Index

Paper 8.1

Subsea Deepwater Measurement – Technology Gaps and Solutions

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1 INTRODUCTION

As early as 1999 when Gulf of Mexico Deepwater projects passed the one-mile water-depth mark, the importance of good flow measurement on the deep sea floor was apparent. In contrast to the comparatively simple exploration and production operations carried out on the continental shelf, similar work in deepwater is exponentially more challenging. A good example of this is the recently started Perdido development in the Alaminos Canyon region of the GoM, about 350 kilometers south of the city of Galveston, Texas near the boundary with Mexican waters. Shell operates the Perdido Regional Development (35%) on behalf of partners Chevron (37.5%) and BP (27.5%). As illustrated in the Figure 1 below and described in Reference [1], there are currently three fields in development, all being produced back to a common set of production facilities on the Perdido Regional Spar. Wells in the Great White, Silvertip, and Tobago developments are in water depths ranging from 2360 to 2940 meters.

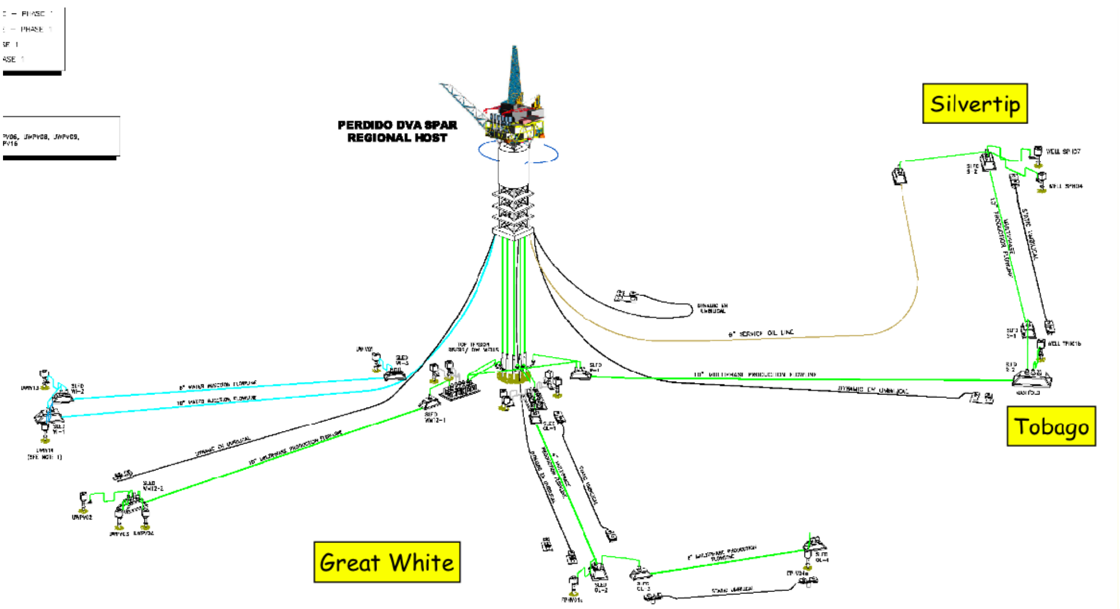

Figure 1. Schematic of the Perdido Regional Development.

The level of technical difficulty in creating this deepwater production system is truly enormous. In addition to the water-depth records that the spar platform and individual wells will set, a number of other problems required solutions to efficiently produce the hydrocarbons. The commingling of wells both within and among fields required multiphase measurement on many, though not all wells. Electrically submersible pumping systems (ESP) were required to enable the production, which necessitated subsea caissons as separators of liquid and gas.

Additional innovations were required to complete this complicated production system. While the Perdido development is indeed a difficult and complicated system, it is certain that future developments will be equally challenging, often more so.

The implications on measurement techniques and technology of challenging developments like Perdido are considerable, and have been recognized for a number of years. Beginning in the first half of the 1990's, operators in the GoM began to realize that measurement technology was ill equipped to deal with these future deepwater requirements, and began to discuss what could be done. A group of measurement specialists representing several of the major operators decided to address the issues collectively rather than individually.

In Q3 of 2005, after a one-day DeepStar workshop to identify deepwater measurement gaps, a CTR for DeepStar funding was submitted and approved, resulting in the two-year Project 8302, *Improved Multiphase Metering for Subsea Tiebacks*. These gap investigations brought together skills from operators, engineering companies, and vendors to address the issues. The project goals were, however, somewhat limited by budget; funding was not sufficient to perform laboratory experiments, build prototype equipment, etc.

During its final year, the DeepStar 8302 Steering Committee decided to extend the research by submitting a CTR to the Research Partnership to Secure Energy for America (RPSEA). Because the need for new exploration and production technology is large and growing, the US Department of Energy (DoE) established RPSEA in 2006 to fund promising approaches to innovative E&P technology. Recognizing that improved deepwater measurement is a critical need in the development of America's reserves, RPSEA in 2008 awarded a contract to the Letton-Hall Group for Project DW1301, *Improvements to Deepwater Subsea Measurement*, to address gaps in deployment and use of multiphase and wet gas meter technology in deepwater production systems. The DeepStar work had been a key precursor to the RPSEA effort – essentially the "pre-project" to DW1301, in which the stage was set. More on the DeepStar Project 8302 can be found in Reference [2].

Six DW1301 Tasks were identified as pivotal in closing the gaps:

- **Deepwater Subsea Sampling.** Development of methods for standardized deepwater well fluid sampling
- **ROV-Assisted Subsea Measurement.** Development of techniques for conveyance by ROV of clamp-on measurement to the sea floor
- **HP/HT Sensor Qualification.** Development and qualification of DP sensors for HP/HT applications
- **Evaluation of Flow Modelling.** Evaluation of the effectiveness of wellbore flow models, such as virtual flow meters
- **Meter Fouling Effects.** Understanding of how fouling of meters affects their response
- **Metering System Uncertainty**. Development of tools to model uncertainties in a subsea-topside measurement system

Work on these six tasks began in October 2008 and is scheduled to conclude in Q1 2011.

2 WHY SUBSEA MEASUREMENT? WHY IS IT DIFFICULT?

Before considering the specifics of the RPSEA Project DW1301, the reasons for subsea measurement should be reviewed. In particular, the question of why measurement should be made at the sea floor rather than topside should be answered.

Although there are many reasons for subsea metering, the most universal is simply this: the world of deepwater production is driven by economics. The cost of equipment rules how the fluids will be produced and conveyed to the surface, forcing measurement practices to adapt to this reality. Given the fact that the cost of deepwater, high-pressure oil or gas flowlines are typically $5 – 10 million per kilometer, the business driver here is clear, viz., minimize the need for subsea pipelines in any given situation. By commingling production as soon as feasible, test lines are eliminated, saving tens of millions of dollars.

The implications of commingling on well flow measurement are significant, however. Tests on Individual wells through production flowlines are simply not practical, mostly due to the cost of deferring production. Thus, one is inevitably led to the conclusion that in deepwater scenarios some form of local subsea measurement is the only practical way to get individual well rates.

But one must question how reliably the measurement of multiphase flow from each well can be made. Can a meter that was installed on a well at the startup of the field be relied upon to give reasonable oil, gas, and water flow rates measurements five, ten, or twenty years later? Is it possible that something will change? Might the properties of the produced fluids have changed? Perhaps the well has produced substances that now coat the inner walls of the meter, and if so would the normal meter response be altered?

The important point is that conditions likely will change with the passage of time. Whether due to the properties of the fluid or the condition of the meter itself, responses of multiphase flow meters change over time, and not always in a small way. When one considers the possible costs of poor measurement, understanding what is required for proper flow rate measurement is clearly of crucial importance.

3 ADDRESSING THE GAPS

All six major Tasks have been underway for the past two years. Although the final results of each have not been compiled yet, example results from each are provided in what follows.

3.1 Deepwater Subsea Sampling

In this task, existing sample systems and conceptual designs of sampling systems deployed via ROV were reviewed for their potential as standardized sampling systems. From a total of eleven different ideas that were considered, the concept selected for implementation is shown in the schematic of Figure 2. This candidate system was designed and fabricated, and has undergone testing at both the SwRI multiphase reference flow loop in San Antonio, Texas, and the Oceaneering ROV Subsea Simulation Facility in Morgan City, Louisiana.

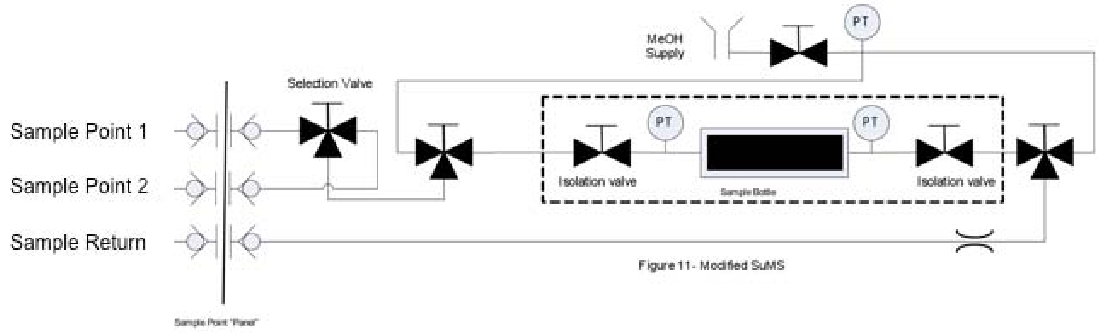

Figure 2. Sampling concept chosen for implementation.

In the schematic the three-way valves permit the selection of the appropriate sample point from either of the two in the figure, or from the MeOH flushing supply as shown. This flow-through concept was that selected from among the eleven that were considered, but is by no means the only form of sampling system that can be accommodated by the design, nor are there limitations on the numbers of sampling points that could be used.

A key objective of this Task is to encourage a market for innovative deepwater sampling services. Draft standards for sampling interfaces and operations are being developed and will be provided as task deliverables. The intent is to encourage other ROV operators and providers of sampling equipment to offer sampling services for the industry.

A possible rendition of the system as it is being carried by an ROV to a wellhead tree is shown in Figure 3 below. The front and rear of the actual prototype ROV-conveyed sampling panel while it was in test at SwRI are shown in Figure 4.

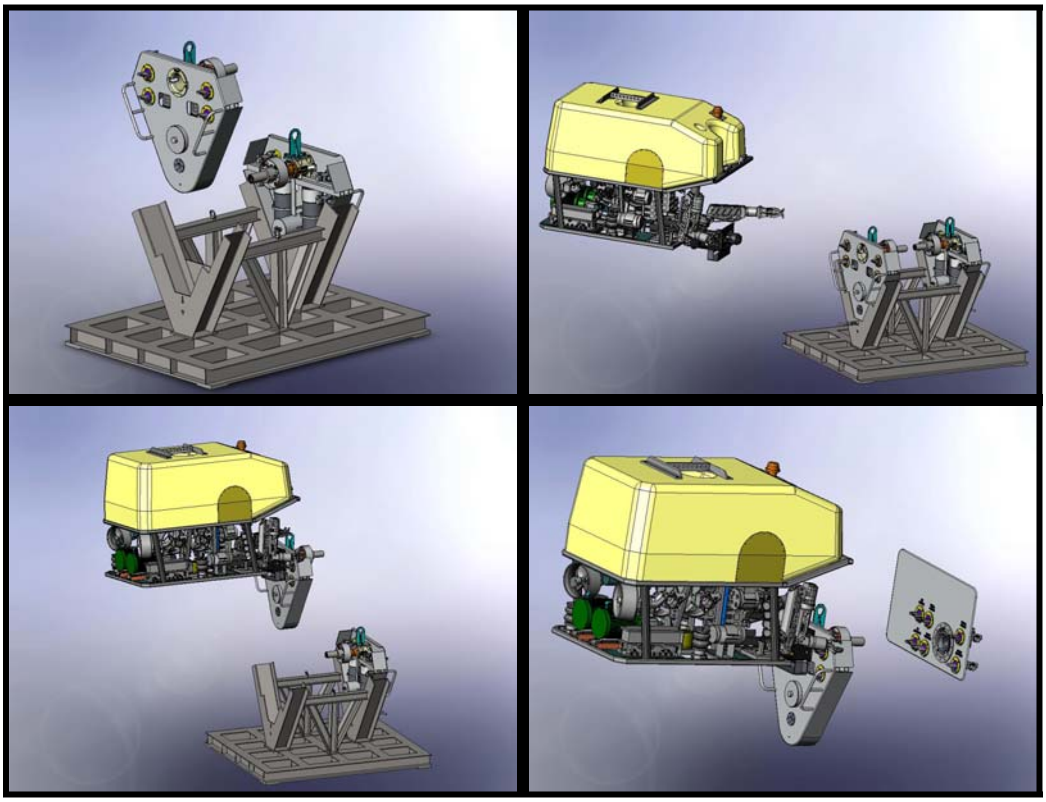

Figure 3. Operational concept showing subsea sampler module and deployment frame, ROV approach to deployment frame, sampler module retrieval, and tree panel approach.

Figure 4. Front and rear of ROV-conveyed sampling panel, sample bottle shown on right.

3.2 ROV-Assisted Subsea Measurement

The goal of this task is to develop methods through which supplementary measurement can be delivered to a subsea metering site to verify the proper operation of a multiphase meter already in place in the subsea pipework.

As was the case with the subsea sampling task, a major objective here is also to develop and document standard interfaces between the metering equipment and the ROV, in order that other meter vendors and ROV operators can use the results to become market participants.

Much consideration was given to constraints on the measurement equipment, resulting in the development of a path forward for deployment of increasingly complex measurement systems at deepwater subsea locations as documented in Reference [3]. After much deliberation, the approach taken for this work was that of a clamp-on meter, i.e. one in which there is no penetration of the pipe wall. In the current work the device was not deployed at an arbitrary point in the pipework, but required a landing zone, a portion of pipework equipped so that the meter clamps on in the same location and orientation each time it is used.

A diagram of the operational concept is shown in Figure 5. Once the ROV has successfully placed the unit on the landing zone and established a clamp to the pipe, the source and detector units are pushed forward into their proper position on the sides, and measurement activity can begin.

The measurement device chosen for developing and demonstrating the methodology in a prototype system was the Neftemer multiphase flow meter, which consists of a gamma ray absorption system coupled with innovative data processing algorithms. More about the Neftemer offering can be found at http://www.neftemer.com/ or in Reference [4].

The Neftemer meter, which had never seen service offshore, was marinized in a prototype system similar to that shown in Figure 5. The prototype system has undergone testing both at the SwRI multiphase reference flow loop in San Antonio, Texas, and at the Oceaneering ROV Subsea Simulation Facility in Morgan City, Louisiana. In Figure 6 are shown the assembled, marinized prototype and the setup for testing the unit at SwRI.

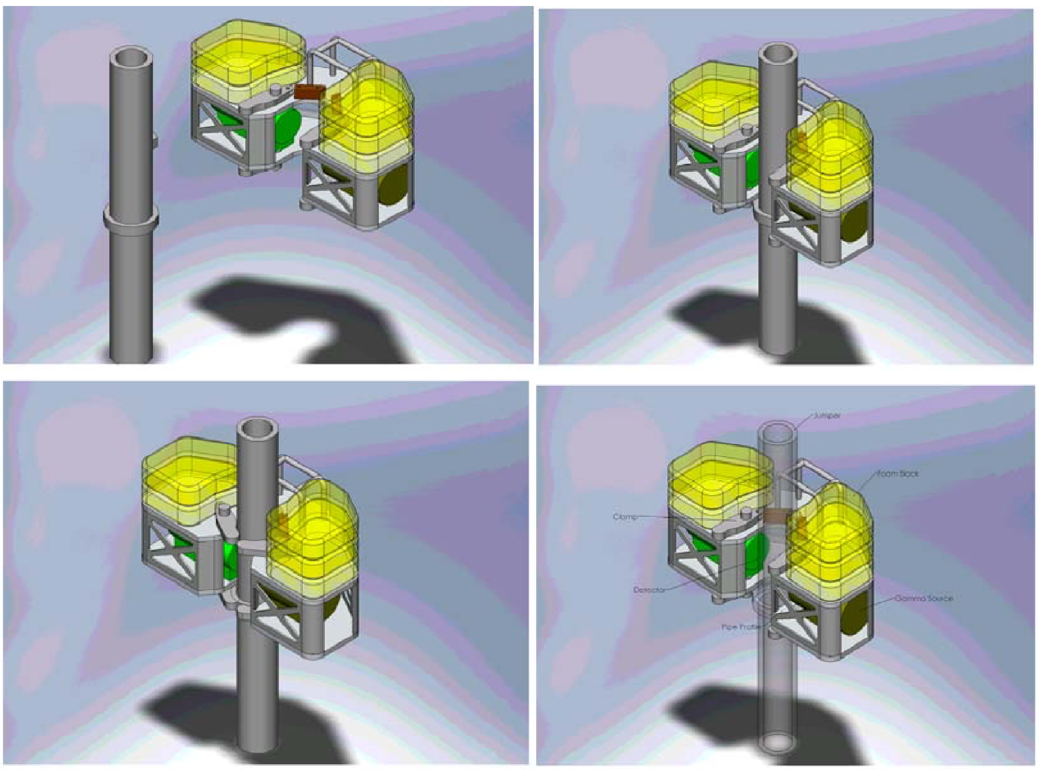

Figure 5. Concept of ROV measurement conveyed to vertical pipe with landing zone. The yellow sections are flotation foam; green source and detector elements are shown beneath.

Figure 6. On left, marinized ROV-conveyed Neftemer meter in delivery frame. Flow test setup at SwRI shown on right, with wooden tank for submersion of meter during tests.

3.3 HP/HT Sensor Qualification

Most of today's subsea multiphase and wet-gas flow meters are limited in operational environment to a maximum temperature of 125°C and pressure of 10,000 psi. To qualify for operating pressures of 15,000 psi and temperatures of 250°C, the flow meters must be tested at 22,500 psi, which requires improvements in the design of their mechanical components. Both pressure and temperature limits are daunting, especially for differential pressure (DP) sensors, a key component in virtually every multiphase or wet gas meter.

The goal of the task is thus to develop prototypes of packaged HP/HT sensor cells, using micro machined silicon components, for DP measurement in the "extreme" HP/HT operating range. The cell will include a line-pressure sensor to correct the DP measurement for common-mode effects. Prototypes of the sensor cells will be packaged as transmitter assemblies for HP/HT testing.

A reasonable question one might ask is why DoE and RPSEA should develop a component that is normally purchased commercially by meter vendors. The simple answer is that this market for high-performance DP sensors will be quite small, probably fewer than 1000 units over the life of the product, and therefore not very attractive for makers of such devices.

Samples of the micro-machined silicon differential and line pressure sensors are shown in Figure 7 below. In Figure 8 is shown the prototype oil-filled cell that houses both elements.

Figure 7. HP/HT differential and line pressure sensor prototypes

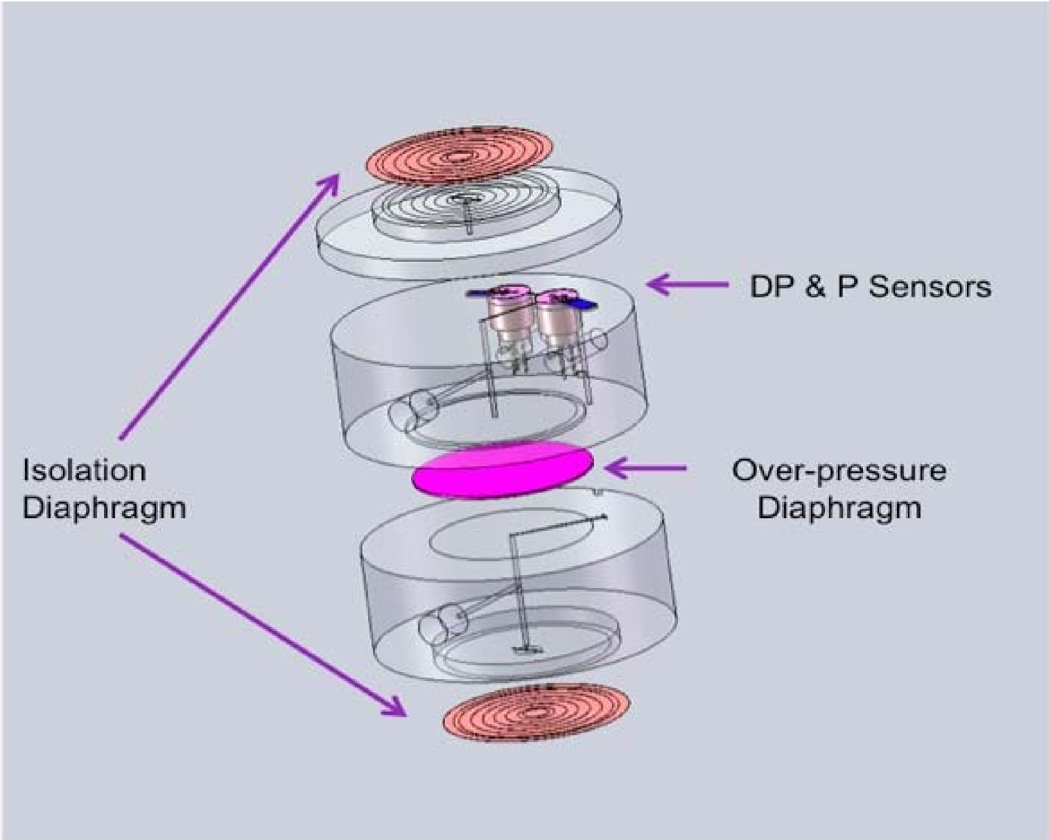

Figure 8. Exploded view of cell containing xHP/HT sensor chips.

3.4 Evaluation of Flow Modelling

The objective here is to address the gap in documented studies of virtual flow meter (VFM) technology by critically evaluating the performance of current VFMs. This is being done by comparing the predictions of VFMs with simulated field data constructed from commonly used flow models. The intent of these evaluations is to document the performance of VFMs as a group, and as generic sub-groups within the larger family, identifying areas of strength and weakness. If successful, the effort will encourage the utilization of VFM technology in monitoring or allocation applications, in those cases where it is an appropriate fit.

Originally it was intended to perform the evaluations using actual field data from flow meters and other measurement sources. Unfortunately, getting actual field data proved so difficult that the decision was made to use only simulated data in the current effort.

In order to enlist the active cooperation of the commercial VFM vendors, the results of the investigations will be presented in an anonymous fashion, avoiding the identification of specific vendors.

3.5 Meter Erosion and Fouling Effects

This work addresses gaps in understanding the ways in which production alteration of meters affects their response. It is well known from field operations that meters can become fouled or altered by deposits of scale, wax, asphaltenes, and hydrates, as well as from the processes of corrosion and erosion. The effects of these on measurement are not well understood, thus the primary objective of the work has been to understand their nature and magnitude.

The original plan was to perform experiments to evaluate the effects of alteration on some commonly used multiphase meter elements such as Venturi, Cone, and wedge. Alteration mechanisms would be either deposition (scale or wax) or erosion. The Task Working Group (WG) agreed that scale and erosion were the major alteration problems in deepwater, therefore these were the two phenomena chosen for investigation. Additionally, the WG made a key decision early on to augment the laboratory measurements through the use of Computational Fluid Dynamics (CFD). Through the generosity of ConocoPhillips, a sand erosion experimental data set for a Venturi meter was made available at the start of work, and was used as a guide in building a CFD model for the Venturi meter. A start was made at a CFD erosion model for other meters, though this must be revisited since lab erosion work has been completed for the three meters in both liquid-sand and air-sand tests,

The resultant research program has included both lab and CFD experiments run on Venturi, cone, and wedge meters, for both scale build-up and erosion effects, the latter in both liquid and gas mixtures. For more on this use of CFD the reader is referred to Reference [5].

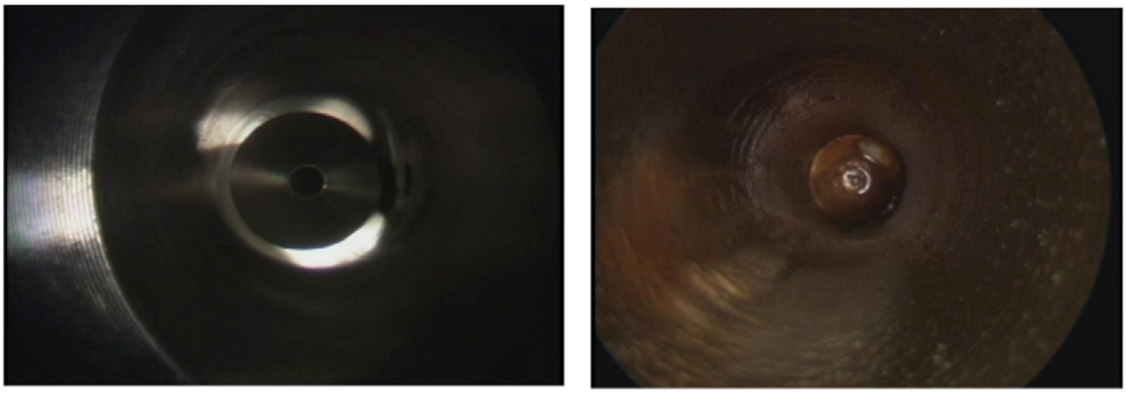

Figure 9. Interior of a cone meter and its associated pipework before and after scale deposition on its surfaces

An example of the kinds of experimental results achieved is shown in Figure 9 above, with the deposition of scale on the interior surfaces of a cone meter. The work, performed at Intertek's facilities in Houston, demonstrated the dramatic effect scale can have on the response of the three kinds of devices tested, with the measured discharge coefficient reduced by as much as 35% in some cases.

Another example illustrating a comparison of the laboratory and CFD results obtained thus far is shown in Figure 10. In this case, the experimental results of water-sand erosion on a cone meter are shown in the upper part of the figure, with the corresponding CFD results shown in the lower portion. Although it is difficult to compare the two in a strict dimensional sense, it is evident that the erosion features experienced on the actual meter are clearly visible on the CFD-simulated meter.

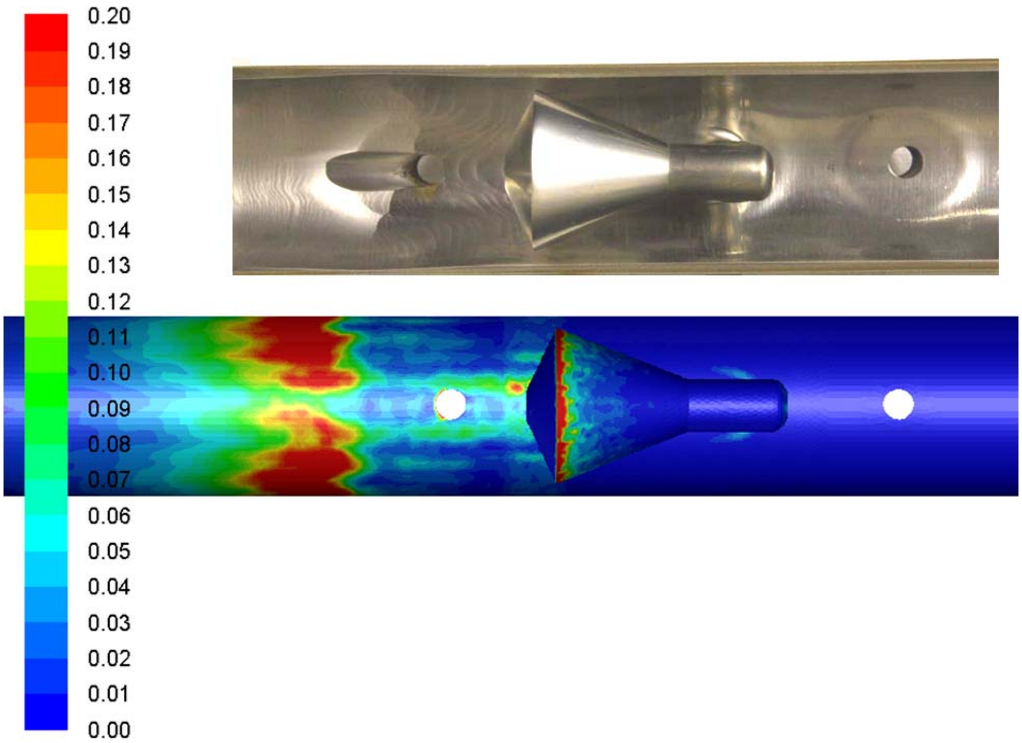

Figure 10. Comparison of water-sand experimental and CFD erosion results on a cone meter

3.6 Metering System Uncertainty

The intent of this task is to develop methods to provide users the ability to calculate the uncertainty in flow measurement at the subsea meter, at the topside separator, and at other points in between. Merging carefully developed models of multiphase flow with separator and meter models in a unified system provides a useful tool for the production engineer.

Figure 11 illustrates some of the components used by the tool. Uncertainty performance of the various components of the system – downhole and subsea pressure and temperature sensors, subsea or topside multiphase meters, a length of tieback pipeline, a topside separator with single-phase flow and watercut meters – are input into the system through spreadsheets, as is the system geometry.

The tool uses separate models for gas-dominant and liquid-dominant systems. Base Cases have been built to cover typical subsea measurement system configurations.

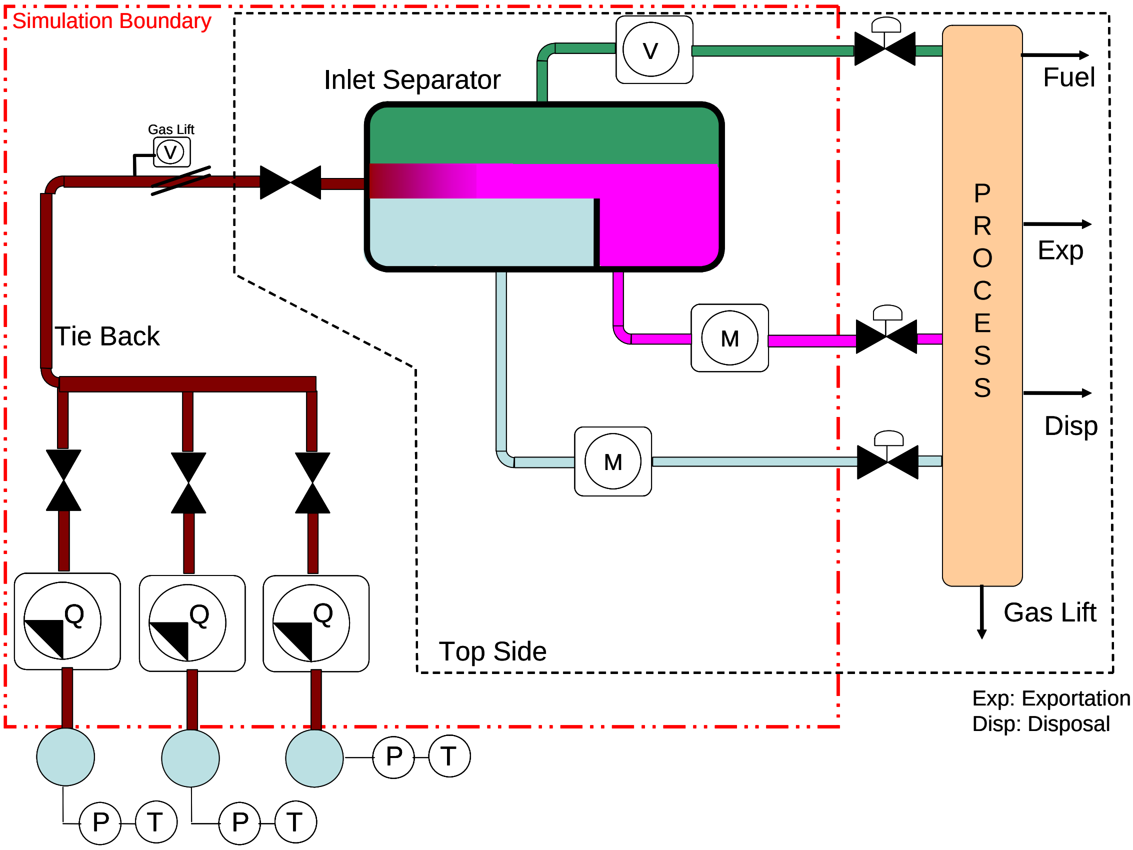

Figure 11. Production system diagram showing uncertainty components

4 FUTURE OF DEEPWATER MEASUREMENT

Having said this, there is still work to be done in several of the deepwater measurement task areas. For example:

- Deepwater Subsea Sampling. Development of a refined version of the prototype deepwater subsea sampling system. Create guides and other tools for use by those who must understand when and how to use the system. Field tests of applications that utilize the DW1301 system, probably on land.
- ROV-Assisted Subsea Measurement. Re-work of the delivery system based on test results. Extension of the DW1301 clamp-on measurement system to brownfields, and to more typical deepwater conditions. Incorporating another sensor package should be considered.
- HP/HT Sensor Qualification. Development of prototype downhole DP/P/T gauges using DW1301 xHP/HT differential pressure sensors by making them available to vendors of commercial downhole pressure gauges.
- Evaluation of Flow Modelling. Completion of the performance evaluation of wellbore flow models (Virtual Flow Meters, or VFMs) begun in DW1301 using real well data (DW1301 has used only numerically simulated data).
- Meter Fouling Effects. New methods for using the DP measurements to indicate fouling on the interior of a meter could be developed – DP diagnostics.

5 CONCLUSIONS. ACKNOWLEDGEMENTS

There can be no doubt that programs such as the RPSEA DW1301 have contributed much to improve our understanding and capabilities. By bringing the major deepwater operating companies together, numerous key technical issues have been resolved. Further, because this was accomplished with their cooperation, and because these same operators work together as partners in large deepwater applications in the Gulf of Mexico and beyond, it is more likely that the deepwater community at large will accept the directions chosen.

There are many examples in the deepwater Gulf of Mexico that serve to underscore the need for technological improvements in deepwater oil and gas exploration and production operations. Complex activities in field developments such as Perdido will be the norm in the future, and will undoubtedly require even better measurement and control than what is described here. R&D activities such as those of the DW1301 Project therefore are essential if these future needs are to be addressed.

The authors would like to acknowledge the US Department of Energy and RPSEA, which have provided the impetus and major funding for the work described here. We also salute the member companies of the DW1301 Joint Industry Project, who provided not only financial support for the project, but who also contributed the expertise of their brightest and best subsea and measurement engineers. DW1301 JIP member companies are: BP, BHP, Chevron, ConocoPhillips, Shell, Statoil, and Total.

Thanks also go to our expert sub-contractors Oceaneering International, Multiphase Systems Integration, axept, and Neftemer, Ltd.

Finally, we want to acknowledge our colleague, the late Rich McCoy of Oceaneering, whose numerous innovative contributions populate both the Deepwater Sampling System and ROV-Conveyed Measurement designs.

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North Sea
FLOW
Measurement Workshop

Paper 8.2

The Effects of Upstream Piping Configurations on Cone Meter and Venturi Meter Discharge Coefficients

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1 ABSTRACT

Solartron ISA has been a leading manufacturer of differential pressure flow meters for over 40 years. Due to a significant interest in the employment of cone meter technology within the industry, Solartron ISA decided to develop their own meter during 2009. This project was undertaken with a particular focus on subsea single phase flow measurement for well management applications.

As part of the research and development programme, various cone meters were calibrated at TUV NEL in order to establish discharge coefficient characteristics. Of particular interest to Solartron ISA were the effects of non-ideal upstream pipe configurations and the general claims relating to cone meters being insensitive to these upstream disturbances.

This paper presents the findings relating to potential errors created by having various upstream configurations for a number of cone meters, one of these manufactured by a leading supplier and the others manufactured by Solartron ISA.

In addition to these tests, a classical Venturi tube was also calibrated under the same conditions. This paper will present these findings by way of a comparison to the cone meter performance data.

In conclusion, this paper will present practical recommendations when using cone meters for realistic single phase flow applications.

2 PHASE I TEST PROGRAMME

2.1 Meter Selection

Initially Solartron ISA investigated the gas flow conditions that could be achieved by several test facilities. After some analysis of this data, a specification was drafted for two cone meters, one being a nominal 2 inch unit and the other a nominal 6 inch unit. The nominal pipe diameters were selected in such a way that they would be typical of a 2 1/16 inch and a 5 1/8 inch unit, which are the most common sizes utilised for subsea injection flow meters in well management applications. This application data, along with a request for the effective diameter ratio to be 0.6 was submitted to a leading cone meter manufacturer as an enquiry to purchase these two devices. In both instances, due to the range of the meters and the relatively high pressure drops at the potential maximum flows, it was recommended by the vendor that the effective diameter ratio in both instances should be 0.85. Solartron ISA accepted this advice and proceeded to purchase the items on this basis.

Initial sizing calculations furnished by the Vendor indicated that the nominal discharge coefficients for both the 2 inch unit and the 6 inch unit would be 0.75. Both units were also to be provided with a water calibration from the manufacturers own facility. It was acknowledged that this would not cover the entire operating Reynolds number range desired. The results of these calibrations are shown in Tables 1 and 2 and Figures 1 and 2 below.

Table 1 Water calibration data for 2 inch nominal bore cone meter

Meter Serial No.	Actual Pipe Internal Diameter	Actual cone Outside Diameter	Actual Beta Value	Fluid	Temp	Diff Pressure	Pipe Reynolds number	C_d
(-)	(inches)	(inches)	(-)	(-)	(°F)	(in WG)	(-)	(-)
09-1161	2.065	1.086	0.8505	Water	69.1	95.851	274,370	0.7342
					69.1	60.500	216,890	0.7305
					69.1	29.537	151,080	0.7282
					69.1	11.712	95,040	0.7275
					69.1	1.084	28,330	0.7128

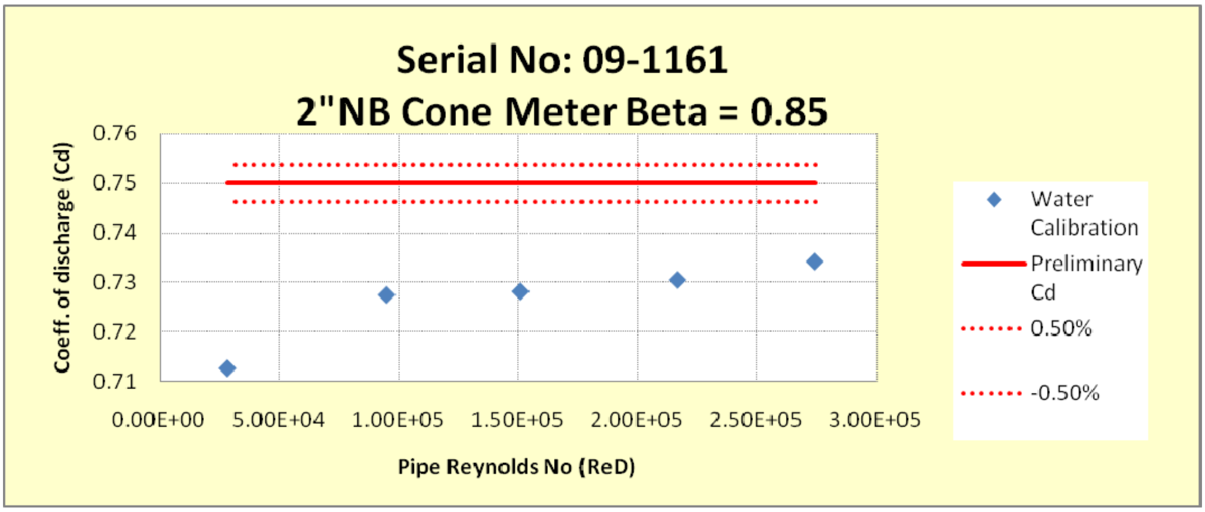

Figure 1 Water calibration for 2 inch nominal bore cone meter

Table 2 Water calibration data for 6 inch nominal bore cone meter

Meter Serial No.	Actual Pipe Internal Diameter	Actual cone Outside Diameter	Actual Beta Value	Fluid	Temp	Diff Pressure	Pipe Reynolds number	C_d
(-)	(inches)	(inches)	(-)	(-)	(^oF)	(in WG)	(-)	(-)
09-1162	5.255	2.814	0.8445	Water	78.7	397.448	1,585,940	0.7450
					78.6	243.244	1,238,520	0.7446
					78.6	147.714	959,720	0.7404
					78.7	90.905	748,310	0.7350
					78.6	50.425	549,000	0.7249
					78.6	4.599	164,460	0.7191

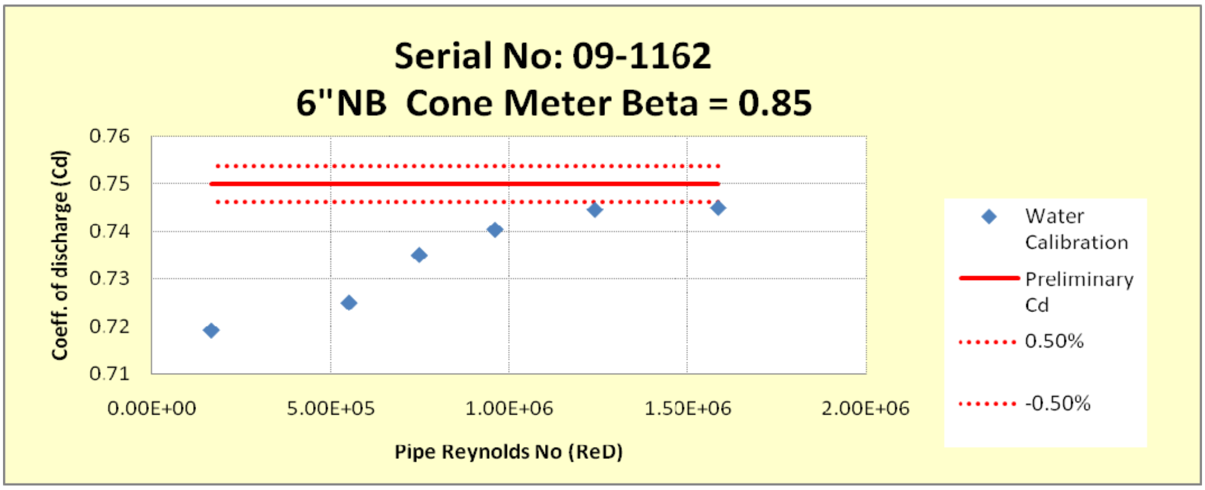

Figure 2 Water calibration for 6 inch nominal bore cone meter

As can be seen from the figures, the discharge coefficients in water are some way off the manufacturers estimated value of 0.75. For the 2 inch nominal bore cone meter, the discharge coefficient varied by ± 1.4% from the mid value, while for the 6 inch cone meter this variation increased to ± 1.7%.

Once the two meters were received at Solartron ISA and all of the data was reviewed, a test programme was devised that would give the maximum benefit from the available equipment and timescale. It was decided that for the 2 inch nominal bore cone meter, a standard dry gas calibration with sufficient upstream straight pipe lengths would be performed to give a comparison to the water calibration and that no testing relating to the effects of piping configurations would be executed for this meter during this programme. The results of the dry gas testing for this meter are shown in Figure 3. The gas calibration mid-point discharge coefficient was 0.764 with a variability over this range of ±2.08%. When this data is considered inclusive of the water calibration data, the mid-point discharge coefficient was 0.746 with a large variability over the range of ± 4.46%.

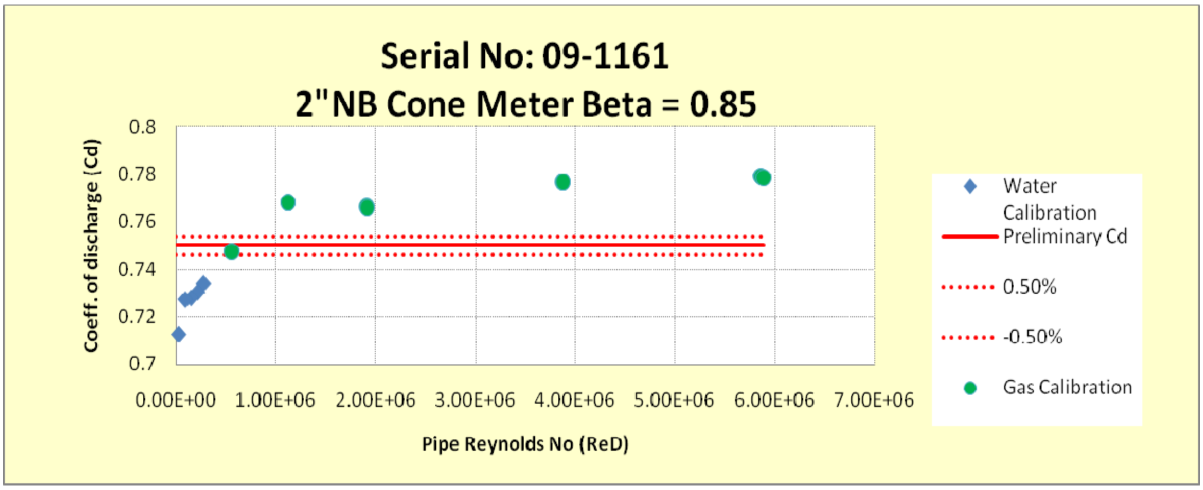

Figure 3 Gas and water calibrations for the 2 inch nominal bore cone meter

For the 6 inch cone meter it was decided that this should be tested along with a 0.55 beta value Solartron ISA Seastream Venturi meter, to show the effects of common piping configurations that may be encountered in subsea installations. The outline test programme was drafted as shown in Table 3 and it was agreed that because of their experience, the services of TUV NEL should be engaged to conduct all of the testing.

Table 3 Phase I Test Programme

Test Build No.	Meter Under Test	General Upstream Conditions	Notes
1	Cone meter	30D min of straight pipe	Venturi also included in 30D downstream of cone meter
2	Cone meter	1 off 90 degree bend immediately upstream of meter	Venturi also included in 30D downstream of cone meter
3	Cone meter	2 off 90 degree bends in the same plane immediately upstream of meter	Venturi also included in 30D downstream of cone meter
4	Cone meter	2 off 90 degree bends in different planes immediately upstream of meter	Venturi also included in 30D downstream of cone meter
5	Cone meter	1 off 90 degree bend then 3D of straight pipe immediately upstream of meter	Venturi also included in 30D downstream of cone meter
6	Venturi meter	1 off 90 degree bend immediately upstream of meter	Cone meter also included in 30D downstream of Venturi
7	Venturi meter	2 off 90 degree bends in the same plane immediately upstream of meter	Cone meter also included in 30D downstream of Venturi
8	Venturi meter	2 off 90 degree bends in different planes immediately upstream of meter	Cone meter also included in 30D downstream of Venturi
9	Venturi meter	1 off 90 degree bend then 3D of straight pipe immediately upstream of meter	Cone meter also included in 30D downstream of Venturi

2.2 The TUV NEL High-Pressure Gas Re-Circulating Test Facility

The high-pressure gas re-circulating test facility at TUV NEL is based around a 6-inch nominal bore flow loop. A schematic diagram of the nominal facility arrangement for dry-gas tests is provided in Figure 4. Although nominally 6-inch in diameter, the two parallel test sections can accommodate line sizes ranging from 2-inch through to 10-inch. The gas used for testing is oxygen-free nitrogen, supplied by BOC in 230 bar gauge cylinder banks. The facility operates at a nominal temperature of 18 °C over a nominal pressure range of 10 to 63 bar gauge, which corresponds to a gas density range of 12.76 to 74.54 kg/m^3.

Referring to the schematic diagram in Figure 4, the gas is driven around the test loop by a 200 kW fully encapsulated gas blower. The maximum calibrated (pressure-independent) dry gas volumetric flow rate is nominally 1500 m^3/h. The maximum achievable dry gas volumetric flow rate is dependent upon the size and type of reference/test flow meter installed. The gas temperature is controlled to within ± 0.1 °C using a chilled-water-controlled shell-and-tube heat exchanger. The gas flow rate is controlled by varying the speed of the blower.

The gas reference volumetric flow rate is measured using a calibrated 6-inch model 3400 Daniel SeniorSonic gas ultrasonic flow meter. For the test work described in this paper, the expanded uncertainty estimate on the gas reference volumetric flow rate is 0.5% at the 95% confidence level. All static pressure, differential pressure and temperature measurements are taken using traceable calibrated instrumentation.

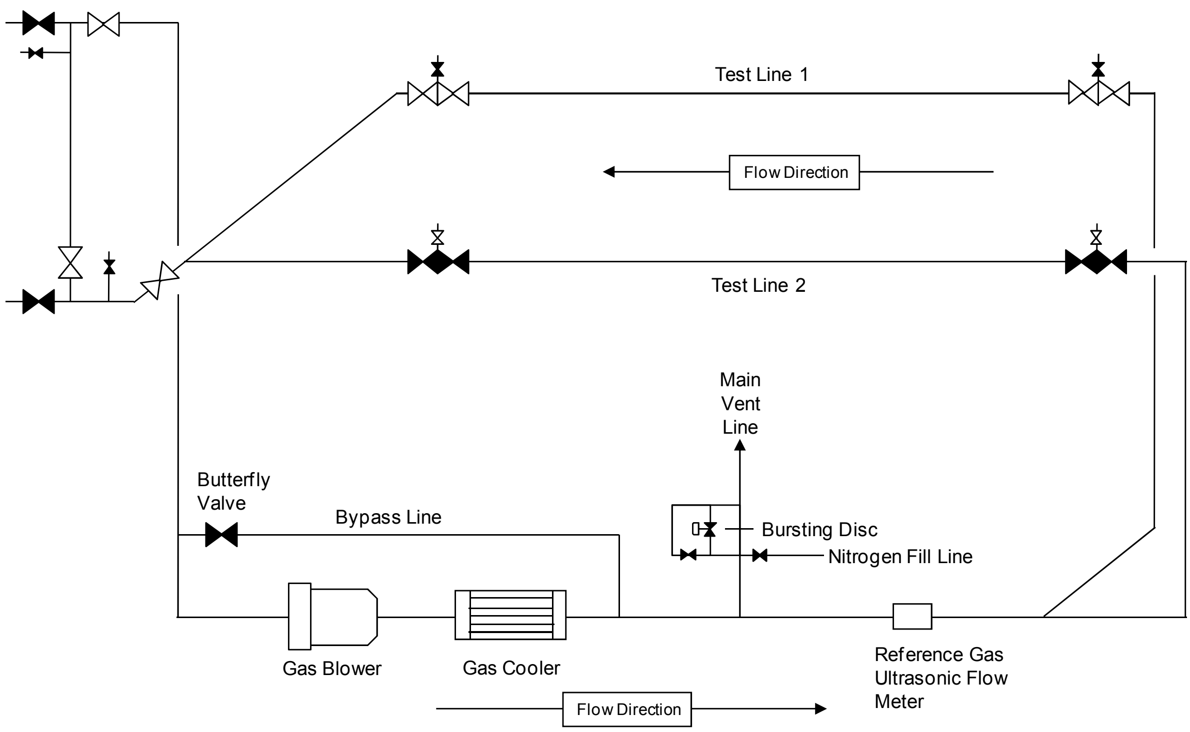

Figure 4 Schematic of the TUV NEL high pressure gas re-circulating test facility.

2.3 Meter Installations and Piping Configurations

For this test programme one 6 inch schedule 160 beta 0.85 cone meter (Serial No. 09-1162) and one 6-inch schedule 160 beta 0.55 Solartron ISA Seastream Venturi meter (Tag No. FE-5195) were installed in Test Line 2 of the TUV NEL high-pressure gas re-circulating test facility. A total of nine different pipe spool configurations were used to check the installation effects performance of each meter (labelled 1 to 9 in Table 3). Apart from the initial straight pipe baseline test run four of the installations had the cone meter upstream of the Venturi meter, and four had the Venturi meter installed downstream of the cone meter (with identical upstream pipe configurations).

The upstream 6 inch pipe spools required for the test programme were supplied by Solartron ISA. Suitable 6 inch closing pipe-work was supplied by TUV NEL to allow the completion of the test line build, with the closing spools having a 6 inch schedule 80 bore.

Tests were carried out over the nominal pipe Reynolds number range 1.5 x 10^6 to 9.8 x 10^6. Figures 5 to 13 are photographs of each installation. Each test build was run at one pressure only, nominally 42.8 bar gauge. This was to generate a nominal operating density of 51 kg/m^3 at 18 ^oC. During the test programme TUV NEL logged all gas reference and test meter data. Each test point was logged for a period of 300 seconds. Prior to the logging of each test point, test line conditions were allowed to stabilize for a period of one to two minutes.

Figure 5 Test build 1

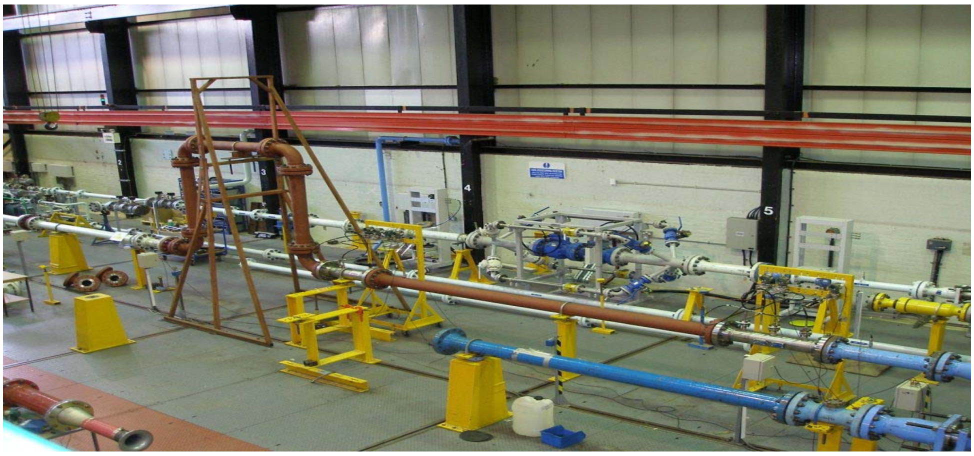

Figure 6 Test build 2

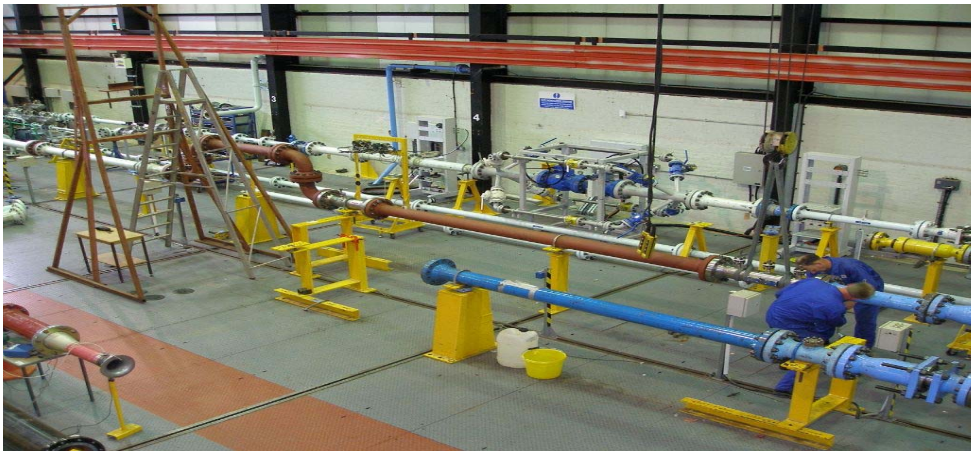

Figure 7 Test build 3

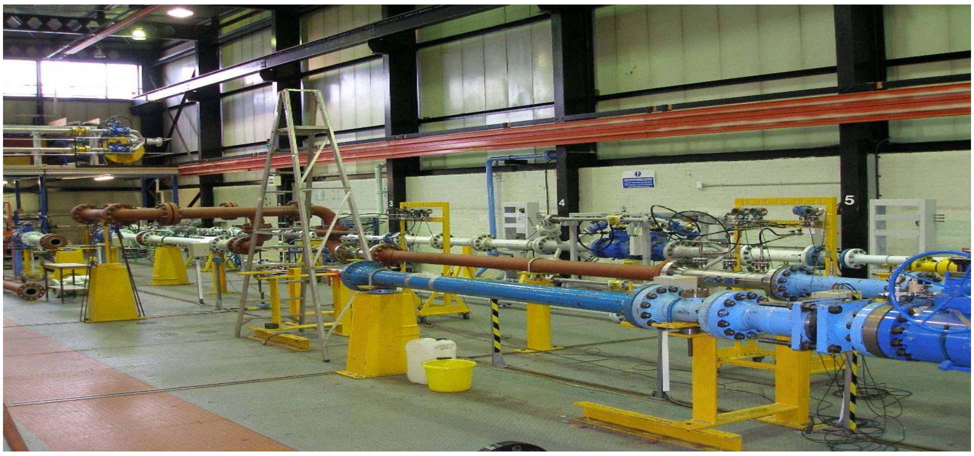

Figure 8 Test build 4

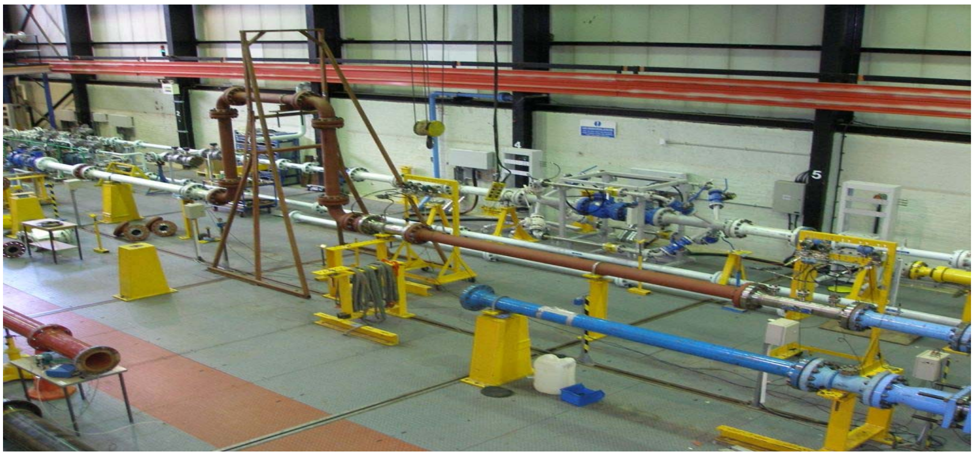

Figure 9 Test build 5

Figure 10 Test build 6

Figure 11 Test build 7

Figure 12 Test build 8

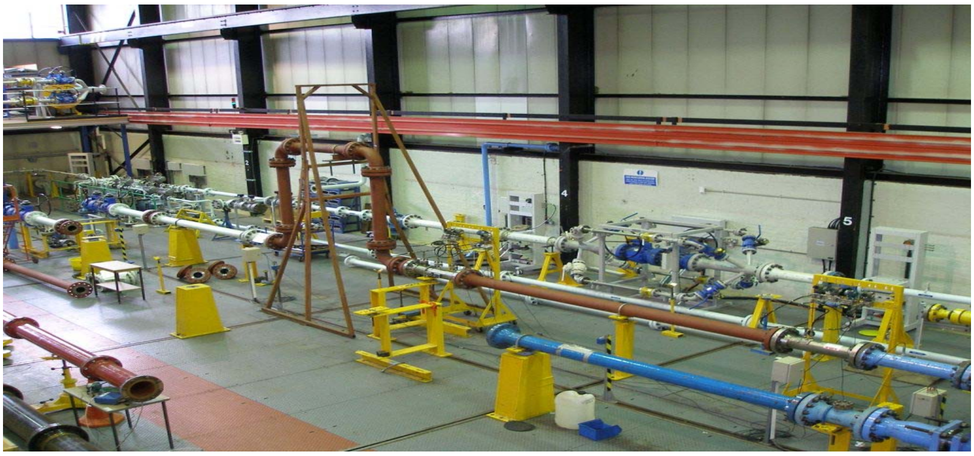

Figure 13 Test build 9

3 PHASE I TESTING

3.1 Calculations

The discharge coefficient for the Venturi meter and the cone meter were calculated from equation 1.

$$C = \frac{4 m_{ref} \sqrt{1-\beta^4}}{\pi \varepsilon d^2 \sqrt{2 \Delta p \rho_1}} \tag{1}$$

The Venturi meter expansibility (ε) and its relative uncertainty (in per cent) are taken from ISO 5167-4:2003 [1], and are reproduced in equations 2 and 3 below.

$$\varepsilon = \left[\left(\frac{\kappa\tau^{2/\kappa}}{\kappa-1}\right)\left(\frac{1-\beta^4}{1-\beta^4\tau^{2/\kappa}}\right)\left(\frac{1-\tau^{(\kappa-1)/\kappa}}{1-\tau}\right)\right]^{1/2} \tag{2}$$

$$\left(4+100\beta^8\right)\frac{\Delta p}{p_1} \tag{3}$$

This has a maximum value (over the Reynolds number range tested) of 0.21%. The cone meter expansibility [2] is given by equation 4.

$$\varepsilon = 1-(0.649+0.696\beta^4)\frac{\Delta p}{\kappa p_1} \tag{4}$$

This was derived for $0.45 \le \beta \le 0.75$. Fitting the original expansibility data to give the equation for the uncertainty and extrapolating it gives a value for the absolute uncertainty at $\beta = 0.8445$ of

$$0.127\frac{\Delta p}{\kappa p_1} \tag{5}$$

This has a maximum value (over the Reynolds number range tested) in relative terms of 0.06%.

The other source uncertainties used are provided in Table 4 (all the uncertainties are stated as percentage of reading). The figure given for differential pressure applies for a differential pressure greater than or equal to 0.096 bar. The differential-pressure uncertainty increases for the lowest Venturi meter point. For the lower half of the cone meter data a differential pressure calibration at atmospheric pressure was undertaken, because it was not possible to calibrate the low range transmitter at a static pressure of 42.8 bar gauge). On the basis of the manufacturers specification an additional uncertainty of 4.7 Pa was added in quadrature to the 0.1% uncertainty. It was however possible to calibrate the top end of the 0 to 0.1 bar transmitter both at atmospheric pressure and at an elevated pressure, and on that basis a value of 4.7 Pa appears conservative.

The expanded uncertainty estimates for the cone meter and Venturi meter discharge coefficients are in the range 0.52% to 0.56%, except at the lowest Reynolds number for the cone meter, for which the uncertainty in the discharge coefficient is 0.63%.

Table 4 Source Uncertainty Values (at the 95% Confidence Level) – Phase I Tests

Source	Expanded Uncertainty Estimate (%)
Reference Gas Volumetric Flow Rate	0.5
Reference Gauge Pressure	0.1
Reference Barometric Pressure	0.015
Reference Absolute Temperature	0.05
Reference Gas Compressibility	0.02
Test Meter Gauge Pressure	0.1
Test Meter Absolute Temperature	0.05
Test Meter Differential Pressure	0.1*
Test Meter Gas Compressibility	0.02

*For a differential pressure greater than or equal to 0.1 bar.

3.2 Test Results

The cone meter baseline calibration was determined from build 1, as shown in Figure 14. The gas calibration mid-point discharge coefficient value was 0.740 with a variability over the range of ± 0.40%. For all subsequent tests on this meter, this data was used as the baseline with the effects of different piping configurations being compared relative to it. The data from the water calibration was not used any further during this programme, however it is noteworthy that the cone meter did display a dependency upon Reynolds number for this lower range, and if this had been included in the analysis then the mid-point discharge coefficient value would have been 0.732 with a variability over the range of ± 1.8%.

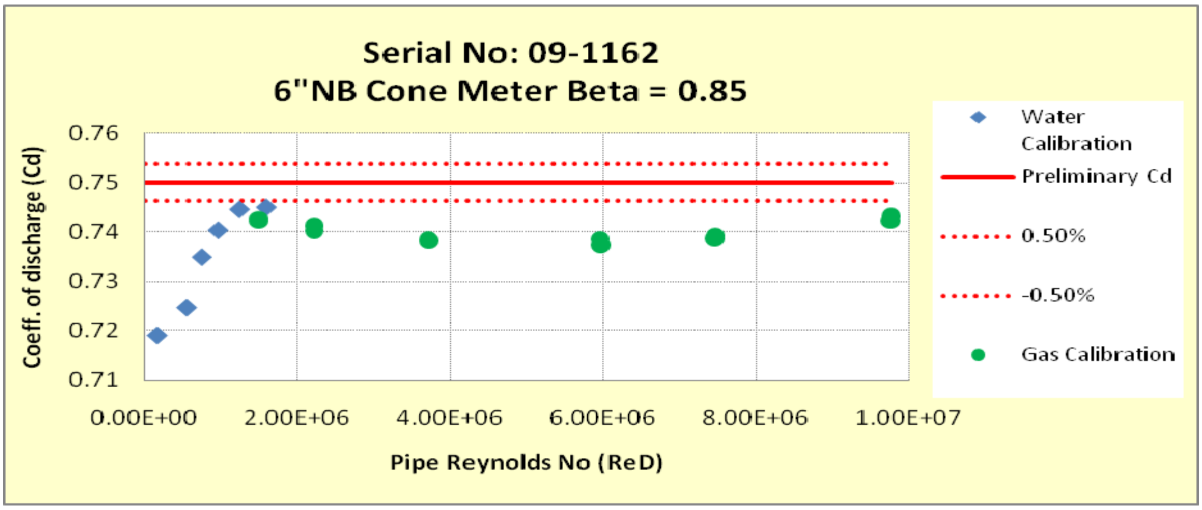

Figure 14 Gas and water calibrations for 6 inch nominal bore cone meter

The Venturi meter baseline discharge coefficient was also determined from build 1. The results of this test are shown in Figure 15 and are consistent with ISO 5167-4:2003. The gas calibration mid-point discharge coefficient value was 0.997 with a variability over the range of ± 0.43%. As with the cone meter, subsequent tests on the Venturi utilised this data as the baseline, with the effects of different piping configurations being compared relative to it.

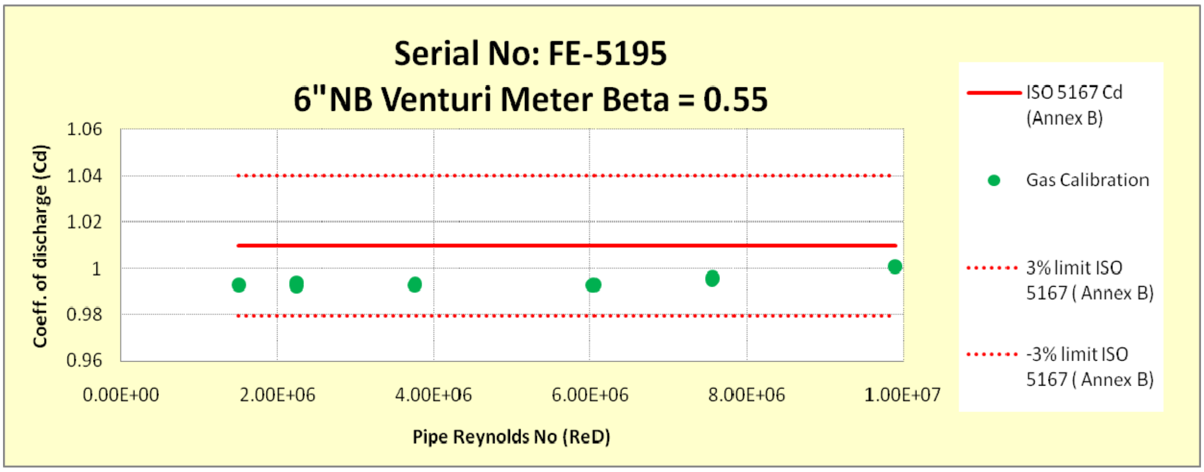

Figure 15 Gas calibration for 6 inch nominal bore Venturi meter

<u>Build 2 Installation Effect</u>: A single 90 degree bend, immediately upstream of the cone meter, Serial Number 09-1162, displayed a shift in the discharge coefficient of up to +2.27%, as shown in Figure 16.

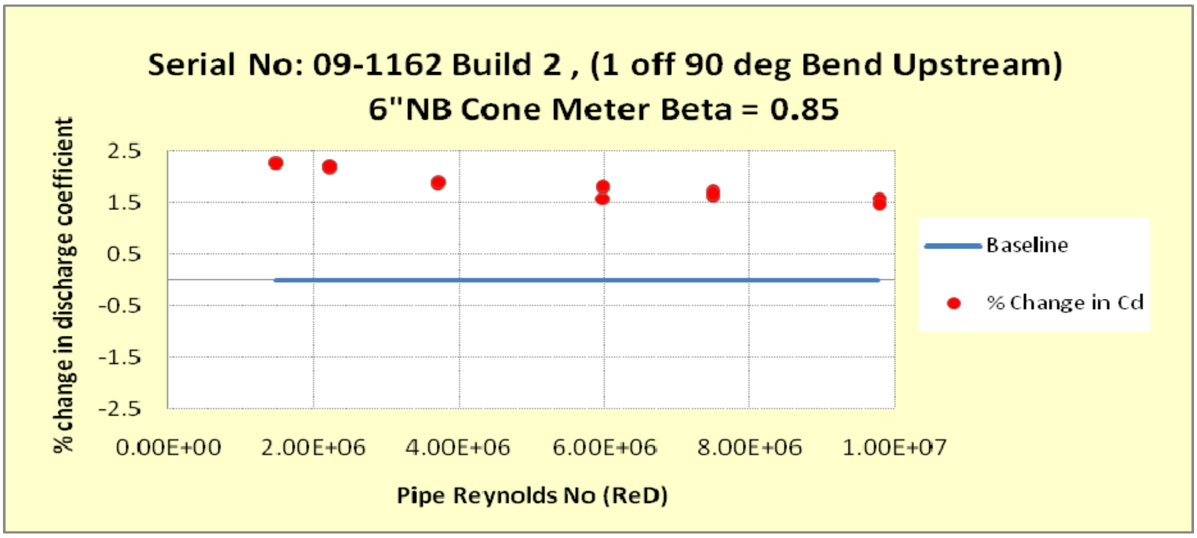

Figure 16 Percentage change in discharge coefficient from build 2

Build 3 Installation Effect: Two 90 degree bends in the same plane, immediately upstream of the cone meter, Serial Number 09-1162, displayed a shift in the discharge coefficient of up to +0.45%, as shown in Figure 17.

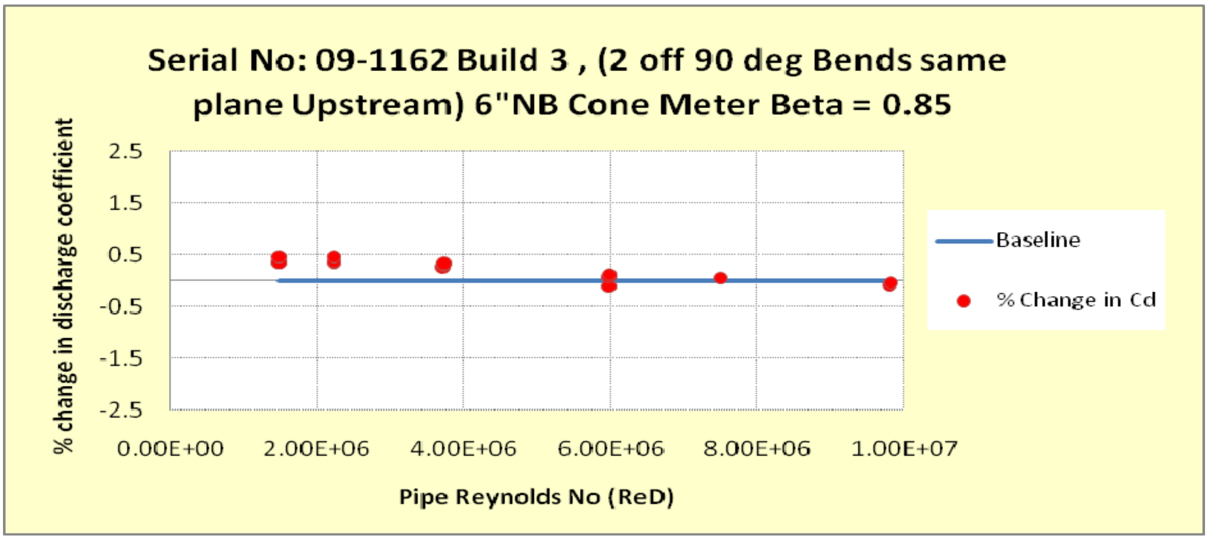

Figure 17 Percentage change in discharge coefficient from build 3

Build 4 Installation Effect: Two 90 degree bends in different planes immediately upstream of the cone meter, Serial Number 09-1162, displayed a shift in the discharge coefficient of up to +0.69%, as shown in Figure 18.

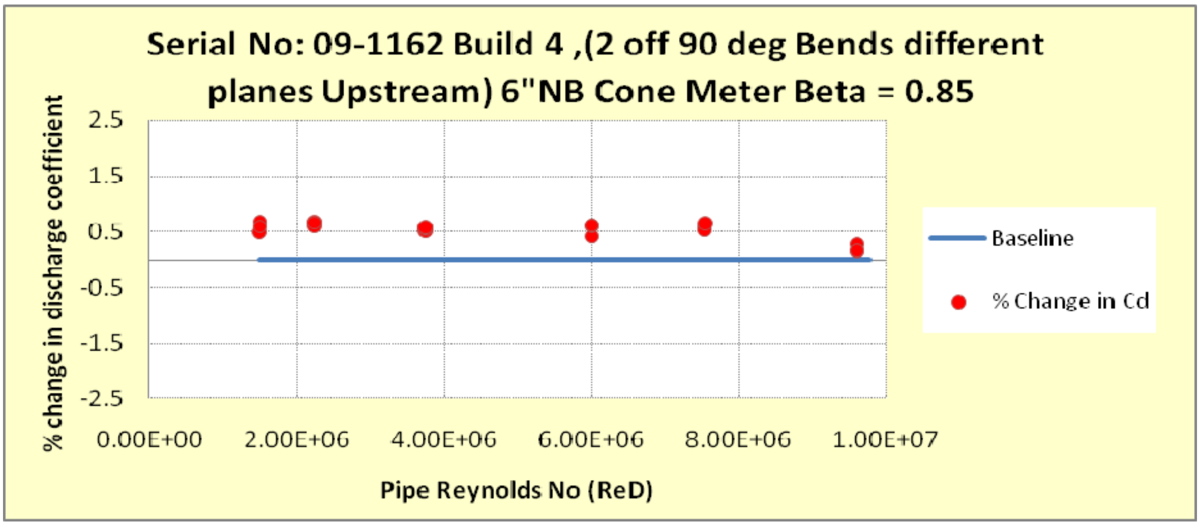

Figure 18 Percentage change in discharge coefficient from build 4

Build 5 Installation Effect: A single 90 degree bend and then three diameters of straight pipe immediately upstream of the cone meter, Serial Number 09-1162, displayed a shift in the discharge coefficient of up to +1.38%, as shown in Figure 19.

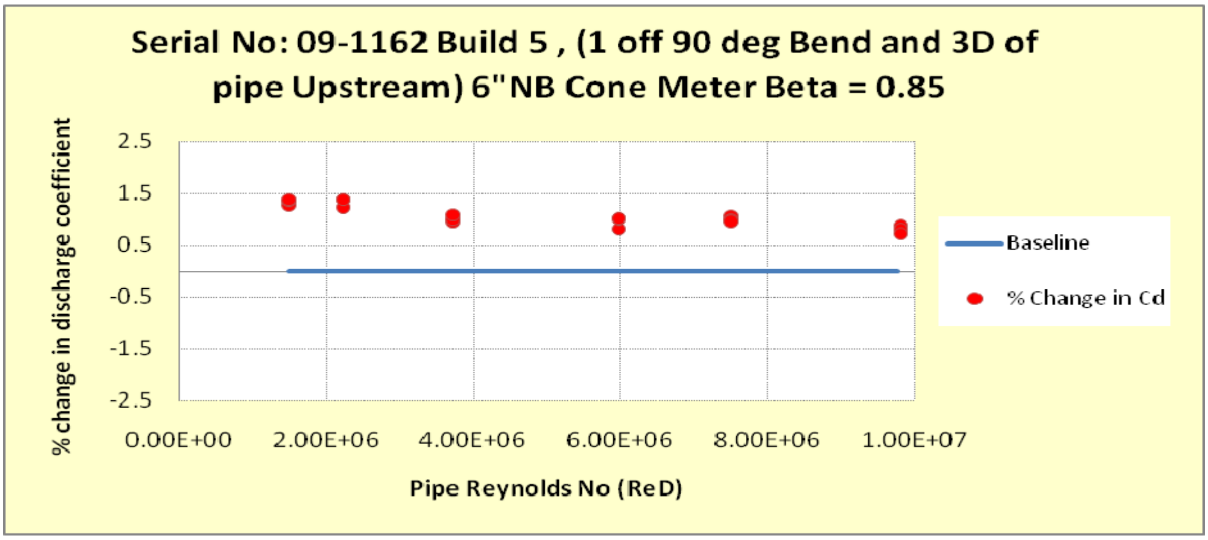

Figure 19 Percentage change in discharge coefficient from build 5

Build 6 Installation Effect: A single 90 degree bend immediately upstream of the Venturi meter, Serial Number FE-5195, displayed a shift in the discharge coefficient of between -0.79% and +0.62% as shown in Figure 20.

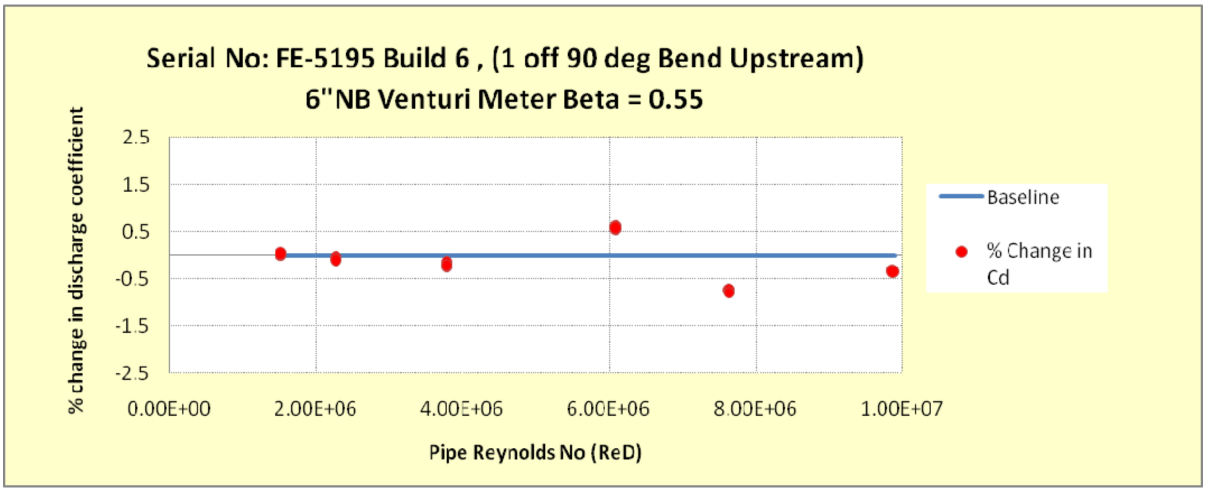

Figure 20 Percentage change in discharge coefficient from build 6

Build 7 Installation Effect: Two 90 degree bends in the same plane, immediately upstream of the Venturi meter, Serial Number FE-5195, displayed a shift in the discharge coefficient of between -0.50% and +0.49%, as shown in Figure 21.

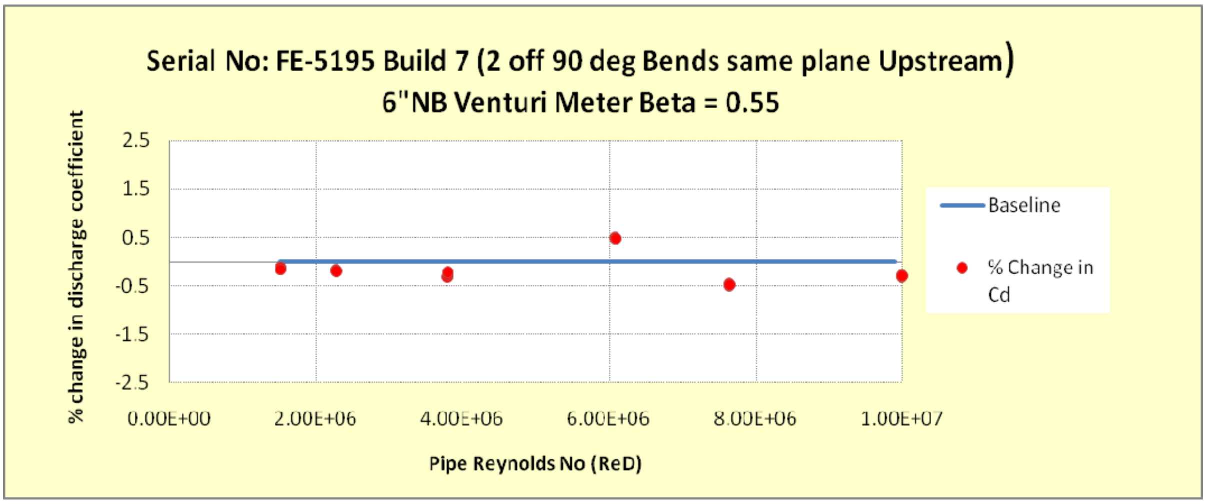

Figure 21 Percentage change in discharge coefficient from build 7

Build 8 Installation Effect: Two 90 degree bends in different planes, immediately upstream of the Venturi meter, Serial Number FE-5195, displayed a shift in the discharge coefficient of between -0.26% and +0.49%, as shown in Figure 22.

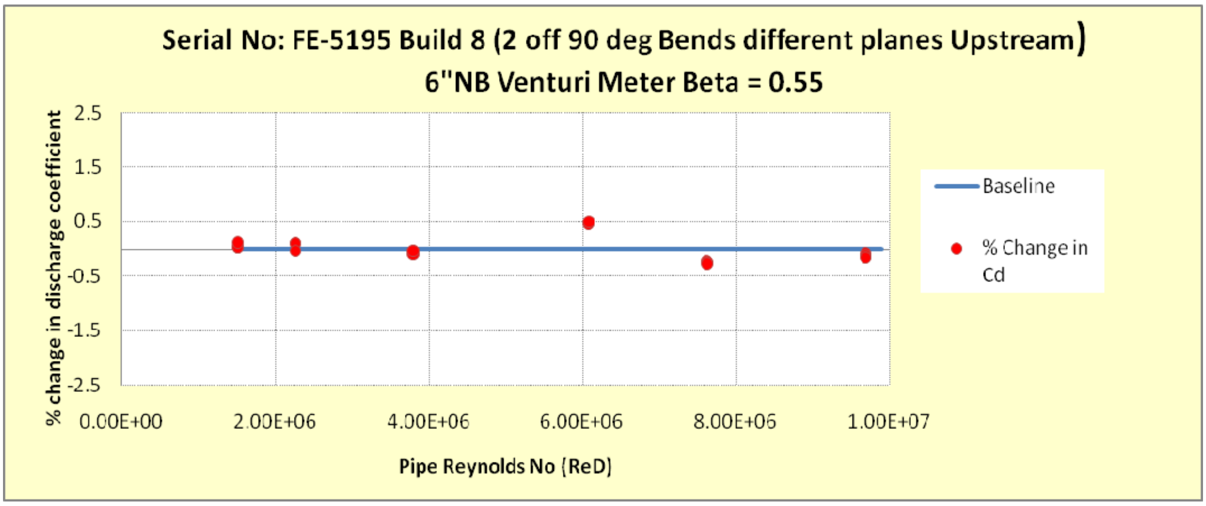

Figure 22 Percentage change in discharge coefficient from build 8

Build 9 Installation Effect: A single 90 degree bend and then three diameters of straight pipe, immediately upstream of the Venturi meter, Serial Number FE-5195, displayed a shift in the discharge coefficient of between -0.70% and +0.33%, as shown in Figure 23.

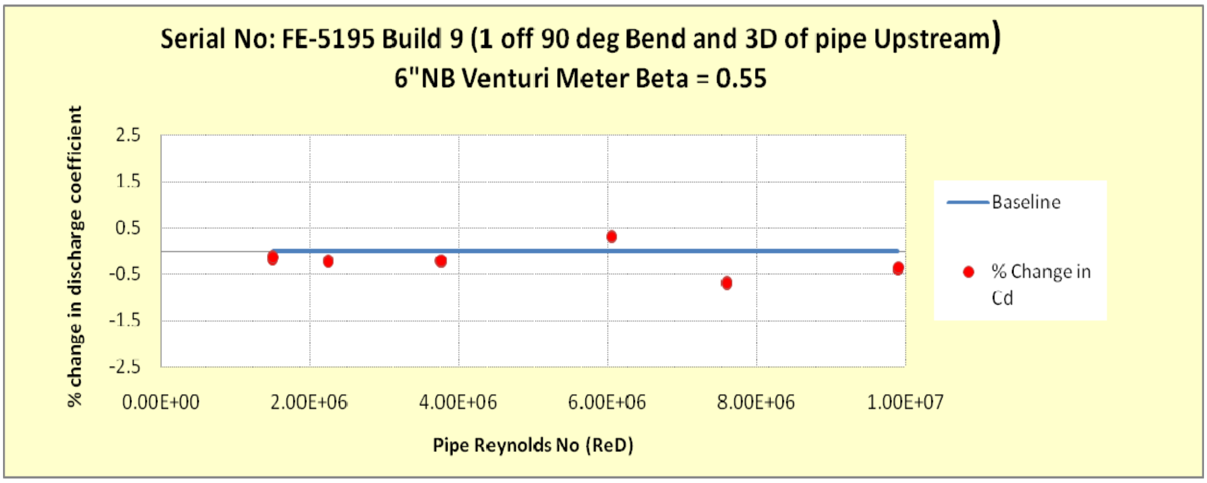

Figure 23 Percentage change in discharge coefficient from build 9

As stated in Table 3, while the primary meter of interest was being calibrated to show the effect of the upstream piping configuration, the secondary meter was placed 30 pipe diameters downstream and the results of this testing recorded as detailed below.

During builds 2, 3, 4 and 5 the Venturi meter was placed downstream of the cone meter and the discharge coefficients were compared against the original baseline calibration as shown in Figure 24.

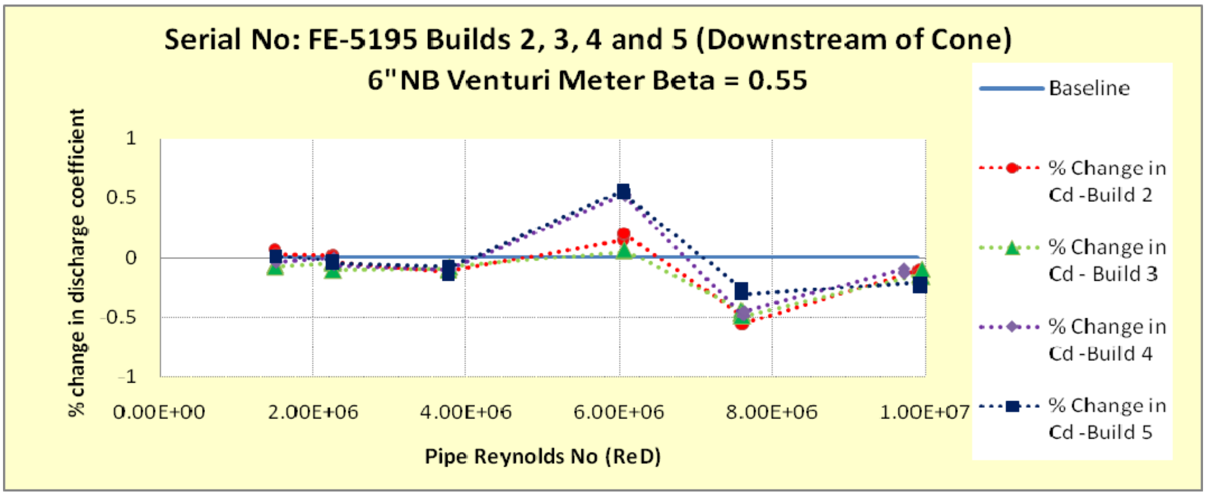

Figure 24 Change in discharge coefficient for the Venturi meter when downstream of the cone meter

Similarly, during builds 6, 7, 8 and 9 the cone meter was placed downstream of the Venturi meter and the discharge coefficients compared against the original baseline calibration as shown in Figure 25.

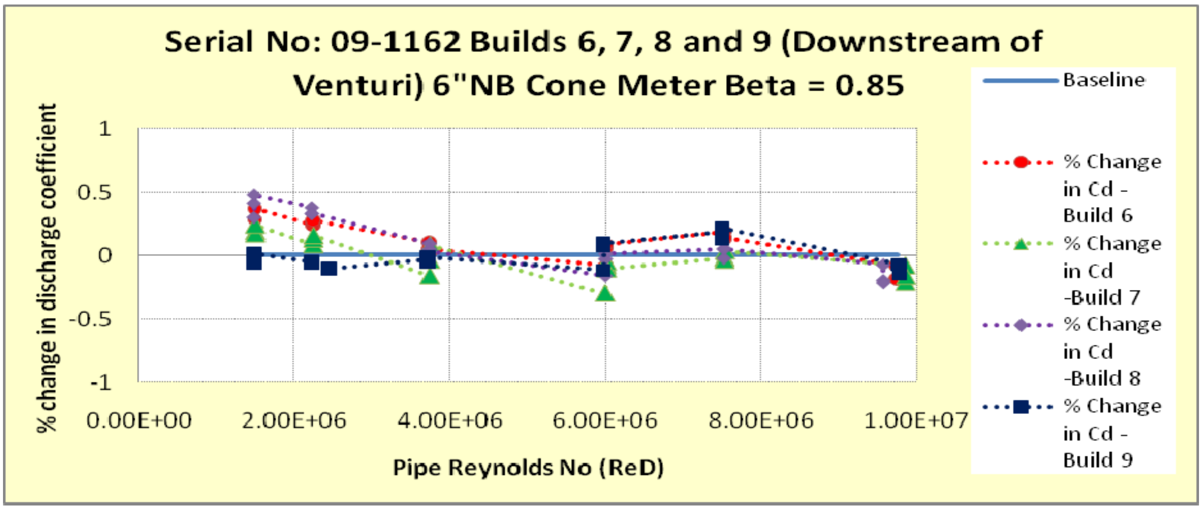

Figure 25 Change in discharge coefficient for the cone meter when downstream of the Venturi meter

4 PHASE II TESTING

4.1 Test Programme

The second phase of testing consisted of the calibration of two Solartron ISA manufactured cone meters using the same piping configurations as for the Phase I test programme.

For the Phase II test programme one 6 inch schedule 160 (beta 0.6013) Solartron ISA cone meter (Serial No. FE-5195-003), and one 6 inch schedule 160 (beta 0.8444) Solartron ISA cone meter (Serial No. FE-5195-004) were manufactured. Both meters were installed in Test Line 2 of the TUV NEL high-pressure gas re-circulating test facility.

The nine different pipe spool configurations from Phase I were used to check the installation effects performance of each device as detailed in Table 5. For the initial straight pipe baseline test run meter

FE-5195-004 was installed upstream of meter FE-5195-003 so as to minimize the effect of any disturbance to the flow velocity profile between the two meters.

Table 5 Phase II Test Programme

Test Build No.	Meter Under Test	General Upstream Conditions	Notes
1b	Cone meter ß 0.85	30D min of straight pipe	Test 1b carried out for cone meter ß 0.85 and cone meter ß 0.6 simultaneously
2b	Cone meter ß 0.6	1off 90 degree bend immediately upstream of meter	Cone meter ß 0.85 also included in 30D downstream
3b	Cone meter ß 0.6	2 off 90 degree bends in the same plane immediately upstream of meter	Cone meter ß 0.85 also included in 30D downstream
4b	Cone meter ß 0.6	2 off 90 degree bends in different planes immediately upstream of meter	Cone meter ß 0.85 also included in 30D downstream
5b	Cone meter ß 0.6	1 off 90 degree bend then 3D of straight pipe immediately upstream of meter	Cone meter ß 0.85 also included in 30D downstream
6b	Cone meter ß 0.85	1off 90 degree bend immediately upstream of meter	Cone meter ß 0.6 also included in 30D downstream
7b	Cone meter ß 0.85	2 off 90 degree bends in the same plane immediately upstream of meter	Cone meter ß 0.6 also included in 30D downstream
8b	Cone meter ß 0.85	2 off 90 degree bends in different planes immediately upstream of meter	Cone meter ß 0.6 also included in 30D downstream
9b	Cone meter ß 0.85	1 off 90 degree bend then 3D of straight pipe immediately upstream of meter	Cone meter ß 0.6 also included in 30D downstream

Figures 26 to 30 provide representative photographs of some of the installations. Photographs for tests 3b, 8b, 6b and 9b are not included here as they are of the same type as the corresponding tests 7b, 4b, 2b and 5b, with only the cone meter locations reversed. Tests were carried out over the nominal pipe Reynolds number range of 1.4×10^6 to 7.6×10^6. Five gas flow rates were logged over that range, giving nominal test volumetric flow rates of 186, 392.5, 599, 805.5 and 1012 m^3/h.

Each test was performed at one pressure only, which was nominally 42.8 bar gauge. This pressure was chosen to provide a nominal test operating density of 51 kg/m^3 at 18 ^oC. During the test programme TUV NEL logged all gas reference and test flow meter data. Each test point was logged for a period of 300 seconds. Prior to the logging of the first test point at a given gas volumetric flow rate, test line conditions were allowed to stabilize for a period of several minutes, the aim being to keep any static pressure variation to within a 0.05% band over the stated logging period.

Figure 26 Test build 1b

Figure 27 Test build 2b

Figure 28 Test build 4b

Figure 29 Test build 5b

Figure 30 Test build 7b

4.2 Calculations

The logged test data have been used to determine the discharge coefficients for both cone meters for each of the nine test configurations. Of primary interest in this test programme was the shift in discharge coefficient, relative to the baseline value, caused by the upstream pipe layout. The discharge coefficient and the expansibility for the cone meters were calculated using equations 1 and 4 provided in section 3.1 of this paper.

As noted in that section the equations in [2] were derived for $0.45 \leq \beta \leq 0.75$. The uncertainty equation in [2] gives a maximum gas expansibility relative uncertainty value for meter FE-5195-003 (over the Reynolds number range tested) of 0.06%. The absolute uncertainty for meter FE-5195-004 is given in equation 5, and the maximum gas expansibility relative uncertainty value for meter FE-5195-004 (over the Reynolds number range tested) is 0.04%.

Other source uncertainties used in the analysis are provided in Table 6 below. All the uncertainties in the table are stated as a percentage of reading.

For the lower half of cone meter FE-5195-004's data range, a low range (0 to 0.1 bar) differential pressure transmitter was used. These are calibrated at atmospheric pressure only, because it is not possible to calibrate them at high static pressure on the TUV NEL Desgranges et Huot standard. To include the effect of static pressure shift on the transmitter output, on the basis of the manufacturer's specification, an additional uncertainty of 4.7 Pa was added in quadrature to the 0.1% stated differential pressure transmitter calibration uncertainty value. Historical checks using the Desgranges et Huot standard at the top end of the 0 to 0.1 bar transmitter range, at both atmospheric and elevated pressure, show that the 4.7 Pa estimate appears conservative, and so the expanded uncertainty estimate on the discharge coefficient is unlikely to be overly optimistic.

The expanded uncertainty estimates for the cone meter discharge coefficients are in the range 0.813% to 1.08%.

Table 6 Source Uncertainty Values (at the 95% Confidence Level) – Phase II Tests

Source	Expanded Uncertainty Estimate (%)
Barometric Pressure	0.015
Specific Gas Constant	0.01
Reference Gas Volumetric Flow Rate	0.5
Reference Gas Volumetric Flow Rate Drift Allowance	0.25
Reference Gauge Pressure	0.1
Reference Absolute Temperature	0.05
Reference Gas Compressibility	0.02
Test Gas Gauge Pressure	0.1
Test Gas Absolute Temperature	0.05
Test Gas Differential Pressure	0.1*
Test Gas Compressibility	0.02
Pipe Diameter	0.1
Cone Diameter	0.1

*For a differential pressure greater than or equal to 0.1 bar.

4.3 Test Results

The cone meter baseline calibrations were determined from build 1b, as is shown in Figures 31 and 32. For cone meter FE-5195-004 (beta 0.85), the gas calibration mid-point discharge coefficient value was 0.745 with a variability over the range of ± 1.02%. For cone meter FE-5195-003 (beta 0.6), the gas calibration mid-point discharge coefficient value was 0.836 with a variability over the range of ± 1.13%.

For all subsequent tests on these meters, this data was used as the baseline with the effects of different piping configurations being compared relative to them.

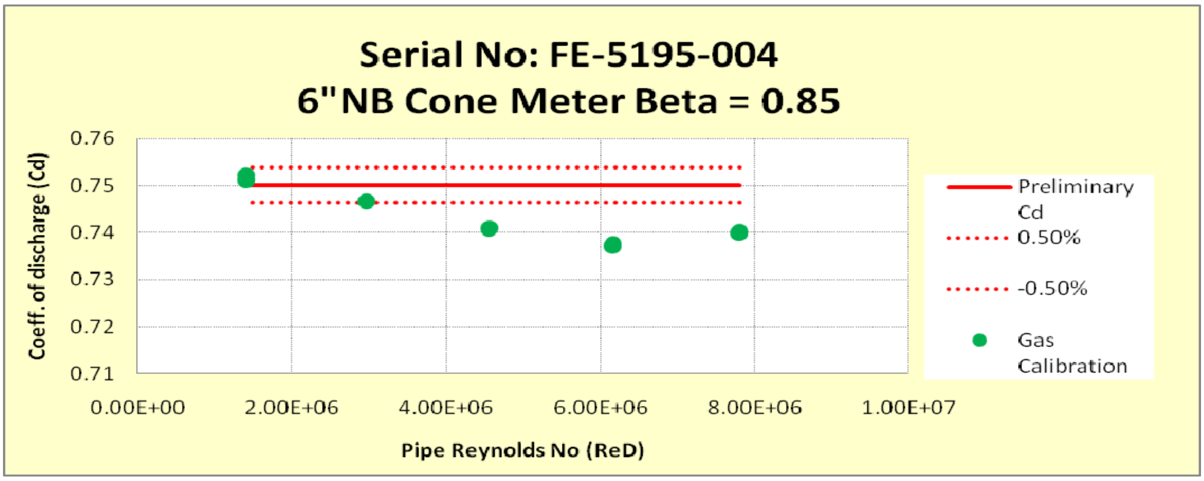

Figure 31 Gas calibration for 6 inch nominal bore β 0.85 cone meter

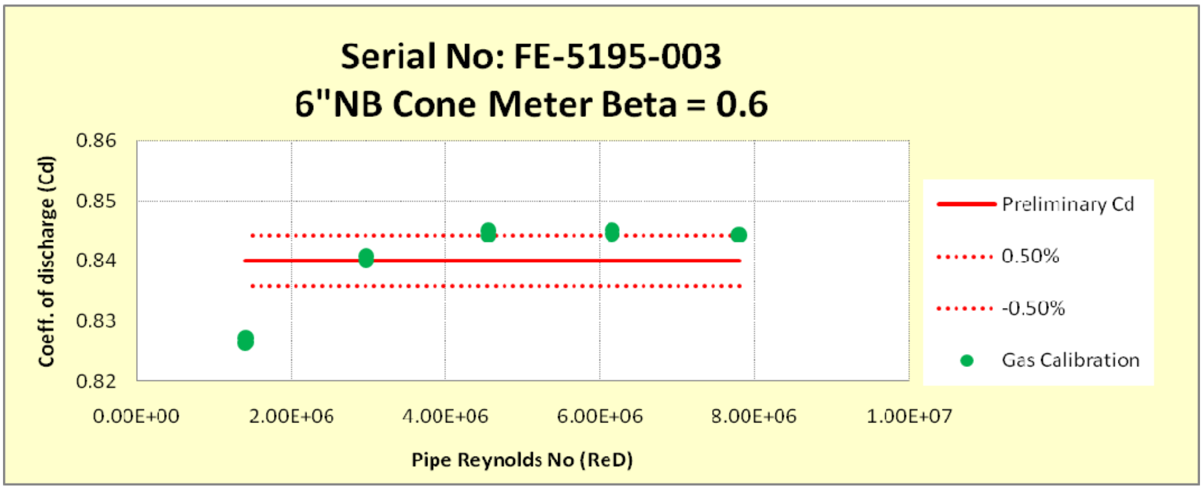

Figure 32 Gas calibration for 6 inch nominal bore β 0.6 cone meter

Build 2b Installation Effect: A single 90 degree bend immediately upstream of the cone meter, Serial Number FE-5195-003 (beta 0.6), displayed a shift in the discharge coefficient of between -0.04% and +0.31%, as shown in Figure 33.

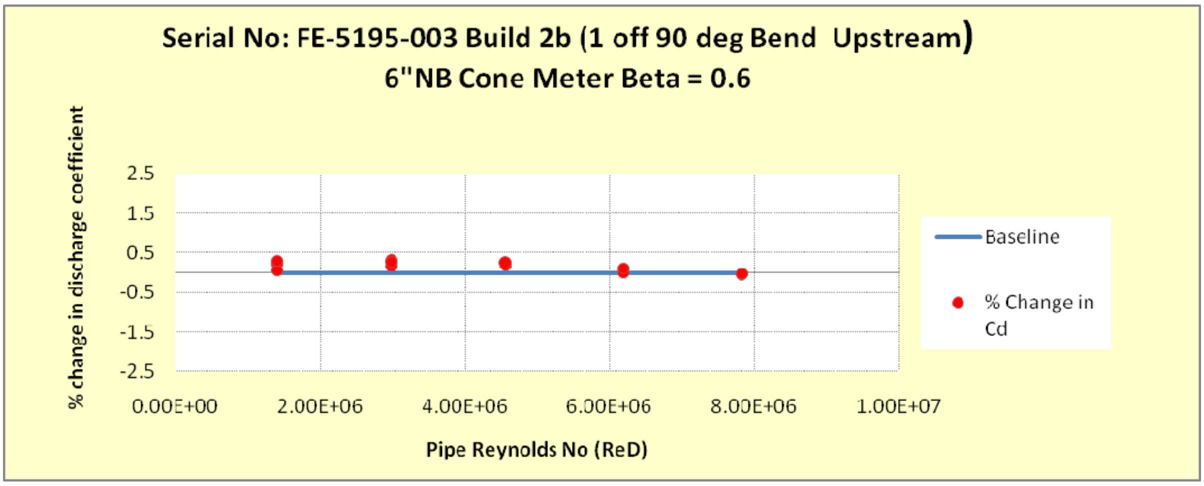

Figure 33 Percentage change in discharge coefficient from build 2b

Build 3b Installation Effect: Two 90 degree bends in the same plane, immediately upstream of the cone meter, Serial Number FE-5195-003 (beta 0.6), displayed a shift in the discharge coefficient of between -0.19% and +0.12%, as shown in Figure 34.

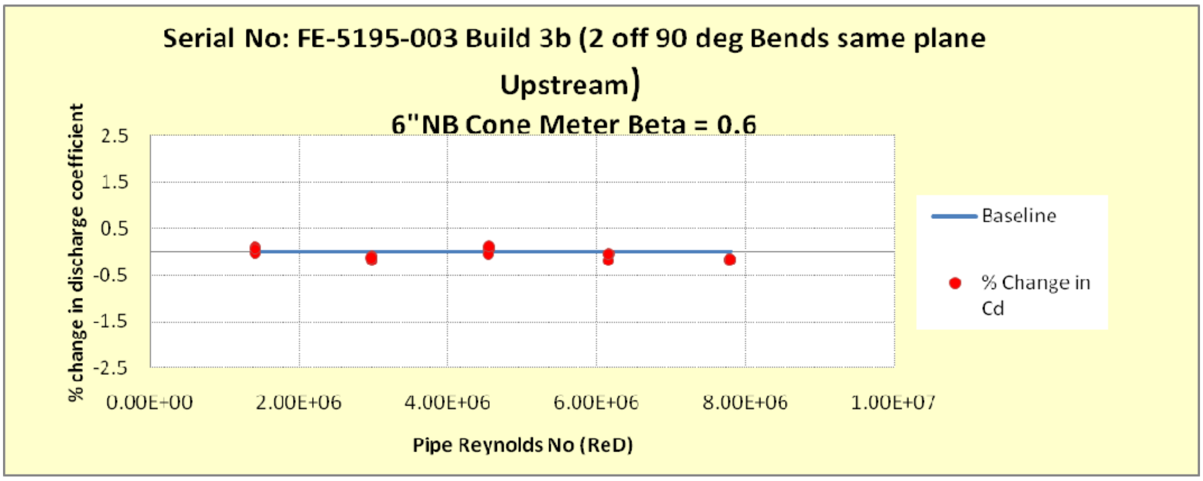

Figure 34 Percentage change in discharge coefficient from build 3b

Build 4b Installation Effect: Two 90 degree bends in the different planes, immediately upstream of the cone meter, Serial Number FE-5195-003 (beta 0.6), displayed a shift in the discharge coefficient of between -0.27% and +0.01%, as shown in Figure 35.

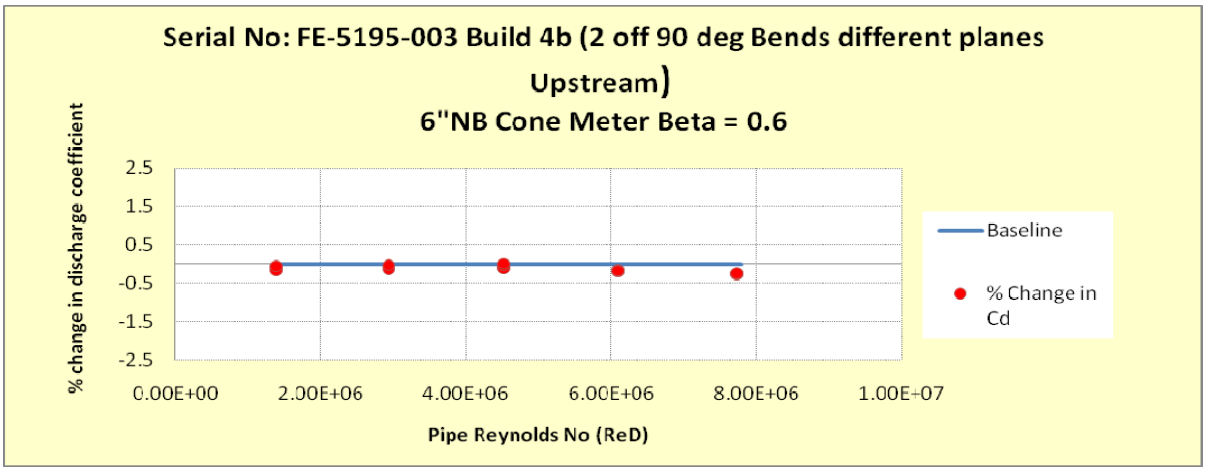

Figure 35 Percentage change in discharge coefficient from build 4b

Build 5b Installation Effect: A single 90 degree bend and then three diameters of straight pipe immediately upstream of the cone meter, Serial Number FE-5195-003 (beta 0.6), displayed a shift in the discharge coefficient of between -0.10% and +0.22%, as shown in Figure 36.

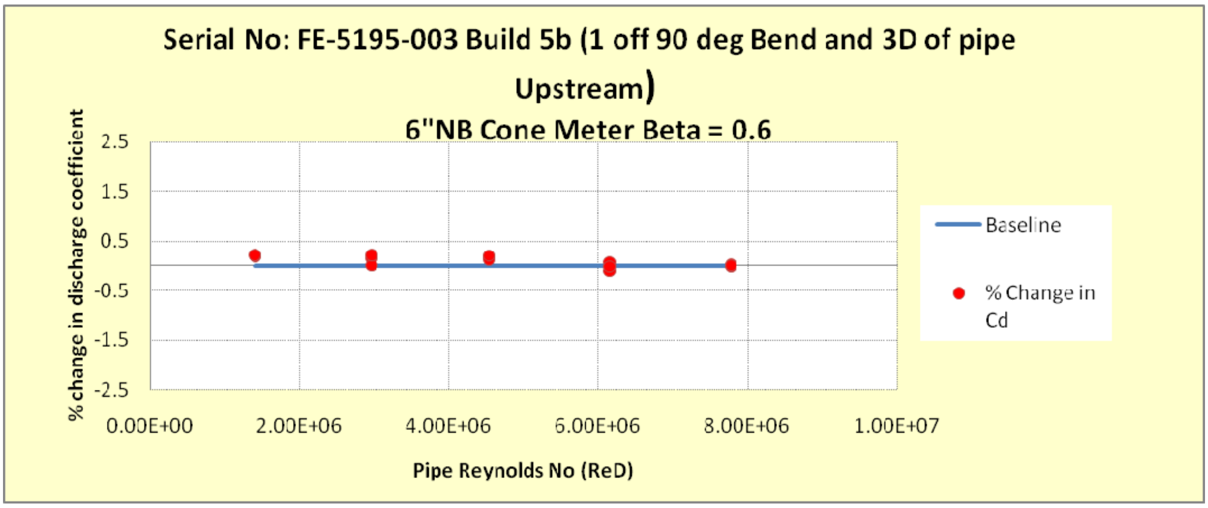

Figure 36 Percentage change in discharge coefficient from build 5b

Build 6b Installation Effect: A single 90 degree bend immediately upstream of the cone meter, Serial Number FE-5195-004 (beta 0.85), displayed a shift in the discharge coefficient of up to +1.37%, as shown in Figure 37.

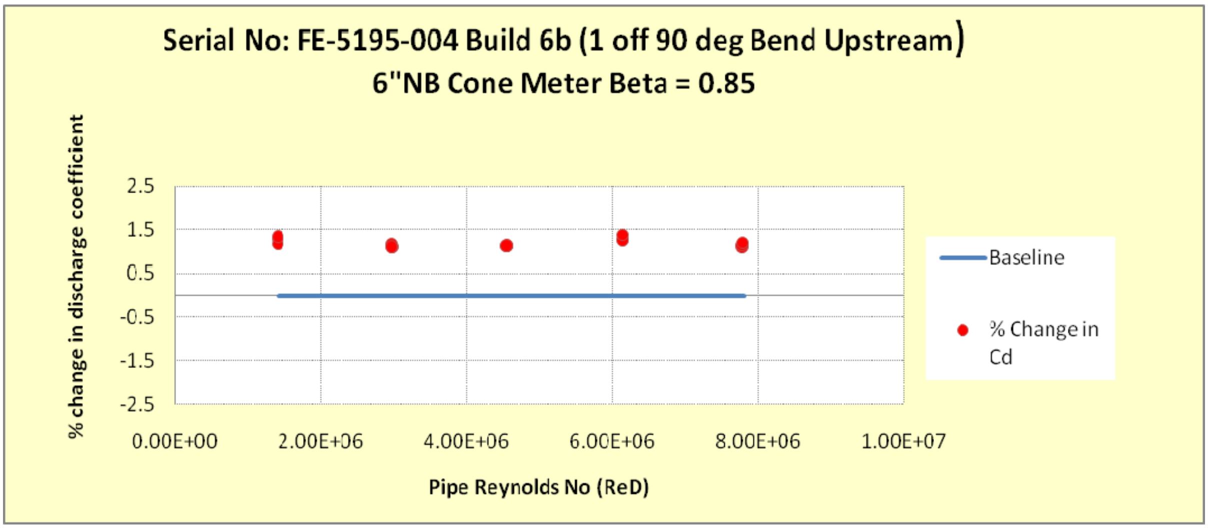

Figure 37 Percentage change in discharge coefficient from build 6b

Build 7b Installation Effect: Two 90 degree bends in the same plane, immediately upstream of the cone meter, Serial Number FE-5195-004 (beta 0.85), displayed a shift in the discharge coefficient of up to +0.68%, as shown in Figure 38.

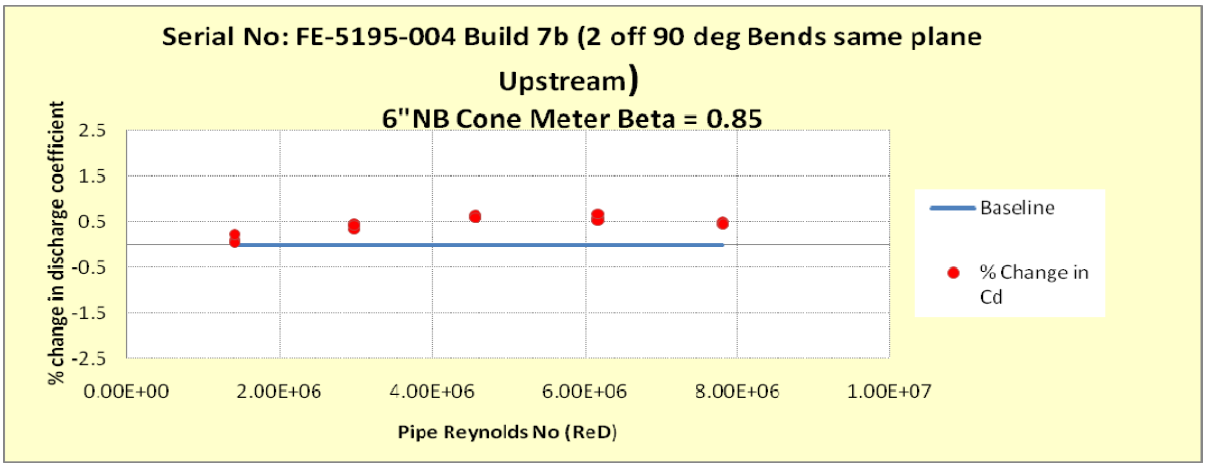

Figure 38 Percentage change in discharge coefficient from build 7b

Build 8b Installation Effect: Two 90 degree bends in different planes, immediately upstream of the cone meter, Serial Number FE-5195-004 (beta 0.85), displayed a shift in the discharge coefficient of up to +0.63%, as shown in Figure 39.

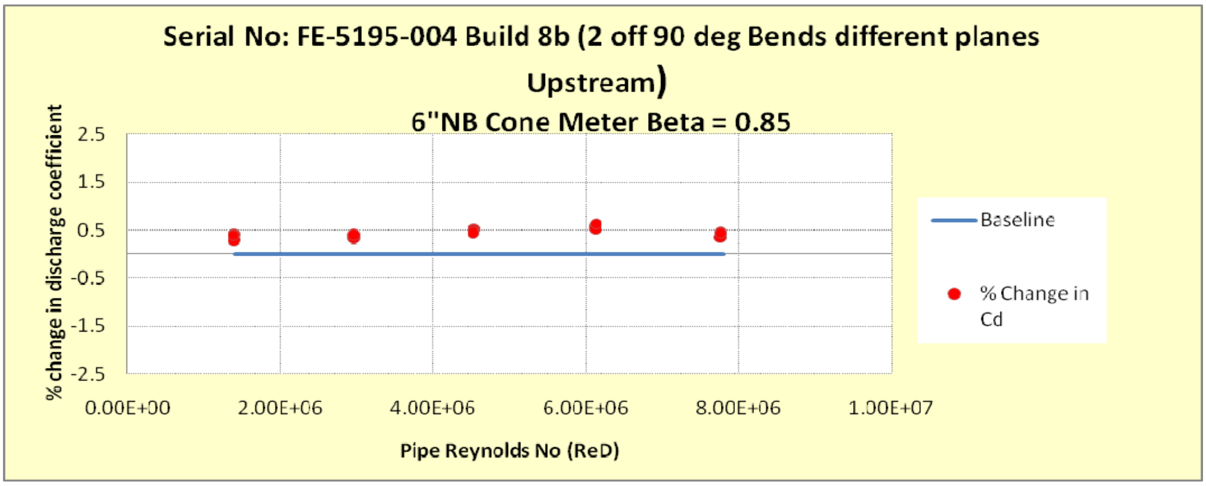

Figure 39 Percentage change in discharge coefficient from build 8b

Build 9b Installation Effect: A single 90 degree bend and then three diameters of straight pipe immediately upstream of the cone meter, Serial Number FE-5195-004 (beta 0.85), displayed a shift in the discharge coefficient of up to +0.86%, as shown in Figure 40.

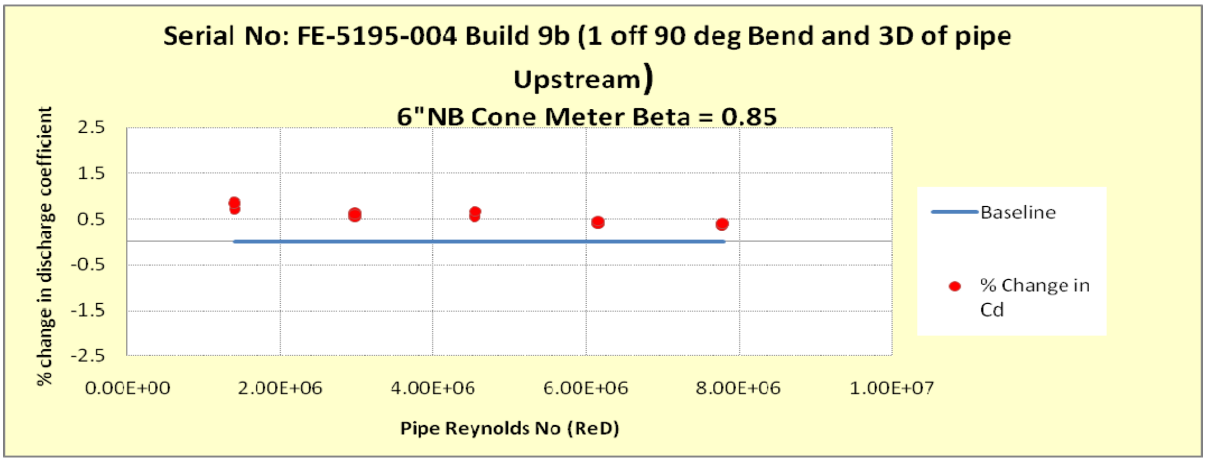

Figure 40 Percentage change in discharge coefficient from build 9b

As with the first phase of the overall test programme, and as detailed in Table 5, while the primary meter of interest was being calibrated to show the installation effect of the piping configuration, the secondary meter was placed 30 pipe diameters downstream and the results of this testing recorded as detailed below.

During builds 2b, 3b, 4b and 5b, cone meter FE-5195-004, with a beta value of 0.85, was placed downstream of cone meter FE-5195-003, with a beta value of 0.6, and the discharge coefficients compared against the original baseline calibration, as shown in Figure 41.

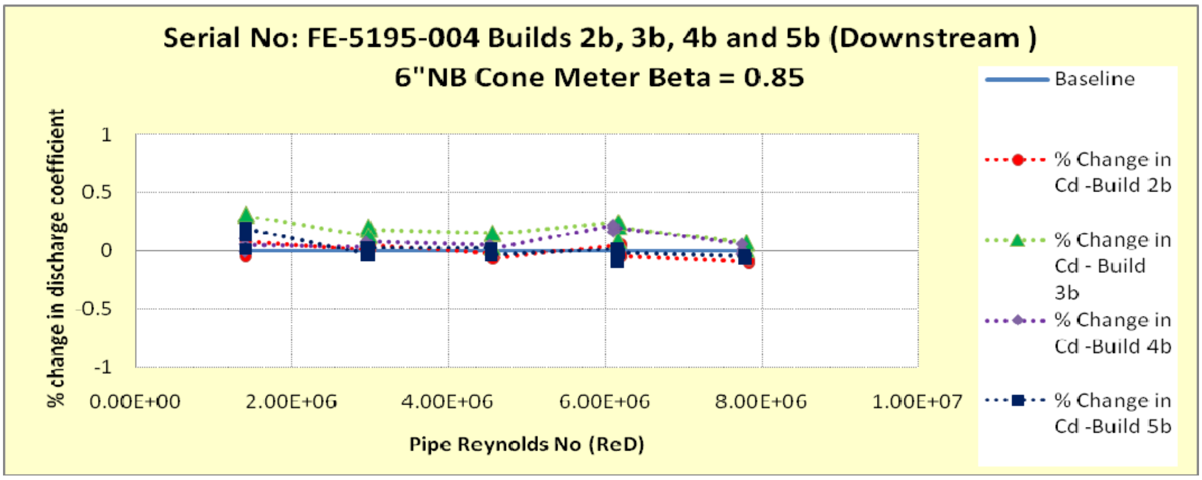

Figure 41 Change in discharge coefficient for the β 0.85 cone meter when downstream of the β 0.6 cone meter

Similarly, during Builds 6b, 7b, 8b and 9b, cone meter FE-5195-003, with a beta value of 0.6 was placed downstream of cone meter FE-5195-004, with a beta value of 0.85, and the discharge coefficients compared against the original baseline calibration, as shown in Figure 42.

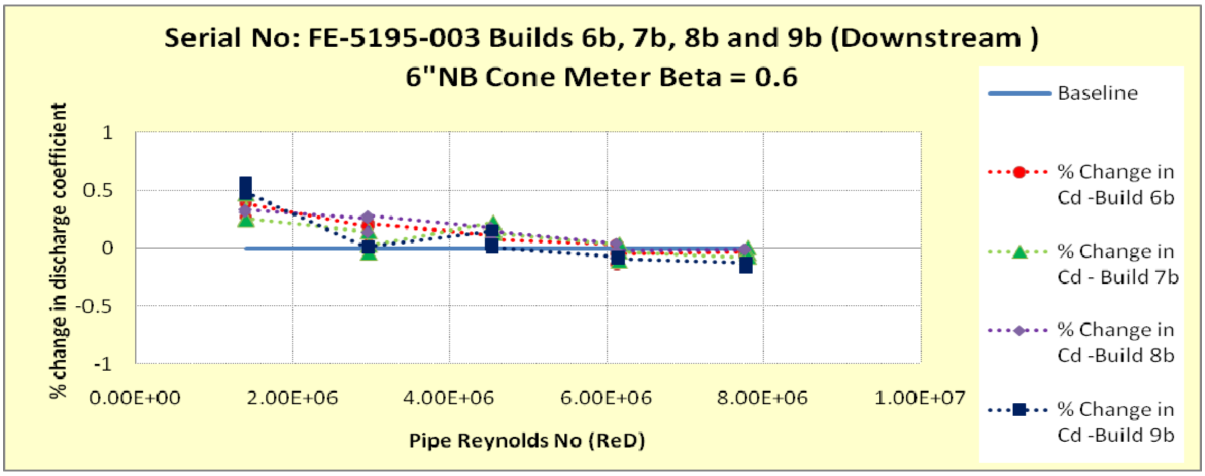

Figure 42 Change in discharge coefficient for the β 0.6 cone meter when downstream of the β 0.85 cone meter

5 CONCLUSIONS

5.1 Baseline Calibration

The Venturi meter complied with the guidance information published in Annex B of ISO-5167-4:2003 [1]. This was as expected, as Solartron ISA have calibrated several hundred Venturi meters at different facilities over many years, and have always found this to be consistent.

The discharge coefficients of all of the cone meters appear to be less predictable, and also show a dependency on both the beta value and pipe Reynolds number. This is supported by the paper presented by Hodges et al at the 27th International North Sea Flow Measurement Workshop [3], which provided the data for several cone meters calibrated at the CEESI test facility.

5.2 Effects of Piping Configuration

A summary of the data collected from the non-ideal piping configuration tests is shown in Tables 7 to 10 below:

Table 7 Summary of the effect of a single 90 degree bend upstream of the meter

Serial No	Manufacturer	Meter Type	β value	Below Baseline	Above Baseline
09-1162	'3rd party'	Cone meter	0.85	0 %	2.27%
FE-5195-004	Solartron ISA	Cone meter	0.85	0%	1.37%
FE-5195-003	Solartron ISA	Cone meter	0.6	0.04%	0.31%
FE-5195	Solartron ISA	Venturi meter	0.55	0.79%	0.62%

Table 8 Summary of the effect of a single 90 degree bend and 3 pipe diameters upstream of the meter

Serial No	Manufacturer	Meter Type	β value	Below Baseline	Above Baseline
09-1162	'3rd party'	Cone meter	0.85	0%	1.38%
FE-5195-004	Solartron ISA	Cone meter	0.85	0%	0.86%
FE-5195-003	Solartron ISA	Cone meter	0.6	0.1%	0.22%
FE-5195	Solartron ISA	Venturi meter	0.55	0.70%	0.33%

Table 9 Summary of the effect of two 90 degree bends in the same plane upstream of the meter

Serial No	Manufacturer	Meter Type	β value	Below Baseline	Above Baseline
09-1162	'3rd party'	Cone meter	0.85	0.11%	0.45%
FE-5195-004	Solartron ISA	Cone meter	0.85	0%	0.68%
FE-5195-003	Solartron ISA	Cone meter	0.6	0.19%	0.12%
FE-5195	Solartron ISA	Venturi meter	0.55	0.50%	0.49%

Table 10 Summary of the effect of two 90 degree bends in different planes upstream of the meter

Serial No	Manufacturer	Meter Type	β value	Below Baseline	Above Baseline
09-1162	'3rd party'	Cone meter	0.85	0%	0.69%
FE-5195-004	Solartron ISA	Cone meter	0.85	0%	0.63%
FE-5195-003	Solartron ISA	Cone meter	0.6	0.27%	0.01%
FE-5195	Solartron ISA	Venturi meter	0.55	0.26%	0.49%

From the results tabulated above, it can be seen that cone meters with a 0.85 beta value are significantly affected by 90 degree bends located immediately upstream (by up to 2.27%). The effect of adding 3 pipe diameters after the final 90 degree bend reduces the relative offset by approximately 40%. For this size of cone meter the effect of 2 bends, either in the same or in different planes, is similar and gives an offset of up to 0.69%, suggesting that the high beta value cone type meters are more sensitive to velocity profile asymmetry than to swirl.

The beta value 0.6 cone meter was shown to be the least sensitive instrument to upstream disturbances, as for all configurations the maximum (absolute) offset was approximately 0.25%. On the whole, for all three cone meters, the different upstream configurations caused a positive offset to the baseline discharge coefficient.

For the Venturi meter the offsets were generally fairly small except at two Reynolds numbers for one of which the offsets were negative, for the other positive.

6 RECOMMENDATIONS

Ultimately any recommendation will depend upon several end user requirements; however, the following may be considered as guidelines.

6.1 Venturi Meters

When a Venturi meter is to be employed with a sufficient upstream straight length of pipe, and the uncertainty of the flow measurement is typical for well management applications (± 5% for example), it would not always be essential to flow-calibrate the device as it would be expected that a correctly manufactured instrument would comply with ISO 5167-4:2003, even when the pipe Reynolds numbers are above 1 x 10^6.

For the same application, but with reduced upstream straight piping, it is likely that for pipe Reynolds numbers below 1 x 10^6 the same uncertainty would be achievable without flow calibration. However in order to meet the requirements of ISO 5167-4:2003, compliance with Table 1 of Section 4 should be maintained. This, for example, would require at least three diameters of pipe after a single 90 degree bend, with an additional uncertainty contribution being a necessary requirement.

For a Venturi meter application in which the uncertainty is required to be small or modest with reduced upstream straight piping and Reynolds numbers above 1 x 10^6, it would be advisable both to flow-calibrate the device over the entire pipe Reynolds number range that it will encounter in service and to simulate the upstream piping configuration during the calibration.

6.2 Cone Meters

The discharge coefficient of a cone meter is difficult to predict to any degree of uncertainty without calibration; therefore, it is recommended that irrespective of the uncertainty requirements, any application requiring this instrument should be flow calibrated, and moreover, to include the entire pipe Reynolds number range that will be seen in service. If piping configurations are non-ideal it is recommended that for large beta value devices, a simulation of the in-service piping configuration is utilized during the flow calibration.

For small beta value devices, such as the 0.6 beta value meter used during this test programme, it may be the case that only a calibration in straight pipe is required since the effect of common installation configurations appears to be relatively small. However, it would be prudent, given the opportunity and relatively low additional cost, to consider flow calibrating the device using piping that simulates the actual in-service upstream configuration.

6.3 Summary

It is important to note that whether a cone meter or Venturi meter is selected, and providing it has been correctly manufactured and calibrated over the entire operating Reynolds number range, the uncertainty on the discharge coefficient will be similar for either device.

Perhaps more importantly, whichever is the preferred device, it is paramount to discuss the application and the requirements with the flow meter vendor regarding the metering accuracy and how this can be best optimized. For example the correct selection of the subsea differential pressure transmitter can often be the most critical item within the metering system. Since many other factors determine the ultimate uncertainty of the measured flow rate, the vendor should be in a position to provide an uncertainty budget or analysis for the preferred flow metering solution and furnish technical and practical suggestions to ensure that this is best achieved.

7 FURTHER CONSIDERATIONS

7.1 Sand

When sand is present in the process fluid, over a sufficient time period changes to the meter internal geometry can occur that will affect the meter discharge coefficient. CFD predictions presented by Barton et al at The Americas Workshop 2010 [4] suggested that the presence of sand that would cause a -1% shift in discharge coefficient for a Venturi meter would result in a +40% shift for a cone meter.

7.2 Vibration and Wake Frequency

For normal operating conditions Venturi meters are considered to be robust and unaffected by wake frequency. The same is not true for cone meters, where for many designs the cone is suspended from a strut which is prone to resonant frequency issues, which could ultimately lead to mechanical failure. Often additional supports are added to dampen this effect, but there is very little data available regarding this subject. Solartron ISA has already embarked upon a research programme including both FEA and qualification testing so as to obtain a better understanding and improved design relating to this issue.

8 NOTATION

C_d The coefficient of discharge of the flow meter (-)

d Venturi tube throat diameter at operating conditions (m) or

Cone meter cone diameter or the equivalent diameter that would give the same area as the annulus created between the cone outside diameter and the pipe inside diameter at operating conditions (m)

D The upstream pipe internal diameter at operating conditions (m)

m_{ref} The mass flow rate obtained from the test facility reference flow meter (kg/s)

p_1 The absolute pressure at the upstream location (Pa)

p_2 The absolute pressure at the throat or cone edge location (Pa)

β For a Venturi tube, the diameter ratio d/D (-) or

For a cone meter this is given by $\sqrt{\frac{D^2-d^2}{D^2}}$ (-)

ε The expansibility factor (-)

Δp The measured differential pressure (Pa)

ρ_1 The fluid density at upstream conditions (kg/m^3)

κ The isentropic exponent of the fluid

τ The pressure ratio p_2 / p_1 (-)

9 REFERENCES

[1] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO): Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - ISO 5167-4:2003.

[2] STEWART, D., READER-HARRIS, M. J. and PETERS, R. J. W.: Derivation of an expansibility factor for the V-Cone meter. In Proc. of Flow Measurement 2001 International Conference, Peebles, May 2001,

[3] HODGES, C., BRITTON C., JOHANSEN, W. and STEVEN, R.: Cone DP Meter Calibration Issues. 27th International North Sea Flow Measurement Workshop, Tonsberg, Norway, October 2009.

[4] BARTON, N., ZANKER, K. and STOBIE, G.: Erosion Effects on Venturi and Cone Meters. The Americas Workshop, Houston, USA, April 2010.