# The Effects of Scale Deposition in Subsea Multiphase Flow Meters

**Neil Barton, NEL**
**Klaus Zanker, Letton-Hall Group**
**Gordon Stobie, ConocoPhillips Company**

---

## ABSTRACT

The work presented here was performed as part of the RPSEA DW 1301 program: "Improvements to Deepwater Subsea Measurement" [1]. The RPSEA project addresses gaps in the deployment and use of multiphase and wet gas meter technology in deepwater production systems.

Differential pressure meters are a key element in many multiphase meters. Scale formation is often associated with produced water, flow restrictions and also with the high-pressure and high-temperature conditions typically encountered subsea. However, very little information was previously available on how scale affects the accuracy of differential pressure meters. This project aimed to address this issue.

Tests were performed in which saturated brine was flowed through a Venturi, a cone and a double wedge meter. The flow conditions induced scale formation resulting in a significant change in the discharge coefficient of each of the meters. Computational Fluid Dynamics (CFD) simulations were also run to extend the range of conditions considered in the study and to investigate how meter design might affect the sensitivity of metering accuracy to scale formation.

Results of both the experimental and CFD work are presented.

## BACKGROUND

This project was originally proposed to be an experimental program to investigate the effects of fouling and erosion on meter performance. At the first JIP meeting, at the start of the project, participants agreed that scale deposition was the major problem, followed by erosion. The JIP members felt that hydrate, wax and asphaltenes were not a deep subsea problem due to the high temperatures associated with the flow meter's location.

Erosion issues were addressed in one half of the project [2, 3] and the original scale investigation was extended to cover testing of a double wedge meter, in addition to the Venturi and cone meter, and some CFD simulation work.

The scale investigation primarily considered whether the hydraulic design of different meter types affected their sensitivity to scale effects. Scale formation mechanisms and chemistry were not considered in detail as these factors are the subject of wide study already and any remedial methods used for pipework will generally be effective in flowmeters. The study did not consider the effects of scale on the nuclear or electrical instruments that may form the composition measurement part of a multiphase or wet gas meter. These effects will vary considerably from meter to meter, but they are likely to cause large uncertainties in addition to the meter effects considered in this study.

Scale is usually a mineral compound. It can take the form of very thin films on fluid-wetted surfaces to significant blockages on process water-wetted surfaces in pipes. In cases it can be mixed with other substances such as iron or sand grains. The nature of scales varies significantly from case to case. Some basic formation behaviours are known, although many scaling events involve combinations of phenomena making scale distribution inherently unpredictable. The conditions prevalent during formation often affect the scale's structure and properties. Hence even chemically-identical scale formation can vary in, say, strength and porosity over short distances.

Common scales include calcium carbonate, barium sulphate, strontium sulphate and calcium sulphate. Their formation is usually associated with factors such as high temperatures and the mixing of chemically incompatible waters (such as sea water and formation water). Local accumulations may be associated with rough surfaces, rust, sudden pressure changes and accretion of particles on upstream-facing surfaces.

An initial information search found sparse information on the effects of scale and fouling on flowmeters. One published example was identified showing scale on a subsea wet gas differential pressure flow meter [4]. This severely affected its accuracy.

Scaling has been observed in turbine meters [5, 6]. Large metering errors occurred and attempts to rectify metering problems by applying surface treatments produced mixed results. It is also known that scale has been seen on the upstream faces of orifice plates in fiscal gas metering applications and that this can cause errors of 10% or more if the contamination is close to the orifice edge [7].

A cone meter manufacturer has published some information claiming that cone meters suffer less from contamination effects than other types of differential pressure meter in coke oven gas applications [8, 9]. If scale accumulates in a similar manner this may have some relevance to subsea applications.

Further investigation involved accelerated scale formation tests of a Venturi, cone and double wedge meter at Intertek [10] and CFD modelling performed by NEL [11].

## TESTING

As part of this project, tests were run in which brine was circulated through a 2-inch beta 0.5 Venturi, a beta 0.5 cone meter and a beta 0.707 double wedge meter (see Figure 1). The latter forms part of the Solartron ISA Dualstream II wet gas meter, with a Venturi and wedge in series.

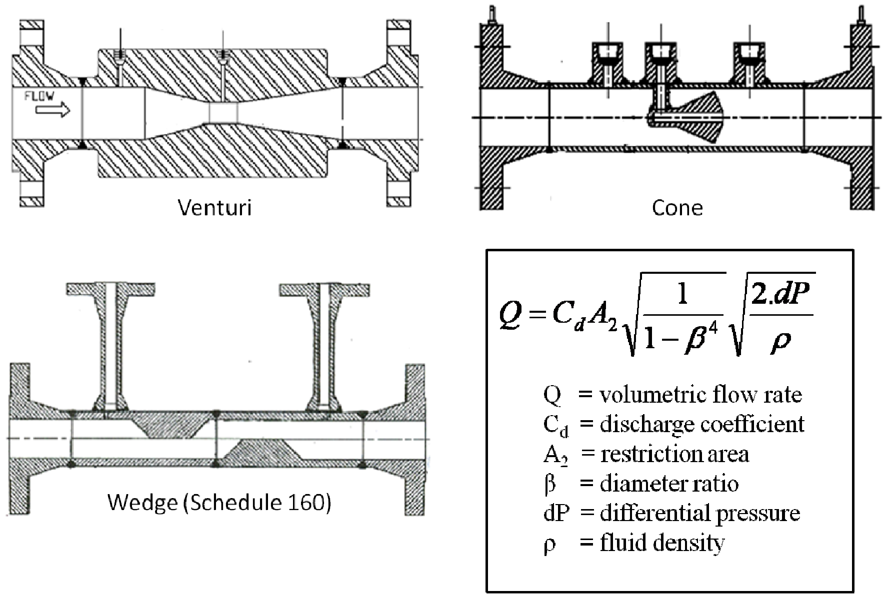



**Figure 1: Meters Tested**

Note that each meter has a different discharge coefficient and a +2% flow measurement error equates to a shift in the discharge coefficient of approximately -2%.

A schematic of the Intertek test loop is shown in Figure 2. The test rig was designed to eliminate all uncontrolled scale formation except that in the meter itself. Hence all pipework was made of PVC, the saturated brine was filtered to remove particulates and the use of a reference flowmeter was avoided. Instead the flow rate was measured by diverting the flow into a container of known volume and the fill time was recorded. A variable speed centrifugal pump was used. In the Venturi no heating or cooling was used. In the cone and wedge tests heating and cooling elements were used to induce scale formation.

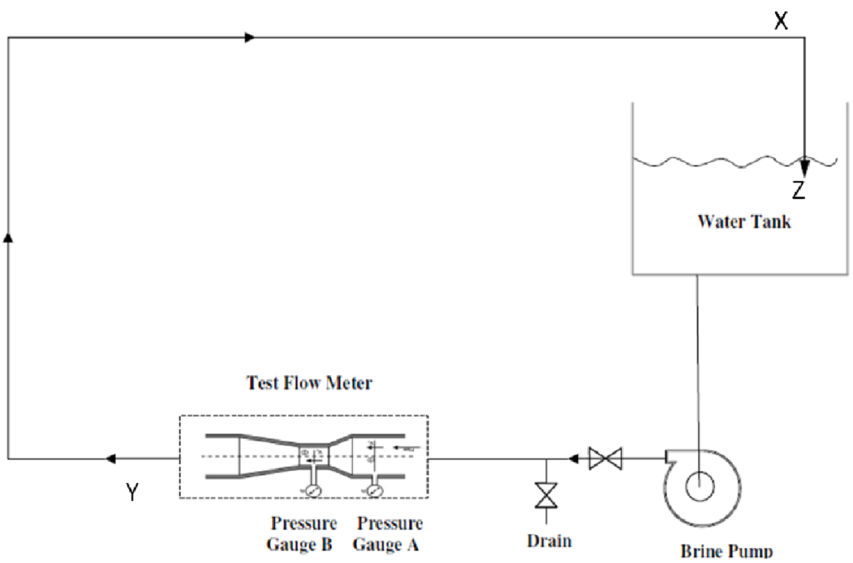



**Figure 2: The Intertek Flow Loop**

Figure 3 shows the results of the Venturi test. The flow rate was initially set to 11.1 gpm, corresponding to a velocity of 0.34 m/s in the 2 inch pipe. On day 5 the tube that returned the brine to the tank was submerged to minimise air entrainment and change in salinity due to evaporation. This changed the head on the pump resulting in a 20% increase of flow. Based on a starting value of 0.97 at a Reynolds number of 14000 the discharge coefficient reduced by about 20% over the 11 day test.

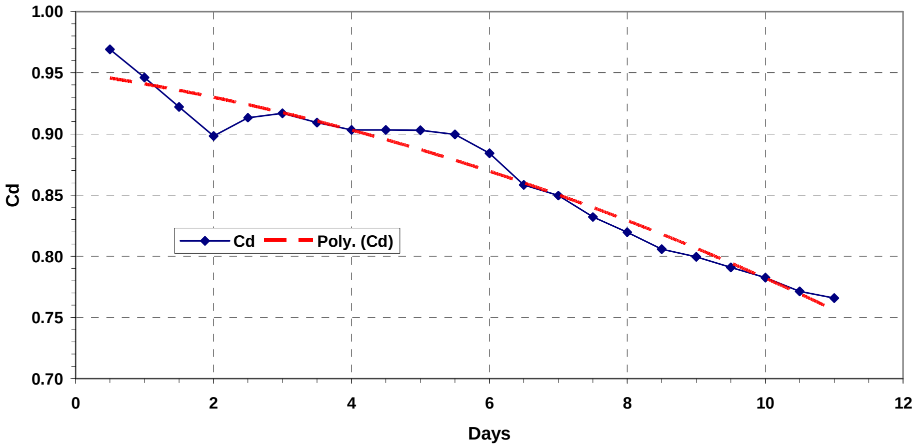



**Figure 3: Discharge Coefficient during the Venturi Tests**

Figure 4 shows scaling within the Venturi after testing. Rust was apparent near the join of the carbon steel flanges with the stainless steel body and it seems likely that this enhanced scale formation. Most scale was present on the convergent section of the Venturi with less seen in the throat. In all of the tests the scale was soft and wet making it difficult to measure the thickness and distribution of scaling in any of the meters. In the Venturi, the reduction in the throat diameter was measured as being approximately 1.9 mm.

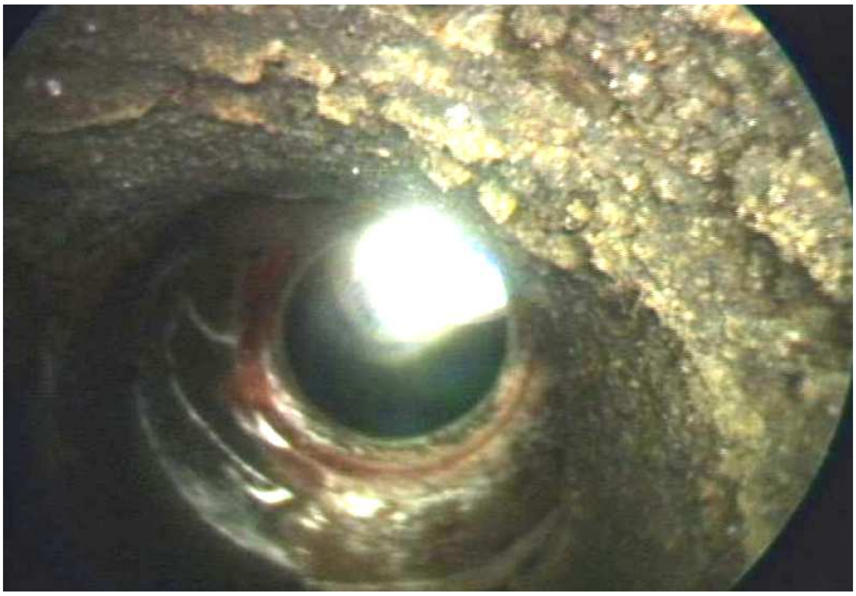


**Figure 4: The Venturi Throat and Convergent Section after the Scale Test**

Figures 5 and 6 show similar results for the cone meter. Initially brine was circulated at 11 gpm for more than three weeks (prior to the data shown in Figure 5) without any measured change in the discharge coefficient. The flow rate was then reduced to 7.5 gpm and the flow circulated for a further 2 days without apparent effect. A fresh batch of brine was then added into the system. Again, this caused no change. After this the cone meter was cooled to 10 $^{o}$F below room temperature. After 5 days the differential pressure increased by 38%, equating to a 17% reduction in the discharge coefficient.

Figure 6 shows that the scale in the cone was smoother and more uniform than that in the Venturi. There appear to be areas downstream of the cone where the flow has scoured the scale away.

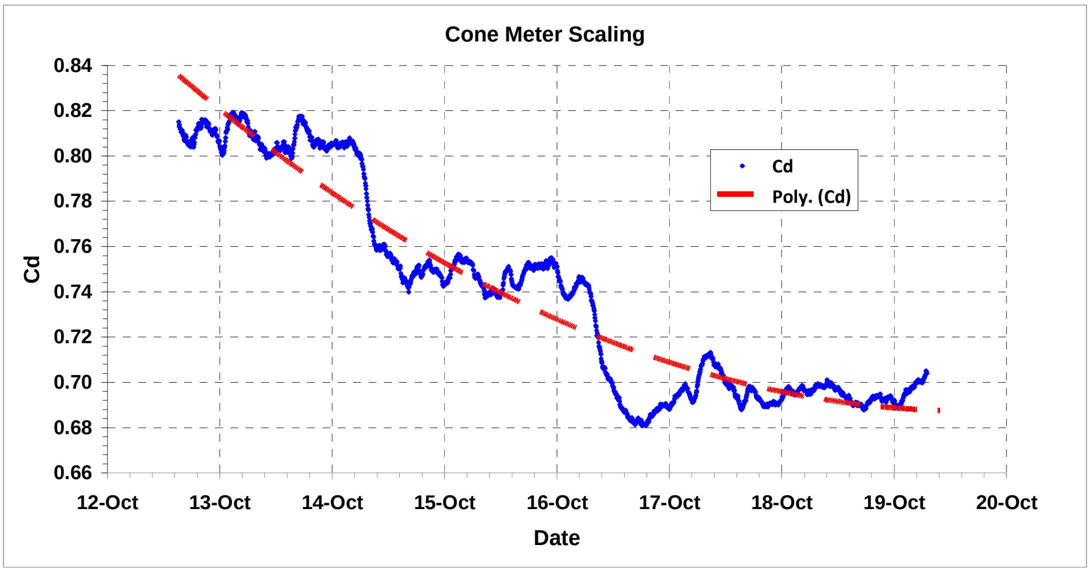



**Figure 5: Discharge Coefficient during Cone Tests**

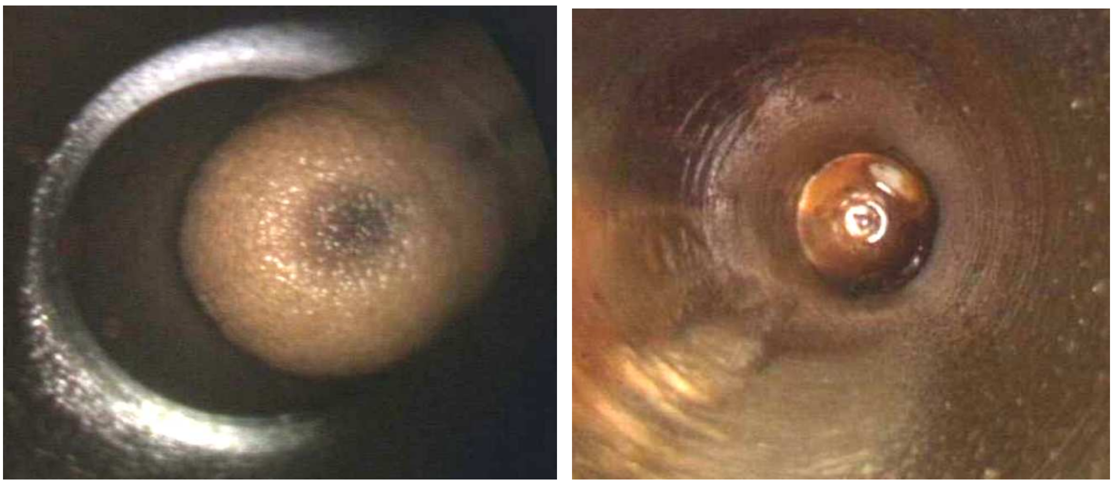


**Figure 6: Cone Meter after the Scale Test**

Figures 7 and 8 show the results of the wedge meter test. The test was performed at a flow rate of 11 gpm and the meter was heated and cooled to induce scale formation. After 6 days, the differential pressure reduced to almost zero. On inspection, it was found that the meter was heavily scaled and the differential pressure taps were blocked.

The taps of the scaled wedge were unblocked and the meter was re-calibrated at 8 gpm producing a shift of about -37% in the discharge coefficient.

The wedge test results appear to have been dominated by the fact that the taps had become blocked. This may have been because the wedge impulse lines were steel and contained relatively large volumes of cold brine whereas the other meter used narrow, flexible PVC impulse lines. A very sudden reduction in differential pressure was seen on 24 November after heating and cooling of the meter seems to have induced scale formation. Thick, highly granular, crystalline scale occurred in the wedge (Figure 8). This may have been because of its rougher spark-eroded finish.

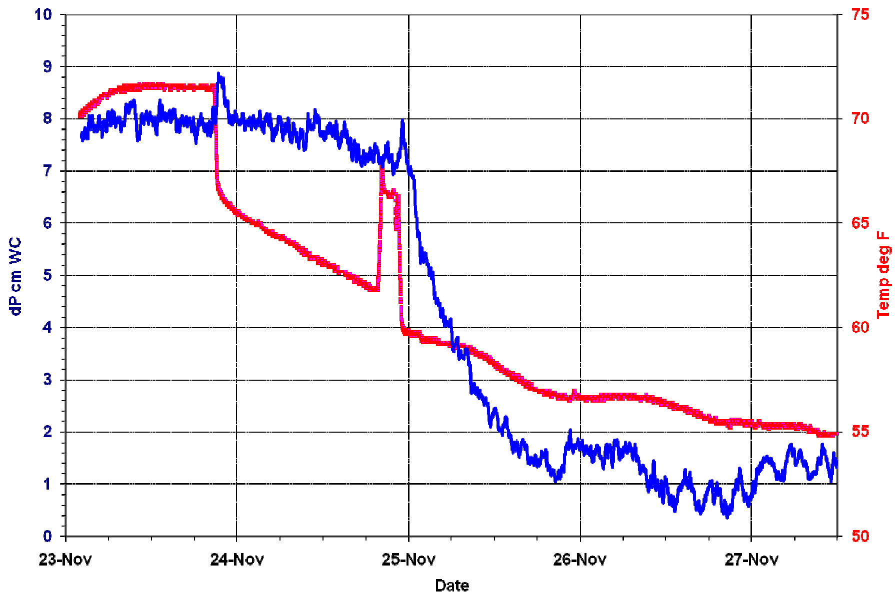



**Figure 7: Differential Pressure and Temperature during the Wedge Tests**

**Figure 8:  The Wedge Meter after the Scale Test - Looking at the Wedges**

These tests were the most practical testing option available and provided a significant amount of useful information. The measured shifts in discharge coefficient ranged from -17% to -37% although it should be noted that the tests were not necessarily a like-for-like comparison of the meters.  It was not clear whether one meter performed better than the other because it was inherently more tolerant of scale or because less scale formed.  It also seemed likely that the amount and distribution of scale was strongly influenced by factors such as the surface finish and material as well as the fluid flow behaviour.

## THEORETICAL AND COMPUTATIONAL FLUID DYNAMICS STUDY

Further work used a theoretical and CFD-based approach to assess how the distribution of scale affected metering accuracy. This work aimed to improve our understanding of the test results and to identify rules of thumb that could assist with meter selection or error estimation. This approach also allowed study of scaling effects at conditions closer to those likely to be encountered subsea.

The Effect of Smooth Evenly-Distributed Scale

Figure 9 shows a simple theoretical analysis in which it is assumed that a smooth, even 0.5 mm thick layer of scale forms on all wetted surfaces of cone and Venturi meters. The shift in the discharge coefficient was calculated by simply considering the resultant change in the meters' beta ratios.

This shows that quite thin scale accumulations can cause significant errors. Meters with larger beta values suffer less from scaling than smaller beta meters because a given thickness of scale produces a smaller percentage change in the throat area. Similarly, Venturis suffer less than equivalent cones because a given scale thickness causes a smaller change in throat area.

This simple approach gave a reasonable order-of-magnitude agreement with the tests (particularly for the Venturi) and also agreed with like-for-like CFD models.

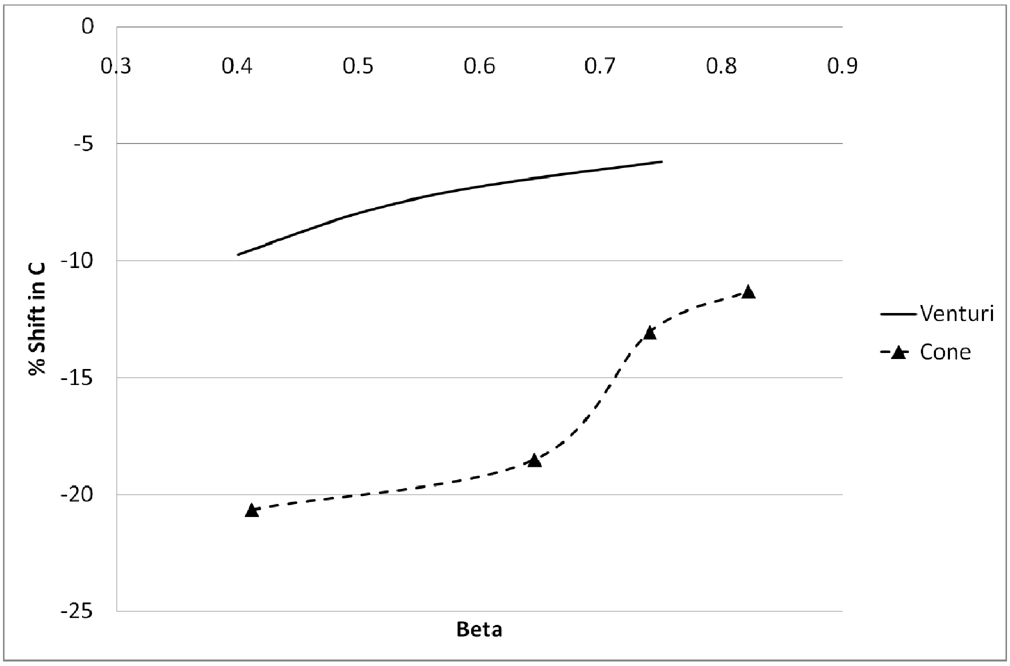



**Figure 9: Effect of an Even, Smooth 0.5 mm Scale Layer on the Discharge Coefficient of a 50.8 mm (2 inch) Venturi and Cone Meters**

The Effect of Surface Roughness

Figure 10 shows the results of a CFD analysis in which the meters' walls are roughened. Again fairly large negative shifts in discharge coefficient are seen. In this case the cone is least affected. The wedge is probably most affected because it has a larger effective beta ratio (0.707) and hence pressure drop caused by wall friction comprises a greater proportion of the overall pressure drop through the meter.

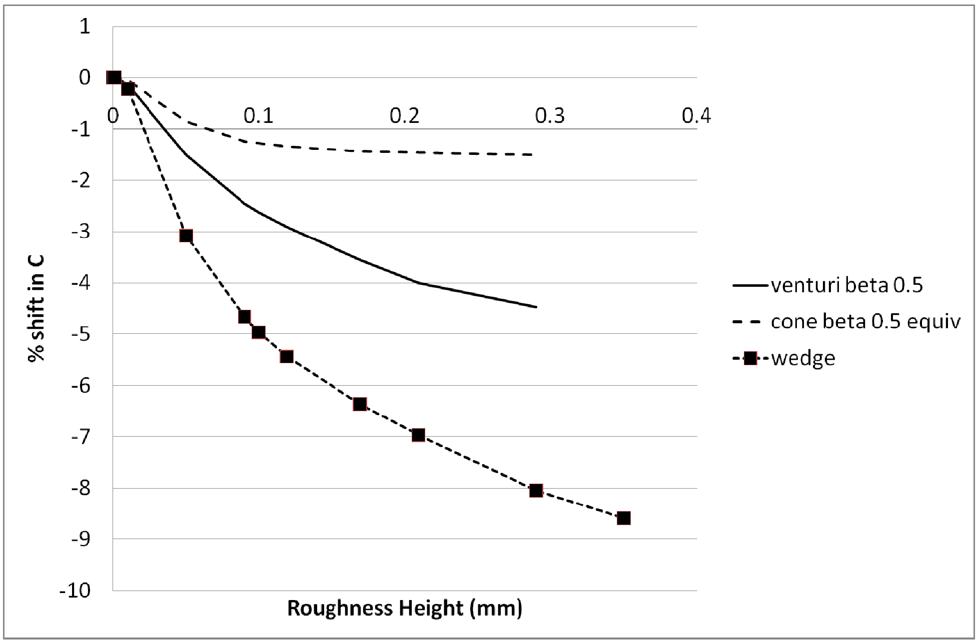



**Figure 10: Effect of Evenly Distributed Roughness on all of the Walls of a 2 inch Venturi, Cone and Wedge Meter**

The Effect of Unevenly-Distributed Scale

A series of CFD simulations was run in which Venturi and cone meters were modelled with patches or blocks of scale applied at different locations. Figure 11 and 12 show a typical example showing how a cone meter responds as a blockage on the pipe wall is moved upstream into its throat. When the blockage is close to the cone (Figure 12b) the vena contracta is restricted and causing a negative shift in discharge coefficient. When the blockage is moved further downstream (Figure 12c), the vena contracta is deflected and effectively enlarged, causing a positive shift. Thus the cone meter can over-read or under-read depending on the distribution and size of the scale deposit.

Similar runs showed both negative and positive shifts in discharge coefficient for both Venturis and cones. Very large shifts were predicted in both meters when blockages were located in the throat.

In principle, if the location and extent of scale build-up is known then the results of this work or additional CFD simulations could be used estimate the resultant metering error. In practice this could probably only be done as part of a historical assessment of a meter that has been retrieved from the sea bed.

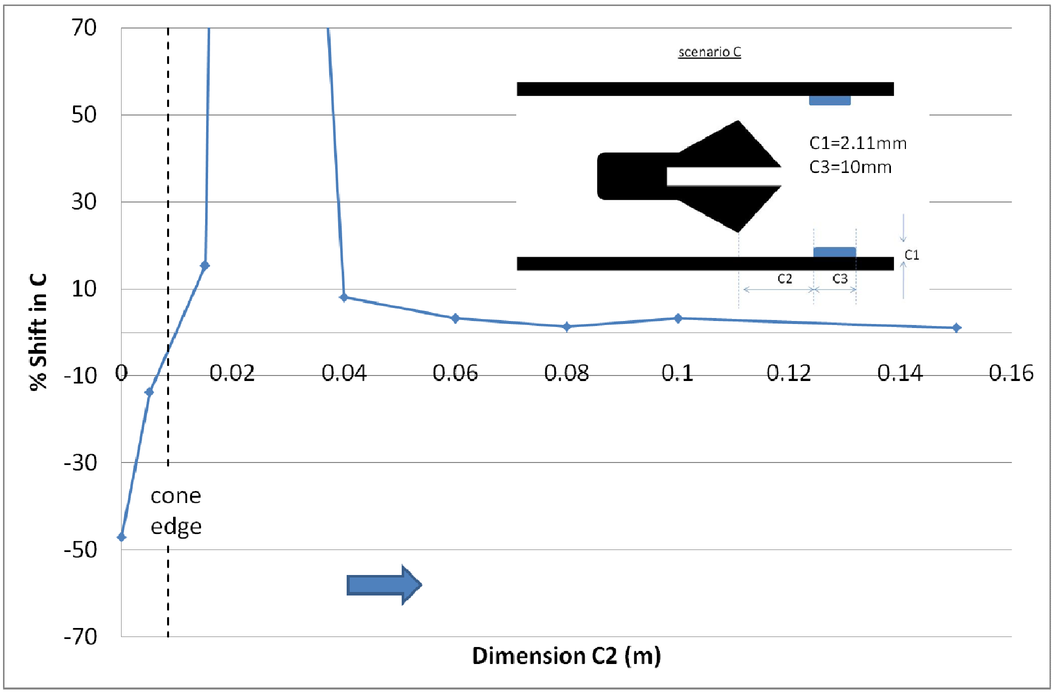
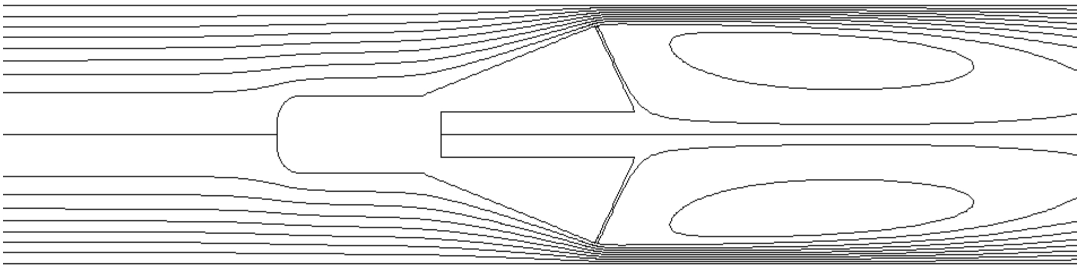
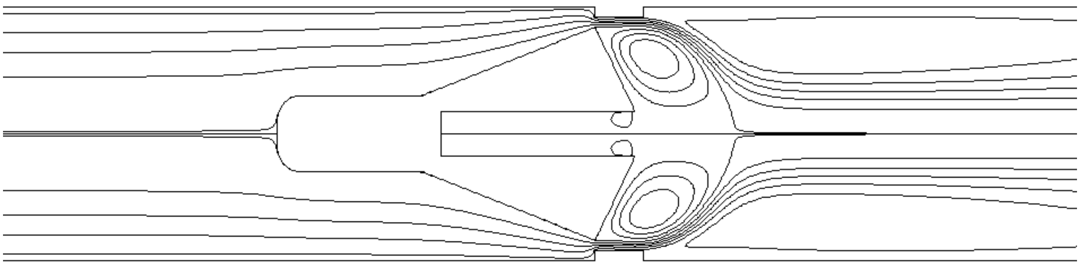


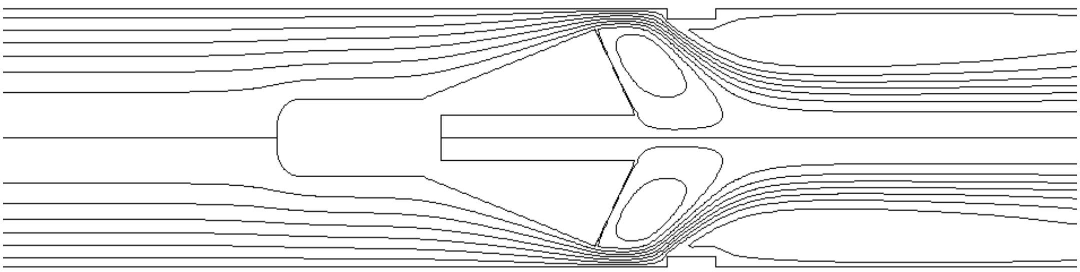

**Figure 11: Effect of Material Build–Up on the Downstream Pipe Wall of a Beta 0.5424, 2 inch Cone (Maximum Shift ~ +400%)**



**a) No Scale**



**b) Scale Build Up at The Cone Edge (C2 = 0m)**



**c) Scale Build Up Downstream of the Cone (C2 = 0.04m)**

**Figure 12: Streamlines showing the Effect of Material Build–Up on the Downstream Pipe Wall of a Cone Meter**

The Effect Scale Growth Controlled by Scour, Pressure and Particle Accretion

Additional CFD simulations were run in which the meter walls were distorted to mimic scale build-up over time. In the first set of these simulations, scale was allowed to build-up provided that the wall shear stress did not exceed a defined threshold. This mimics the situation in which scale may form and then be scoured from some locations if it is too weak or poorly bonded to the pipe wall. Figure 13 shows typical predicted scale distributions generated by this model. Figure 14a shows that, for this case, the beta 0.6 Venturi is least sensitive.

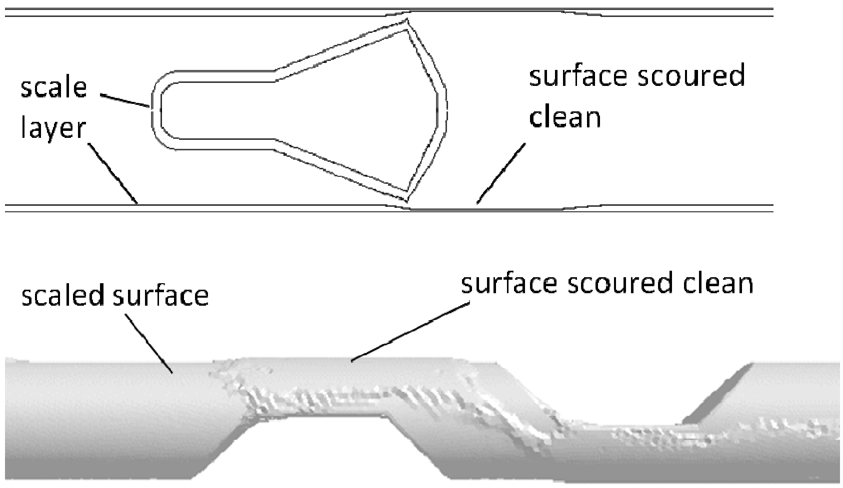
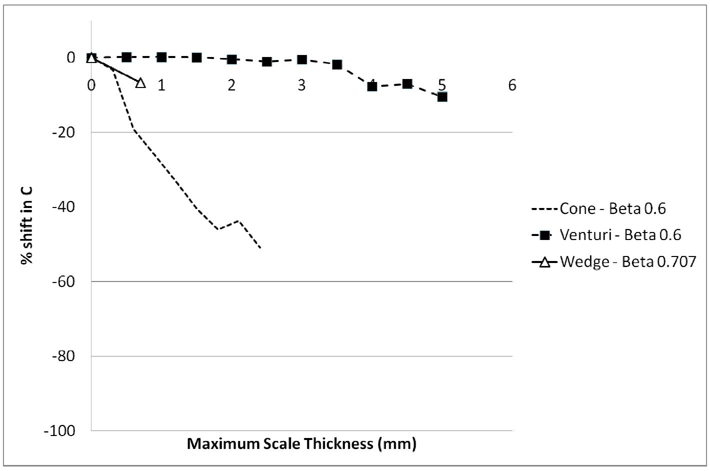



**Figure 13: Simulated Scour-Sensitive Scaling on the Cone and Wedge**

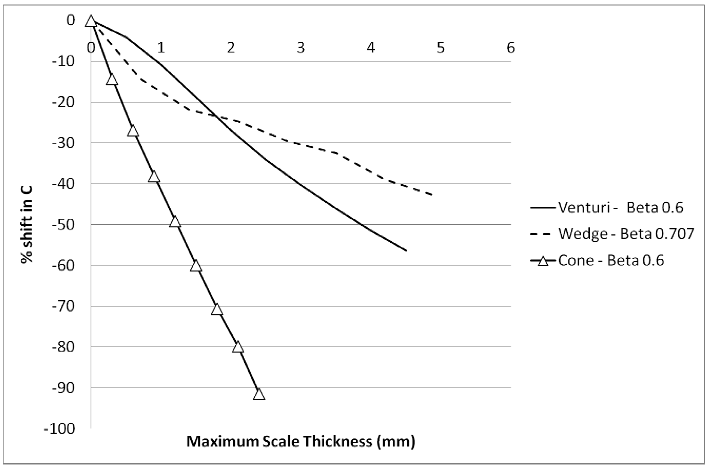
Similar models were run in which scale formed on walls when the local pressure was below a specified pressure (Figure 14b). This mimics the mechanism typically associated with calcium carbonate scale formation. In this case the wedge fairs better, probably because it has a larger beta ratio.

Figure 14c shows the results of a model in which “sticky” 50 micron particles were injected into the flow and scale growth by accretion was controlled by the rate at which they built up on the walls. In this model the cone is more sensitive than the Venturi.

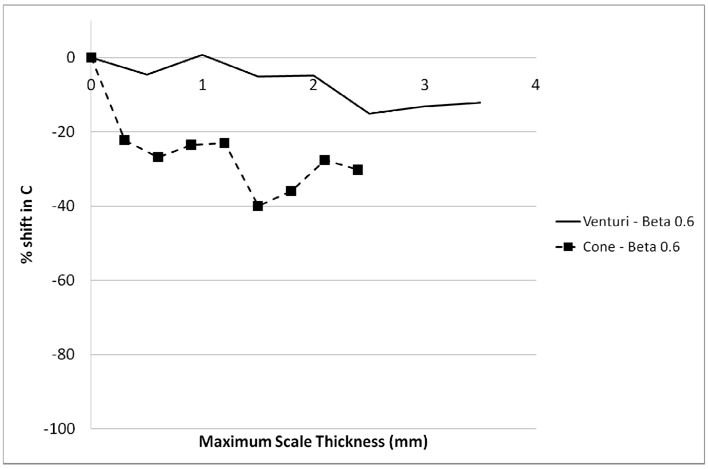
The models that produced the results in Figure 14 are somewhat artificial in that they are based on qualitatively observed behaviours rather than well-established, quantitatively-correct representations of real scale development. However, all of the models predict negative shifts in discharge coefficient mostly in the -10 to -50% range and they resemble the test results shown in Figures 3, 5 and 7 moderately well. As with the other results, they show that even thin layers of scale can cause significant errors and that the metering error depends on a complex relationship between the scale development mechanism and the meter design.




**a) Shear-Sensitive Scale**




**b) Pressure-Sensitive Scale**




**c) Accretion-Sensitive Scale**

**Figure 14: Response of Different 2 inch Meters to Like-for-Like Scale Build-Up Scenarios**

Thermally Sensitive Scales

CFD-based investigations of thermally-controlled scaling in un-insulated meters showed that in most low Gas Void Fraction (GVF) applications the wall temperature will be almost the same as the fluid temperature. Hence, if the fluid temperature crosses a scale formation threshold then scale is likely to form on all water-wetted surfaces regardless of the meter design.

In low flow rate-high GVF applications significant surface temperature differences may occur and some meter designs may be marginally superior to others in this respect. However, in practice, cooling during shut-down is likely to dominate the formation of thermally sensitive scales in subsea installations.

The Effect of Blocking Taps

Rounding and other defects on the edges of taps are known to affect metering accuracy. Simulations mimicking partially blocked pressure taps confirmed that a build up of material will cause errors of the order of 1% or smaller. However, this effect is small compared to the errors caused by similar thickness of scale on the wetted walls of the main meter body. It was concluded that, as a first approximation, scale build up in the taps will have a secondary effect and it can be neglected provided the taps are not completely blocked.

## CONCLUSIONS

Laboratory tests, CFD simulations and a theoretical analysis have been performed to investigate scale deposition effects in Venturi, cone and wedge meters, with particular reference to subsea installations. The following conclusions have been drawn based on this work:

- Scale formation is a complex process and will vary significantly from case to case.

- Scale can result in large positive or negative errors. On balance, the information available suggests that over-reading is more likely in most cases due to a reduction in the effective discharge coefficient.

- Scale formation is highly dependent on the surface condition. The use of meters with smooth, polished surfaces or surfaces coated with a smooth material may reduce scale effects.

- There is therefore no clear and consistent advantage of Venturi, wedge or cone meters over each other because scale formation mechanisms are very variable.

- Larger beta ratio meters and larger bore meters are generally less prone to the effects of scaling than small beta ratio and smaller bore meters because a given thickness of scale will cause a smaller percentage blockage of the throat.

- Large taps are less prone to blockage. However, the extra static fluid in large tap impulse lines may promote faster scale formation. There is therefore no clear recommendation for tap size.

- If a subsea meter can be inspected and the distribution of scale can be established then the results of this study or additional CFD analysis could be used to estimate the resultant metering error.

Note that this work only considers the effects of scale on differential pressure measurements. Other sensors (such as nuclear densitometers, capacitance and microwave sensors) could be severely affected by scale.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the US Department of Energy and RPSEA for providing the impetus and major funding for the work described here. We also thank the member companies of the DW1301 Joint Industry Project, who provided financial support and contributed the expertise of their best and brightest subsea and measurement engineers. DW1301 JIP member companies are: BP, BHP, Chevron, ConocoPhillips, Shell, Statoil, and Total.

## REFERENCES

1 RPSEA Project Website, http://www.rpsea.org/

2 BARTON, N., ZANKER, K. & STOBIE, G.. Erosion effects on Venturi and Cone Meters. The Americas Workshop, 27-29 April 2010, Houston.

3 BARTON, N., MACLEOD, M., ZANKER, K. & STOBIE, G.. Erosion in Subsea Multiphase Flow Meters. The Americas Workshop, 25-28 April 2011, Houston.

4 THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Wet Gas Flow Metering Guideline. MFC-19G – 2008.

5 KLEPPE, K. & DANIELSEN, H.B. Scaling problems in oil metering system at the Veslefrikk Field. North Sea Flow Measurement Workshop, 26 – 28 October 1993, Bergen.

6 PAULSEN, F. & HANSEN, Ø. Scaling problems in oil metering system at the Gyda Field. North Sea Flow Measurement Workshop, 26 – 28 October 1993, Bergen.

7 READER-HARRIS, M.J. & HODGES, D. The effect of contaminated orifice plates on the discharge coefficient. TUV NEL report 2008/266, September 2008.

8 McCrometer Website, V-Cone Coke Oven Gas Case Study http://www.mccrometer.com/library/pdf/24509-10.pdf

9 MCIVER, A. & PETERS, R.J.W. The Use of a V-Cone Fuel Flow Meter to Measure the Coke Oven Gas and Natural Gas Flow in a Combined Heat and Power Plant. IDEA 95th Annual Conference & Trade Show, Seattle, Washington, June 27-30th, 2004 http://www.mccrometer.com/library/pdf/24509-99.pdf

10 Scale deposition effect on performance of subsea flow meters. Intertek report WTC-09-001304, March 2010.

11 BARTON, N.A. CFD analysis of the effects of scale on the accuracy of differential pressure flowmeters. NEL Report No. 2010/490, December 2010.