34th International North Sea Flow Measurement Workshop
25-28 October 2016

Technical Paper

Diagnosis and Mitigation of Contamination Build-up in Multipath Liquid Ultrasonic Meters on the Danish Oil Pipe

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1 INTRODUCTION

This paper describes an investigation and remedial work carried out on multipath liquid ultrasonic meters installed on the Danish Oil Pipe, owned by DONG Oil Pipe A/S (DOP). The meters in question were installed in an effort to improve the performance of the onshore metering system at the receiving end of the pipeline. When the second of two replacement meters was installed, 10 months after the first, and the two meters operated in series, it was discovered that the first replacement meter was not in good agreement with the second meter. Investigations revealed that the problem was the result of contamination build-up inside the first meter and work began to understand and to attempt to resolve the problem.

2 THE OIL PIPE METERING STATION

The Danish Oil Pipe system includes the offshore tie-in platform Gorm "E" which feeds the 330 km pipeline. Seven export pumps on Gorm "E" pump the oil across the 220 km pipeline to the Filsø pumping station, seven kilometres from the west coast of Jutland. At Filsø the pressure is increased with the aid of five more export pumps so that the oil can be transported the final 110 km across the peninsula of Jutland to DOP's crude storage and export facilities adjacent to the Shell Refinery in Fredericia.

At the receiving end of the pipeline there is a metering system that is used primarily for leak detection. A photograph of the metering system (before upgrading) is shown in Figure 1 below. The system is configured for maximum flexibility and redundancy. Flow enters from one of the two headers on the right hand side and exits from the header on the left. The flow can be routed through only the first (top) metering stream to the downstream header, or it can enter on the other inlet header and flow through the second (bottom) metering stream, or it can flow through the first metering stream and then through the second meter stream by means of the cross-over line that is between the two streams. The metering streams can also be bypassed completely.

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Fig.1 - The DOP metering system at Fredericia

3 FLOW METER UPGRADING

When originally commissioned the system used two 2-path process-grade liquid ultrasonic meters. Each meter employed a pair of direct diametrical paths in orthogonal planes at plus and minus 45 degrees to the horizontal.

The performance of these meters on site, evaluated by means of comparison with the custody transfer tank gauging downstream, did not meet expectations. Over the course of time efforts were made to improve performance, for example by calibrating the 2-path meters with their upstream pipework, but still performance on site did not improve.

Figure 2 shows a trend of the deviation of one of the 2-path meters relative to the flow rate computed using the tank gauging at the DOP storage and export facilities. Flow rate comparisons in this paper between the tanks and flow meters are presented as a 20-day average to reduce 'scatter' in the data that results from various factors including data archiving methods and tank switching operations.

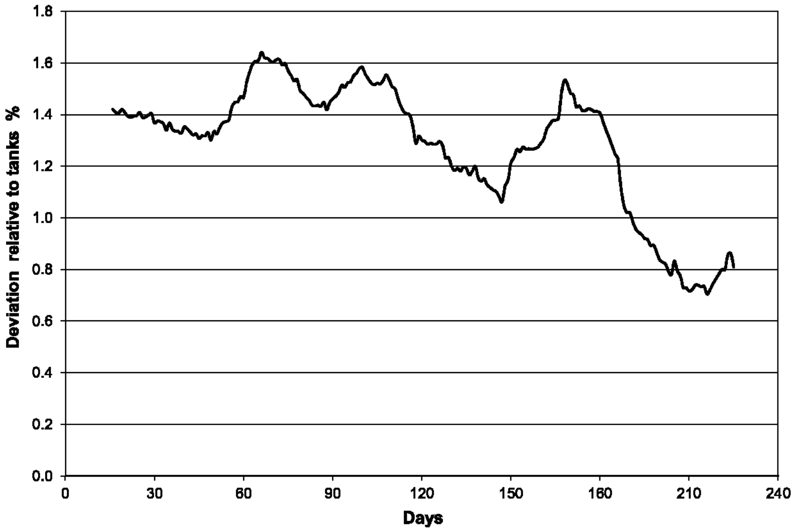

Fig. 2 - Typical performance of one of the 2-path meters

Following a visit to site by Cameron (Caldon) to review the installation, it was concluded that the upstream arrangement of bends in the metering system was non-ideal, as the arrangement of out-of-plane bends is well known to produce distortions of the axial profile and high levels of swirl. Therefore it was recommended that the 2-path meters be replaced by 4-path custody transfer grade meters, and that a flow conditioner be installed upstream to eliminate swirl. Nowadays, it would be usual to recommend an 8-path meter rather than a 4-path meter and conditioner, but at that particular point in time the Caldon 8-path meter for the petroleum industry had not yet been launched.

The upstream pipe section had an integral reducer to adapt the diameter from the 20-inch flange of the ball valve to the 16-inch diameter of the meter run. Although not ideal, the flow conditioner was installed between the ball valve and the reducer. This location was chosen for a number of reasons: (a) the primary purpose of the conditioner was swirl removal, and there was approaching 20 pipe diameters of separation between the conditioner and the meter (b) the location in the 20-inch section would result in lower pressure loss and (c) modifications to the existing system could be minimised, requiring only a short make-up spool downstream of the new meters.

The flow conditioner used was a Spearman type perforated plate conditioner, supplied by NEL. A drawing of the modified meter run is shown in Figure 3 below.

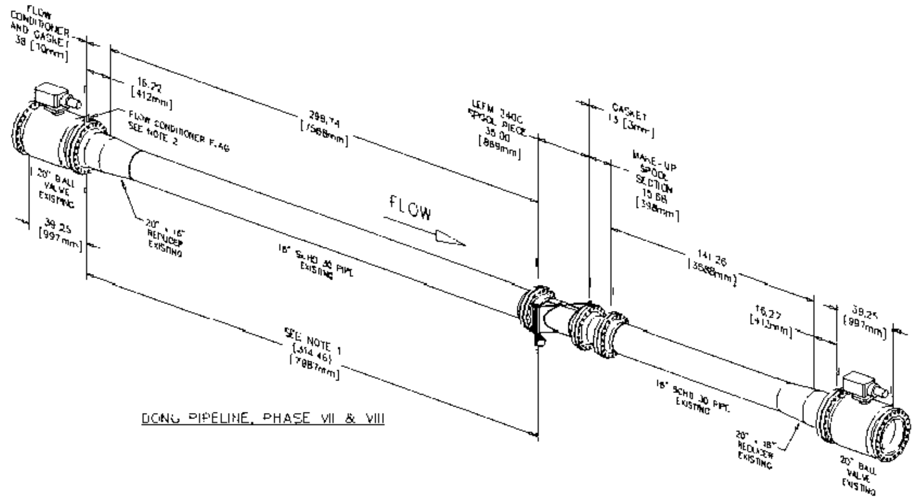

Fig 3. - The meter run layout following modification

4 FLOW METER CALIBRATION

The two replacement 4-path meters were ordered, calibrated and installed separately, approximately 10 months apart, owing to budget considerations. The meters supplied were 4-path chordal meters of the Gaussian (Westinghouse) design, with stainless steel meter bodies and transducer housings. Both meters were calibrated at the COFRAC accredited Trapil calibration facility in France. For each calibration the flow conditioner and its respective upstream length from the site were used. The flow conditioner was installed upstream of the meter tube and the 20-inch reduced bore ball valve was simulated in the calibration by using an expansion from 16-inch to 20-inch situated upstream of the flow conditioner.

The first 4-path meter (Meter 1) was calibrated in February and installed a month later. The second meter (Meter 2) was calibrated in December of the same year and installed in January of the following year.

The meters were calibrated over a Reynolds number range of approximately 40,000 to 1,000,000. Only a single adjustment factor was used to bring the meters into agreement with the calibration lab and the resulting linearity was better than +/- 0.1 %, comfortably within specification the specification of +/- 0.15 % as shown in Figure 4 below for Meter 2.

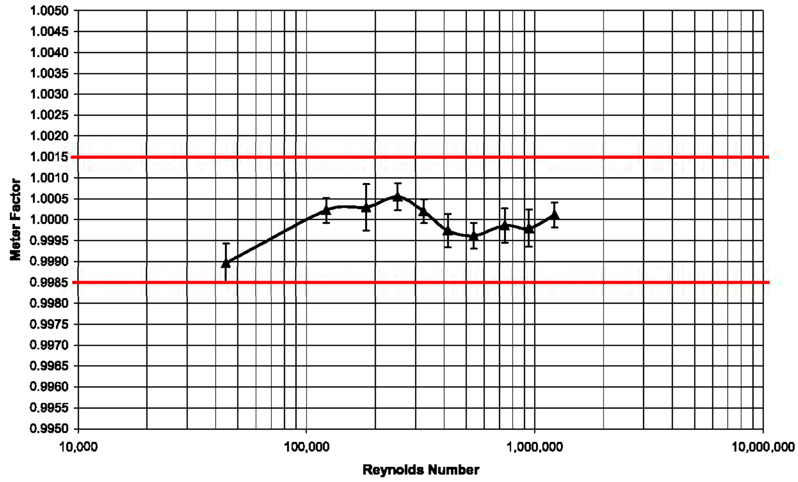

Fig. 4 - Trapil calibration result for a 4-path meter (Meter 2)

5 COMMISSIONING OF THE SECOND 4-PATH FLOW METER

By the time that the second 4-path meter was installed and commissioned, the first meter had been in service for 10 months. For commissioning the metering system the valves were configured to route flow through both meters in series. Once the second meter was commissioned it was immediately apparent that the two meters were reading differently, by approximately 1 %, with the newly installed meter reading higher than the first meter.

A diagnostic check had already been performed on the newly commissioned Meter 2 and had not highlighted any concerns. Therefore attention quickly turned to Meter 1 and a diagnostic log was taken from that meter for analysis. It was quickly determined, by analysis of various diagnostics, such as the velocity profile plot shown in Figure 5 below, that either the meter itself *or* the conditions of operation were different from what had been observed during commissioning.

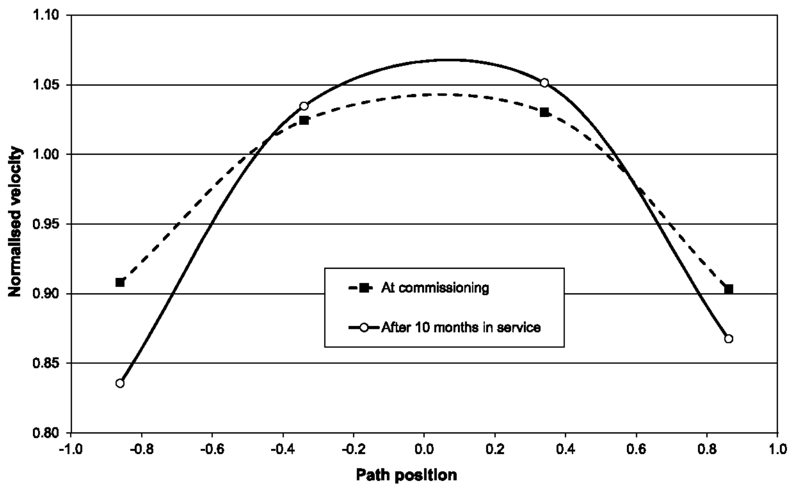

Fig. 5 - Comparison of velocity profiles at commissioning and after 10 months in service (Meter 1)

Of the various diagnostic parameters that were examined, it was noted in particular that the signal gain had reduced relative to commissioning. What drew attention to gain was that it had changed in a way that was not expected. As shown in Figure 6, the gain on the shorter, outside paths had reduced more than on the long paths. This was unexpected as the crude oil characteristics do not vary much and any change in absorption would be expected to affect the long paths more than the short paths. This led to a suggestion that perhaps the meter could be contaminated internally, as wax deposition could act like an acoustic matching layer on the stainless steel transducer housings of the meter. When this suggestion was made, the response from the technician on site was that, yes that could be the cause, as he had noticed that the decommissioned 2-path meters had been contaminated when they had been taken out of line.

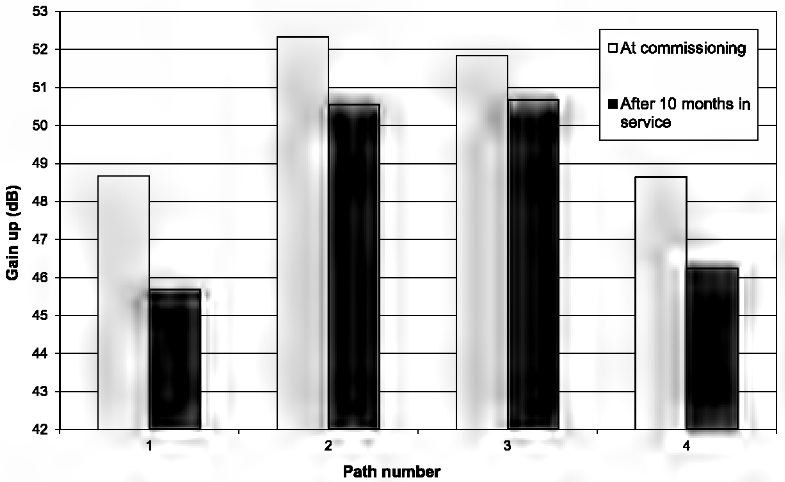

Fig. 6 - Comparison of applied gain at commissioning and after 10 months in service (Meter 1)

6 INSPECTION OF THE DECOMMISSIONED 2-PATH METERS

It transpired that the 2-path meters that had been decommissioned from the system were in storage not far from the metering station, and therefore it was decided that these should be inspected.

One of the two 2-path meters, the one removed from the line most recently, appeared to have been partly cleaned. The partly cleaned 2-path meter was corroded internally (being made of carbon steel) but was largely free of deposition in the bore. It did however have sticky deposits in the transducer housing cavities, partially covering the face of the transducer housings, as shown in the photograph of Figure 7.

Fig. 7 - Deposition in the transducer cavity of a partially cleaned 2-path meter

The second 2-path meter had been removed from service some 10 months earlier and did not appear to have been cleaned at all. It was found in a more severe state of contamination. As well as having deposits in the transducer housing cavities, the internal surface of the meter was covered in a heavy, wavy deposition that had dried to a hard crust that was a few millimetres thick in places. Photographs of the interior of the second 2-path meter are shown in Figures 8, 9 and 10.

Fig. 8 - Interior of a contaminated 2-path meter (transducer housing in centre of photograph)

Fig. 9 - Interior of a contaminated 2-path meter (close up of a transducer housing cavity)

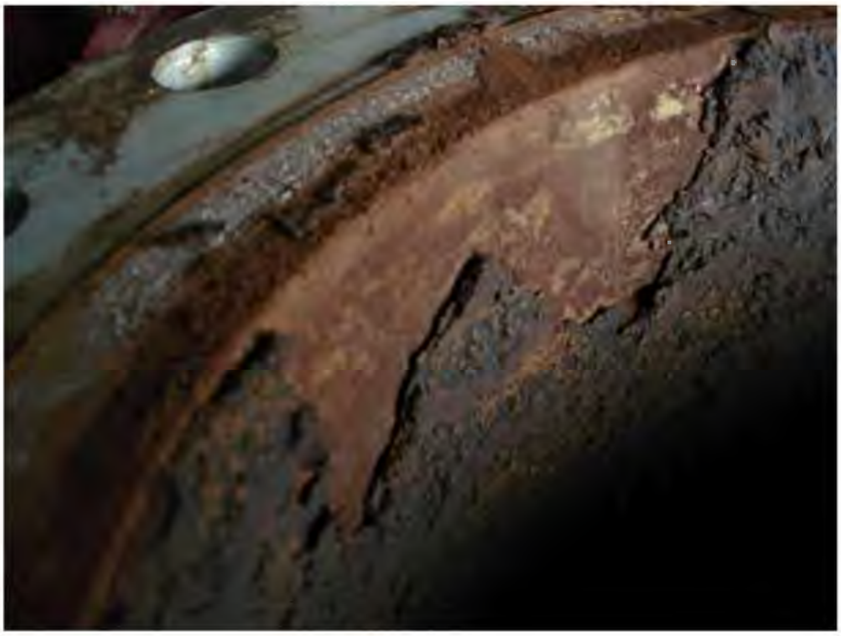

Fig. 10 - Contaminated 2-path meter showing the thickness of the deposition (which had solidified/dried to a 'crust' during 10 months in storage)

7 INSPECTION AND CLEANING OF METER 1

Following the discovery of the condition of the decommissioned meters, it was agreed that Cameron would return to site at the earliest convenient time to participate in an internal inspection of the first 4-path meter that had been installed on site (Meter 1). The plan, agreed in advance, was that the meter, upstream pipe, and flow conditioner would each be inspected and cleaned if necessary. The inspection of Meter 1 was carried out 1 month after the commissioning of Meter 2, i.e. 11 months after Meter 1 had been put into service.

Figure 11 shows the Spearman flow conditioner. The Spearman plate was found to be in good condition with no deposition on its surfaces and no upstream blockage or debris trapped in the holes.

Fig. 11 - Spearman conditioner after 11 months in service

Figure 12 shows the interior of the upstream pipe. It was observed that this carbon steel pipe had corrosion and deposition broadly similar to the 2-path meter body that had not been cleaned.

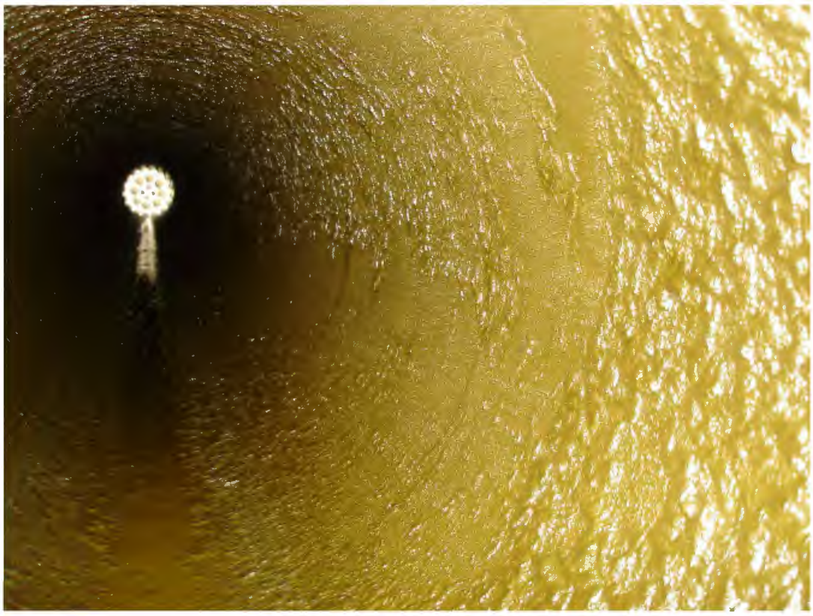

Fig. 12 - Photograph showing deposition in the upstream meter tube

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When the bore of the 4-path stainless steel ultrasonic meter body was inspected it was found that it was not as badly contaminated as the bore of the carbon steel upstream pipe (or the bore of the carbon steel 2-path meter bodies), as shown in Figure 13.

Fig. 13 - Photograph showing the bore of the stainless steel 4-path meter after 11 months in service (Meter 1)

On closer inspection of the interior of the meter, there was clear evidence of deposition in the transducer housing cavities, particularly those that were facing downstream. This can be seen by comparing Figure 14 which shows two transducer cavities facing upstream and Figure 15 which shows a transducer cavity that is facing downstream. In every case, the deposition was worse in the cavities facing downstream than those facing upstream, suggesting that the flow was having a beneficial 'scouring' effect on the cavities that face into the flow.

Fig. 14 - Photograph showing transducer housing cavities facing upstream

Fig. 15 - Photograph showing a transducer housing cavity facing downstream

Following the inspection, the upstream pipe was cleaned first and then the meter was returned to service. The cleaning of the upstream pipe altered the velocity profile and brought Meter 1 and Meter 2 into slightly better agreement but only by about 0.1%. In other words, although the actual velocity profile was altered, it did not have a very significant effect on the calibration of the meter. This finding is in line with expectations given knowledge of the robustness of the chordal integration technique used in these meters and corroborated by the linearity of the meters demonstrated at calibration.

The next step was to take Meter 1 out of service again and clean it. When this had been completed the diagnostic indicators such as normalised velocity of sound (VOS) and Gain came back into very close agreement with the commissioning data (see Figures 16 and 17). Cleaning Meter 1 had the effect of reducing the difference between the two meters from ~0.9 % to ~0.2 %.

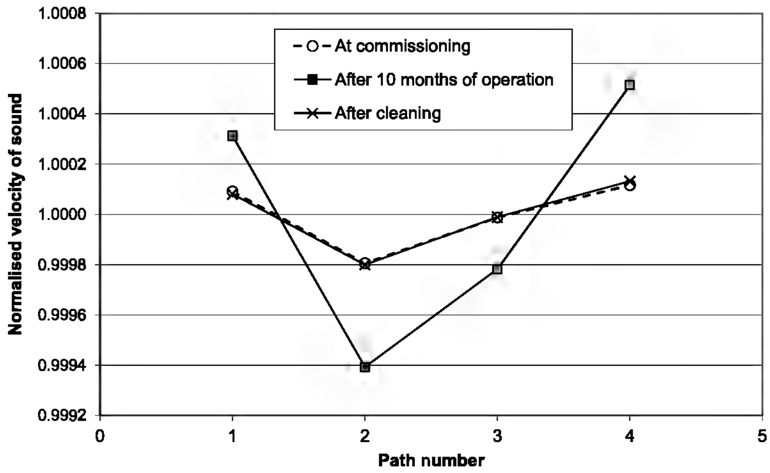

Fig. 16 - Velocity of sound comparison with commissioning baseline; after 10 months in service and following cleaning

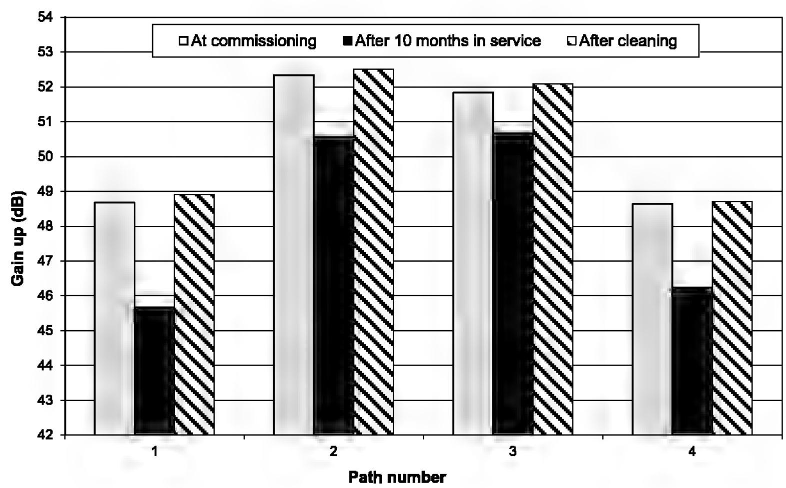

Fig. 17 - Gain comparison with commissioning baseline; after 10 months in service and following cleaning

8 ANALYSIS AND MITIGATION PLANNING

Once it had been confirmed that deposition was indeed the cause of the discrepancies observed, work began to obtain a better understanding of the problem and to develop mitigation plans.

Although some efforts were made to understand the nature of the deposition, the factors contributing to the deposition are still not very well understood. A sample taken from one of the meters was said to be mainly wax, with a high melting point of 76 degrees C, and approximately 2 % asphaltenes. Wax is present in the crude from Gorm and large amounts are regularly removed at the PIG receiver at Filsø. Drag reducing agent (DRA) is also used in the pipeline and it was often speculated that this might be contributing to the deposition problem. Some drag reducing agents exhibit some temperature dependent behaviour with a tendency to degrade at high temperatures and to clump or cluster at lower temperatures.

Diagnostic data logging was set up at site so that more information could be obtained while mitigation plans were discussed. It was also agreed that data from the tank gauging system downstream of the metering system would be examined so that the meters could be compared against an independent measurement. When this data was later analysed it was determined that the meters would be in good agreement with the tanks (and one another) when installed clean, and would stay that way for some time, which could be variable, but then they would begin to 'drift' relative to the tanks and then would settle at a fairly constant value somewhere between -0.5 % and -1.2 % relative to the tanks. Figure 18 below shows the deviation relative to the tanks, starting each time after a meter had been cleaned, and illustrates the variability of the deposition process and the resultant effect on the meters.

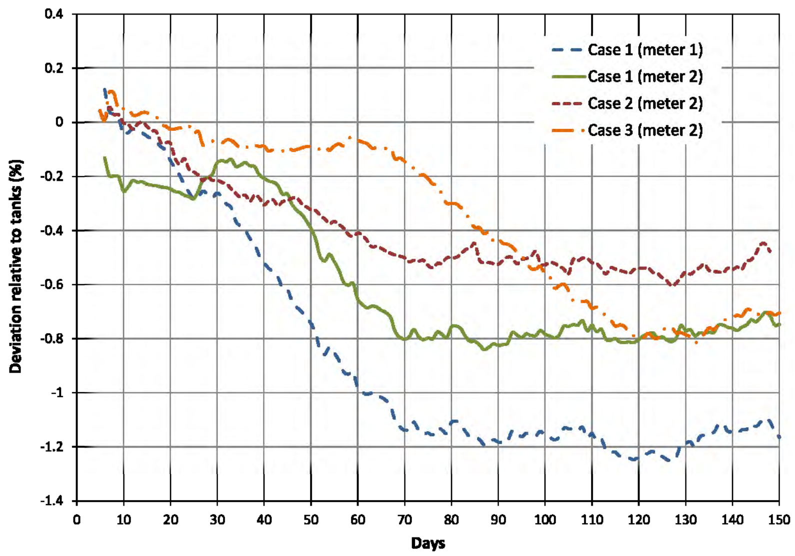

Fig. 18 - Flow rate deviation as a result of deposition, plotted versus time after cleaning, for three independent time periods

Diagnostic data was also analysed over these time periods. Of the various diagnostic available it was found that a carefully constructed Gain Diagnostic gave the most reliable correlation with the deviations due to contamination build up, though VOS monitoring was also found to be useful.

Figure 19 below show a gain diagnostic and a VOS diagnostic plotted versus the number of days since the meter was cleaned. This data corresponds with Case 1, Meter 1 in Figure 18 above. The Gain Diagnostic could easily be used to trigger an alarm in the first 10 to 15 days before the meter has shifted much, whereas the VOS Diagnostic does not give a clear indicate of a problem until around day 25, by which time the deviation was approximately 0.25 %.

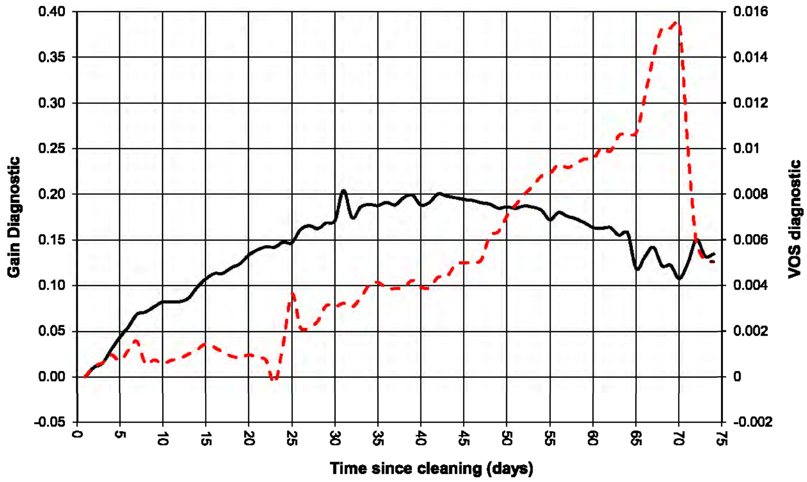

Fig. 19 - Gain and VOS diagnostic monitoring, Case 1, Meter 1

Analysing the data and considering the physics at work, it was concluded that the primary cause of the 'drift' was the deposition of material in the transducer housing cavities causing acoustic impedance changes and refraction effects and leading to a change in the path angle. This is illustrated in Figure 20. The angle between the path and the pipe axis increases, with the result that the measured transit time difference is reduced and the flow velocity is under-estimated.

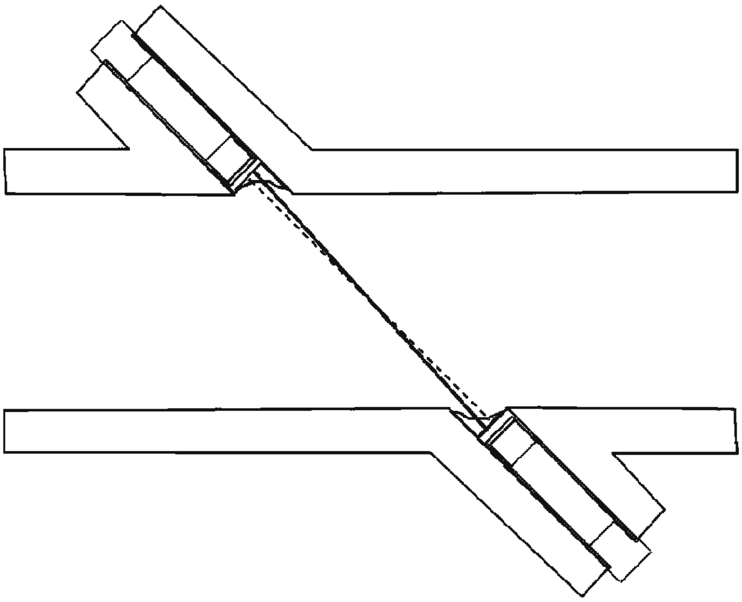

Fig. 20 - An illustration of path angle change resulting from deposits forming in the transducer housing cavities

Ideas that were then discussed in terms of mitigating the contamination build up were as follows:

- Filling the cavities in front of the housings with an acoustically conductive material of some sort
- Increasing the length of the transducer housings such that they would protrude into the flow and eliminate the cavity
- Applying an adhesion resistant coating to the wetted surfaces of the meter body and transducer housings

Filling the cavities with some other material was ruled out on the basis that it would just create a refraction issue of a different sort, causing the path angle to change with variations in the sound velocity of the fluid, e.g. due to temperature changes.

Intruding the transducers would be advantageous in terms of eliminating the problem area for deposition, but it was known from previous research and development work that this would make the uncalibrated (or 'dry' calibrated) meter much more non-linear than usual.

Coating the wetted surfaces was appealing as there was no potential downside, so long as the coating would be thin enough to be negligible in acoustic terms, and also assuming that it would continue to adhere to the surfaces in long term operation and would not peel or bubble.

Following a prolonged period of discussion and an investigation of various adhesion resistant coating processes, a decision was made to both intrude the transducers and coat the wetted surfaces of meter body and housings of Meter 1. The decision to intrude the housings was made on the assumption that the increased raw non-linearity could be corrected by calibration in the laboratory.

9 CALIBRATION OF METER 1 WITH MODIFICATION

Meter 1 was returned to Cameron for modification. First the transducer housings were removed and replaced with longer housings such that the face of the housing would protrude fully into the flow. Then the meter body was sent to be coated internally using a proprietary fluoropolymer coating formulation and application method.

Figure 21 shows a picture of the interior of the meter at the Trapil calibration lab, with the transducer housings protruding and the coating applied.

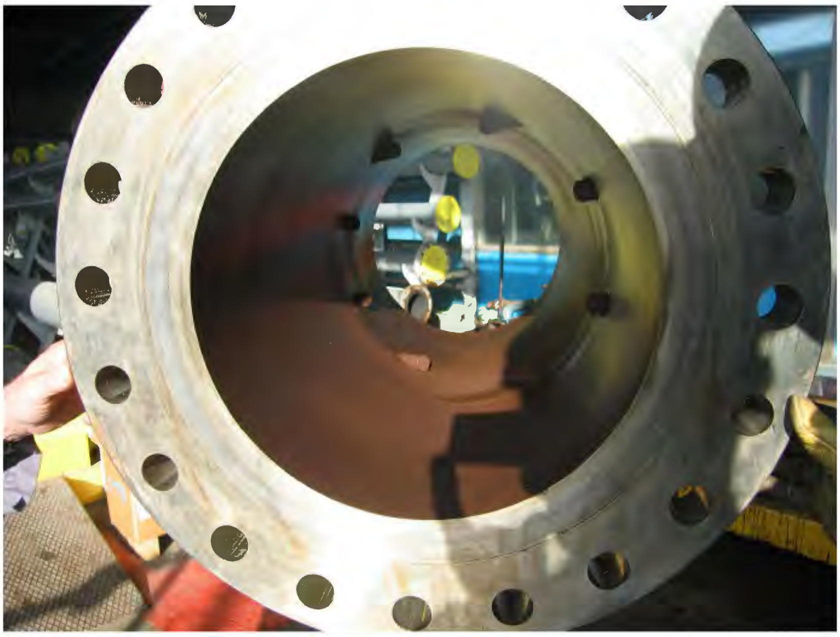

Fig. 21 - Meter 1 with protruding transducer housings and internal coating, photographed prior to calibration

When calibrated the meter had a 'raw' non-linearity of +/- 1% with an offset of -3.5 % relative to the calibration lab. This was more extreme than expected, but was corrected by adjusting the path velocity weighting factors. Following adjustment of the weighting factors, the calibration was repeated with two oils (kerosene and gas oil of approximately 2 and 5 cSt viscosity respectively) and the performance verified to be within +/- 0.15 % linearity over the meter's specified turndown,as shown in Figure 22 below.

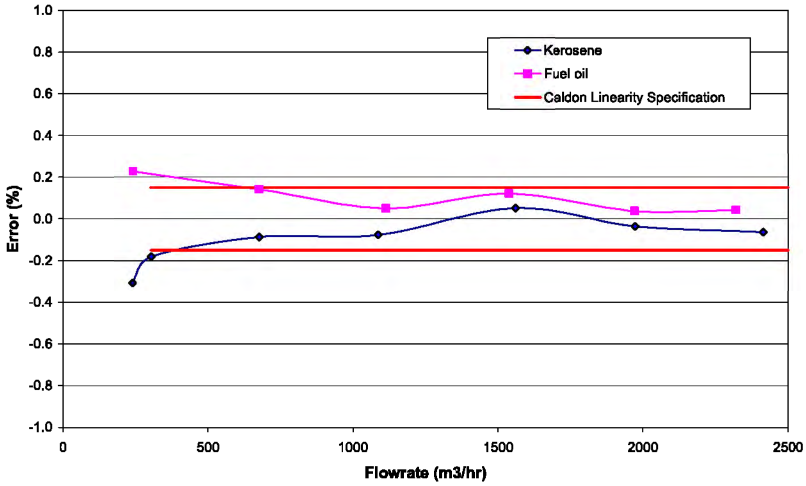

Fig. 22 - Calibration of Meter 1 post modification and weighting factor adjustment

10 COMMISSIONING AND MONITORING OF METER 1 AFTER MODIFICATION

When Meter 1 was re-commissioned, it was immediately checked against Meter 2, which had been left in service while Meter 1 was modified. Based on earlier comparisons of the contaminated meters with the tanks after some time in service, it was expected that Meter 1 in a clean and calibrated condition would register approximately 0.5 to 1 % higher than Meter 2 (i.e. it was expected that Meter 1 in a clean condition would be in close agreement with the tanks and that Meter 2 would be reading 0.5 to 1 % low). Contrary to expectations, it was found that the modified Meter 1 was reading approximately 2.9% higher than Meter 2, and about 2 % higher than the tanks.

Immediately an evaluation of diagnostic parameters was undertaken to determine the cause of this discrepancy. No fault could be found in the meter but when comparing diagnostic data from site against the calibration data it was noted that the flatness of the velocity profile at site was significantly higher than during calibration (0.815 flatness ratio in service versus a maximum of 0.775 at calibration). This was unexpected as the meter had been calibrated at Trapil using the upstream conditioner and pipework and the viscosity oils used had spanned the viscosity of the Danish crude oil.

Following some discussions with personnel at site, it was hypothesised that the drag reducing agent (DRA) that was in use might be affecting the flow velocity profile behaviour.

As the meter had been adjusted by means of the weighting factors, the effect on the meter behaviour is the same as applying a linear correction to the meter as a function of velocity profile flatness ratio. Figure 23 below shows the Trapil calibration data plotted in this way, with a point representing the operating condition at the time of commissioning. This shows that the operating condition at the time of commissioning was, in profile flatness terms, very far from the calibration conditions. Based on the comparison of Meter 1 with Meter 2 and with the tank data it was clear that this linear extrapolation was not producing the desired measurement result at the field conditions.

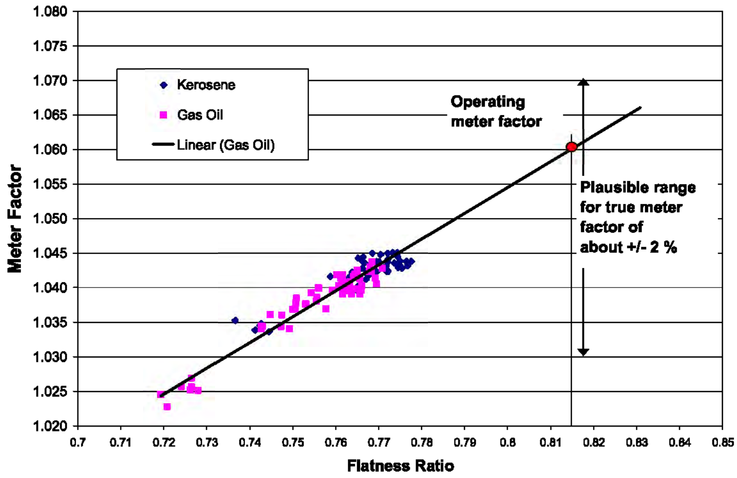

Fig. 23 - Calibration of Meter 1 post modification and weighting factor adjustment

In an effort to overcome this issue, and considering that the meter was not a custody transfer meter, the weighting factor adjustment that had been applied to the meter at the calibration was removed and the meter re-linearised using the computed Reynolds number as the calibration correlation parameter. This removed the influence of the unusually high flatness and brought the two meters into closer agreement, though it appeared that the modified meter was still reading approximately 0.6 % higher than expected.

The modified meter was then monitored for a period of some months and in this time it was easily determined that it was not performing as well as had been hoped. Figure 24 below shows the response of Meter 1 after modification, relative to the tank gauges.

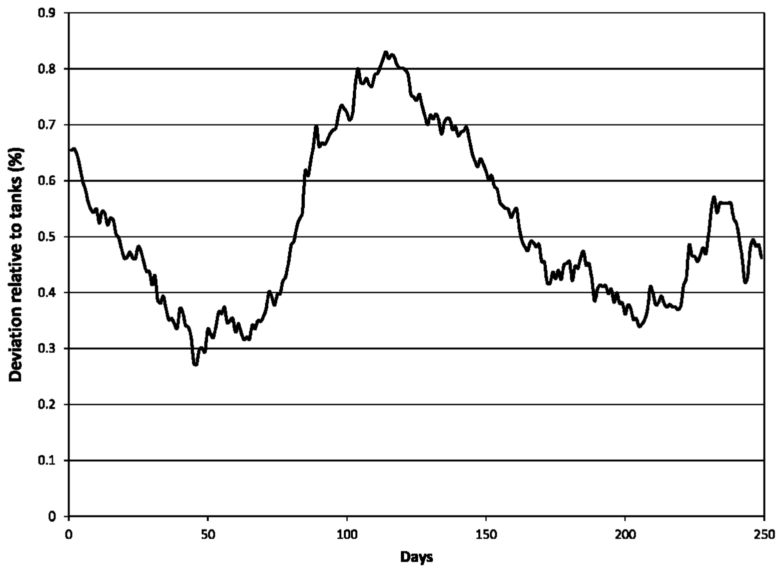

Fig. 24 - Comparison of Meter 1 (modified, with protruding transducer

Housings) against the tanks

During the same time period, the influence and effectiveness of the drag reducing agent was discussed and it was noted that more DRA was used when the water content of the crude was high. Subsequent analysis showed that there was a degree of correlation between the water extraction flowrates and dewatering tank level indications at Fredericia and the indicated profile flatness, as shown in Figure 25 below. Given the suggestion that the DRA dose was increased when the water content of the crude is high, this was taken as corroboration that the profile flatness was varying in response to changes in the dosage of DRA.

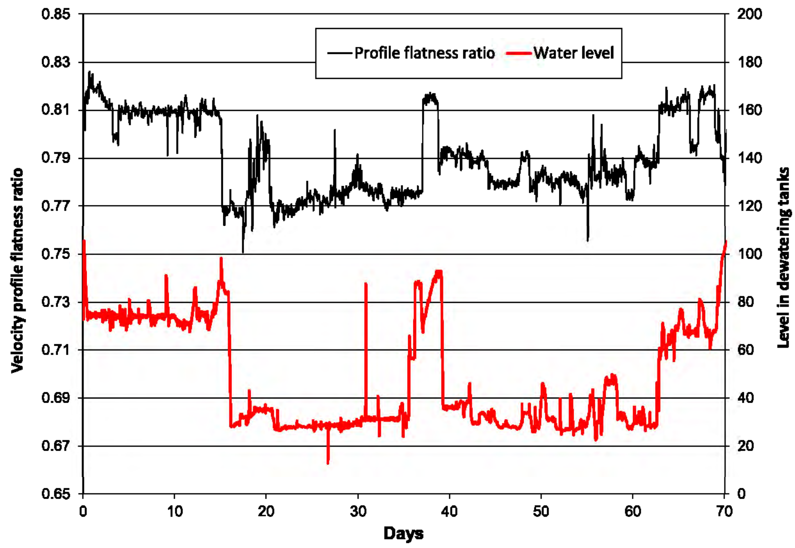

Fig. 25 - Water content and profile flatness correlation, linking DRA injection rates to profile flatness changes

Based on diagnostic analysis and an internal inspection of the meter after 9 months in service (see the photograph show in Figure 26), it was clear that the modified meter was no longer suffering from the problem of deposition in front of the transducer housings. However it was also clear that the decision to protrude the transducer housings had resulted in a different problem. As a result of protruding the transducer housings, the meter design did not respond appropriately to changes in the boundary layer of the flow. In other words, protruding the transducer housings had impaired the ability of the meter to properly integrate the velocity profile. This, in combination with the fact that DRA was being used, made it impossible for the meter to accommodate the changes in flow profile in the area close to the pipe wall, a problem that the standard, unmodified meter did not have.

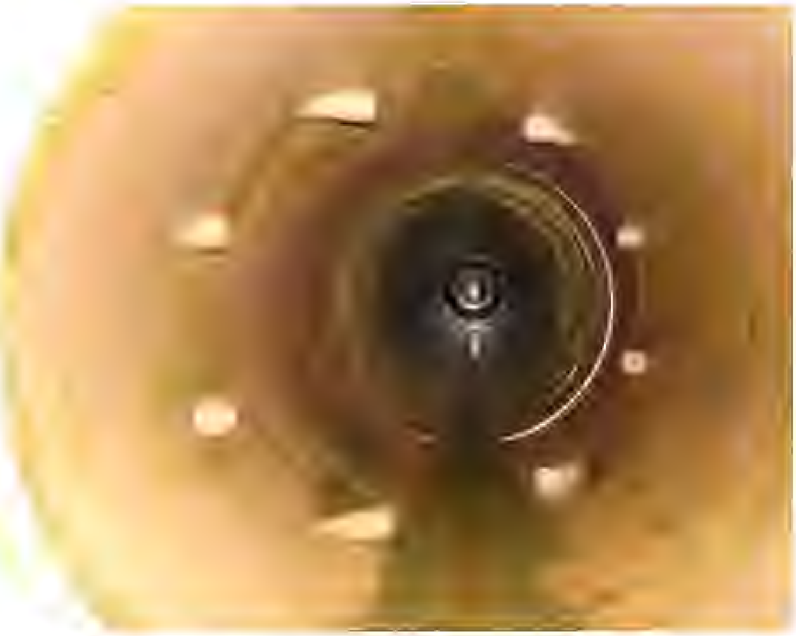

Fig. 26 - Inspection of the meter with protruding transducer housings and internal coating, after 9 months in service

Having discussed the conclusions above with the customer a decision was reached to return Meter 2 to Cameron and have it coated internally, but this time without also taking the step of protruding the transducers.

11 CALIBRATION AND OPERATION OF METER 2 ONCE COATED

The second meter was coated internally, with the transducer housings in their normal location and was then re-calibrated. When compared with the original calibration of Meter 2, meter factors obtained at similar Reynolds numbers agreed with the earlier calibration within the uncertainty of the results, as shown in Figure 27.

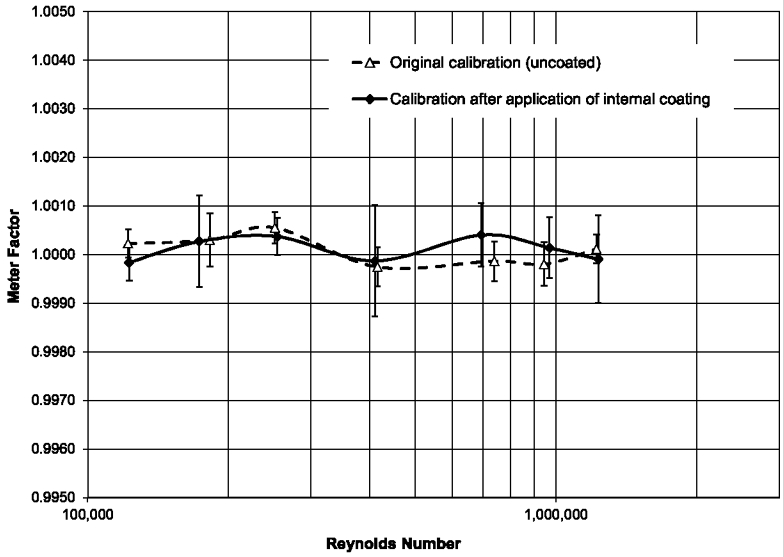

Fig. 27 - Comparison of calibration data for Meter 2; original calibration without internal coating, and after the coating was applied

After Meter 2 had been coated, calibrated and installed, it was monitored relative to the tanks. When the data was analysed it appeared that the meter was relatively stable at first, showing a slight downward trend, and then changed its behaviour after a couple of months in operation. It was feared that contamination problems had developed again, but analysis of the diagnostic data did not suggest that was the case. The tank comparison data for this period is shown in Figure 28 below. Initially this data was baffling, as the comparison with the tanks suggested that after about 75 days in service the meters started over-reading. The 4-path meters with transducer housings recessed had never shown over-reading behaviour prior to this point, even when contaminated. As a result of much discussion and speculation it was then discovered that the date of the change in meter behaviour coincided with the commissioning of a new de-gassing facility. The degassing facility is situated between the metering station and the tanks. As a result, the comparisons that were being carried out were no longer valid as they did not account for the inventory change in the degasser tanks, nor the change in volume due to extraction of gas and additional water from the degassing facility. Figure 28 shows that it is only after the point in time when the degasser unit was brought online, 56 days into the operation of the coated meter, that the deviation begins to trend upwards.

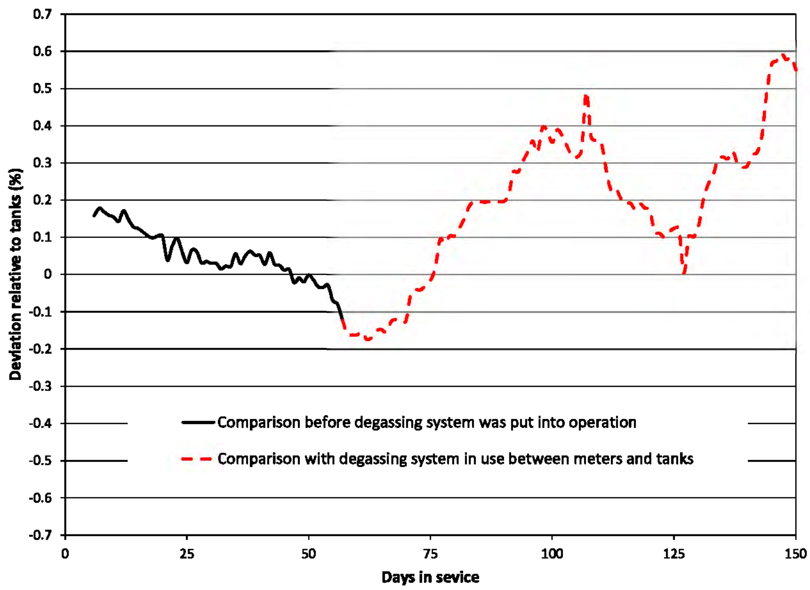

Fig. 28 - Comparison the coated meter with the tanks, not accounting for the operation of the degassing system

The next step was to try to account for the gas and water extracted from the crude oil in order that a comparison could be carried out over a longer time period. Efforts were made to improve the method of comparison, with corrections being made using data available from instrumentation on the degassing system. At first there were difficulties in obtaining good agreement. This was in part due to a defective temperature measurement on one of tanks. It was then discovered that the comparison should also account for recovered oil from the refinery could be added to the line between the meters and the tanks. Once the corrections had been made, a reasonable comparison could be obtained, albeit with greater uncertainty than before.

Figure 29 shows a longer-term comparison of the coated meter versus the tanks with corrections applied in an attempt to compensate for the volume changes owing to operation of the degassing system. It should be noted that this comparison is subject to significant uncertainty, as evidenced by the scatter in the daily comparison data. Given that uncertainty, it is difficult to ascertain if the fluctuations apparent in the 20-day average are influenced at all by contamination or if they are simply the result of the scatter in the daily comparisons. It is clear however, when compared with Figure 18, that there not the same systematic 'drift' due to contamination that was apparent with the uncoated meter.

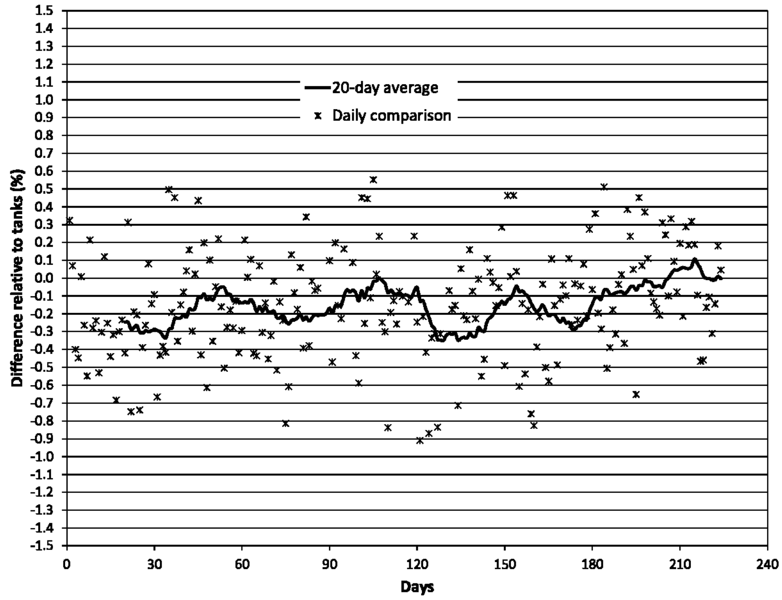

Fig. 29 - Comparison the coated meter with the tanks, including corrections for water and gas extracted, level changes, and recovered oil added

Following the evaluation Meter 2 after modification (coated and with transducer housings recessed as normal), Meter 1 was returned to the factory and made the same as Meter 2. Subsequent diagnostic checks and periodic inspections have shown that the meters are not completely free from the effects of contamination. However, the coating applied to the meters has substantially reduced the build-up problem. Figures 30 and 31 show photographs of the interior of Meter 2 after it had been coated and had been in service for approximately 10 months without cleaning. Although the interior surfaces are not free from contamination, it was observed that the contaminants have greater difficulty in adhering to the coated surface than they did with stainless steel, and in some places it appeared that the flow had stripped the contaminants off of the pipe wall, leaving the coated surface clean. Of particular importance it was observed that the problem of contamination build-up forming in the cavities of the upstream transducer housings was significantly reduced, as can be observed by comparing Figure 31 with that of Figure 15, which both show the deeper cavities of the outside paths. In the case of the uncoated meter the deposition covers the whole of the interior of the cavity and the face of the housing. With the coated meter there is much less deposition and it appears not to have consolidated in the same way as for the uncoated meter, suggesting the coating results in a 'self-cleaning' effect.

Fig. 30 - Photograph showing the coated meter with transducer housing cavities facing upstream

Fig. 31 - Photograph showing a the coated meter with a transducer housing cavity facing downstream

12 DISCUSSION AND CONCLUSIONS

Contamination build-up inside ultrasonic meters can affect performance. Often it is thought that the main error mechanism would be over-reading owing to a reduction in cross-sectional area. However, in this application the main effect of the contamination build-up was an alteration the effective path geometry relative to the conditions of calibration, causing the meter to under-read.

The precise mechanisms causing the contamination to build up in this case are not well understood, and although there is no evidence for or against the drag reducing agent (DRA) playing a part, there is a suspicion that the DRA may be contributing to the build-up. To date this is one of only two cases known to Cameron where contamination build up inside multipath meters on crude oil has been confirmed.

Contamination build-up can be detected and monitored by means of diagnostic information. For the 4-path meters in this case, a signal gain monitoring diagnostic was developed and could be shown to correlate well with the development of measurement deviations on the uncoated meters.

An initial attempt to resolve the problem by both coating the interior of the meter with fluoropolymer coating *and* protruding the transducer housings was effective as far as contamination build-up was concerned, but ultimately was unsuccessful as the protrusions prevented the meter from properly measuring changes in the boundary layer of the flow. Sensitivity to changes in the boundary layer of the flow was accentuated in this application owing to velocity profile variations being linked to the dosage of drag reducing agent.

Applying the fluoropolymer coating to the wetted surfaces (bore and transducer housings) of a standard meter with recessed transducer housings, did not alter its calibration performance and has been shown to be beneficial in terms of reducing the degree and effects of contamination build-up.

The meter with protruding transducer housings was modified a second time and both meters have now been in service for several years with their transducer housings recessed as normal with all wetted surfaces coated with the fluoropolymer coating. The meters are removed for calibration at annual intervals and are cleaned before they are sent to the laboratory. In the spring Meter 2 is also cleaned just before Meter 1 is removed and sent for calibration. In the fall Meter 1 is cleaned before Meter 2 is sent for calibration. This results in a maximum of 6 months operation in between each calibration and/or cleaning of a meter.

The internal coating has not shown any signs of deterioration in service, being described by the technician on site as being "in very good condition on both meters".

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.