

## CENTAUR ROUND ROBIN TEST TRACEABILITY OF TRANSCANADA CALIBRATIONS FACILITY

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*Abstract— TransCanada Calibrations' (TCC's) new high pressure, large diameter calibration facility is designed to meet the needs of the changing natural gas industry. With year-around access to gas volumes in excess of 50,000 actual m<sup>3</sup>/h, the TCC facility is designed to provide full range calibrations of flow meters ranging from 0.15 m (6 inch) to 0.75 m (30 inch) in diameter. In order to ensure that the facility meets user expectations of accuracy and repeatability, a round robin testing program was initiated by TCC.*

*The CENTAUR (Canadian, European, North American, Turbine And Ultrasonic, Round Robin) program was designed to provide established facilities with a 0.2m (8inch) diameter transfer standard package for calibration. The package, consisting of a turbine and ultrasonic meter in series with the associated piping, was calibrated at established facilities such as Bishop Auckland, Didsbury, GRIMRF, Groningen, pigsar<sup>TM</sup>, Westerbork and the TCC facility. This package is unique since it uses two devices, which operate on different principles. Past transfer standard packages have used, for example, two turbine meters in series.*

*It was concluded from the CENTAUR round robin program that the participating facilities are in good agreement to within  $\pm 0.25\%$ . Based on the results of past round robin programs, this is an excellent outcome. It was also evident that the concept of using two meters with different operating principles can be successful if the test flow rates are optimum for both meters. With such an arrangement, it is possible to isolate installation effects at a facility.*

*The test results clearly show that the TCC facility is on par with the established facilities. The TCC facility was within  $-0.15\%$  from the average of all facilities and the facility claim to an uncertainty of  $\pm 0.2\%$  is certainly justified.*

*Keywords— Calibration, CENTAUR, Round-Robin, TransCanada, Traceability, Turbine, Ultrasonic.*

### 1 INTRODUCTION

The natural gas industry has become increasingly demanding in the requirements for measurement accuracy and repeatability. This is evident from the considerable effort recently expended to improve the accuracy of the orifice meter with a revised API and ISO standard. At the present time, the user insists that newer technologies such as the ultrasonic meter and the Coriolis mass flow meter be flow

calibrated. This is driven by the fact that the benefits from meter calibrations are substantially greater than the calibration costs. Meter users have high demands from the facilities used to calibrate these meters. This is not totally unexpected considering the large amounts of natural gas transactions taking place annually. These transactions have to be accounted for at custody transfer points and the costs associated with measurement uncertainties and errors are high and continue to increase with increased trade. Manufacturers of metering devices also have similar expectations from calibration facilities so that their devices are fairly evaluated.

In the absence of a flow standard, round robin testing is the best avenue to judge the accuracy and repeatability of a facility. Such programs have been used in the past, for example, the published work of Diritti et al. (1993, 1995), Spencer et al. (1993), Takamoto et al. (1993) and Karnik et al. (1996, 2000). Other similar unpublished inter-comparisons have also been performed. Thus, when TransCanada Calibrations (TCC) decided to embark on their goal of providing the world natural gas industry with a unique calibration facility, a round robin testing program was initiated. The purpose of this program is:

1. to provide established facilities around the world with a transfer standard and obtain a relative comparison of these facilities.
2. to use this transfer standard at the TCC facility in Winnipeg in order to assure users that this new facility has a performance comparable to these established facilities.
3. to evaluate the use of the ultrasonic meter as a transfer standard.

A 0.2 m transfer standard was chosen for this effort and consisted of a turbine meter and an ultrasonic meter in series with the associated piping. The program was initiated in January 1999 and completed with the commissioning of the TCC facility in March 2000.

## 2 DESCRIPTION OF FACILITIES

A comparison of the various facilities that participated in the present tests is shown in Table 1.

**Table 1.** Comparison of the participating facilities

	Bishop Auckland	Didsbury	GRI MRF HPL	Groningen	pigsar™	Westerbork	TCC
Line Pressure kPa	3000 to 6000	4000 to 6000	1035 to 8275	900 to 4100	1500 to 5000	6200	7040
Operating Fluid	Natural gas	Natural gas	Nitrogen or Natural gas	Natural gas	Natural gas	Natural gas	Natural gas
Maximum Flow Capacity	314 kg/s	24 kg/s	44 kg/s	8.2 kg/s	72 kg/s	622 kg/s	770 kg/s
Primary Reference	N/A	Wöhwa Scale	Wöhwa Scale	CVM meters	Piston Prover	N/A	Rotary Piston Prover
Secondary Reference	Calibrated turbine	Calibrated nozzles, turbines, orifice	Calibrated nozzles, turbines, orifice	Calibrated turbine	Calibrated turbine	Calibrated turbine	Calibrated turbine
Uncertainty in Primary Mass Flow	N/A	±0.06%	±0.04%	±0.18%	±0.01%	N/A	N/A
Uncertainty in Secondary Mass Flow	±0.21% < 40 kg/s ±0.25% > 40 kg/s	±0.2%	±0.2%	±0.19%	±0.15%	±0.15% > 16kg/s ±0.3% < 16 kg/s	±0.2% > 25kg/s ±0.3% < 25 kg/s

Each facility was to use an experimental set-up that best represented their calibration conditions for meters.

At Bishop Auckland, the test set up consisted of a 0.3 m (12 inch) to 0.2 m (8 inch) reducer followed by 40D of 0.2 m diameter pipe followed by a tube bundle and then 10D of 0.2 m diameter straight pipe to the package.

The experimental set up for the tests conducted at Didsbury consisted of a NOVA 50E flow conditioner followed by 18D of straight 0.2 m diameter pipe before the upstream flange of the transfer standard package.

In the case of the GRI MRF, the set up consisted of 100D of 0.3 m diameter pipe followed by 48D length of 0.25 m (10 inch) diameter pipe, 20D length of 0.3 m pipe, a concentric 0.3 m to 0.2 m diameter reducer and a 7D long 0.2 m diameter spool which was flanged to the upstream flange of the package.

At the Groningen facility, following the heat exchanger, the package was installed with 20D of 0.2 m diameter straight pipe flanged to the upstream end of the package.

At the Pigsar facility, the two meters could not be tested simultaneously. Thus, the turbine meter and associated piping and the ultrasonic meter and associated piping were tested separately downstream of a single elbow with a tube bundle flow conditioner. The distance between the flow conditioner and the upstream meter 0.2 m diameter piping was 10D.

The transfer standard package was installed in the standard calibration set-up at Westerbork. The flow from a 0.4 m (16inch) diameter elbow was conditioned by means of a tube bundle before entering a 0.4 m to 0.2 m diameter reducer. Following the reducer was 20D of 0.2 m diameter straight pipe, which was flanged to the upstream end of the package.

There was no prescribed experimental set up and most facilities installed the meter in their typical "calibration" configurations. Thus, the installation upstream and downstream of the package may vary slightly between facilities. The values of flow rates were specified and each facility was advised to take 3 points at each flow rate. Each point was to be an average of data taken over 100s. The facility performance was evaluated as the percentage deviation of the flow rate of the meter from that of the facility reference. The specified actual flow rates were between 100 m<sup>3</sup>/hr and 1600 m<sup>3</sup>/hr. These rates spanned the entire range of the turbine meter and corresponded to around 50% of the range of the ultrasonic meter.

### 3 THE CENTAUR PACKAGE

The CENTAUR package shown in Figure 1 was provided in two parts.

1. The ultrasonic meter with the 1.343 m (6.63D) spool piece followed by a NOVA 50E flow conditioner and the 1.678 m (8.3D) spool piece upstream.
2. The turbine meter with the 2.095 m (10.33D) upstream spool and the 1.35 m (6.66D) downstream spool as the second piece.

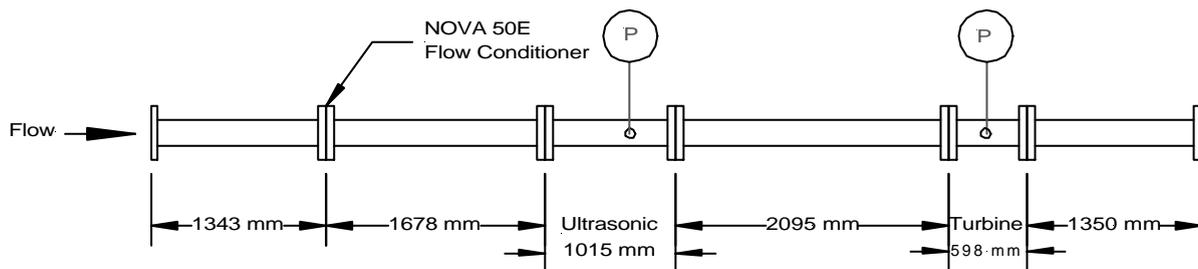


Figure 1. The CENTAUR Transfer Standard Package.

The package was manufactured such that it could only be broken into these two parts. All other flanges were sealed. The direction of flow was to be such that the ultrasonic meter was always upstream of the turbine meter. These two "parts" of the transfer standard were transported in well packed boxes so as to minimize any effect on the device during shipping.

The coefficients and parameters for the ultrasonic meter were set at the beginning of the round-robin program and remained unchanged for the duration of the program. The K-factors for the meters were obtained by flow calibrations and were 1647.76 pulses/m<sup>3</sup> and 5174.98 pulses/m<sup>3</sup> for the turbine meter and ultrasonic meter respectively.

## 4 EXPERIMENTAL RESULTS

The average curve for all facilities was obtained in two steps. Firstly, at each flow rate, average values of the 3 data points from each facility were used. Secondly, it was important that the average curve should not be affected by a large data set from any one facility. Some facilities had taken data at more than one pressure resulting in up to 25 points whereas other facilities had taken data at one pressure, thus generating around 9 points. Hence, for a narrow range of Reynolds numbers, the average data from multiple pressures was further averaged thus reducing the 25 points to at most 13 points. Thus, a possible bias towards any one facility was avoided.

In general the turbine meter showed a better overall repeatability over the entire Reynolds number range in comparison to the ultrasonic meter. Hence, most conclusions on the facility performance are based on the results from the turbine meter. It should be noted that the  $2\sigma$  values presented for each facility are a reflection of the accuracy and repeatability of the flow facility as well as the test meter during the tests.

After considerable deliberation, it was decided not to use the harmonization procedure outlined by NMI and PTB in November 1999, for the present data set. Thus, the present results demonstrate the performance of the facilities without any external adjustments.

The present tests were conducted over a range of static pressures from 2000 kPa to 7100 kPa.

### 4.1 Facility A

#### Turbine Meter

The results of facility A are shown in Figure 2. The data for this facility were taken twice and Test 2 was repeated 3 months after Test 1. The data, shown in Figure 2a, for the turbine meter indicates that facility A exhibits good short-term repeatability (within  $\pm 0.05\%$ ), as indicated by successive repeat points at the same flow rate. The long-term repeatability of the facility is also good, as indicated by data taken in Test 1 and Test 2 at the same Reynolds number. The two data points at the lower Reynolds numbers do not show good long-term repeatability. However, this is not necessarily a representation of the facility performance, but could be the random local departure of the turbine meter from linearity at low flow rates.

The calibration of the turbine meter shows that the device is fairly linear. The difference between the facility meter deviation and the average meter deviation using the data from all facilities is  $-0.19\%$ .

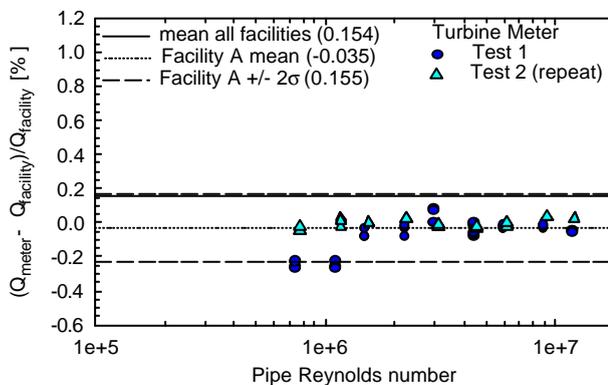


Figure 2a. Testing of turbine meter at facility A.

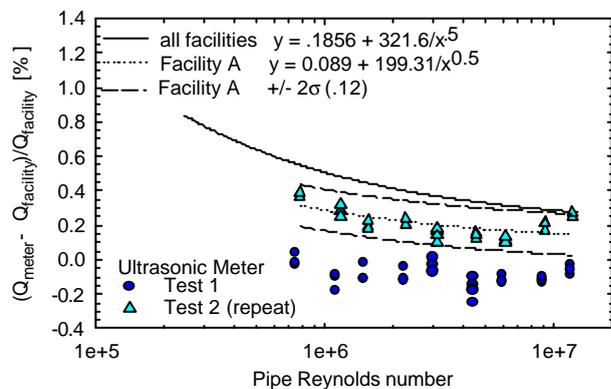


Figure 2b. Testing of ultrasonic meter at facility A.

#### Ultrasonic Meter

In the case of the ultrasonic meter (Figure 2b), the data trends are quite different for the two calibrations. Test 1 seems to show that the ultrasonic meter is linear over the range of tested Reynolds numbers, however from the results of test 2, it appears that the response is different. Given the repeatability of the facility with the turbine meter and that the calibration set-up is unchanged, it is difficult to attribute this lack of repeatability to the facility. Following Test 1, it is clear that the performance of the ultrasonic meter seems to have changed and hence the curve from Test 2 is used to represent this facility.

At a mid range Reynolds number of  $4 \times 10^6$ , the difference between this facility and the average curve using the data from all facilities is around  $-0.16\%$ . This is similar to the difference seen with the turbine meter, namely,  $-0.19\%$ .

## 4.2 Facility B

### Turbine Meter

The results of facility B are shown in Figure 3. The data for the turbine meter, shown in Figure 3a, indicates that facility B exhibits short-term repeatability to within  $\pm 0.05\%$ . The turbine meter once again shows a near linear response with some variation at the low flow rates. The difference between the mean facility meter deviation and the average meter deviation using the data from all facilities is  $0.03\%$ .

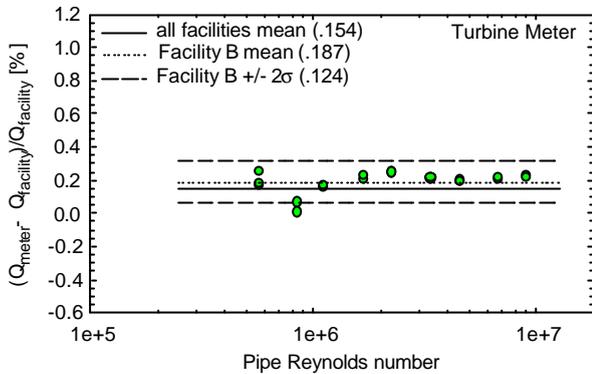


Figure 3a. Testing of turbine meter at facility B.

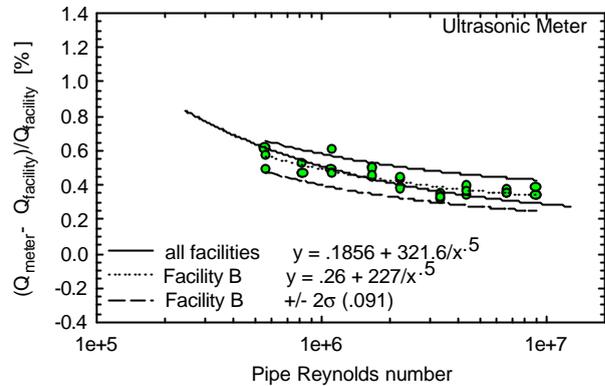


Figure 3b. Testing of ultrasonic meter at facility B.

### Ultrasonic Meter

In the case of the ultrasonic meter (Figure 3b), for the range of Reynolds numbers tested, the facility curve is in reasonably close agreement with the average curve using the data from all facilities. The maximum difference of the facility mean curve from the all facilities mean curve is  $-0.05\%$  at the lowest Reynolds number ( $6 \times 10^5$ ).

## 4.3 Facility C

### Turbine Meter

The results of facility C, taken at two test pressures, are shown in Figure 4. The data for the turbine meter, presented in Figure 4a, shows that the data at the two test pressures are in good agreement. The short-term repeatability is within  $\pm 0.07\%$ . At the lower Reynolds numbers corresponding to the lower pressure 1, the data deviates significantly from linearity. The difference between the mean facility meter deviation and the average meter deviation using the data from all facilities is  $-0.05\%$ .

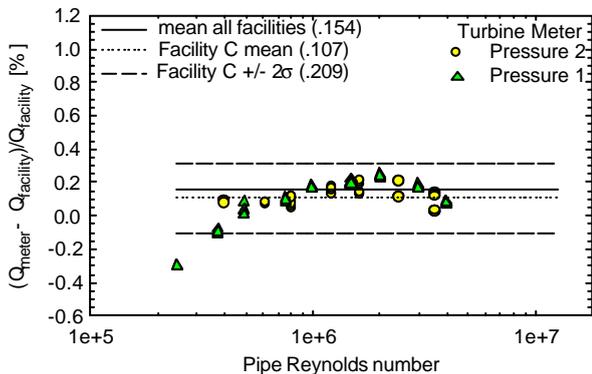


Figure 4a. Testing of turbine meter at facility C.

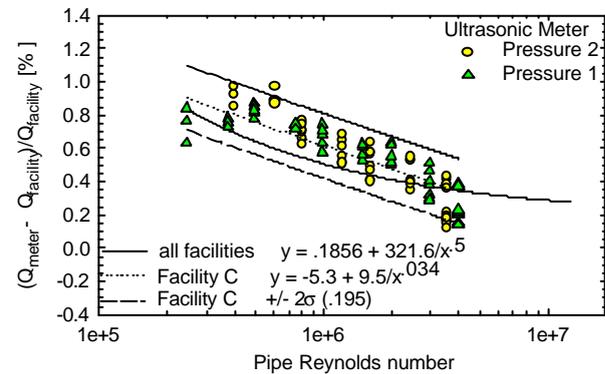


Figure 4b. Testing of ultrasonic meter at facility C.

### Ultrasonic Meter

In the case of the ultrasonic meter (Figure 4b), for the range of Reynolds numbers tested, the facility curve is in reasonably close agreement with the average curve using the data from all facilities. It appears that once again two data points at the lower Reynolds numbers (at pressure 1) deviate from the

general trend in a direction similar to that exhibited by the turbine meter. The magnitude of this deviation is less for the ultrasonic meter.

The short-term repeatability of the ultrasonic meter appears to be around  $\pm 0.15\%$  whereas that for the turbine meter is around  $\pm 0.07\%$ . The turbine meter appears to have a slightly better short-term repeatability than the ultrasonic meter. The maximum difference of the facility mean curve from the all facilities mean curve is 0.14% at a Reynolds number of  $6 \times 10^5$ .

#### 4.4 Facility D

##### Turbine Meter

The results of facility D are shown in Figure 5. The data for the turbine meter, shown in Figure 5a, indicates that compared to the other facilities, there is larger scatter at the lower Reynolds numbers. The short-term repeatability at higher Reynolds numbers is comparable to that of the other facilities. On the average the meter seems to show linearity. The difference between the mean facility meter deviation and the average meter deviation using the data from all facilities is 0.23%.

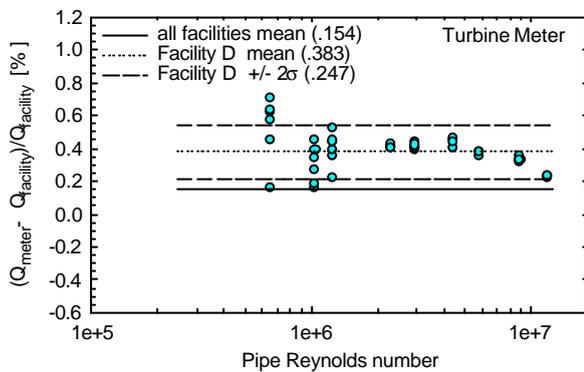


Figure 5a. Testing of turbine meter at facility D.

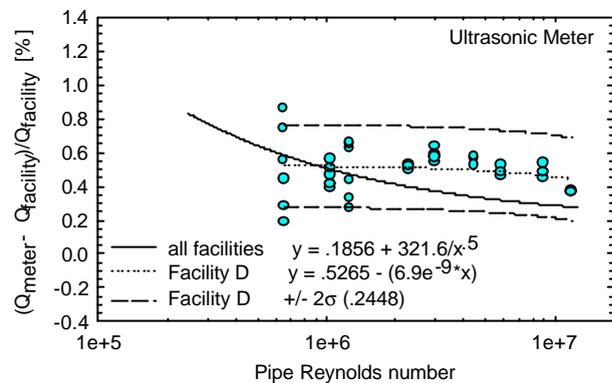


Figure 5b. Testing of ultrasonic meter at facility D

##### Ultrasonic Meter

In the case of the ultrasonic meter (Figure 5b), once again, as in the case of the turbine meter tests, there is considerable scatter in the data at the low Reynolds numbers. At the higher Reynolds numbers (e.g.  $5 \times 10^6$ ), the difference of the facility mean curve from the all facilities mean curve is 0.16%.

#### 4.5 Facility E

##### Turbine Meter

The results of facility E are shown in Figure 6. The data for this facility was taken at three pressures. At each pressure, the data for the five highest Reynolds numbers was averaged. The average and the corresponding  $2\sigma$  values for pressures 1, 2 and 3 are  $0.14 \pm 0.04\%$ ,  $0.005 \pm 0.04\%$  and  $-0.003 \pm 0.11\%$  respectively. The variations at the three pressures are well within the overall repeatability of the meter and the facility. Thus, for the purpose of this paper, any pressure effects for the turbine meter have been neglected, particularly since the analysis is based on Reynolds number.

The data shows that the turbine meter is nearly linear. The difference between the mean facility meter deviation and the average meter deviation using the data from all facilities is  $-0.10\%$ .

##### Ultrasonic Meter

In the case of the ultrasonic meter (Figure 6b), for the range of Reynolds numbers tested, the facility curve is in close agreement with the average curve using the data from all facilities. Again the data shows a slightly higher scatter for the ultrasonic meter in comparison to the turbine meter. Comparing the two meters at the same Reynolds number, it is clear that the short-term repeatability of the turbine meter is slightly better ( $\approx \pm 0.05\%$ ) than that of the ultrasonic meter ( $\approx \pm 0.15\%$ ). The maximum difference of the facility mean curve from the all facilities mean curve at a Reynolds number of  $2 \times 10^6$  is  $-0.06\%$ .

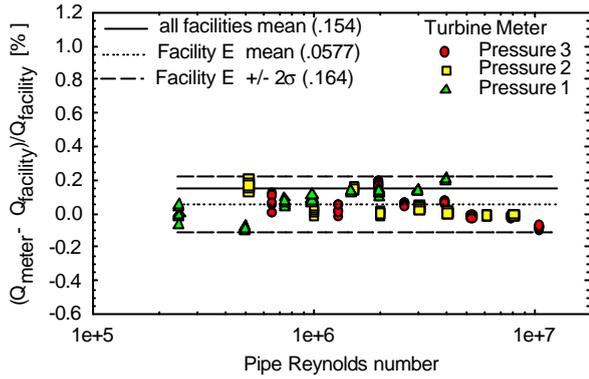


Figure 6a. Testing of turbine meter at facility E.

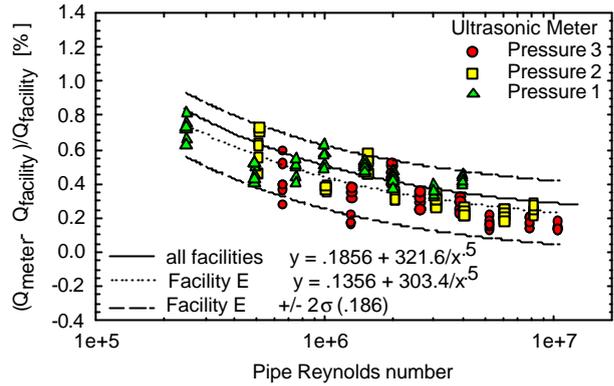


Figure 6b. Testing of ultrasonic meter at facility E.

Analysis of this data for pressure effects is done based on the average of the last 3 points, corresponding to the highest pipe velocities. The average values for pressures 1,2 and 3 are  $0.42 \pm 0.13\%$ ,  $0.23 \pm 0.06\%$  and  $0.16 \pm 0.05\%$  respectively. Thus, the maximum shift in the mean values is around 0.26% over around 4000kPa (600psi). However, it should be noted that values chosen for pressure 1 are at a lower Reynolds number than those chosen for pressures 2 and 3. Since the ultrasonic meter responds to mainly the velocity profile, which in turn is a function of the Reynolds number, the comparison between several pressures, for the ultrasonic meter, should be done at the same Reynolds number. The data shows that at a given Reynolds number, there is good agreement between data at the three different pressures, within the repeatability of the meter. Thus, the analysis in this paper is based on the Reynolds number.

## 4.6 Facility F

### Turbine Meter

The results of facility F are shown in Figure 7. The data for this facility was taken at two pressures. The data for the turbine (Figure 7a) shows that the data at the two test pressures show good agreement. As in the case of other facilities, the data shows that the turbine meter is nearly linear. The difference between the mean facility meter deviation and the average meter deviation using the data from all facilities is 0.10%.

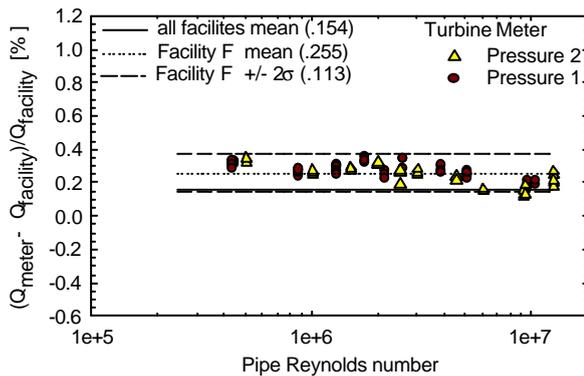


Figure 7a. Testing of turbine meter at facility F.

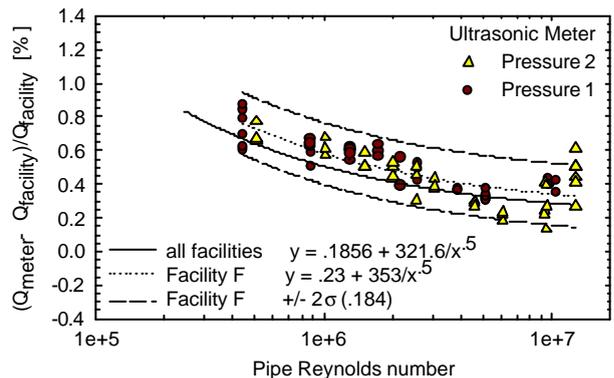


Figure 7b. Testing of ultrasonic meter at facility F.

### Ultrasonic Meter

In the case of the ultrasonic meter (Figure 7b), for the range of Reynolds numbers tested, the facility curve is in good agreement with the average curve using the data from all facilities. As observed in the case of some other facilities, the data also shows a slightly higher short-term scatter for this meter in comparison to the turbine meter. The difference of the facility mean curve from the all facilities mean curve is 0.07% at a Reynolds number of  $2 \times 10^6$ .

## 5 PERFORMANCE OF THE TCC FACILITY

The CENTAUR package was calibrated at the TCC facility using their 0.2 m diameter reference turbine meter. The TCC reference turbine meter was calibrated at the Westerbork facility and was subsequently re-calibrated on site with NMI's 0.2 m, 0.25 m, 0.3 m transfer standard meters. The experimental set-up for the package consisted of a 0.3 m diameter header followed by a 0.3 m to 0.2 m diameter reducer, a 10D straight 0.2 m diameter spool piece, a 0.2 m diameter 90 degree elbow and finally 60D of 0.2 m diameter straight pipe connected to the upstream end of the package. Each data point was an average of a 300-second sample.

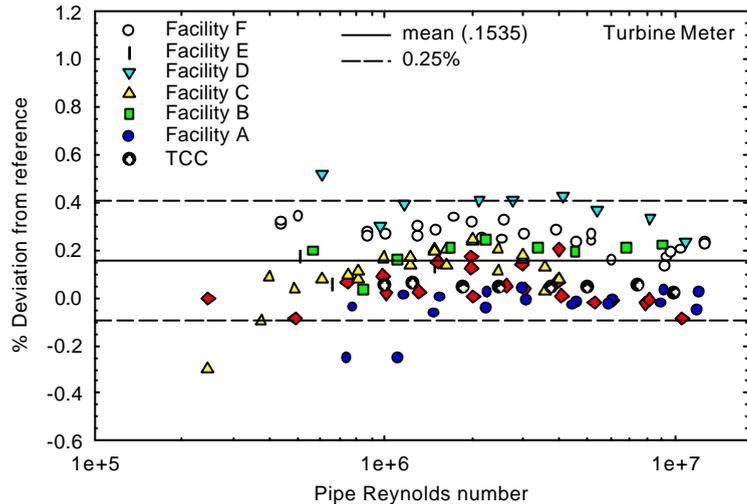
The performance of the TCC facility is shown in Figures 8, 9 and 10. It is clear that the performance of the facility is well within the tolerance limits of  $\pm 0.25\%$ . In the case of the turbine meter, the mean deviation of the TCC facility from the average curve is around  $-0.15\%$  whereas for the ultrasonic meter this deviation is of the order of at most  $-0.19\%$ . The 2sigma level for the 300 sec sample was at worst  $\pm 0.06\%$ . Note that the TCC data was not used in evaluating the all facilities average.

## 6 INTERPRETING THE TURBINE METER DATA

Considering that the present tests are conducted with a turbine/ultrasonic meter package rather than the more stable sonic nozzle, a tolerance of  $\pm 0.25\%$  was used. This is similar to the tolerance used in the last GERG program (Diritti et al., 1993, 1995).

**Table 2.** Facility performance using the turbine meter

Facility	Facility deviation from all facility average
A	-0.19%
B	0.03%
C	-0.05%
D	0.23%
E	-0.10%
F	0.10%
TCC	-0.15%



**Figure 8.** Comparison of facilities using the turbine meter data

It is evident, from Table 2 that the turbine meter is quite repeatable and apart from a couple of points at some facilities, the meter is fairly linear. It appears, from Figure 8, that all facilities lie within the  $\pm 0.25\%$  tolerance limits placed around the average curve.

The performance of the turbine meter during this program has been good, and has probably benefited from the good packaging for transportation.

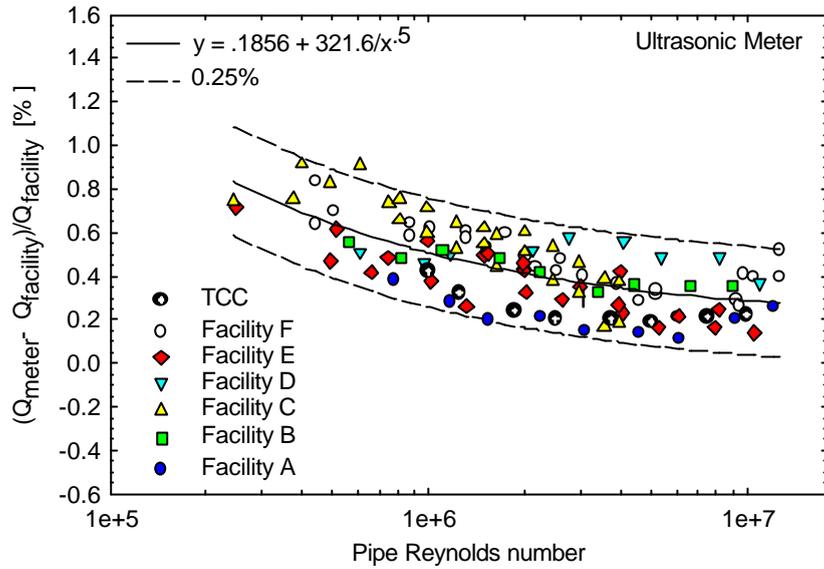
## 7 INTERPRETING THE ULTRASONIC METER DATA

In contrast to the turbine meter, which was consistently linear, the ultrasonic meter has shown slightly different trends. The apparent variation in the trend could be attributed to the fact that at the lower Reynolds numbers, the pipe velocities are very low.

For the recommended test flow rate range i.e. 100m<sup>3</sup>/hr to 1600m<sup>3</sup>/hr, the pipe velocity ranges between 1m/s and 14m/s. The ultrasonic meter (whose maximum velocity capacity is around 30m/s) is therefore being tested in its lower 50% range. The turbine meter on the other hand is being tested in its entire range of flow rates.

In comparison with past performance (Karnik et al., 1997), the present repeatability of the ultrasonic meter is much improved with the random departure of this meter from the mean curve, at most individual

facilities, being within  $\pm 0.2\%$ . The data at different pressures have also overlapped quite well and it can be seen from Figure 9, that all facilities agree quite well within the  $\pm 0.25\%$  bounds of the average curve.

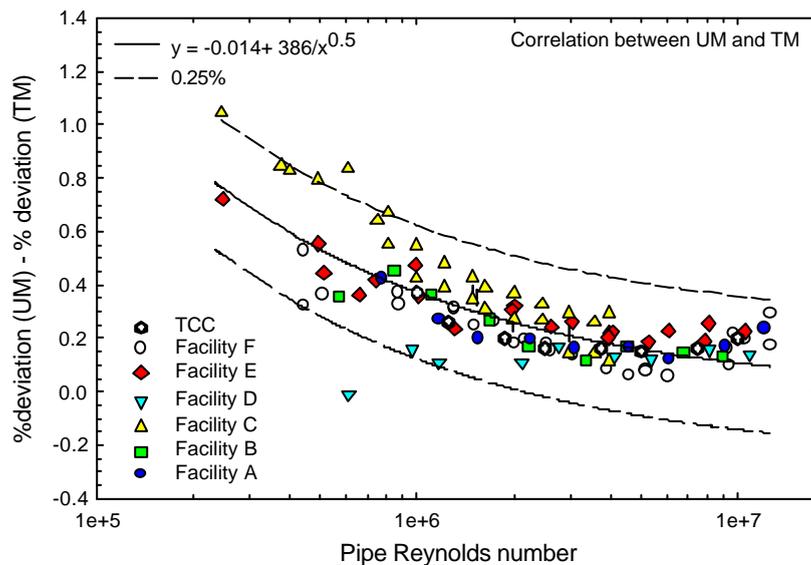


**Figure 9.** Comparison of facilities using the ultrasonic meter data.

The short-term repeatability of the turbine meter appears to be slightly better than that of the ultrasonic meter. Apart from the low mean velocities in the pipe, this may be also be due to the fact that the turbine meter is an averaging flow meter whereas the ultrasonic meter is a more dynamic flow meter that responds quickly to any changes in the flow stream. However, the mean of the ultrasonic meter showed good repeatability. Thus, it is suggested that for calibrating ultrasonic meters, the average of several samples (not one long time sample) should be used as an estimate of the flow.

## 8 ANALYSIS OF THE TRANSFER STANDARD PACKAGE

Figure 10 is a representation of the difference in the meter factors for the two meters as a function of the Reynolds number. This plot can be interpreted as a correlation between the two meters.



**Figure 10.** Correlation between the two meters.

At higher Reynolds numbers (greater than  $2 \times 10^6$ ), the data is much tighter ( $\approx \pm 0.1\%$ ) than the individual plots ( $\approx \pm 0.25\%$ ). Since the package consists of two devices which operate on different

principles and possibly react differently to flow profiles, one could conclude that, for the higher Reynolds numbers there were minimal installation effects on the package.

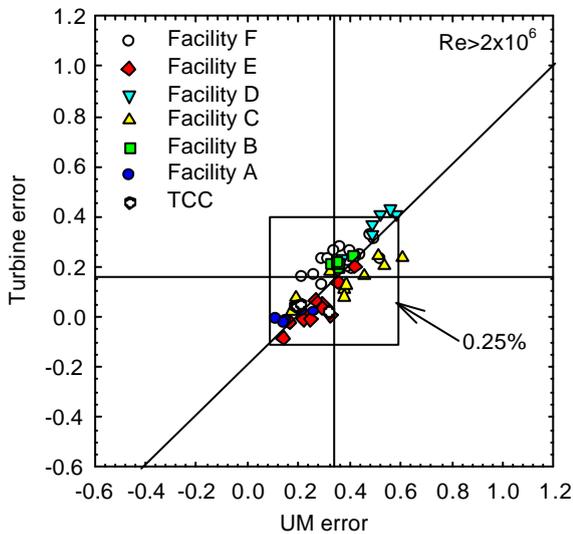
Secondly, the good correlation between the two meters indicates that this package can be used, with a higher degree of confidence, in drawing conclusions on the performance of the facilities. It appears that there is some deviation from the mean correlation at low Reynolds numbers. This cannot be attributed to facility problems alone, since the deviation in correlation may possibly be due to the relatively poor short-term repeatability of the ultrasonic meter, particularly at the lower Reynolds numbers. For example, in the case of facility F, at the lowest Reynolds number the correlation data shows that one point is close to the mean curve whereas another is on the  $-0.25\%$  boundary. If one examines the individual data sets, in the case of the turbine meter, the points cannot be distinguished whereas in the case of the ultrasonic meter, there is a difference of  $\approx -0.22\%$ .

The advantage of using two meters based on different operation principles is partially negated in this case at the low Reynolds numbers by the fact the ultrasonic meter is operating at very low pipe velocities i.e. the low end of its range unlike the turbine meter. This could be remedied, for example, by using a 0.3m (12inch) turbine with a 0.2m (8inch) ultrasonic meter. Thus, utilizing the turbine meter through its full flow rate would allow the use of the ultrasonic meter in its range of peak performance.

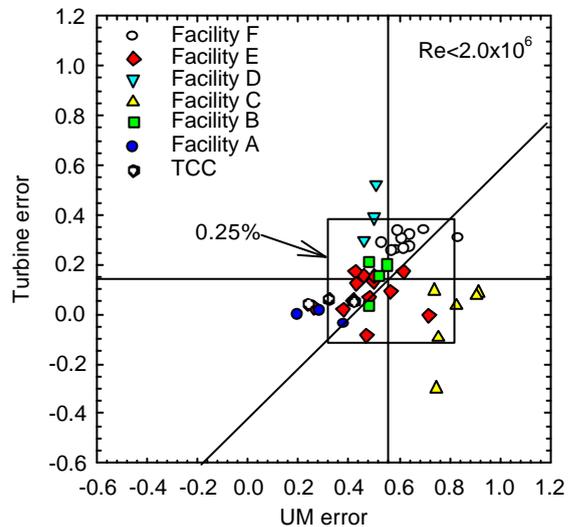
## 9 YOUTEN ANALYSIS OF THE DATA

The present data is also presented in the form of Youden plots in Figures 11a and 11b. This method of representation has been used in the past, for example by Diritti et al. (1993) and by Spencer et al. (1993). Based on a qualitative assessment of Figure 10, the data is split into two Reynolds number regimes.

For the region greater than  $2 \times 10^6$ , the correlation between the two meters is good as seen from Figure 10. The mean deviations with corresponding  $2\sigma$  ranges for all facilities for the turbine meter and the ultrasonic meter are  $0.16 \pm 0.27\%$  and  $0.34 \pm 0.26\%$  respectively. It can be seen from Figure 11a that the data lie within  $\pm 0.25$ . The data also fall closely on the line of slope = 1 thus stating that the effects are mainly systematic (i.e. measure high or low) and are associated with facilities rather than each meters long-term repeatability.



**Figure 11a.** Turbine meter error versus ultrasonic meter error:  $Re > 2 \times 10^6$ .



**Figure 11b.** Turbine meter error versus ultrasonic meter error:  $Re < 2 \times 10^6$ .

For the region less than  $2 \times 10^6$ , the mean deviations and associated  $2\sigma$  ranges for all facilities for the turbine meter and the ultrasonic meter are  $0.14 \pm 0.33\%$  and  $0.56 \pm 0.33\%$  respectively. As expected, the mean for the turbine meter is nearly the same for the two Reynolds number ranges due to the nearly linear behaviour of the meter. However, the mean for the ultrasonic meter differs by 0.22% indicating that there is a slight slope to the data from low Reynolds numbers to high Reynolds numbers. The data from some facilities show that in addition to systematic effects there are also some random effects. This could occur due to, for example, installation effects at the facility or that the ultrasonic meter is not as

linear as the turbine meter at low Reynolds numbers. This latter fact may also be the reason that more data lie outside the influence of  $\pm 0.25\%$  for the low Reynolds number range.

## 10 CONCLUSIONS

The CENTAUR round robin program has been successful in providing the data necessary to compare the participating facilities. The results show that the participating facilities are in good agreement to within  $\pm 0.25\%$ . Based on the results of past round robin programs, this is an excellent outcome. It is also evident that for such programs to be successful, repeatability of the transfer standard package is vital. Further, if two devices operating on different principles are used, it must be ensured that the range of flow rates must be optimum for both meters.

The test results show that the TCC facility is clearly on par with the well-established facilities worldwide and its uncertainty claims of  $\pm 0.2\%$  are certainly justified.

Data taken at different pressures indicate that although the behaviour of the meters differs at different pressures, there seems to be good overlap of data with Reynolds number.

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