected) flow rates on removal. A typical example is shown in Figure 47.

Typical Flow Profile of Tests

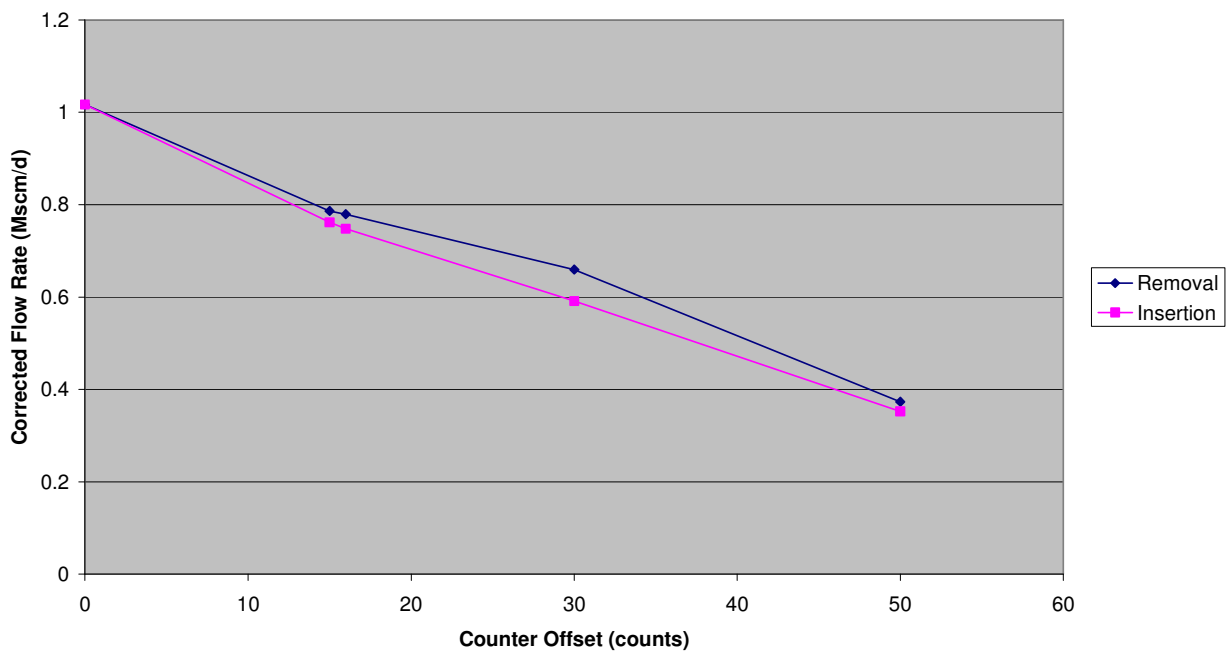


Figure 47 - Typical Flow Rate Profile of Tests

The process of an orifice plate change removes the plate fully from the carrier for replacement and then inserts it back into the pipe. It is assumed that the orifice plate was inserted up to the counter reading, rather than inserted fully and then removed back out to the counter reading. Although it cannot be known for sure which direction the orifice plate was moving in, it is more plausible and much more likely that it was inserted to the counter reading.

2.6 CFD Analysis

An independent Computational Fluid Dynamics (CFD) expert modelled the abnormal orifice plate configurations and used CFD analysis to predict the resulting differential pressures at the tapping points.

The analysis was carried out in stages as detailed below to allow for validation of the model because there is no guidance or prior experience for the abnormal cases. Stages 1 to 4 were used for validation of the model and stages 5 to 8 were used to produce the final results.

1. Creation of normal model
2. CFD results of normal model compared to real site process data
3. Creation of abnormal model (99970)
4. CFD results of abnormal model (99970) compared to experimental results
5. Creation of abnormal model (99985)
6. CFD results of abnormal model (99985) compared to experimental results
7. Creation of abnormal model (99950)
8. CFD results of abnormal model (99950) compared to experimental results

The CFD model validation and final CFD predicted results form part of the CFD analysis report^[3] which is reproduced in part here and reproduced in full in Appendix D.

2.6.1 Description of Model

Two common CFD models were investigated, ' k - ω /SST (Shear Stress Transport)^[4] and 'standard k - ϵ '^[5], both based on Reynolds-Averaged Navier-Stokes turbulence models. They are both commonly used two-equation turbulence models, which means they include two extra transport equations to represent the turbulent properties of the flow. This allows a two equation model to account for history effects like convection and diffusion of turbulent energy.

Both models use the turbulent kinetic energy, k , as the first transported variable, which determines the energy in the turbulence. The second transported variable in the ' k - ω /SST' model^[4] is the specific dissipation, ω . The second transported variable in the ' k - ϵ ' model^[5] is the turbulence dissipation, ϵ . Both ω and ϵ determine the scale of the turbulence.

The ' k - ω /SST' model^[4] is suggested for modelling orifice plates which conform to ISO 5167^[6] in existing guidance documents^[7]. No specific guidance exists for modelling orifice plates which fall outside the scope of ISO 5167^[6]. The ' k - ω /SST' model^[4] was used initially for the orifice plate in normal measurement position and produced good results when compared to the real site process data. Attempts to use this model for the abnormal measurement position at a counter reading of 99970 (and later 99985) were unsuccessful producing large errors when compared to the experimental data.

The 'standard k - ϵ '^[5] model was then used for both the normal and abnormal measurement positions producing good results for both. This model was selected as the most accurate for the modelling of orifice plates which fall outside the scope of ISO 5167^[6].

2.6.2 Validation of Model

Dimensional data was provided to the CFD expert from a combination of site measurements and drawings to build up a model of the orifice plate, carrier and upstream and downstream pipework in normal and abnormal measurement positions.

The real site process data and experimental data that were provided did not include the resultant differential pressure which was to be calculated by the CFD analysis. The differential pressures were made available for comparison, only once the results of the CFD analysis were provided. The comparison of results was

made taking into consideration the uncertainty in the differential pressure measurement as this is the dominant source of measurement uncertainty. ISO TR 12767^[1] states that ‘a further effect of eccentric positioning of an orifice plate is an increased unsteadiness of the DP signal obtained. Observations have shown, for example, a marked increase in DP reading fluctuations with increasing eccentricity for all values of β between 0.4 and 0.7.’ Other sources of uncertainty from the experimental data include pressure, temperature and gas composition measurements, flow rate fluctuations and flow rate calculation method. Other sources of uncertainty from the CFD analysis include orifice plate position, orifice plate dimensions, pipe dimensions, carrier dimensions and analysis method.

2.6.2.1 Grid Independence

In CFD modelling the results may vary depending on the resolution of the grid elements used, particularly around important features. Three grids of increasing resolution were used for each test case and the results were compared to determine the extent to which grid independence had been reached. The grid with the highest resolution is considered most accurate and this is the value presented in the CFD results.

2.6.2.2 Validation of Normal Measurement Position

The CFD results for the normal measurement position differed from the real site process data by 0.6 % to 1.5 % at low flow rates where the DP measurement uncertainty was calculated to be between ± 3 % and ± 6 %. At higher flow rates the results differed by 0.2 % to 0.6 % where the DP measurement uncertainty was calculated to be around ± 1 %.

2.6.2.3 Validation of 99970 Abnormal Measurement Position

Data was provided for four of the tests (3, 7, 8 and 10) for the abnormal measurement position at a counter reading of 99970 (on insertion). The results are shown in Table 15.

Test	Actual Flow Rate (m ³ /h)	Experimental DP (mbar)	CFD DP (mbar)	Error (%)	DP Measurement Uncertainty (%)
3	2430.7522	140.19	142.43	-1.6 %	± 1.5 %
7	2259.955	127.96	126.73	1.0 %	± 2.0 %
8	1741.5158	65.19	62.23	4.5 %	± 1.5 %
10	2472.6176	133.62	132.81	0.6 %	± 1.5 %

Table 15 - CFD Results for 99970 Counter Reading

The results are around the level of the DP measurement uncertainty apart from test 8. In this case the flow rates were slightly lower, however the error was still higher than expected. This may be due in part to the increased unsteadiness of the DP signal, caused by the eccentricity, which is not accounted for. From the CFD modelling it was also possible to see the location of the plate and visualise the flow profile around it as shown in Figure 48 and 47.

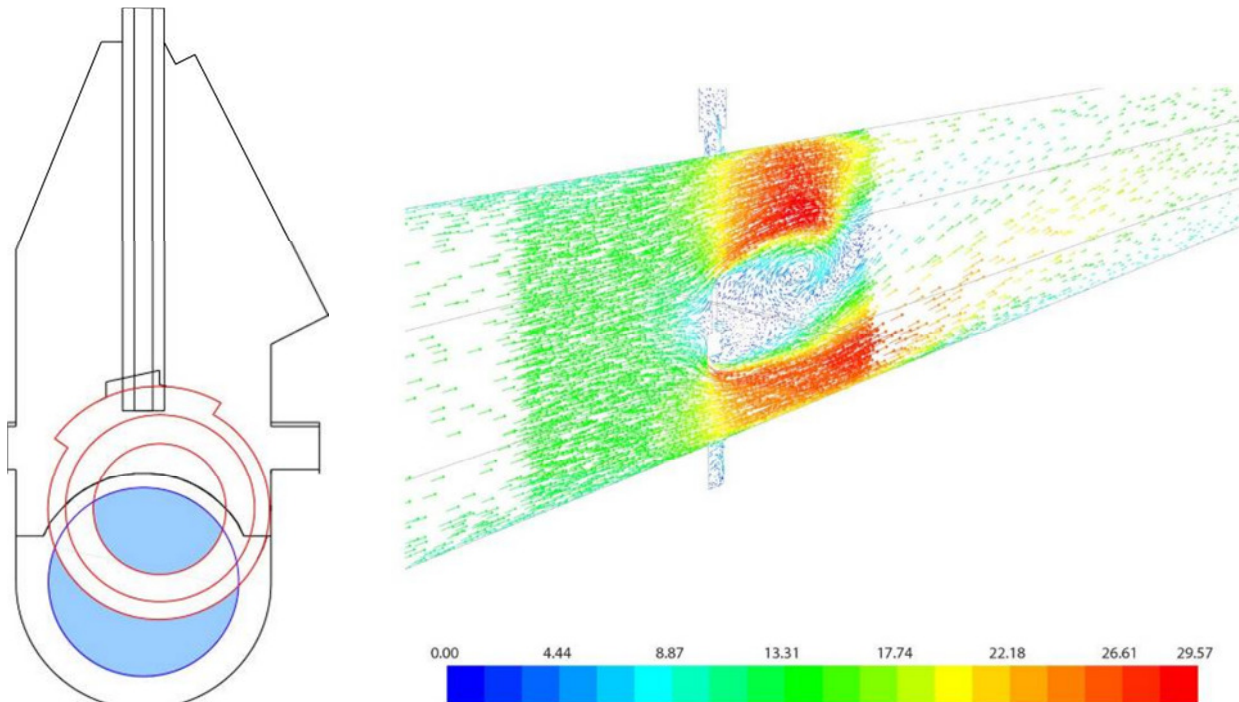


Figure 48 - [left] 99970 Abnormal Measurement Position; Figure 49 - [right] 99970 Velocity Vector Distribution in Mid x-y Plane (m/s; flowing left to right)

2.6.3 Results of 99985 Abnormal Measurement Position

Data was provided for all tests (1, 2, 3, 4, 6, 7, 8, 9, 10 and 11) for the abnormal measurement position at a counter reading of 99985 (on insertion). The results are shown in Table 16.

Test	Actual Flow Rate (m ³ /h)	Experimental DP (mbar)	CFD DP (mbar)	Error (%)	DP Measurement Uncertainty (%)
1	594.4561	13.78	14.40	-4.5 %	±5.0 %
2	1598.6628	103.14	104.36	-1.2 %	±2.0 %
3	2396.1463	242.94	237.43	2.3 %	±1.0 %
4	1540.5865	102.49	102.43	0.1 %	±2.0 %
6	534.9225	12.06	12.38	-2.7 %	±6.0 %
7	2174.3146	208.33	203.99	2.1 %	±1.0 %
8	1729.112	112.57	113.87	-1.2 %	±1.5%
9	609.996	14.07	14.35	-2.0 %	±5.0 %
10	2415.2228	217.58	223.02	-2.5 %	±1.0 %
11	648.0378	15.98	16.08	-0.6 %	±4.5 %

Table 16 - CFD Results for 99985 Counter Reading

The results showed very good agreement with the experimental data and were within the level of the DP measurement uncertainty apart from tests 3, 7 and 10. This may be due in part to the increased unsteadiness of the DP signal, caused by the eccentricity, which is not accounted for. These results were within 2.5 % of the experimental data. The experimental results are compared to the CFD results in Figure 50 illustrating that there is no significant change in the discharge coefficient (or error) over the range of Reynolds numbers (or process conditions). The close agreement between CFD grids 2 and 3 (<0.5 %)

demonstrate acceptable grid independence. Figure 51 and 50 illustrate the location of the plate and the flow profile around it.

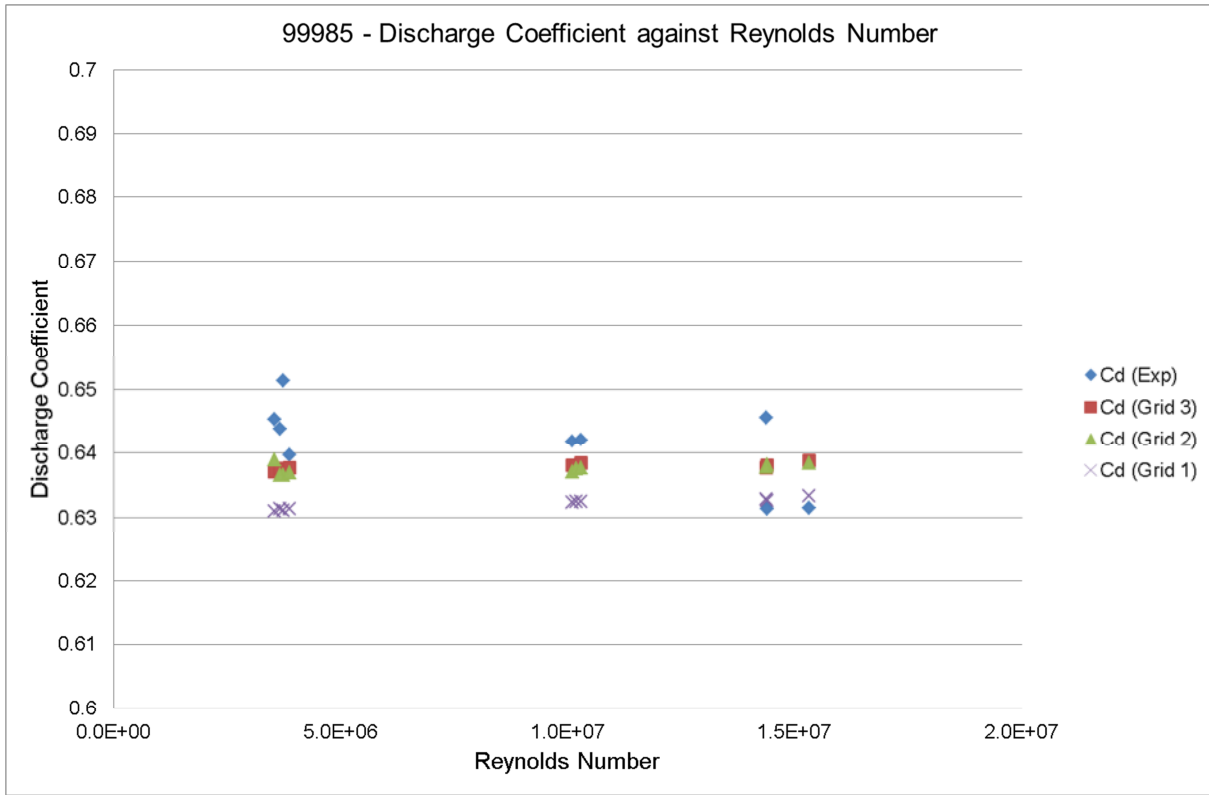


Figure 50 - Comparison of Experimental and CFD results for 99985 Counter Reading

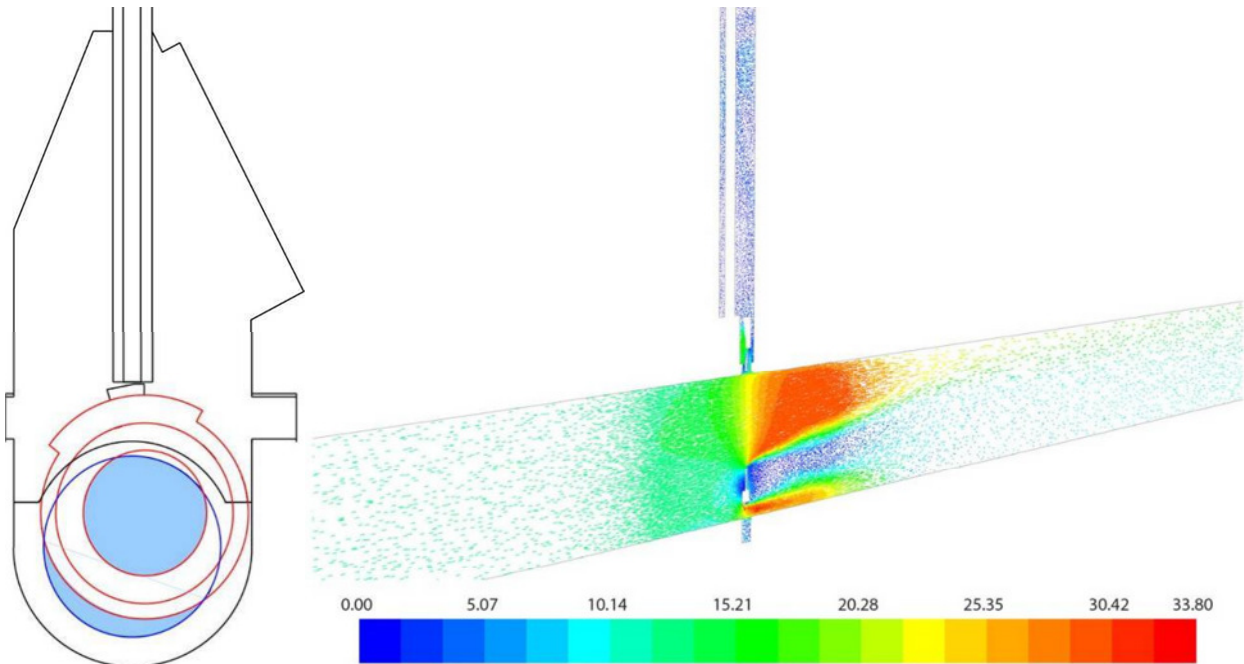


Figure 51 – [left] 99985 Abnormal Measurement Position; Figure 52 – [right] 99985 Velocity Vector Distribution in Mid x-y Plane (m/s; flowing left to right)

2.6.4 Results of 99950 Abnormal Measurement Position

Data was provided for all tests (1, 2, 3, 4, 6, 7, 8, 9, 10 and 11) for the abnormal measurement position at a counter reading of 99950 (on insertion). The results are shown in Table 17.

Test	Actual Flow Rate (m ³ /h)	Experimental DP (mbar)	CFD DP (mbar)	Error (%)	DP Measurement Uncertainty (%)
1	588.60	1.40	1.99	-42 %	±40 %
2	1619.6945	16.07	16.32	-1.6 %	±5 %
3	2459.8613	37.29	37.98	-1.9 %	±2.5 %
4	1564.3494	14.61	16.09	-10 %	±6 %
6	541.2844	1.85	1.91	-3.2 %	±40 %
7	2284.8572	33.42	34.28	-2.6 %	±2.5 %
8	1748.498	17.43	17.77	-2.0 %	±4 %
9	608.80	2.83	2.18	23 %	±30 %
10	2506.863	34.96	36.43	-4.2 %	±2.5 %
11	633.819	3.07	2.35	23 %	±30 %

Table 17 - CFD Results for 99950 Counter Reading

The results showed varying agreement with the experimental data. For tests 2, 3, 6, 8, 9 and 11 the errors were within the level of the DP measurement uncertainty. For tests 1, 4, 7 and 10 the errors were outside the level of the DP measurement uncertainty. This may be due in part to the increased unsteadiness of the DP signal, caused by the eccentricity, which is not accounted for. The experimental results are compared to the CFD results in Figure 53 illustrating that there is no significant change in the discharge coefficient (or error) over the range of Reynolds numbers (or process conditions). The close agreement between CFD grids 2 and 3 (<0.7 %) demonstrate acceptable grid independence. Figure 54 and 53 illustrate the location of the plate and the flow profile around it.

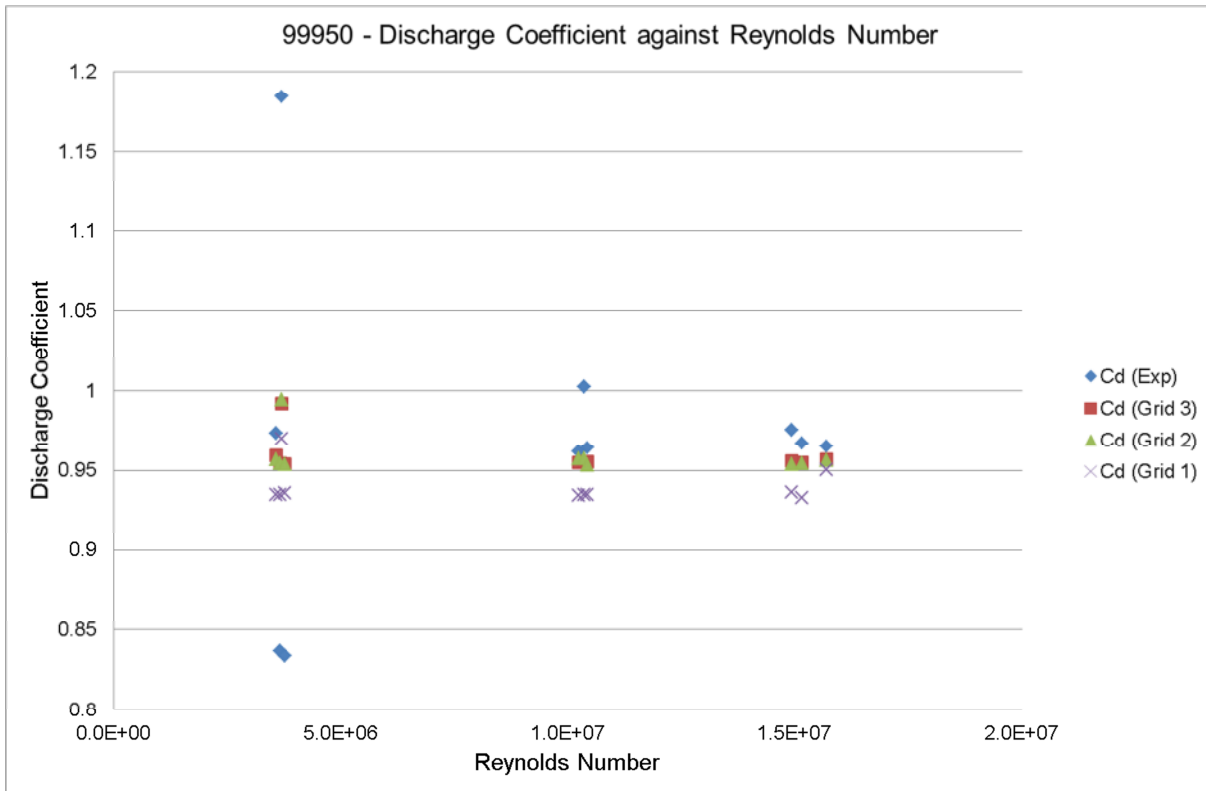


Figure 53 - Comparison of Experimental and CFD results for 99950 Counter Reading

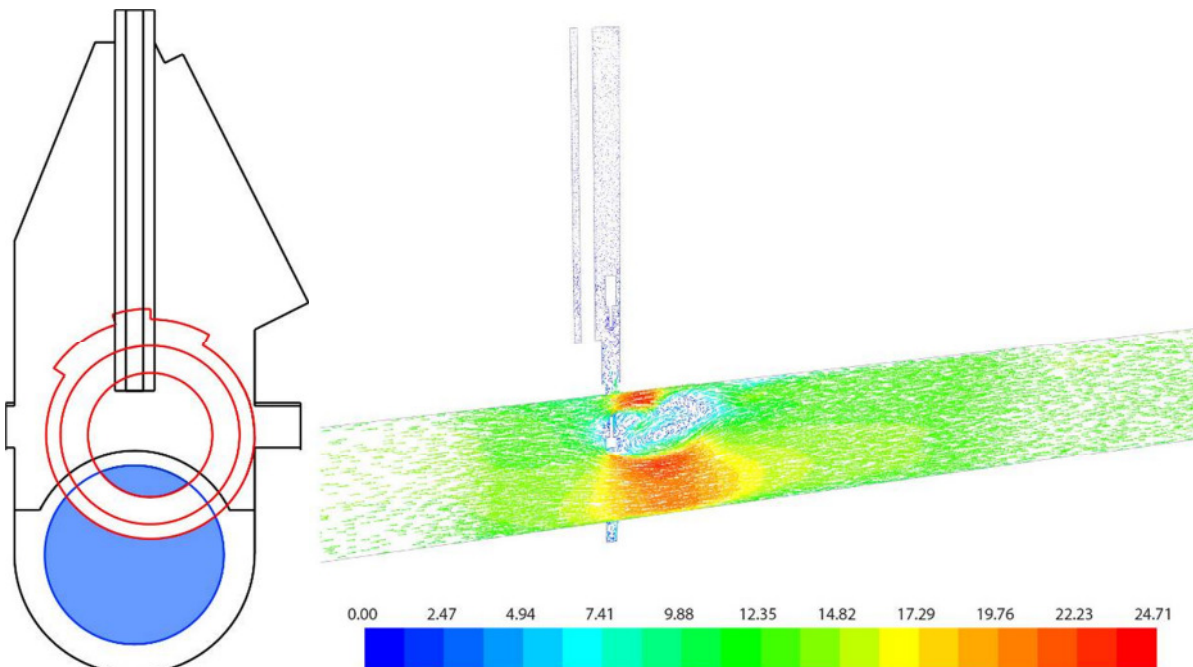


Figure 54 – [left] 99950 Abnormal Measurement Position; Figure 55 – [right] 99950 Velocity Vector Distribution in Mid x-y Plane (m/s; flowing left to right)

2.6.5 Peer Review of CFD Analysis

The CFD analysis report was twice reviewed by NEL and amended.

The final review^[8] (see Appendix E) concluded that grid independence was not achieved in two sets of results. These were the correctly located orifice plate model used in the validation and the 99985 long model used for comparison with the 99985 short model. The final review^[8] also highlighted that some of the recommendations of the interim review had not been addressed sufficiently. These conclusions are discussed in the following sections.

2.6.5.1 Grid Independence of Correctly Located Orifice Plate Model

The three correctly located orifice plate cases were used as a starting point to validate the model. The differences between grid 2 and grid 3 for each case are stated in Table 18.

Case	DP (Grid 3) (mbar)	Error from Experimental (Grid 3) (%)	Change in DP (Grid 2 to Grid 3) (%)
1	12.85	0.6	0.3
2	24.50	0.2	0.3
3	442.41	0.6	0.9

Table 18 - Grid Independence of Correctly Located Orifice Plate Model

This model was used as a guide to the reliability of the CFD modelling and as such a change of 0.9 % was considered acceptable and further refinement was viewed as unnecessary.

2.6.5.2 Grid Independence of 99985 Long Model

The final review^[8] focussed on the difference between the short and long models for the 99985 counter reading and as such only considered grid 1 and grid 2. It is accepted that grid independence was not established between grid 1 and grid 2 as demonstrated in Table 19. When compared to the change between grid 2 and grid 3 it can be seen that grid independence has been achieved to an acceptable tolerance.

Case	Change in DP (Grid 1 to Grid 2) (%)	Change in DP (Grid 2 to Grid 3) (%)
1	1.8	0.3
2	1.5	0.3
3	1.6	0.1
4	1.6	0.0
6	2.5	0.5
7	1.8	0.0
8	1.7	0.3
9	1.7	0.3
10	1.6	0.1
11	1.8	0.2

Table 19 - Grid Independence of 99985 Long Model

2.6.5.3 Interim Review Recommendations

The final review^[8] noted that no comparison had been made between the computed discharge coefficients for the orifice plate in the correctly installed location and the Reader-Harris/Gallagher (1998) equation in ISO

5167-2:2003^[9]. This comparison was made by NEL within the final review^[8] with good results in terms of agreement with the experiment.

The CFD report was revised following the final review to include details of the quality of the mesh and y+ values as well as state that the calculations are treated as incompressible.

The final review^[8] also commented on the pressure recovery stating that it was different to other experimental and computational work, but has little effect on the discharge coefficient.

The only recommendation not met was the requirement for grid spacing around the orifice plate bore edge to be a maximum of 0.1 mm.

2.6.5.4 Rebuttal Statement

The author of the CFD analysis report issued a rebuttal statement. In this statement the author states that the 'call for 0.1 mm meshes is too fine and resulted in meshes which were impractical to use in the present CFD calculations and resources required for such fine meshes were beyond the scope of the work. However, reasonably practical mesh resolutions were used in present calculations by employing 0.5 mm mesh spacing to mesh orifice plate edges.'

The Independent Technical Experts were satisfied that the conclusions and recommendations of the peer review had been met as far as practicable and none of the issues undermine the overall results of the CFD analysis.

3 Error Quantification

Errors were calculated for the various counter readings from the corrected flow rate data from the on-site testing. This produced very good correlation between all tests, as illustrated in Figure 56, which indicates that the error is independent of process conditions.

The results from the CFD analysis were used to produce equivalent error values for the various counter readings. This again produced very good correlation between all tests, as illustrated in Figure 57, which indicates that the error is independent of process conditions.

The combined results from the on-site testing and CFD analysis are shown in Figure 58 and summarised in Table 20. The mean values demonstrate very good agreement between the on-site tests and the CFD analysis.

The standard deviation is higher at a counter reading of 99950, the largest deviations being at lower flow rates. This is to be expected due to the high uncertainty levels in the DP measurement at low DPs. A typical DP measurement uncertainty profile is provided in Appendix C. This does not take into account the increased unsteadiness of the DP signal caused by the eccentricity.

Counter Reading	Experimental Error (%)		CFD Error (%)		Difference in Mean (% relative)
	Mean	Std. Dev.	Mean	Std. Dev.	
99985	26.1 %	0.7 %	25.7 %	0.7 %	-1.4 %
99950	70.6 %	3.1 %	70.6 %	0.6 %	0.0 %

Table 20 - Flow Rate Error at Counter Readings (Insertion)

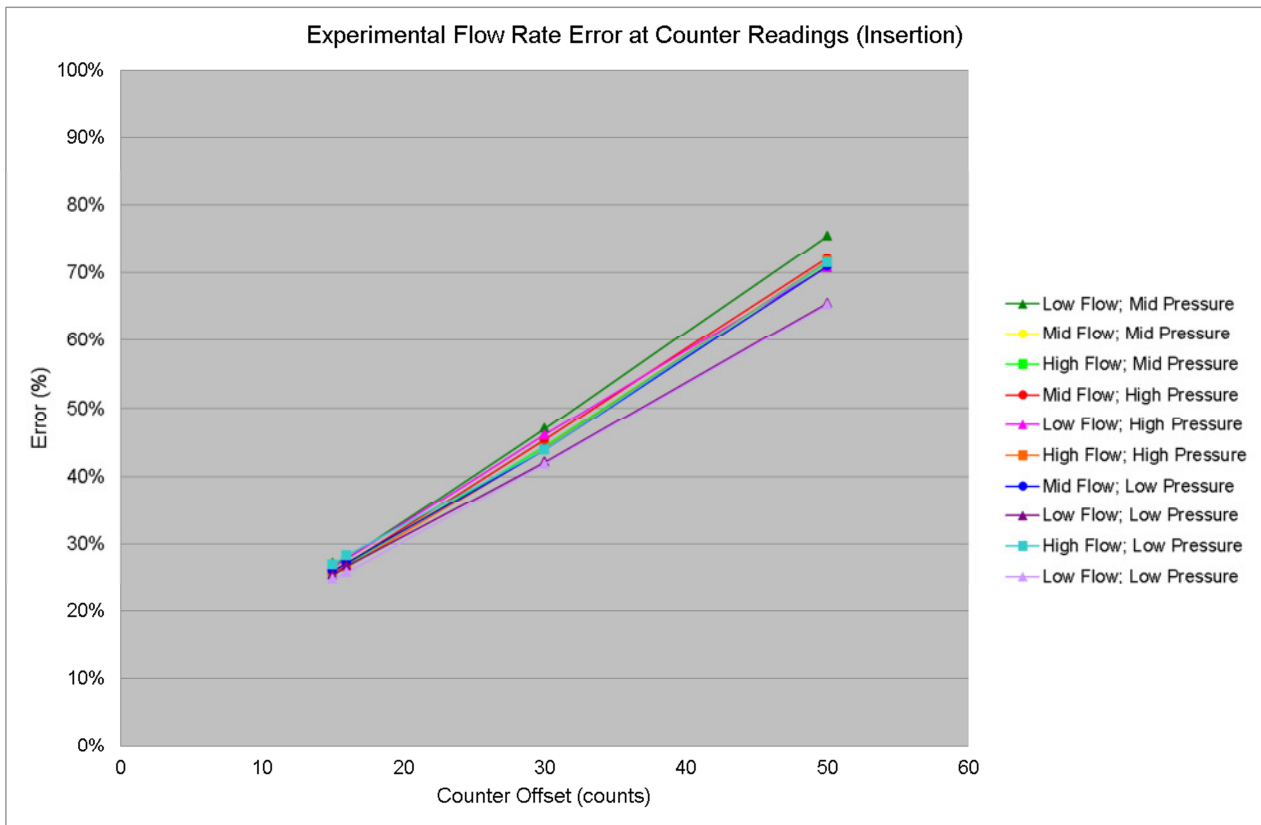


Figure 56 - Experimental Flow Rate Error at Counter Readings (Insertion)

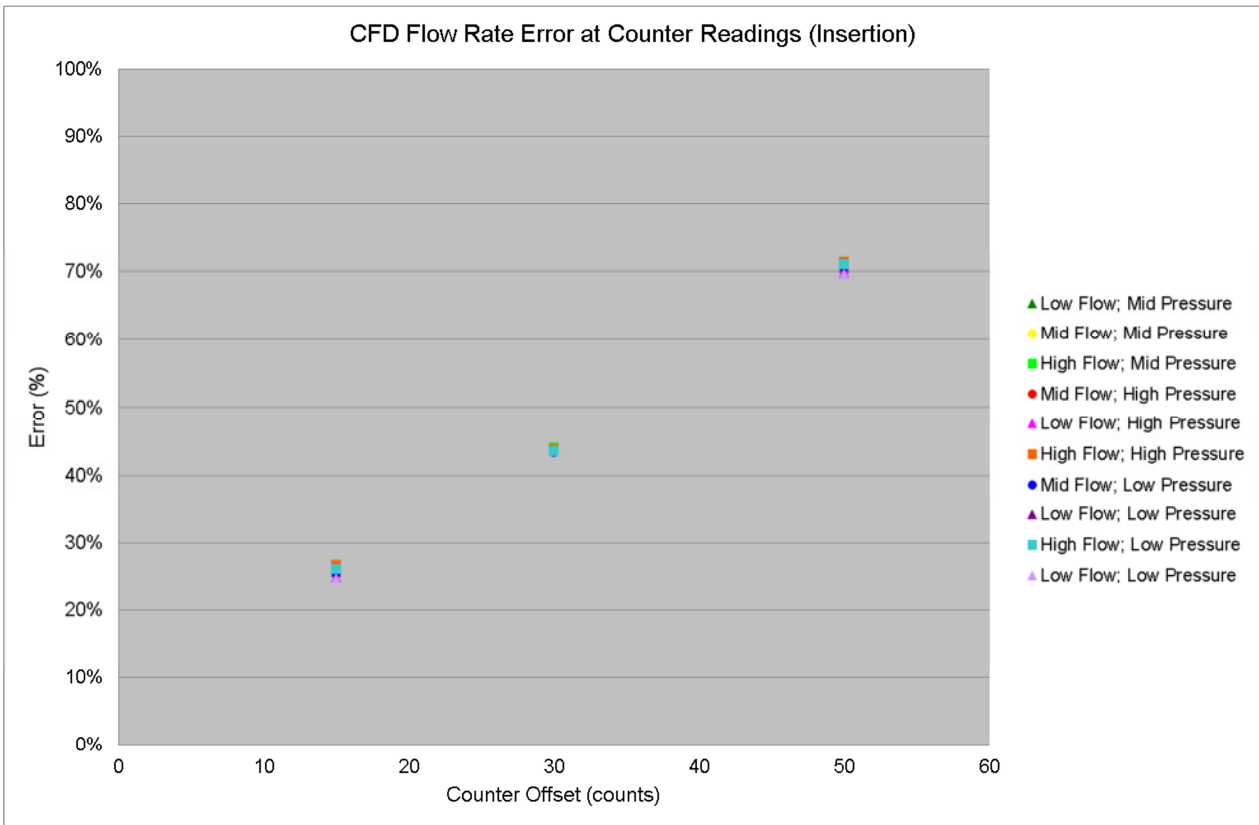


Figure 57 - CFD Flow Rate Error at Counter Readings (Insertion)

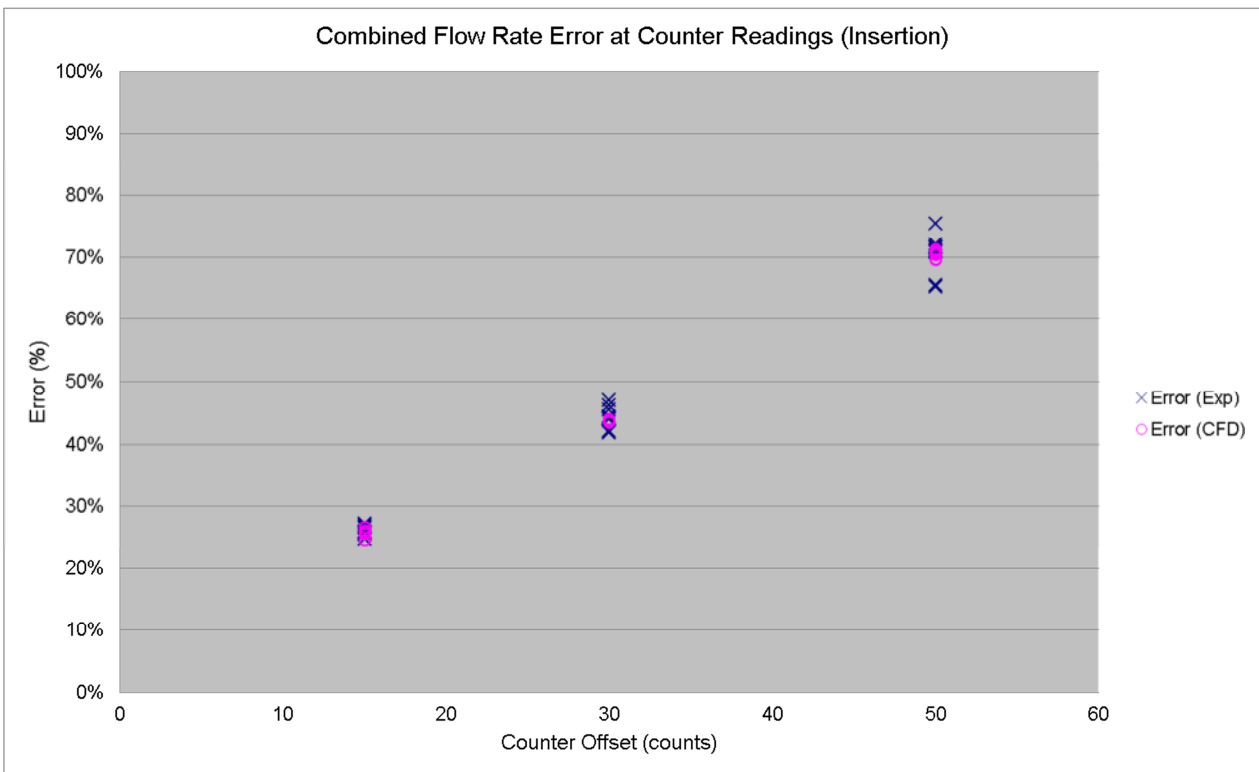


Figure 58 - Combined Flow Rate Error at Counter Readings (Insertion)

The combined results are repeated in Table 21 and Figure 59 with the low DP readings (<10 mbar) removed. The reduction in the standard deviation demonstrates that the two data sets are more reliable and support each other particularly well at DPs above 10 mbar. This is primarily due to the large uncertainties associated with the lower DP measurements.

Counter Reading	Experimental Error (%)		CFD Error (%)		Difference in Mean (% relative)
	Mean	Std. Dev.	Mean	Std. Dev.	
99950	71.5 %	0.4 %	71.0 %	0.3 %	-0.7 %

Table 21 - Flow Rate Error at Counter Readings (Insertion) (Above 10 mbar only)

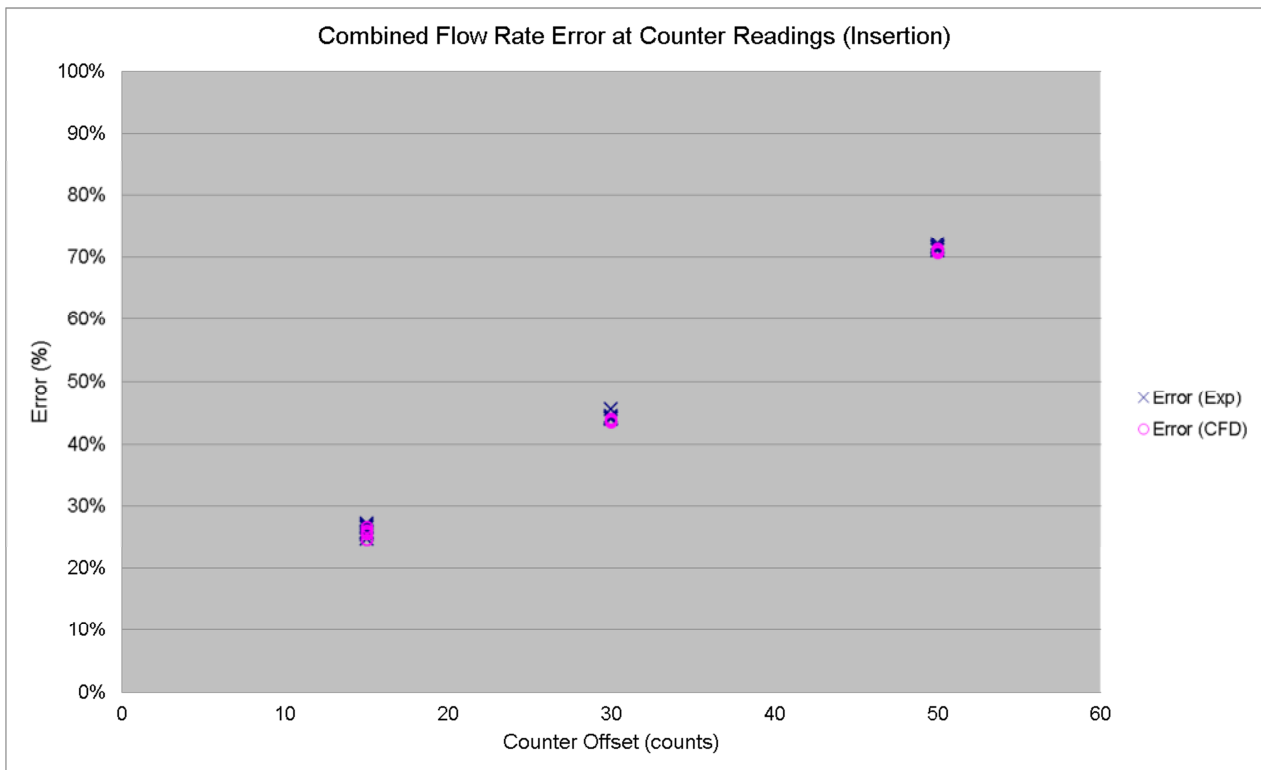


Figure 59 - Combined Flow Rate Error at Counter Readings (Insertion) (Above 10 mbar only)

3.1 First Error Period (21st July 2009 to 27th July 2010)

For the first error period, a counter reading of 99985 has been used based on the evidence available which includes:

- the (~31%) step change in flow rate when the plate was inserted on 21st July 2009;
- the 99885 values stamped on the carrier information plate;
- the pattern of orifice plate contamination found on the plate when removed on 27th July 2010 when compared to the offset location of the plate from physical measurements.

It has been assumed that the plate arrived at a counter reading of 99985 by insertion (not removal).

The on-site testing and CFD analysis show that the error is independent of process conditions and therefore a single value can be applied across the period. The average error from the on-site testing was an under-registration of 26.1 % with a standard deviation of 0.7 %. This results in a daily correction factor of 1.353066.

3.2 Second Error Period (27th July 2010 to 10th August 2010)

For the second error period, a counter reading of 99950 has been used based on the evidence available which includes:

- the (~69%) step change in flow rate when the plate location was corrected on 10th August 2010;
- the 9995 value stamped on the carrier information plate;
- the 99950 reading stated in the interviews conducted with the mechanical operatives that undertook the work.

It has been assumed that the plate arrived at a counter reading of 99950 by insertion (not removal).

The results at low DPs have been excluded to improve the accuracy and reliability of the datasets. The on-site testing and CFD analysis show that the error is independent of process conditions and therefore a single value can be applied across the period. The average error from the on-site testing was an under-registration of 71.5 % with a standard deviation of 0.4 %. This results in a daily correction factor of 3.506731.

4 Recommendations

It is recommended that the error, an overall under-registration of 1,617 GWh, be reconciled using the daily correction factors in Appendix A. The error was only present for part of the day on 21st July 2009 and 10th August 2010, and the error magnitude changed on 27th July 2010 therefore individual correction factors have been calculated for these days. Following this incident the downstream party produced a 'Six Point Plan' (available on the Joint Office of Gas Transporters' website^[10]) aimed at reducing the risk of similar events occurring in future. The site will have been under-odorising the gas during the period of the errors. The site will have been operating with higher uncertainty levels during the period of the errors.

5 References

- [1] BS ISO TR 12767:1998. Measurement of fluid flow by means of pressure-differential devices – Guidelines to the Effect of Departure from the Specifications and Operating Conditions given in ISO 5167-1.
- [2] T/PR/ME/2 Part 3 (SGN Adopted) Work Procedure for Validation of Equipment Associated With Measurement Systems for the Calculation of Mass, Volume & Energy Flowrate of Gas – Part 3: Flow Weighted Average Calorific Value Offtakes.
- [3] Malalasekera, W. Computational Fluid Dynamics Analysis of Orifice Plate Metering Situations Under Abnormal Configurations, Version 3, August 2013. [Reproduced in Appendix D]
- [4] Menter, F.R. (1993) Zonal Two Equation $k-\omega$ Turbulence Models for Aerodynamic Flows, AIAA Paper 93-2906.
- [5] Launder, B.E. & Sharma, B.I. (1974) Application of the Energy Dissipation Model of Turbulence to the Calculation of Flow Near a Spinning Disc, *Letters in Heat and Mass Transfer*, vol. 1, no. 2, pp. 131-138.
- [6] ISO 5167-1:1991. Measurement of fluid flow by means of pressure differential devices – Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full.
- [7] ESDU (2011) ESDU CFD-BPG 11010-2011. CFD Best Practice Guidelines for modelling pressure losses and flow characteristics in square- and knife-edged orifice plates.
- [8] Laing, M. & Reader-Harris, M. Peer Review of “Computational Fluid Dynamics Analysis of Orifice Plate Metering Situations Under Abnormal Configurations”, Version 2, Dr W. Malalasekera, May 2013. [Reproduced in Appendix E]
- [9] ISO 5167-2:2003. Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full – Part 2: Orifice plates.
- [10] SGN, Six Point Plan, published on the Joint Office of Gas Transporters’ website, March 2012. (<http://www.gasgovernance.co.uk/sites/default/files/Six%20Point%20Plan.pdf>)

Appendix A Daily Correction Factors

The error was present only for part of the day on 21st July 2009 and 10th August 2010, therefore specific daily correction factors have been calculated. On 27th July 2010 the magnitude of the error changed part of the way through the day, therefore a specific daily correction factor has been calculated. The daily correction factor to be applied is constant from 22nd July 2009 until 26th July 2010 with a value of 1.353066 and from 28th July 2010 until 9th August 2010 with a value of 3.506731.

Gas Day	Daily Correction Factor
21-Jul-09	1.172596 ^b
22-Jul-09	1.353066
23-Jul-09	1.353066
24-Jul-09	1.353066
25-Jul-09	1.353066
26-Jul-09	1.353066
27-Jul-09	1.353066
28-Jul-09	1.353066
29-Jul-09	1.353066
30-Jul-09	1.353066
31-Jul-09	1.353066
01-Aug-09	1.353066
02-Aug-09	1.353066
03-Aug-09	1.353066
04-Aug-09	1.353066
05-Aug-09	1.353066
06-Aug-09	1.353066
07-Aug-09	1.353066
08-Aug-09	1.353066
09-Aug-09	1.353066
10-Aug-09	1.353066
11-Aug-09	1.353066
12-Aug-09	1.353066
13-Aug-09	1.353066
14-Aug-09	1.353066
15-Aug-09	1.353066
16-Aug-09	1.353066

Gas Day	Daily Correction Factor
17-Aug-09	1.353066
18-Aug-09	1.353066
19-Aug-09	1.353066
20-Aug-09	1.353066
21-Aug-09	1.353066
22-Aug-09	1.353066
23-Aug-09	1.353066
24-Aug-09	1.353066
25-Aug-09	1.353066
26-Aug-09	1.353066
27-Aug-09	1.353066
28-Aug-09	1.353066
29-Aug-09	1.353066
30-Aug-09	1.353066
31-Aug-09	1.353066
01-Sep-09	1.353066
02-Sep-09	1.353066
03-Sep-09	1.353066
04-Sep-09	1.353066
05-Sep-09	1.353066
06-Sep-09	1.353066
07-Sep-09	1.353066
08-Sep-09	1.353066
09-Sep-09	1.353066
10-Sep-09	1.353066
11-Sep-09	1.353066
12-Sep-09	1.353066
13-Sep-09	1.353066
14-Sep-09	1.353066
15-Sep-09	1.353066

^b The error was only present for part of gas day 21st July 2009

Gas Day	Daily Correction Factor
16-Sep-09	1.353066
17-Sep-09	1.353066
18-Sep-09	1.353066
19-Sep-09	1.353066
20-Sep-09	1.353066
21-Sep-09	1.353066
22-Sep-09	1.353066
23-Sep-09	1.353066
24-Sep-09	1.353066
25-Sep-09	1.353066
26-Sep-09	1.353066
27-Sep-09	1.353066
28-Sep-09	1.353066
29-Sep-09	1.353066
30-Sep-09	1.353066
01-Oct-09	1.353066
02-Oct-09	1.353066
03-Oct-09	1.353066
04-Oct-09	1.353066
05-Oct-09	1.353066
06-Oct-09	1.353066
07-Oct-09	1.353066
08-Oct-09	1.353066
09-Oct-09	1.353066
10-Oct-09	1.353066
11-Oct-09	1.353066
12-Oct-09	1.353066
13-Oct-09	1.353066
14-Oct-09	1.353066
15-Oct-09	1.353066
16-Oct-09	1.353066
17-Oct-09	1.353066
18-Oct-09	1.353066
19-Oct-09	1.353066
20-Oct-09	1.353066
21-Oct-09	1.353066

Gas Day	Daily Correction Factor
22-Oct-09	1.353066
23-Oct-09	1.353066
24-Oct-09	1.353066
25-Oct-09	1.353066
26-Oct-09	1.353066
27-Oct-09	1.353066
28-Oct-09	1.353066
29-Oct-09	1.353066
30-Oct-09	1.353066
31-Oct-09	1.353066
01-Nov-09	1.353066
02-Nov-09	1.353066
03-Nov-09	1.353066
04-Nov-09	1.353066
05-Nov-09	1.353066
06-Nov-09	1.353066
07-Nov-09	1.353066
08-Nov-09	1.353066
09-Nov-09	1.353066
10-Nov-09	1.353066
11-Nov-09	1.353066
12-Nov-09	1.353066
13-Nov-09	1.353066
14-Nov-09	1.353066
15-Nov-09	1.353066
16-Nov-09	1.353066
17-Nov-09	1.353066
18-Nov-09	1.353066
19-Nov-09	1.353066
20-Nov-09	1.353066
21-Nov-09	1.353066
22-Nov-09	1.353066
23-Nov-09	1.353066
24-Nov-09	1.353066
25-Nov-09	1.353066
26-Nov-09	1.353066

Gas Day	Daily Correction Factor
27-Nov-09	1.353066
28-Nov-09	1.353066
29-Nov-09	1.353066
30-Nov-09	1.353066
01-Dec-09	1.353066
02-Dec-09	1.353066
03-Dec-09	1.353066
04-Dec-09	1.353066
05-Dec-09	1.353066
06-Dec-09	1.353066
07-Dec-09	1.353066
08-Dec-09	1.353066
09-Dec-09	1.353066
10-Dec-09	1.353066
11-Dec-09	1.353066
12-Dec-09	1.353066
13-Dec-09	1.353066
14-Dec-09	1.353066
15-Dec-09	1.353066
16-Dec-09	1.353066
17-Dec-09	1.353066
18-Dec-09	1.353066
19-Dec-09	1.353066
20-Dec-09	1.353066
21-Dec-09	1.353066
22-Dec-09	1.353066
23-Dec-09	1.353066
24-Dec-09	1.353066
25-Dec-09	1.353066
26-Dec-09	1.353066
27-Dec-09	1.353066
28-Dec-09	1.353066
29-Dec-09	1.353066
30-Dec-09	1.353066
31-Dec-09	1.353066
01-Jan-10	1.353066

Gas Day	Daily Correction Factor
02-Jan-10	1.353066
03-Jan-10	1.353066
04-Jan-10	1.353066
05-Jan-10	1.353066
06-Jan-10	1.353066
07-Jan-10	1.353066
08-Jan-10	1.353066
09-Jan-10	1.353066
10-Jan-10	1.353066
11-Jan-10	1.353066
12-Jan-10	1.353066
13-Jan-10	1.353066
14-Jan-10	1.353066
15-Jan-10	1.353066
16-Jan-10	1.353066
17-Jan-10	1.353066
18-Jan-10	1.353066
19-Jan-10	1.353066
20-Jan-10	1.353066
21-Jan-10	1.353066
22-Jan-10	1.353066
23-Jan-10	1.353066
24-Jan-10	1.353066
25-Jan-10	1.353066
26-Jan-10	1.353066
27-Jan-10	1.353066
28-Jan-10	1.353066
29-Jan-10	1.353066
30-Jan-10	1.353066
31-Jan-10	1.353066
01-Feb-10	1.353066
02-Feb-10	1.353066
03-Feb-10	1.353066
04-Feb-10	1.353066
05-Feb-10	1.353066
06-Feb-10	1.353066

Gas Day	Daily Correction Factor
07-Feb-10	1.353066
08-Feb-10	1.353066
09-Feb-10	1.353066
10-Feb-10	1.353066
11-Feb-10	1.353066
12-Feb-10	1.353066
13-Feb-10	1.353066
14-Feb-10	1.353066
15-Feb-10	1.353066
16-Feb-10	1.353066
17-Feb-10	1.353066
18-Feb-10	1.353066
19-Feb-10	1.353066
20-Feb-10	1.353066
21-Feb-10	1.353066
22-Feb-10	1.353066
23-Feb-10	1.353066
24-Feb-10	1.353066
25-Feb-10	1.353066
26-Feb-10	1.353066
27-Feb-10	1.353066
28-Feb-10	1.353066
01-Mar-10	1.353066
02-Mar-10	1.353066
03-Mar-10	1.353066
04-Mar-10	1.353066
05-Mar-10	1.353066
06-Mar-10	1.353066
07-Mar-10	1.353066
08-Mar-10	1.353066
09-Mar-10	1.353066
10-Mar-10	1.353066
11-Mar-10	1.353066
12-Mar-10	1.353066
13-Mar-10	1.353066
14-Mar-10	1.353066

Gas Day	Daily Correction Factor
15-Mar-10	1.353066
16-Mar-10	1.353066
17-Mar-10	1.353066
18-Mar-10	1.353066
19-Mar-10	1.353066
20-Mar-10	1.353066
21-Mar-10	1.353066
22-Mar-10	1.353066
23-Mar-10	1.353066
24-Mar-10	1.353066
25-Mar-10	1.353066
26-Mar-10	1.353066
27-Mar-10	1.353066
28-Mar-10	1.353066
29-Mar-10	1.353066
30-Mar-10	1.353066
31-Mar-10	1.353066
01-Apr-10	1.353066
02-Apr-10	1.353066
03-Apr-10	1.353066
04-Apr-10	1.353066
05-Apr-10	1.353066
06-Apr-10	1.353066
07-Apr-10	1.353066
08-Apr-10	1.353066
09-Apr-10	1.353066
10-Apr-10	1.353066
11-Apr-10	1.353066
12-Apr-10	1.353066
13-Apr-10	1.353066
14-Apr-10	1.353066
15-Apr-10	1.353066
16-Apr-10	1.353066
17-Apr-10	1.353066
18-Apr-10	1.353066
19-Apr-10	1.353066

Gas Day	Daily Correction Factor
20-Apr-10	1.353066
21-Apr-10	1.353066
22-Apr-10	1.353066
23-Apr-10	1.353066
24-Apr-10	1.353066
25-Apr-10	1.353066
26-Apr-10	1.353066
27-Apr-10	1.353066
28-Apr-10	1.353066
29-Apr-10	1.353066
30-Apr-10	1.353066
01-May-10	1.353066
02-May-10	1.353066
03-May-10	1.353066
04-May-10	1.353066
05-May-10	1.353066
06-May-10	1.353066
07-May-10	1.353066
08-May-10	1.353066
09-May-10	1.353066
10-May-10	1.353066
11-May-10	1.353066
12-May-10	1.353066
13-May-10	1.353066
14-May-10	1.353066
15-May-10	1.353066
16-May-10	1.353066
17-May-10	1.353066
18-May-10	1.353066
19-May-10	1.353066
20-May-10	1.353066
21-May-10	1.353066
22-May-10	1.353066
23-May-10	1.353066
24-May-10	1.353066
25-May-10	1.353066

Gas Day	Daily Correction Factor
26-May-10	1.353066
27-May-10	1.353066
28-May-10	1.353066
29-May-10	1.353066
30-May-10	1.353066
31-May-10	1.353066
01-Jun-10	1.353066
02-Jun-10	1.353066
03-Jun-10	1.353066
04-Jun-10	1.353066
05-Jun-10	1.353066
06-Jun-10	1.353066
07-Jun-10	1.353066
08-Jun-10	1.353066
09-Jun-10	1.353066
10-Jun-10	1.353066
11-Jun-10	1.353066
12-Jun-10	1.353066
13-Jun-10	1.353066
14-Jun-10	1.353066
15-Jun-10	1.353066
16-Jun-10	1.353066
17-Jun-10	1.353066
18-Jun-10	1.353066
19-Jun-10	1.353066
20-Jun-10	1.353066
21-Jun-10	1.353066
22-Jun-10	1.353066
23-Jun-10	1.353066
24-Jun-10	1.353066
25-Jun-10	1.353066
26-Jun-10	1.353066
27-Jun-10	1.353066
28-Jun-10	1.353066
29-Jun-10	1.353066
30-Jun-10	1.353066

Gas Day	Daily Correction Factor
01-Jul-10	1.353066
02-Jul-10	1.353066
03-Jul-10	1.353066
04-Jul-10	1.353066
05-Jul-10	1.353066
06-Jul-10	1.353066
07-Jul-10	1.353066
08-Jul-10	1.353066
09-Jul-10	1.353066
10-Jul-10	1.353066
11-Jul-10	1.353066
12-Jul-10	1.353066
13-Jul-10	1.353066
14-Jul-10	1.353066
15-Jul-10	1.353066
16-Jul-10	1.353066
17-Jul-10	1.353066
18-Jul-10	1.353066
19-Jul-10	1.353066
20-Jul-10	1.353066
21-Jul-10	1.353066
22-Jul-10	1.353066
23-Jul-10	1.353066
24-Jul-10	1.353066
25-Jul-10	1.353066
26-Jul-10	1.353066
27-Jul-10	2.521218 ^c
28-Jul-10	3.506731
29-Jul-10	3.506731
30-Jul-10	3.506731
31-Jul-10	3.506731
01-Aug-10	3.506731
02-Aug-10	3.506731

Gas Day	Daily Correction Factor
03-Aug-10	3.506731
04-Aug-10	3.506731
05-Aug-10	3.506731
06-Aug-10	3.506731
07-Aug-10	3.506731
08-Aug-10	3.506731
09-Aug-10	3.506731
10-Aug-10	1.224412 ^d

^c The magnitude of the error changed on gas day 27th July 2010

^d The error was only present for part of gas day 10th August 2010

Appendix B Carrier Data Plate Text

B.1 Carrier Identification Plate

ROBINSON ORIFICE FITTING
MADE BY
HEECO INTERNATIONAL LTD
THETFORD NORFOLK ENGLAND
LICENCEES FOR
PECO/ROBINSON MINERAL WELLS TEXAS USA

BODY TYPE	E TYPE
FITTING SERIAL NO.	7603758
METER RUN NO.	1001
CALIBRATED DIA UPSTREAM	10.096
CALIBRATED DIA DOWNSTREAM	10.097
WORKING PRESSURE	1440 PSI
TEST PRESSURE	2175 PSI

B.2 Carrier Information Plate

ROBINSON ORIFICE FITTING
HEECO INTERNATIONAL LTD
THETFORD, NORFOLK, ENGLAND
Licencees For
PECO / ROBINSON
Mineral Wells, Texas, U.S.A

Type **E TYPE** Rating **600** CWP **1440** psi
psi **2175** psi. Run No. **1001** Calibrated Size
Fitting Bore **10"** Serial No. **7603758**

OPERATING INSTRUCTIONS

TO REMOVE ORIFICE PLATE

1. Turn top shaft anticlockwise until counter reads **99885**
2. Turn plug valve to closed position as indicated
3. Tighten grease screws to seal plug valve
4. Open Relief Valve marked 'A' ensuring that valve marked 'B' is tight if fitted
5. Loosen large tie bar (if fitted)
6. Loosen centre clamp screws and retrieve clamps and cover plate
7. Continue turning top shaft bringing orifice plate clear with the aid of hoist (if fitted)

TO REPLACE ORIFICE PLATE

1. Lower carrier assembly into top chamber and turn top shaft clockwise until counter reads **99885**
2. Replace cover plate and clamps, tighten equally working from centre
3. Reposition and tighten tie bar
4. Tighten Relief Valve marked 'A' and loosen equaliser valve marked 'B'
5. Turn Plug valve to open position as indicated
6. Turn top shaft clockwise until counter reads 9995

0005

Orifice plate is now central

Appendix C Differential Pressure Measurement Uncertainty Profile

A typical uncertainty profile for differential pressure measurement is shown in Figure 60 with the lower range highlighted in Figure 61.

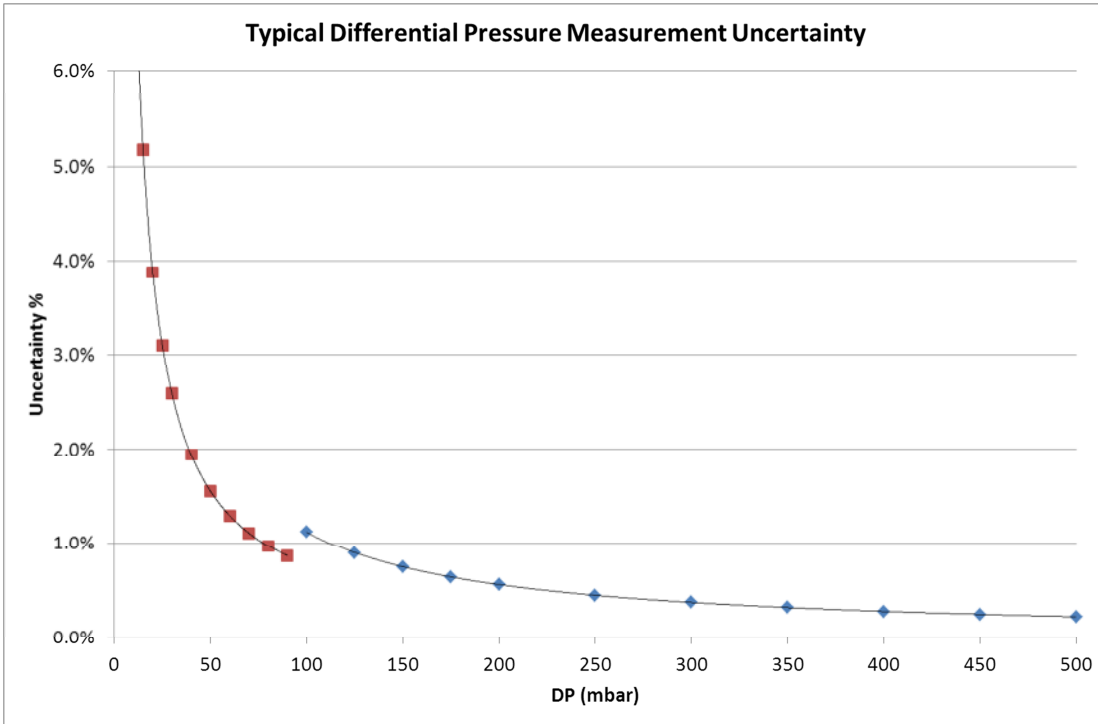


Figure 60 - Typical Differential Pressure Measurement Uncertainty

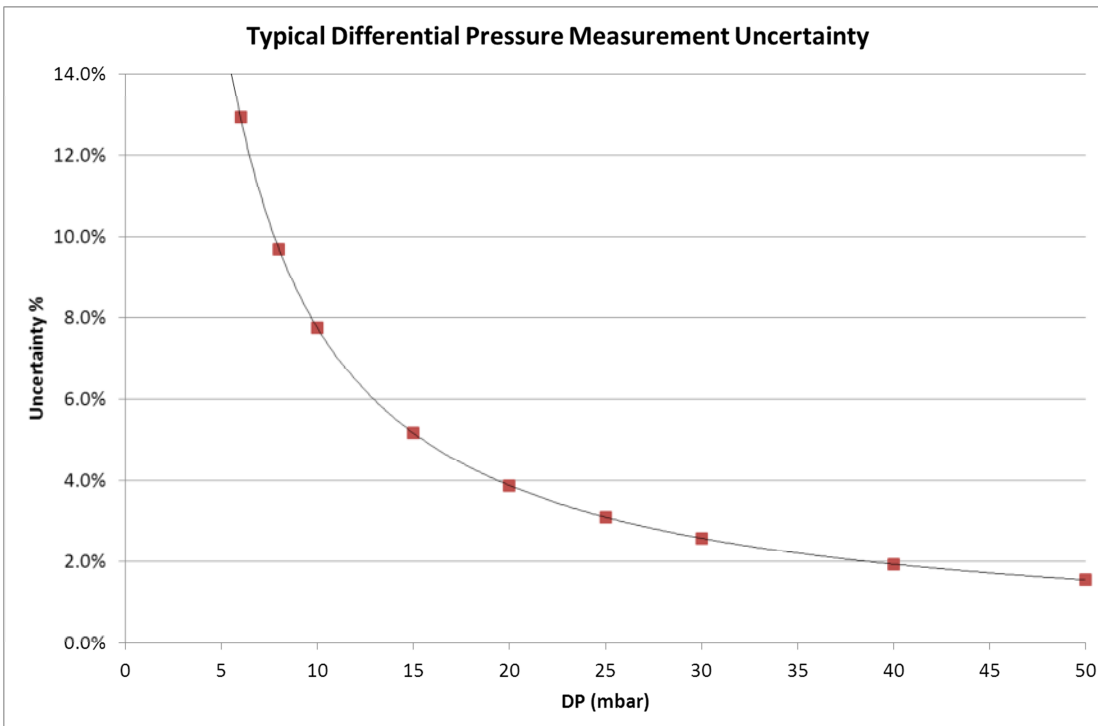


Figure 61 - Typical Differential Pressure Measurement Uncertainty (Low Range)

Appendix D CFD Report

Appendix E Peer Review of CFD Report