Testing the Wafer V-Cone Flowmeters in accordance with API 5.7 “Testing Protocol for Differential Pressure Flow Measurement Devices” in the CEESI Colorado Test Facility

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Abstract: The paper describes the testing of the Wafer V-Cone Meters in accordance with the new API 5.7 “Testing Protocol for Differential Pressure Flow Measurement Devices” in the Colorado Test Facility. This paper will report on the use of this new API standard and some of the points which had to be addressed in order to implement the standard. The results of the testing 2” and 4” Wafer V-Cone meters in water and in gas will be presented. The non-standard testing requirements in the standard will provide evidence of the conditioning effect of the V-Cone as it meters the fluid. The conclusions reached were: API 5.7 tests the claims of the meter manufacturer regarding the product in a demanding manner. As the procedure is implemented the need to make amendments will become apparent and this paper will address some of the limitations which became evident while testing. The results of the Wafer V-Cone Testing Uncertainty will be discussed.

Keywords: API 5.7 Test Protocol, Wafer V-Cone Meter.

1. Introduction

The paper describes the testing of the Wafer V-Cone Meters in accordance with the new API 5.7 “Testing Protocol for Differential Pressure Flow Measurement Devices” [1] at the Colorado Engineering Experiment Station Inc. (CEESI) Test Facility. This paper will report on the use of this new API standard and the points which had to be addressed in order to implement the standard. The results of the testing of 2” and 4” Wafer V-Cone meters with water and gas flows are presented. The non-standard testing requirements in the standard provides evidence of the conditioning effect of the V-Cone as it meters the fluid.

2. API 5.7 “Testing Protocol for Differential Pressure Flow Measurement Devices”

This standard was published in January 2003 “to supply industry with a comparable description of the capabilities of these devices for the measurement of single-phase fluid flow when they are used under similar conditions”. A laboratory traceable to NIST or an equivalent national or international standard is required and McCrometer chose to undertake the first tests of a differential pressure meter, i.e. the Wafer V-Cone meter, in accordance with API 5.7 at CEESI. This paper gives the results and conclusions from this series of tests and recommends some possible modifications to the standard.

3. The Wafer V-Cone

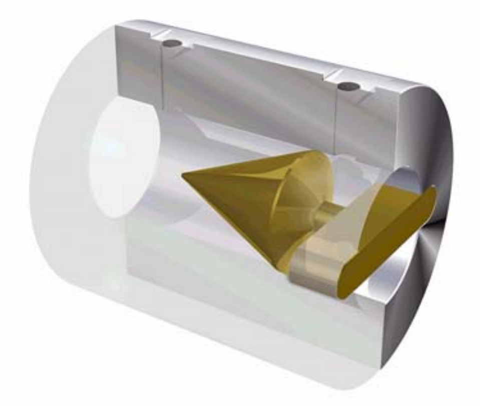

Fig. 1 A Sketch of a Wafer V-Cone Meter

The Wafer V-Cone meter is one of the V-Cone type differential pressure meter designs which use the generic differential pressure meter equation with specific discharge coefficient values, expansibility and beta ratio equations and can be utilized with normal differential pressure meter secondary and tertiary instrumentation. The novel feature of the Wafer V-Cone is that the beta ratio can be changed using a removable cone assembly. Figure 1 shows a schematic of the Wafer V-Cone meter.

The Wafer V-Cone meter design is available in various line sizes ranging from 1" to 6" (all in schedule 80). API Chapter 5.7 requires testing on two nominal line sizes that will produce a minimum 2:1 line size ratio and consequently 2" and 4" Wafer V-Cones were selected for these tests.

The 2" wafer body used a 0.45 beta cone assembly.
The 4" wafer body was tested using cone sizes that gave 0.45, 0.5, and 0.65 beta ratios. The inside diameter of the wafer body was the same as the piping system into which the Wafer V-Cone meter was installed (i.e. 2” and 4” schedule 80 pipe).

4. Description of Test Facility

Testing was performed on two different types of calibration systems.

4.1 Liquid Flow Testing

Water testing was carried out using a gravimetric system, as shown in Figure 2. The water gravimetric system has an uncertainty for the mass flowrate of +/-0.1%.

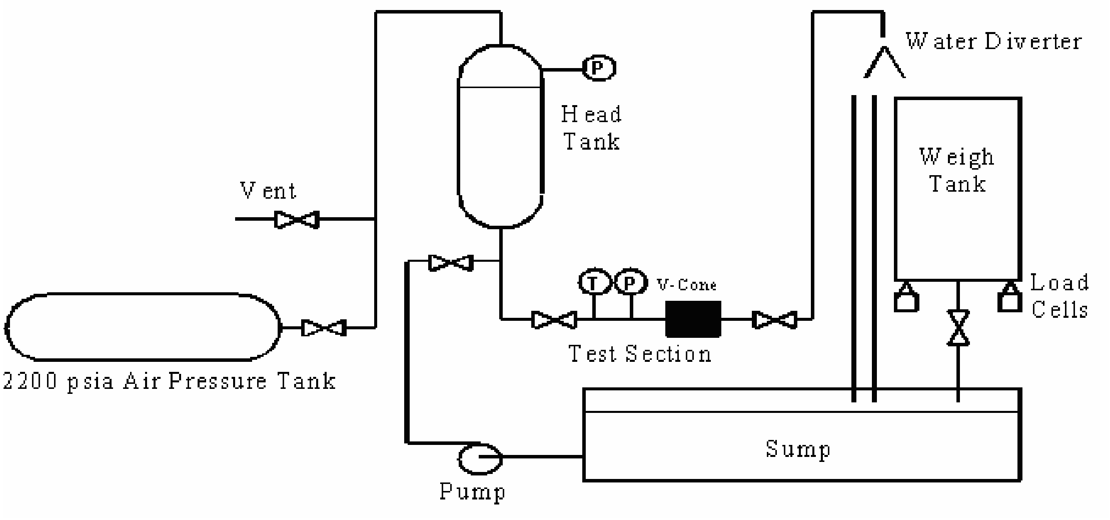

Fig. 2 Water Test System

4.2 Gas Flow Testing

Gas testing was performed using compressed air in a secondary calibration system, as shown in Fig 3. This used a critical flow Venturi (CFV) as the flow standard. The uncertainty associated with the measurement of mass flowrate using a CFV is approximately +/-0.35%.

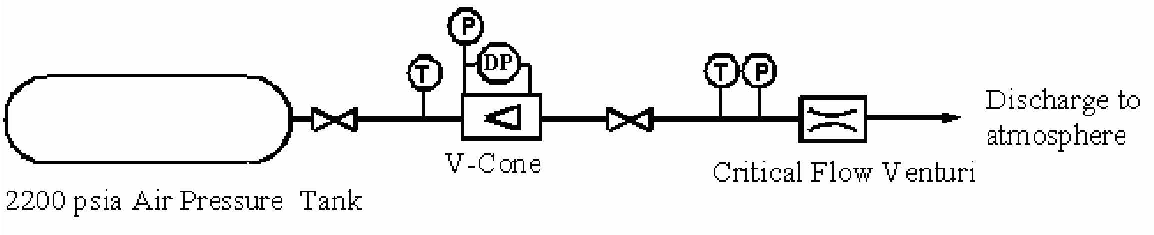

Fig. 3 Air Test System

5. Testing and Results

5.1 Orifice Flowmeter Testing (API Ch. 5.7 Section 4. 1)

Section 4.1 of API 5.7 states "Having established the veracity of the Test Facility, the orifice meter run shall be removed and replaced by the primary element under test." Although this could be interpreted as the orifice meter having the same line size as the meter under test, it was decided to use the line size between the two meter sizes being tested, i.e. a 3" orifice meter. This decision was taken as the 2" orifice data is acknowledged to have a relatively high uncertainty and CEESI lab personnel believed the 3" line size would better meet the intentions and aims of API 5.7.

A 3" sch 40 orifice flange unit, was constructed in compliance with ANSI/API 2530, using a 1.625" bore orifice in an orifice flange unit, resulting in a beta ratio of 0.53. API 5.7 requires that the test facility must give orifice meter results that are “within the 95% confidence interval of the Reader-Harris Gallagher (R-G) equation [2]. For verification of the laboratories, the upstream meter tubes had a 19 tube bundle at seven diameters from the orifice plate, for both the gas and liquid (i.e. water) test systems.

The orifice meter gas flow calibration was performed with air and was conducted at a line pressure of 150 psia. The results of the air calibration are shown in Fig 4. The standard deviation for each of the calibration data points from the R-G equation is 0. 12%.

The calibration performed with water is also shown in Fig 4. In this case the standard deviation for each of the calibration data points from the R-G equation is 0.10%.

The air and water calibration results with the orifice flow meter show that the liquid and gas calibration systems are operating properly. The data is well within the uncertainty bounds of the R-G equation showing that the geometry of the meter was in compliance with standards and that the lab bias is within the stated uncertainty.

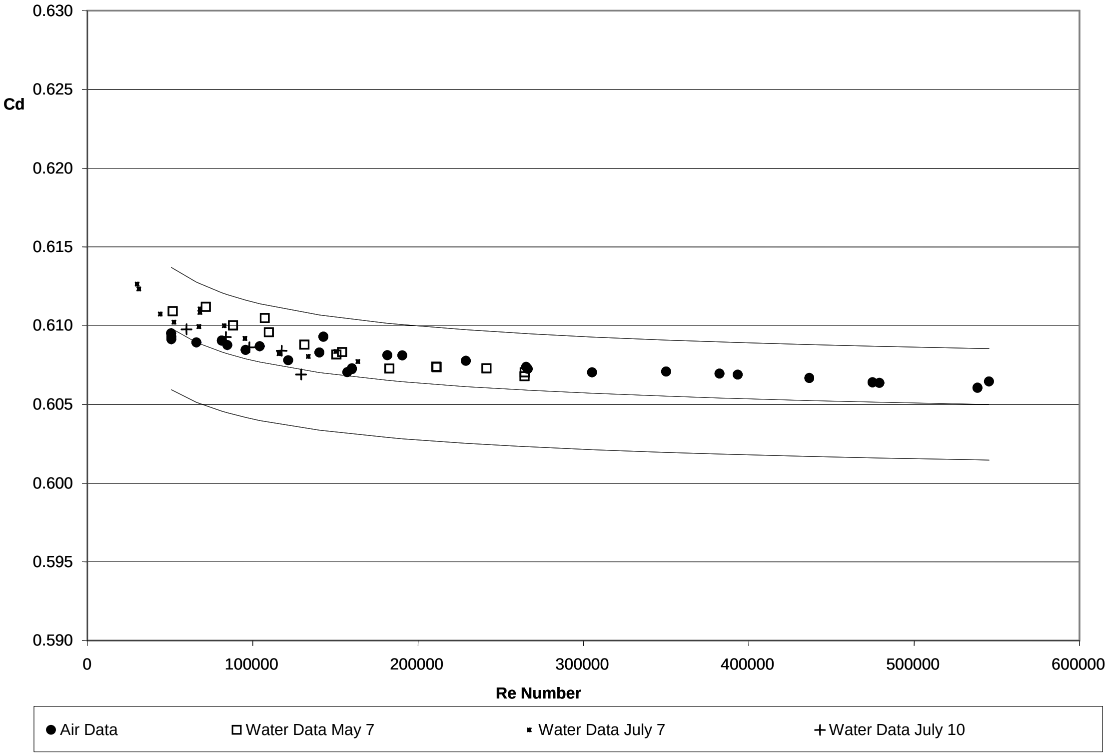

Fig. 4 3” Orifice Plate Test Results with R-G Equation Uncertainty Bands

5.2 Standard Wafer V-Cone Meter Tests (API Ch. 5.7 Section 3.1.1)

Standard Wafer V-Cone meter testing was performed to establish characteristic curves for each of the Wafer V-Cone flow meters. McCrometer sells the meters with a 10:1 turndown on flow so this was the range tested. The 4" meter was tested from 50,000 to 500,000 Reynolds numbers (Re) and the 2" meter from 30,000 to 320,00 Re. The meter sizes and pipe Reynolds number ranges are tabulated below (see Table 1). A pressure variation of 5:1 was tested giving pressures from 36 bar (abs) to 6 bar (abs). API 5.7 states that “For gas flows, the high pressure must be at least five times the low pressure”.

The Wafer V-Cone flow meters were calibrated with 40+ diameters of straight upstream piping and no flow conditioner installed upstream of the meter. The graphs of the uncertainty values across the Reynolds number ranges for the four Wafer V-Cone flow meters tested in the standard pipe configuration are shown in the Appendix as Figures A2–A5.

Line Size	Beta	Pipe Reynolds Number Range
4”	0.45	50,000 to 500,000
	0.50	50,000 to 500,000
	0.65	50,000 to 500,000
2”	0.45	30,000 to 320,000

Table 1. Pipe Reynolds Number Ranges Covered During Testing for each Wafer V-Cone Meter.

The results of the standard testing are shown in Figures A6 to A9. Wafer V-Cone meter users typically want a single (or “constant”) discharge coefficient (Cd) value throughout the flow range. The single Cd value is chosen from analysis of calibration data, covering the desired flowrate range. Here Cd is arrived at by determining the upper and lower Cd bounding values and then calculating the midpoint Cd value (Mid Cd). Mid Cd values were calculated for each of the Wafer V-Cone 87 psia tests (as this condition was chosen by CEESI to be the baseline condition) and are plotted as a solid line with the test results in Figures A6 to A9. Mid Cd values for all the tests are listed for in Figure A1.

The analysis of test results are based on the difference in Mid Cd between any one test and the baseline data for that Wafer V-Cone meter. The uncertainty for the difference is based on the uncertainty analysis results. If the difference between the Mid Cd value for a test and the baseline Mid Cd value is greater than the uncertainty associated with the difference then there is a significant statistical difference between the two sets of data. If the difference between the Mid Cd value for a test and the baseline Mid Cd value is less than the uncertainty associated with that difference then there is no statistical difference between the two sets of data. The differences between Mid Cd values for each test and the baseline Mid Cd are listed in Figure A1 along with the uncertainties associated with the differences in Mid Cd.

With the exception of the low Reynolds number point on the 2" 0.45 beta test, all of the curve shapes are very similar. A trend in the 4" data is also apparent, with increasing Wafer V-Cone meter beta ratio values tending to produce increasing discharge coefficients (as would be expected).

Section 3.3 of API 5.7 requires that the tests “verify the expansibility equation across the stated range of the meter”. The consistent results between a compressible and an incompressible fluid, different line sizes, different beta ratios and different pressures indicate that the expansion of the gas density through the meter is correctly accounted for in all cases and hence the expansibility equation is verified. The conclusion is that the expansibility equation developed by McCrometer and Reader-Harris et al. [3] is appropriate.

The Mid Cd values were determined for each of the Wafer V-Cone meter gas tests and these gas Mid Cd values are listed in Figure A1 along with the differences between the gas Mid Cd values and the baseline Mid Cd values and the uncertainties associated with those differences. When comparing the data sets for each meter it was found that there is no significant statistical difference between the Mid Cd values for the 4" 0.45 beta and 4" 0.65 beta Wafer V-Cone meters. There are small differences between Mid Cd values for the 2" 0.45 beta ratio and the 4" 0.5 beta ratio Wafer V-Cone meters.

5.3 Non-Standard Tests (API Ch. 5.7 Section 3.1.1.2)

Non-standard testing was performed to evaluate the Wafer V-Cone meter’s performance in non-ideal flow conditions. The following non-standard tests were performed in accordance with section 3.1.1.2 of API 5.7, using the 4" Wafer V-Cone meter with the 0.45 beta insertion cone:

API 3.1.1.2a	Close coupled out-of-plane elbows upstream of the meter at 0D
API 3.1.1.2b	Half-moon orifice plate upstream of the meter at 3.1D
API 3.1.1.2b	Half-moon orifice plate upstream of the meter at 0D
API 3.1.1.2c	Swirl Generator upstream of the meter at 0D

Note: As CEESI did not have a half-moon plate in this line size, it was decided to use a half-open gate valve instead. For both positions tested the valve had the opening at the bottom of the pipe and the meter tappings were at the top of the pipe.

These non-standard tests were performed with long straight lengths of pipe upstream of the meter disturbance. For the Wafer V-Cone meter it was decided that there was no requirement for a flow conditioner between the disturbance and the meter under test.

5.3.1 Coupled Out-of-Plane Elbows at 0d

The close coupled out-of-plane elbows test was conducted while maintaining a static line pressure of 87 psia with 0D between the elbows and the Wafer V-Cone meter, see Figure 5. Out-of-plane elbows produce swirl as well as asymmetric velocity profiles. The results are shown in Figure A10 along with the results of the standard tests.

The out-of-plane Mid Cd values are listed in Figure A1 along with, the differences between the out-of-plane Mid Cd values, and the baseline Mid Cd values and the uncertainties associated with those differences. There is no statistical difference between the out-of-plane and baseline Mid Cd values, confirming the ability of the Wafer V-Cone meter to provide accurate results in very asymmetric, swirling flow.

Fig. 5 Out-of-Plane Elbows Test Setup

5.3.2 Open Gate Valve Tests at 3.1D

The half open gate valve, at 3.1 D, tests was conducted while maintaining a static line pressure of 87 psia. A partially opened gate valve with the open portion of the valve 180 degrees away from the Wafer V-Cone meter pressure taps created an asymmetric velocity profile. The results are shown in, Figure A11 along with the results of the standard tests. Figure 6 shows the half-open gate valve used.

The decision to place the disturbance at approximately 3D was made on the basis of the McCrometer claim that the meter can perform in a satisfactory manner when there are disturbances from 0 to 3D from the meter. A partially opened gate valve with the open portion of the valve 180 degrees away from the Wafer V-Cone meter pressure taps was used to create an asymmetric velocity profile.

The difference, between the Half-Open Gate Valve at 3.1D, and the baseline data Mid Cd values is shown in Figure A1. There is no significant statistical difference between the Half-Open Gate Valve at 3.1 D and the baseline Mid Cd values, again showing the ability of the Wafer V-Cone to perform with asymmetric flow.

5.3.3 Half Open Gate Valve at 0D

The half open gate valve at 0D test was once more conducted, while maintaining a static line pressure of 87 psia. Again, the partially opened gate valve had the open portion of the valve 180 degrees away from the Wafer V-Cone meter pressure taps.

The results are shown in Figure A12 with the results of the 87 psia standard test along with a solid line indicating the base line Mid Cd value. The difference between the Half-Open Gate Valve at OD and the baseline data Mid Cd values is shown in Figure A1. The difference between the Half-Open Gate Valve at 0D and the baseline Mid Cd values is 1.961 % +/- 0.827%. This shows that a half open gate valve immediately in front of the meter can result in a 2% error.

Fig 6. Half-Open Gate Valve

5.3.4 Swirl Generator at 0D

A fixed angle swirl generator was used to generate the 24°, required by API 5.7, with the swirl angle being checked by a pitot tube, 18D downstream of the swirl generator. The results are shown in Figure A13 and compared with the results of the 87 psia standard test. A picture of the swirl generator is shown in Figure 7.

The difference between the Swirl Generator at 0D and the baseline Mid Cd value~~s~~ and the uncertainty associated with that difference is shown in Figure A1. There is no significant statistical difference between the Swirl Generator at 0D and the baseline data Mid Cd value. Again this indicates how well the Wafer V-Cone performs in swirling flow.

Fig. 7 Swirl Generator

5.4 Liquid Flow Tests (API Ch. 5.7 Section 3.2)

Liquid flow tests were performed on the 0.45 and 0.65 beta ratio Wafer V-Cone meters in the 4" line and on the 0.45 beta ratio Wafer V-Cone on the 2" line size. The results of the liquid flow tests are shown in all Appendix figures (except Figure A8 as no 4” 0.5 beta ratio water test was carried out).

The differences between the liquid flow tests and air baseline Mid Cd values along with the uncertainty associated with those differences is shown in Figure A1. The test results for the 4" 0.45 and 0.65 beta ratio V-Cone meters showed no significant statistical difference between the low (or high) pressure air and water test results.

The results of the liquid flow testing for the 2" 0.45 beta ratio Wafer V-Cone meter are shown in Figure A6. The difference between the liquid flow test and the air baseline data is shown in Figure A1 along with the uncertainty associated with that difference. The difference between the liquid flow test and the air baseline Mid Cd values is 1.93% ±0.785.

5.5 Acoustic Noise Testing API Ch. 5.7 Section 3.5)

Noise measurements were taken during the low pressure air testing of the Wafer V-Cone flow meters. The noise meter was positioned approximately 3 feet downstream of the Wafer V-Cone flow meter and approximately 3 feet away from the downstream pipe.

The noise measurements taken during the low pressure air testing of the Wafer V-Cone were compared to noise measurements made in different locations within the test area. There was no measurable difference between any of the noise measurements regardless of location. The background noise within the test area dominated the noise measurements.

6. Uncertainty Analysis

An uncertainty analysis was conducted on each of the low pressure air tests and on the water tests to determine the representative uncertainty of the Wafer V-Cone flow meters. The uncertainty analysis was performed in a similar fashion to ANSI/API 2530. The results of the uncertainty analysis are presented in the CEESI API 5.7 Wafer Cone Meter report.

The performance of the Wafer V-Cone meter in the analysis used the Cd Standard Uncertainty term. The Cd Standard Uncertainty term was found by calculating the standard deviation of the individual data acquisition scans from the Wafer V-Cone characteristic curve. The standard deviation was then multiplied by two to produce the 95% confidence level and these are shown in Figure A1.

7. Conclusions for the Testing of the Wafer V-Cone Meter

7.1 Water and air tests were performed on 4 Wafer V-Cone meters for McCrometer. One 2 inch Wafer V-Cone with a beta of 0.45 and three 4" Wafer V-Cone meters with beta ratios of 0.45, 0.5, and 0.65 were tested.

7.2 Testing was performed using compressed air on all of the Wafer V-Cone meters at a line pressure of 87 psia to establish baseline performance. These tests revealed that the characteristic curves of all of the Wafer V-Cone meters were very similar. The similarity of the characteristic curves indicates that the expansibility equation used with the Wafer V-Cone meter is correct.

7.3 Testing was performed at a significantly higher air pressure on all 4 Wafer V-Cone meters. The high pressure test results were compared to the low pressure test results and uncertainty bounds. The 4" 0.45 and 0.65 beta ratio Wafer V-Cone meter test results show no differences between the high pressure and baseline meter performance. The 2" 0.45 beta ratio and 4" 0.5 beta ratio test results show slight differences between the high pressure and baseline test results.

7.4 Liquid testing was performed on the 4" 0.65 and 0.45 beta ratio Wafer V-Cone meters as well as the 2" 0.45 beta ratio Wafer V-Cone meter. The liquid testing was performed using water. The differences between the liquid flow tests and the baseline tests performed on those meters along with the uncertainties associated with those differences are shown in Figure A1. The 4" 0.65 and 0.45 beta ratio Wafer V-Cone meter test results show no differences between the liquid flow and baseline meter performance. The 2" 0.45 beta ratio Wafer V-Cone meter test results show a difference between the liquid flow and air flow baseline test results of 1.93%±0.644%.

7.5 Non-standard testing was performed on the 4" 0.45 beta ratio Wafer V-Cone meter to determine the sensitivity of the Wafer V-Cone meter to asymmetric velocity profiles and swirl. Tests were conducted with a swirl generator at 0D, double out-of-plane elbows at 0D, a half-open gate valve at 3.1D, and a half-open gate valve at 0D. The differences between these tests and the baseline test results on the 4" 0.45 beta ratio Wafer V-Cone meter along with the uncertainty associated with the differences is shown in Figure A1. The only test showing a significant statistical difference between the test results and the baseline data is the Half-Open Gate Valve at 0D. These results indicate that the Wafer V-Cone exhibits a high degree of insensitivity to installation effects.

7.6 Noise measurements were made during all of the low pressure air testing performed on the four Wafer V-Cone meters. It was not possible to differentiate between the background noise in the test area and the noise produced by the Wafer V-Cone meters.

7.7 In conclusion the McCrometer Wafer V-Cone meter in these tests met the claims made by the manufacturer and exhibited an exceptional ability to operate effectively downstream of flow disturbances.

8. Discussion on the API Standard 5.7 " Testing Protocol for Differential Pressure Flow Measurement Devices"

8.1. The Standard provides a comprehensive series of tests for a differential pressure flow measurement device and subjects the meter to onerous flow regimes.

8.2. It specifies the use of an orifice plate to determine the laboratory's ability to test differential pressure meters in a manner which is traceable to NIST. The difficulty for the laboratory is that it is required to have orifice runs for all the sizes of meters which may be tested. This appears to a costly addition when the laboratory must have a mechanism to calibrate meters in accordance with NIST. If this requirement remains within the standard a clearer definition of the orifice size for the test is required in Section 4.1.

8.3. The uncertainty calculations and presentation appears to cause problems with the laboratories. It may be necessary to be more specific in API 5.7. Care would have to be taken in the revision as API 5.7 has to avoid being so specific that the results of the meter under test could be hindered from being presented in a comprehensible manner.

8.4 It is not clear how the expansibility should be evaluated from the tests. The tests do strongly suggest that the expansibility equation must be of the correct order if the tests at different pressures and fluids overlap (as was the case in these tests) but there is no specified procedure to formally verify a test meters expansibility equation.

Reference

[1] Manual of Petroleum Measurement Standards, Chapter 5.7 – Testing Protocol for Differential Pressure Flow Measurement Devices. First Edition, January 2003

[2] ISO 5167 Revision 4, "Measurement of Fluid Flow by Means of Pressure Differential Devices Inserted in Circular Cross-Section Conduits Running Full", Section 2.

[3] Peters R.J.W, Reader-Harris M., Stewart D., "An Experimental Derivation of an Expansibility Factor for the V-Cone and Wafer Meter", North Sea Flow Measurement Workshop, Kristiansand, Norway, October 2001

APPENDICES

Summary of Test Results

Meter Size	Beta	Pressure (psia)	Standard (S) or Non-Standard (N)	Air or Water	Mid. Cd	95% Wafer V-Cone Performance Confidence Bands (%)	Percent Difference (%)	Percent. Difference Uncertainty (%)	Comments
2”	0.45	87		Air	0.881	0.31			Standard Test
2”	0.45	441	S	Air	0.874		-0.795	0.785	Standard Test
2”	0.45		S	Water	0.864		-1.930	0.785	Standard Test
4”	0.45	87	S	Air	0.867	0.394			Standard Test
4”	0.45	441	S	Air	0.865		-0.231	0.827	Standard Test
4”	0.45		S	Water	0.864		-0.116	0.827	Standard Test
4”	0.5	87	S	Air	0.872	0.232			Standard Test
4”	0.5		S	Air	0,864		-0.917	0.637	Standard Test
4”	0.65	87	S	Air	0.891	0.124			Standard Test
4”	0.65	377	S	Air	0.888		-0.337	0.690	Standard Test
4”	0.65		S	Water	0.887		-0.449	0.690	Standard Test
4”	0.45	87	N	Air	0.869		0.231	0.827	Half-Open Gate Valve at 3.1D
4”	0.45	87	N	Air	0.884		1.961	0.827	Half-Open Gate Valve at 0 D
4”	0.45	87	N	Air	0.870		0.346	0.827	Out-of-Plane Elbows at 0D
4”	0.45	87	N	Air	0.868		0.115	0.827	Swirl Generator at 0 D

Fig. A1 Test Result Summary

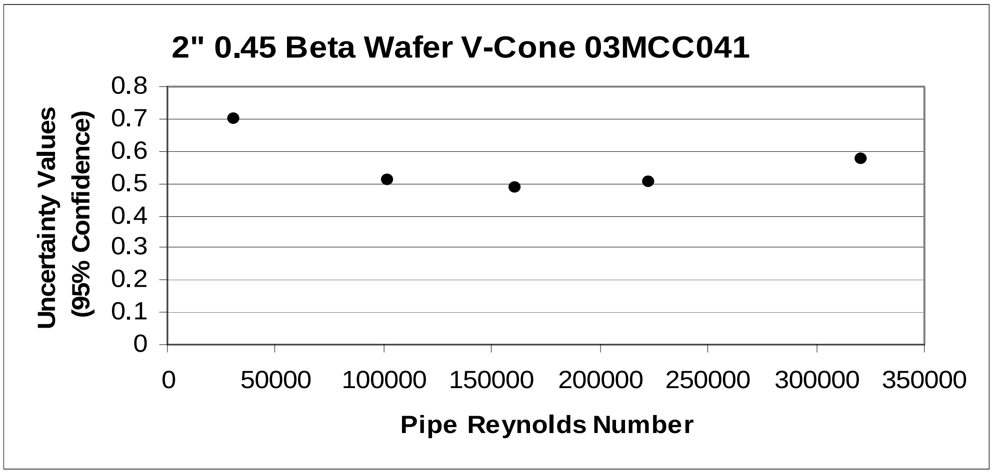

Fig. A2 Uncertainty Analysis for the 2” 0.45 Beta Ratio Wafer Cone.

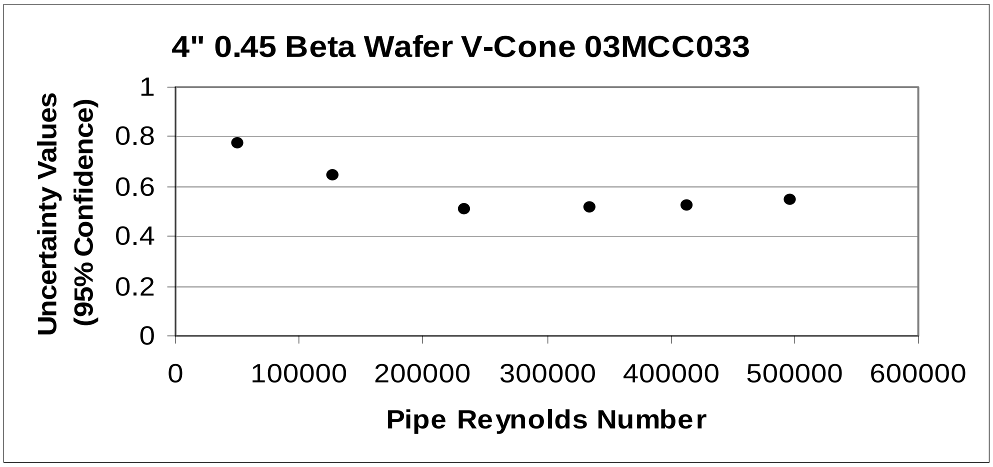

Fig. A3 Uncertainty Analysis for the 4” 0.45 Beta Ratio Wafer Cone.

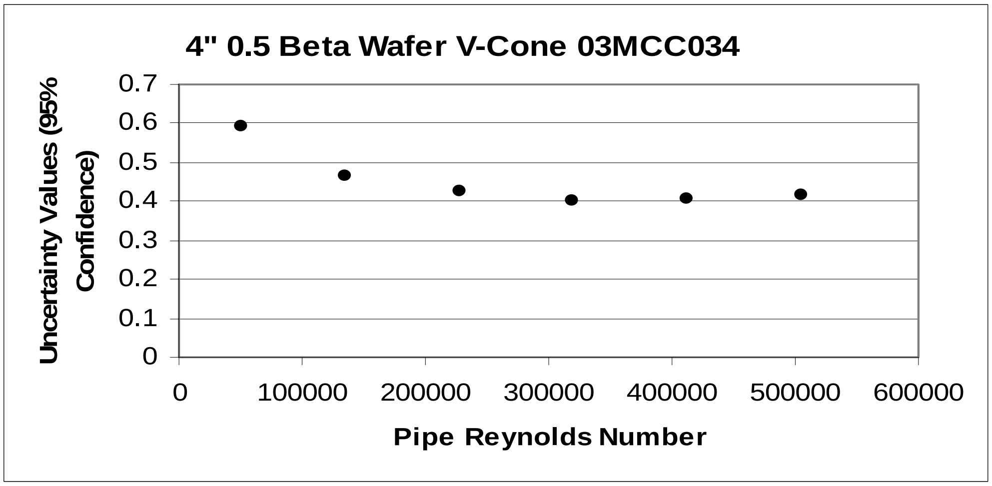

Fig. A4 Uncertainty Analysis for the 4” 0.50 Beta Ratio Wafer Cone.

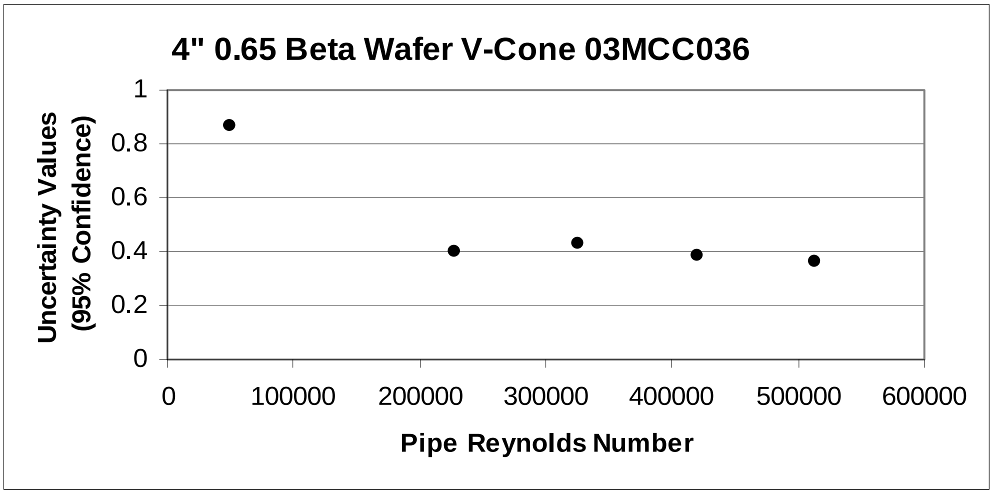

Fig. A5 Uncertainty Analysis for the 4” 0.65 Beta Ratio Wafer Cone.

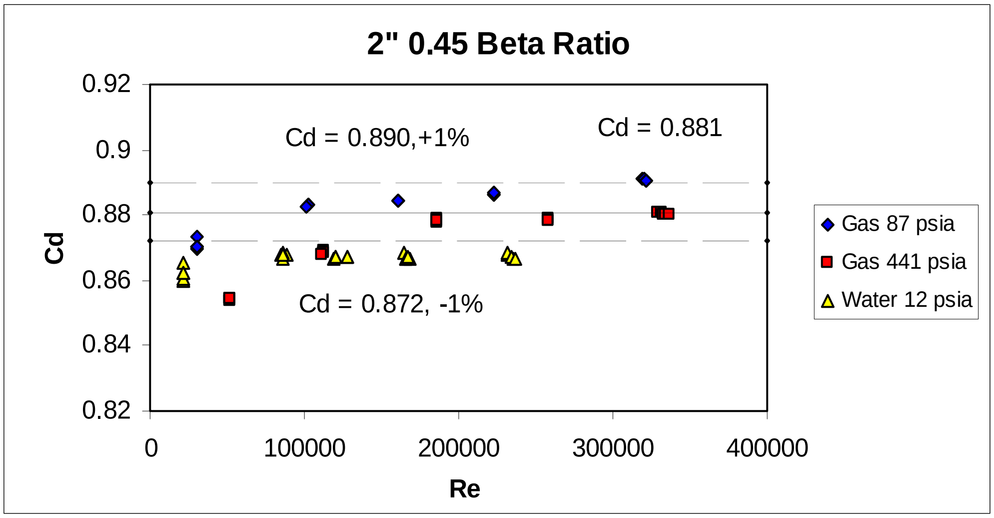

Fig. A6 The 2” 0.45 Beta Ratio Performance.

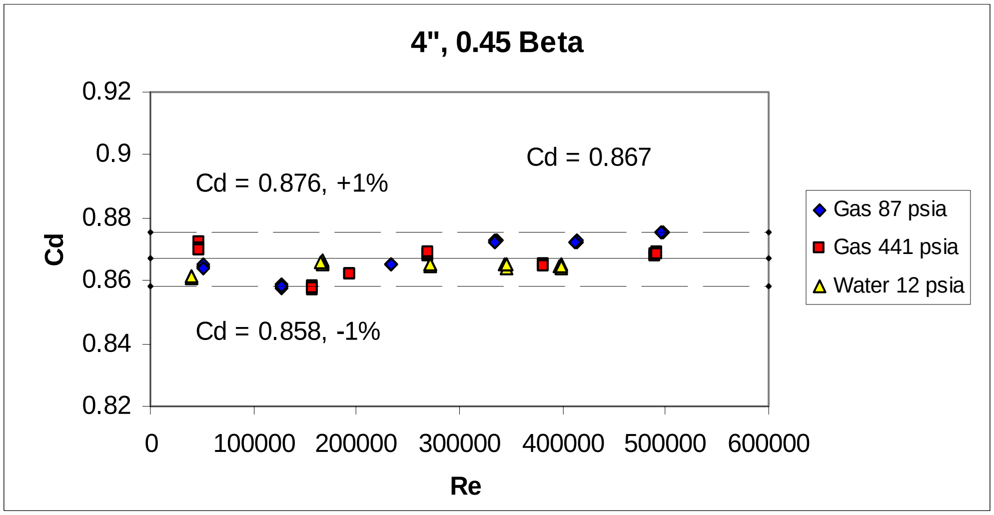

Fig. A7 The 4” 0.45 Beta Ratio Performance.

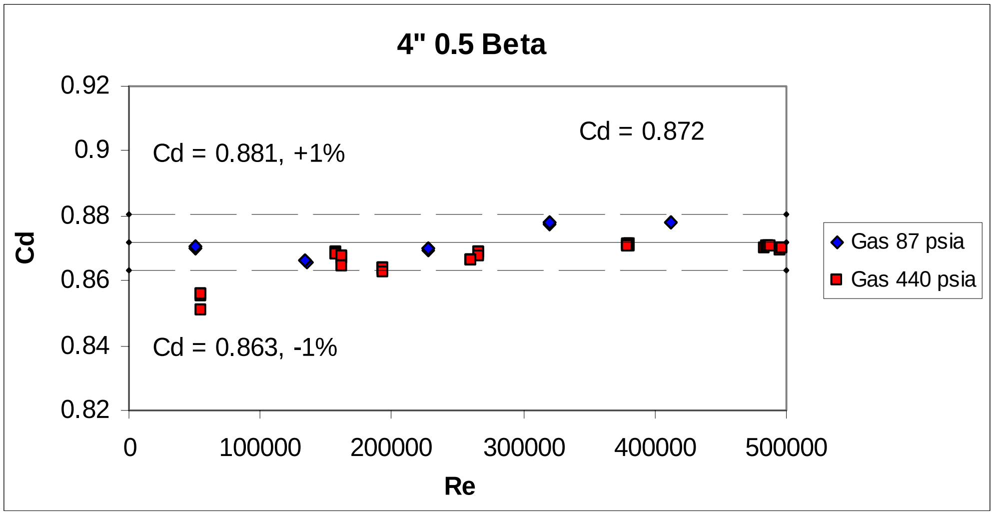

Fig. A8 The 4” 0.50 Beta Ratio Performance.

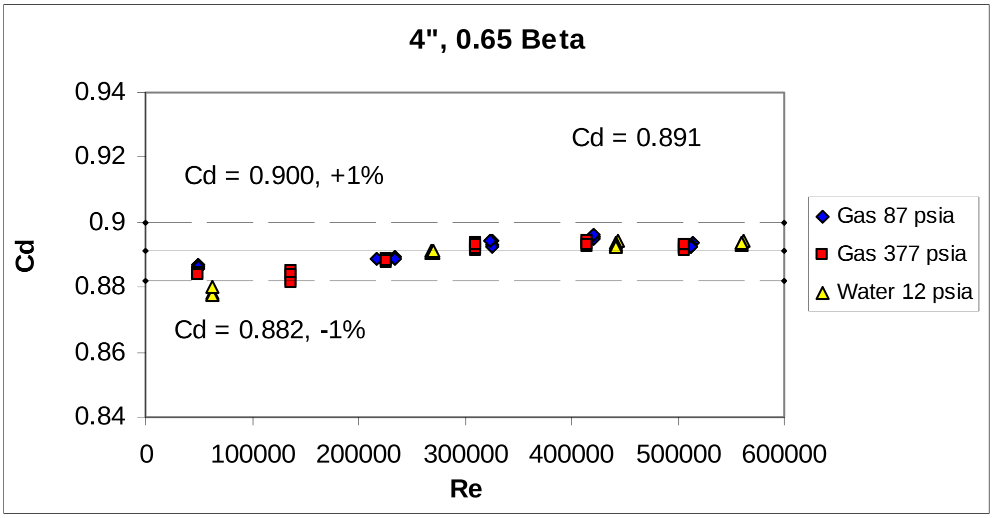

Fig. A9 The 4” 0.65 Beta Ratio Performance.

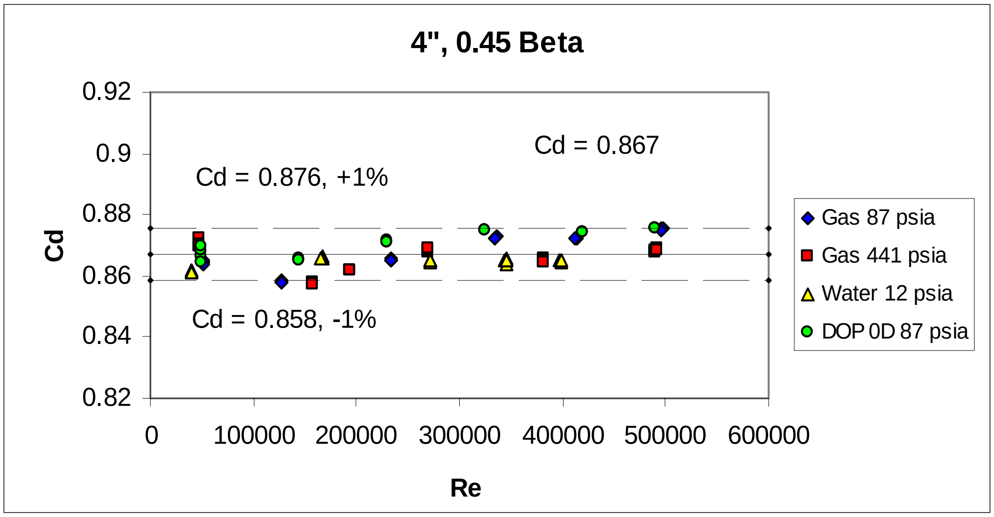

Fig. A10 The 4” 0.45 Beta Ratio Performance with a Double Out of Plane Bend (at 0D).

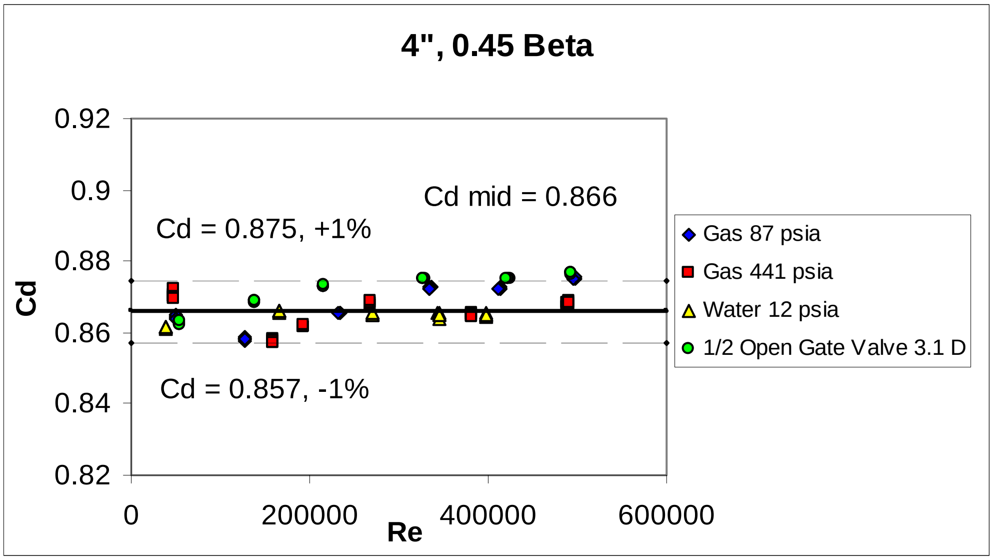

Fig. A11 The 4” 0.45 Beta Ratio Performance with a ½ Open Valve (at 3.1D).

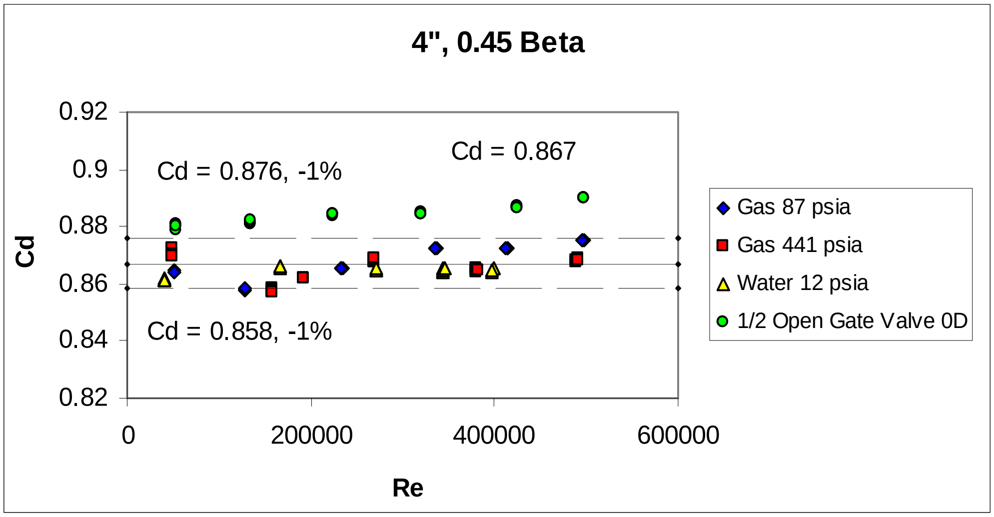

Fig. A12 The 4” 0.45 Beta Ratio Performance with a ½ Open Valve (at 0D).

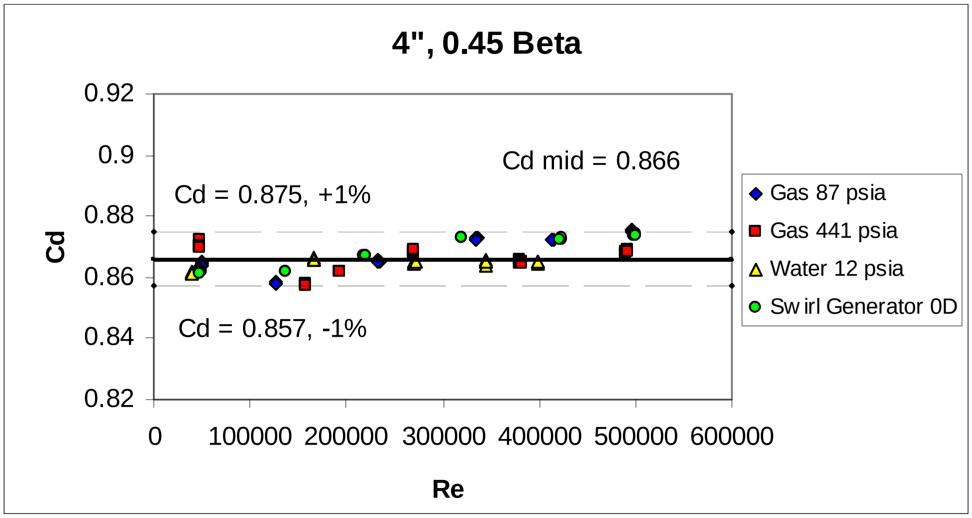

Fig A13. The 4” 0.45 Beta Ratio Performance with a Swirl Generator (at 0D).

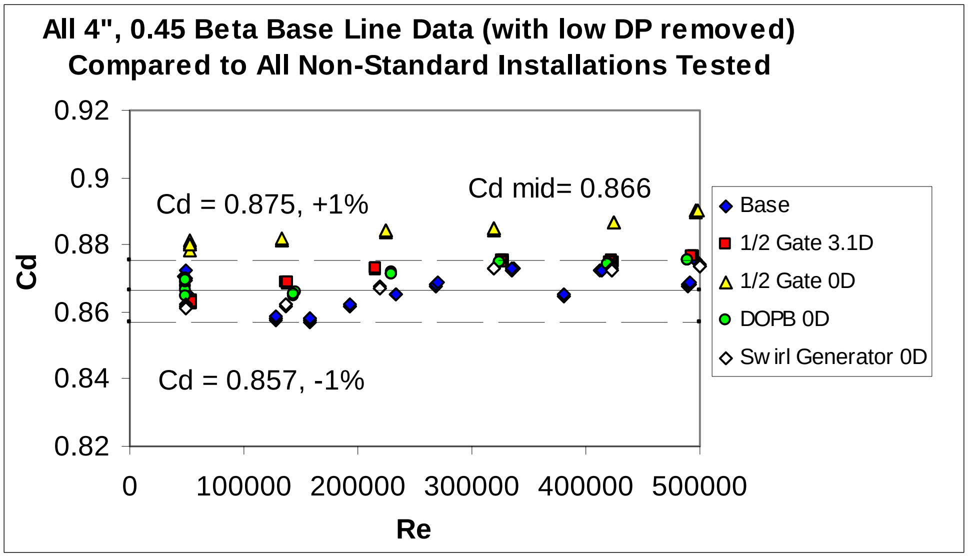

Fig A14. The 4” 0.45 Beta Ratio Performance with All Non-Standard Conditions.